MODELING OF STEADY STATE HEAT RELEASE, OXYGEN PROFILE AND TEMPERATURE PROFILE IN CIRCULATING FLUIDIZED BED COMBUSTORS

By

Dale Wen-Ching Ju

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ABSTRACT

A computer model, using the Monte Carlo method, was developed to predict heat release, oxygen profiles and temperature profiles in Circulating Fluidized Bed (CFB) combustors. The model includes initial devolatilization of the coal feed, a correction in the evolved volatiles region based on the plume model, char combustion, an oxygen mass balance to determine the oxygen profile, and an energy balance to determine the temperature profile. The highly non-linear energy balance equation includes conduction, particle and gas convection and radiative heat transfer terms.

A number of studies were conducted to observe how the model's prediction changes with superficial gas velocities of 6 m/s and 7 m/s, and solids recirculation rates of 15, 30 and 50 kg/m^2s, for both the UBC CFB and the Studsvik CFB.

A validation of the model's partial pressure of oxygen profile predictions compared to experimental data was made for the UBC CFB test case.

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CHAPTER 1

INTRODUCTION

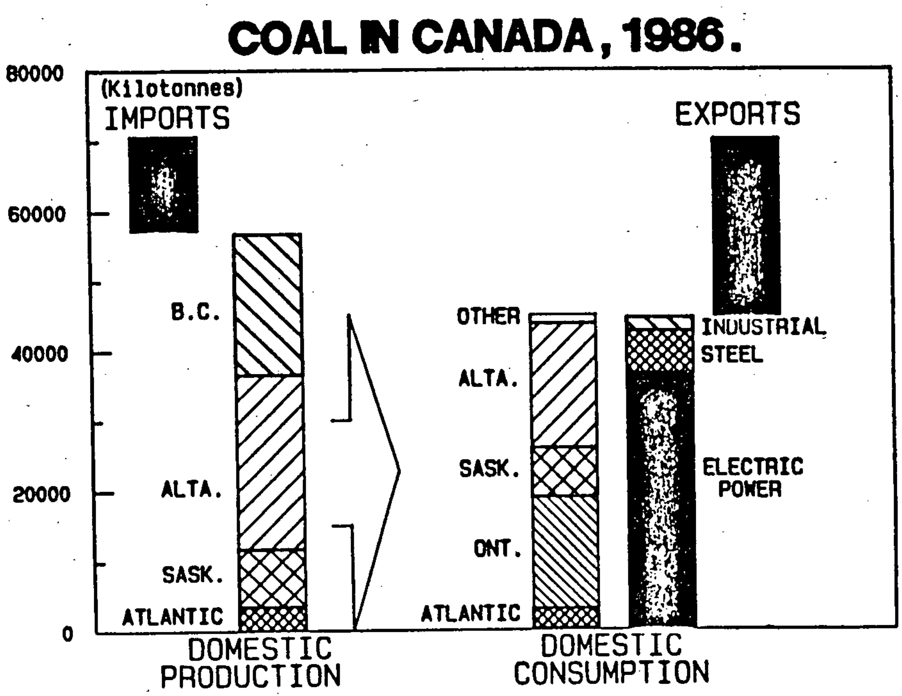
In Canada, the major uses of coal are for the generation of electricity and for coking coal in the steel industry. Because coal is very expensive to transport compared to its energy value, its popularity as an energy source is usually only for the provinces with substantial coal reserves. In addition to transportation costs, environmental concerns are also a factor in coal's competitiveness. Combustion of coal releases sulfurous gases, NOx, unburnt trace elements [Energy, Mines and Resources Canada, 1987], and more carbon dioxide than the combustion of natural gas.

Since 1973, coal production in Canada has steadily increased. In 1985, coal production was estimated to be 60.7 million tonnes, 94% of which was mined in Western Canada. Presently, coal is Canada's third largest mineral export, after oil and natural gas. Coal consumption as a fuel in power generation is mainly in four provinces, Alberta, Saskatchewan, Ontario and Nova Scotia, with Alberta consuming the largest percentage at 47%. In fact, 92% of Alberta's electrical energy production is from the consumption of coal. See Figure 1.1 [Energy, Mines and Resources Canada, 1987].

The future outlook of coal consumption shows Canada with a large remaining reserve of coal, which is 1.5 times as large as oil and gas reserves. At the present rate of coal production, the proven reserves will last more than 100 years. The major competition for thermal coal is from nuclear sources, since nuclear energy production releases little or no gas emissions. Therefore, the challenge in using thermal coal is to develop more cost effective clean coal technologies.

Circulating Fluidized Bed Boilers (CFBBs) have a number of advantages over other solid fuel fired boilers. Some of these advantages include fuel flexibility, high combustion efficiency, in-situ and low cost sulphur removal, low NOx emissions and load turndown capabilities. In addition, CFBs are part of some advanced cycles, such as

Figure 1.1 Coal Production and Consumption in Canada, 1986
[Energy, Mines and Resources Canada, 1987]



topping cycles, which have higher cycle efficiency. Less coal is used for the same amount of thermal energy production; therefore, less carbon dioxide is released.

There are very good gas-solid and solid-solid mixing in CFBs and there are many inert solids present in the bed; therefore, fuels that enter CFBs quickly mix with the bed solids without a significant drop in the bed temperature. This results in CFBs' ability to burn many different fuels without the support of auxiliary fuel.

Compared to bubbling beds, which have combustion efficiencies of 90% to 96%, CFBs have a combustion efficiency of approximately 97.5% to 99.5% [Basu and Fraser, 1991]. The high combustion efficiencies are mainly due to good gas-solid mixing and the fact that unburnt fuel is returned back into the riser. Sulphur capture in CFBs is also better than in bubbling beds. CFBs can capture approximately 90% of the sulphur dioxide released during combustion, using less sorbent than in bubbling beds, where in both cases the beds are made up of sorbent. Sulphur capture reaction is slow; therefore, the longer residence time of particles in the CFB, approximately 3 to 4 sec., makes it more effective compared to 1 to 2 sec. in an average combustion zone.

CFBs also have low NOx emissions. CFBs have the capability to provide the combustion air in stages. Fuel nitrogen is usually released with the volatiles near the base of the riser. If not enough oxygen is supplied in the primary air, the fuel nitrogen will form molecular nitrogen before it reaches the secondary air and form NOx. Once molecular nitrogen is formed, it will not normally form NOx at the relatively low CFB temperatures of 850 °C.

Finally, the ability to control heat absorption allows the CFB to respond quickly to changes in loads. Therefore, CFBs are known to have good turndown capabilities.

All of the mentioned advantages make CFB's ideal for certain operations, depending on the type of fuel available and environmental concerns. Table 1.1 shows a comparison of a typical CFB with other types of boilers.

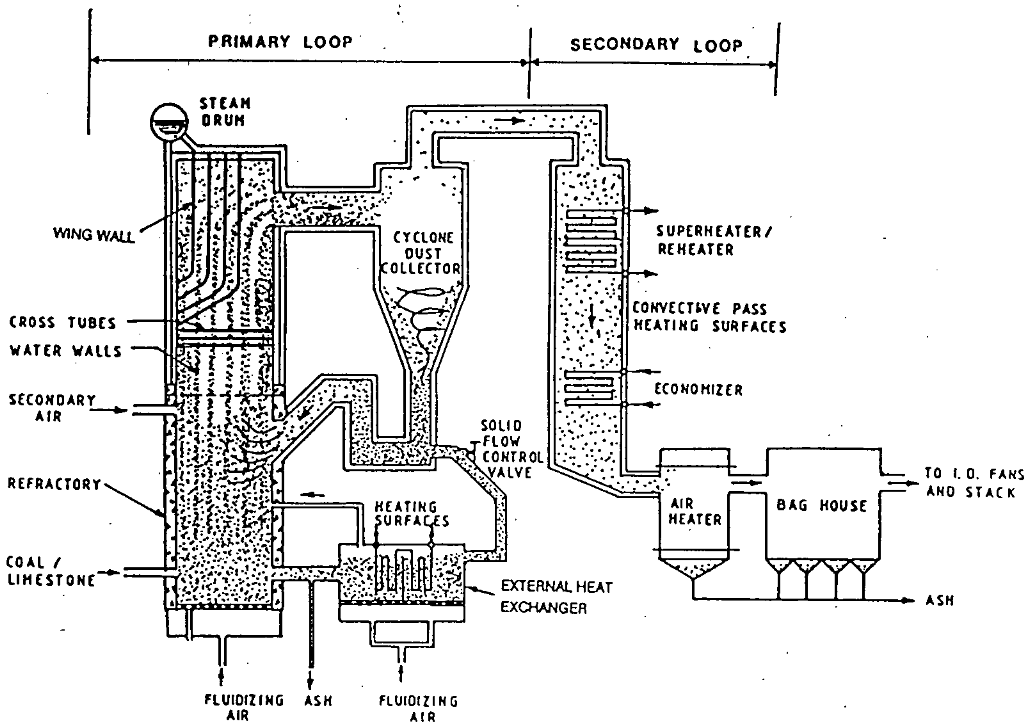
Table 1.1 Comparison of CFB With Other Types of Boilers [Basu and Fraser, 1991]

Characteristics	Stoker	Bubbling	CFB	Pulverized
Height (m)	0.2	1 - 2	15 - 40	27 - 45
U (m/s)	1.2	1.5 - 2.5	4 - 8	4 - 6
Excess air (%)	20 - 30	20 - 25	10 - 20	15 - 30
Grate Heat Release Rate (MW/m2)	0.5 - 1.5	0.5 - 1.5	3 - 5	4 - 6
Coal size (mm)	6 - 32	0 - 6	0 - 6	<0.001
Turndown ratio	4 : 1	3 : 1	3 - 4 : 1	
Efficiency (%)	85 - 90	90 - 96	95 - 99	99
NOx emission (ppm)	400 - 600	300 - 400	50 - 200	400 - 600
SO2 capture (%)	none	80 - 90	80 - 90	small

There are several possible locations and arrangements of heat transfer surfaces in a typical CFB boiler, some of which are shown in Figure 1.2 [Basu and Fraser, 1991]. Generally, heat is removed through vertical membrane wall surfaces, located around the outer reactor wall above the secondary air. For large commercial CFBs, additional internal heat transfer tubes may be added in the reactor or heat may be removed from the cyclone or external heat exchangers.

In order to design an appropriate CFB, designers need to know the heat transfer coefficients for varying operating condition; however, experimental data for CFB operations are few and fundamental understanding of CFBs trails considerably behind commercial advances, making scale-up from pilot plant data a difficult task. Therefore, there is a need for a better understanding of the hydrodynamics and heat transfer mechanism in CFBs.

Figure 1.2 Heat Transfer Surfaces of a CFB Boiler
[Basu and Fraser, 1991]



CFBs dynamics are complex and many variables affect heat transfer to the membrane walls, some of which include particle size distribution, thermal conductivity of the particle and gas, heat capacity of the particle and gas and wall surface temperature, just to name a few. There are actually more than 31 variables that affect heat transfer in CFBs [Wu, 1989].

It is the goal of this thesis work to develop a model to predict heat release, partial pressure of oxygen profiles and temperature profiles in a CFB given the geometry and hydrodynamic properties of the CFB and the physical and chemical properties of the fuel. This model will also be used to observe changes in the CFB's operating conditions when variables such as superficial gas velocity and solids recirculation rate are changed. This model will aid in selecting the appropriate locations for heat transfer surfaces in CFBs, so that a CFB unit can be optimized for turndown and fuel flexibility.

This thesis consists of the results of a literature search into various overall models of CFBCs heat transfer and hydrodynamics, including a description of Senior's hydrodynamic model, described in chapter 2. Chapter 3 consists of a detailed discussion of a model, which was developed in this thesis to predict heat release and heat transfer in CFBs. In addition, this chapter includes a discussion of the various assumptions and convergence problems encountered throughout the model's development stages. And finally in chapter 4, there is brief discussion of the test results from the model and a qualitative comparison of the predicted results with measured experimental data for the UBC CFB. The findings from this research work are then summarized in chapter 5.

1.1 Description of Circulating Fluidized Beds

CFBs are a subset of fluidization operations, called fast fluidization, that lie between turbulent fluidization and pneumatic transport regimes. In other words, the superficial gas velocity through the bed is larger than the transport velocity of the particles, but is small enough that some particles travel downwards or fall back in a region close to the outer wall of the CFB. Figure 1.3 shows a schematic of a typical CFB.

A CFB consists of a "riser", where combustion principally occurs. It is a tall column of relatively small cross sectional area compared to stoker and bubbling bed boilers. Combustion air is normally split into a primary and a secondary air feed. The primary air enters the base of the riser and the secondary air is injected anywhere from 1 m to 10 m above the base. The region below the secondary air ports is usually called the primary zone and the region above the primary zone is called the secondary zone. The superficial gas velocity in the primary zone ranges from 2 m/s to 6 m/s. In the secondary zone, gas velocities range from 5 m/s to 10 m/s. The total height of the riser can range anywhere from 10 m to 20 m or higher, and the mean particle size is approximately 50 μm to 500 μm. There are many different arrangements of CFB systems. A few of the more common configurations can be seen in Figure 1.4.

Solids in a CFB are comprised mainly of ash, sand during startup and fresh calcined and spent sorbent. There is considerable carryover of particles from the riser, depending on the exit geometry. Therefore, solid separators such as cyclones are used to separate the solids from the riser exit gas stream. The solids from the cyclone are returned continuously through a return leg near the base of the riser. Most return legs include a non-mechanical valve such as L-valve, J-valve, V-valve and seal pot, shown in Figure 1.5. Non-mechanical valves do not contain any moving parts. The solids that flow through the return leg are controlled by aeration and the geometry of the pipe.

The primary zone can be designed to have different geometries, such as a tapered or a constant cross-sectional area, which will affect the acceleration of particles in the primary zone as well as fuel mixing.

Figure 1.3 A Typical Commercial CFB [Kullendorf and Andersson, 1985]

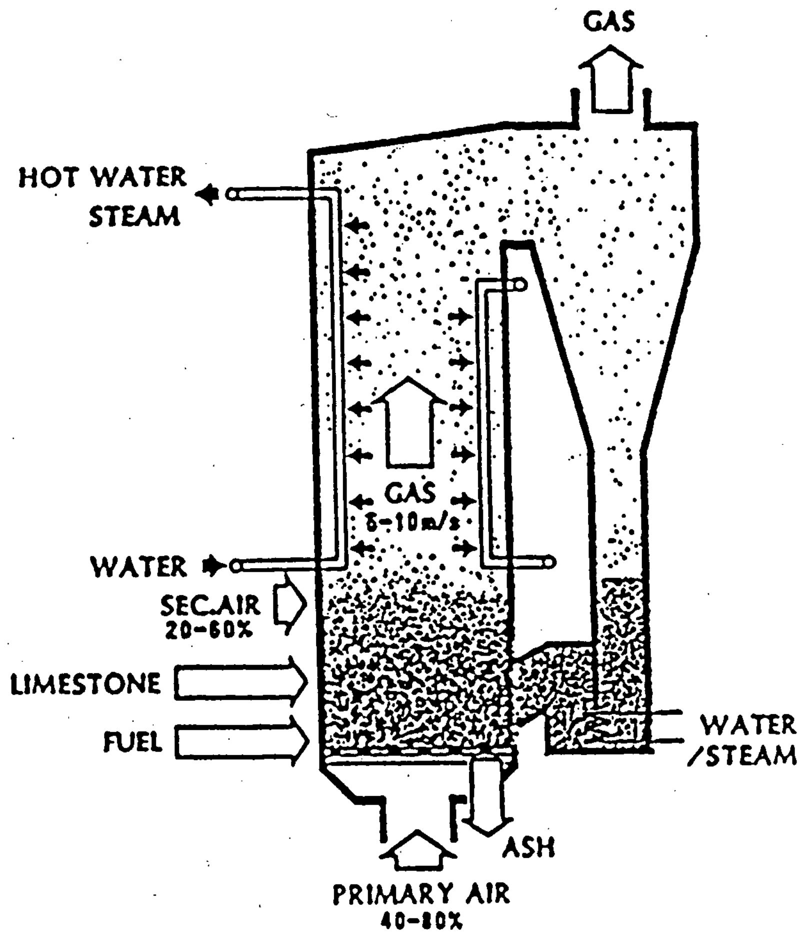


Figure 1.4 Various CFB Configurations
[Yang, 1992]

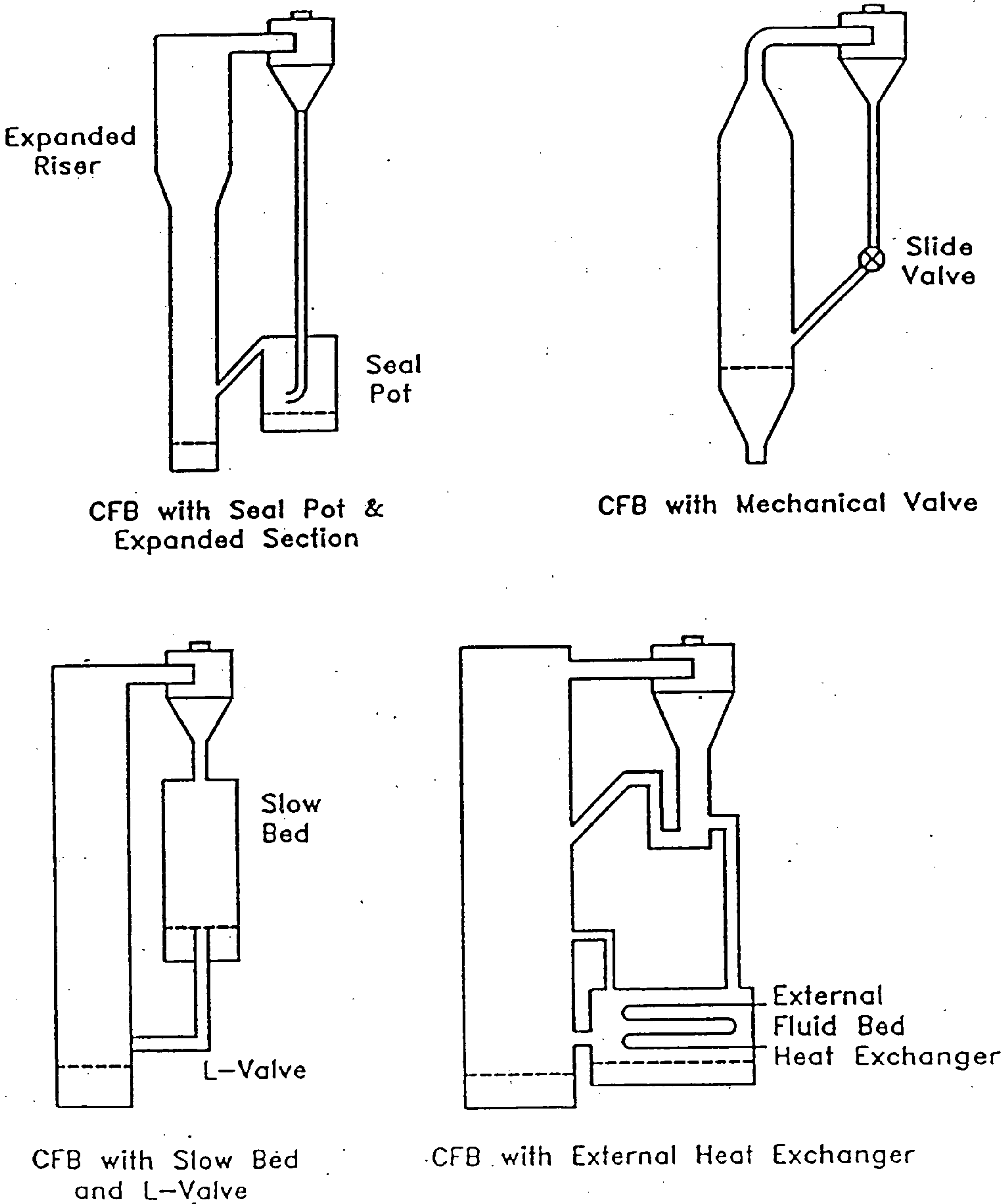
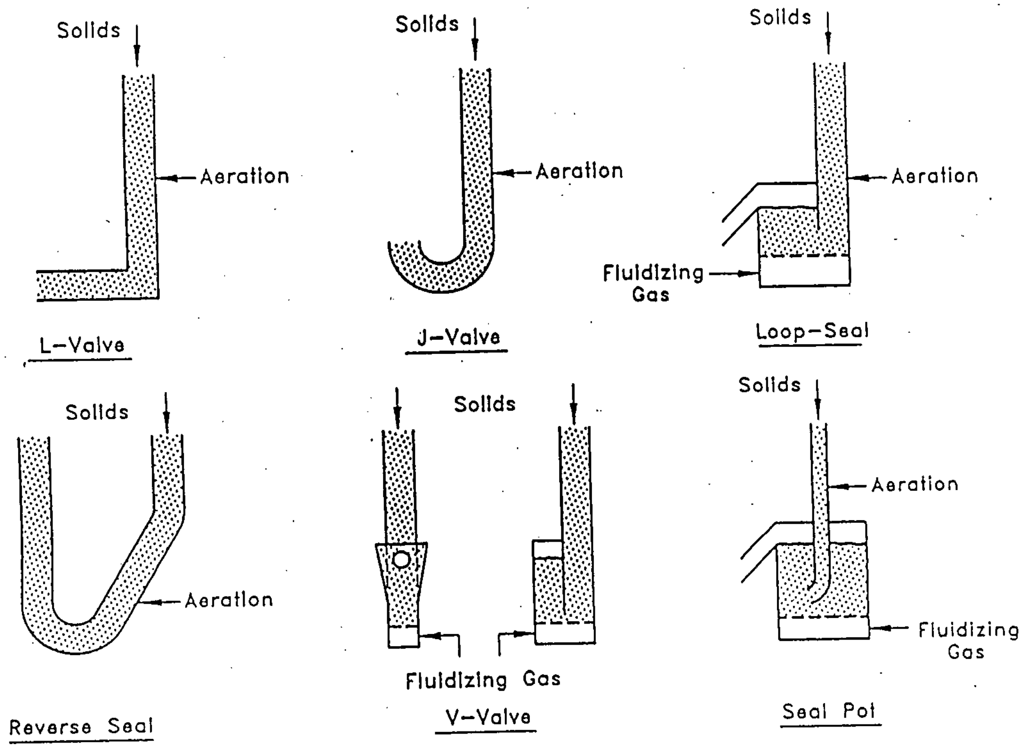


Figure 1.5 Common Non-Mechanical Valves [Yang, 1992]



CHAPTER 2

PREVIOUS MODELS OF CFBs

2.1 INTRODUCTION

There have been several models of fluidized beds and CFBCs developed within the last 10 years. A summary of fluidized bed models can be found in [Saxena et al., 1981] and a summary of CFB models can be found in [Sanderson, 1993]. These models describe various fluidized bed phenomena, in order to gain a better understanding of CFB operations and to predict transient behavior and control of disturbances.

A practical model can be as complex as the power of one's computing system; however, a more complex model does not necessarily mean a more accurate one. In fact, the philosophy of modeling is to include only enough detail to adequately predict the important parameters, since it is usually unrealistic to study all possible parameters. Therefore, deciding the level of complexity needed to obtain an adequate model is highly subjective and depends on what variables the model intends to predict.

2.2 OVERALL MODELS

Overall models of CFBC are complex in nature, since there are many interrelated processes taking place. Generally, a complete overall model will include hydrodynamics, combustion reactions and heat transfer. In addition, the cyclone, particle size distribution, attrition, agglomeration and exit/inlet geometries should be taken into account.

Several overall models, listed in Table 2.1 [Sanderson, 1993], will be briefly described. The assumptions that each model has made in regards to their hydrodynamics and heat transfer models will be mentioned in the following sections. These models vary in complexity and in the variables they predict, such as hydrodynamics, combustion, pollutant emissions, temperature and response to disturbances.

Model 1 focuses mainly on predicting combustion efficiencies, while model 2 is concerned with predicting operating parameters such as hydrodynamics, heat transfer, chemical reaction kinetics and cyclone performance. Model 3 focuses on predicting pollutant emissions and model 4 considers hydrodynamics and oxygen concentration profiles. Models 7 and 9 are steady state models while models 5, 6, 8 and 10 describe static and dynamic behaviors.

Table 2.1 Predictions of Overall CFB Models [Sanderson, 1993]

	1	2	3	4	5	6	7	8	9	10
Hydrodynamics	x	x	x	x	x	x	x	x	x	x
Combustion	x	x	x	x	x	x	x	x	x	x
Emissions	x	x	x	x	x	x	x	x	x	x
Heat Transfer		x	x		x	x	x	x		x
Miscellaneous (e.g. L-valve, additional heat exchanger)					x	x	x	x		x

Models:

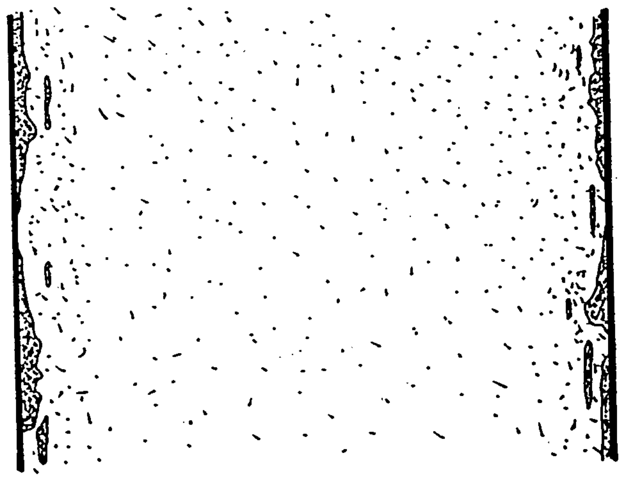
1 Ahlstrom Pyroflow (1987)
2 Basu (1991)
3 IST (1993)
4 Halder & Datta (1993)
5 Zhang (1991)
6 Xu & Mao (1993)
7 IEA (1993)
8 Mori (1991)
9 Lin & Li (1993)
10 Siegen (1987)

2.3 HYDRODYNAMICS

In order to predict heat release and heat transfer in CFBs, knowledge of the flow patterns of solids within the riser must be known. Experimental observations have shown some characteristic hydrodynamics found in CFBs. Some of these observations are a downward flow of dense streamers near the walls of the riser, otherwise known as the annulus region, and an upward flow of dilute suspension in the middle of the riser, known as the core region [Yerushalmi et al., 1978], [Brereton et al., 1986] and [Yang et al., 1991], shown in Figure 2.1. It has also been observed that the core has regions of higher and lower voidages, which seem to suggest "clustering". Clustering is the phenomenon where a group of particles are loosely locked in some random configuration and engulfed in gas. The cluster, sometimes referred to as a "packet" or "streamer", acts as an individual entity, occasionally losing and gaining a few particles.

Models 1, 2, 3, 4 and 6, noted in the previous section, use the core/annulus structure of the riser. The overall models that did not use the core/annulus structure characterized a section of the CFB riser at a given height as a lumped-parameter section. In other words, gas and solids are ideally mixed in each cell and each cell has

Figure 2.1 Illustration of Solids Distribution in a CFB Riser [Senior, 1992]



chemical reactions, particle attrition and cell to wall heat transfer occurring. None of the models simulated the clustering phenomena.

From previous experimental and modelling work, it was found that reactor geometry affects the hydrodynamics [Senior, 1992]. Sharp riser exits result in a higher suspension density at the top of the riser. In addition, the presence of a membrane heat transfer surface will affect the thickness of the streamers formed near the wall. It has also been shown that the position of the solids return entry and the shape of the primary zone tapering affects the solids acceleration in the developing zone. None of the CFB models incorporate reactor geometry effects.

2.3.1 Senior's Hydrodynamic Model

The heat release and heat transfer model developed in this thesis work is based on a mechanistic model of CFB hydrodynamics by Senior [1992]. This hydrodynamic model predicts the suspension density profiles and hydrodynamics of the wall and core regions. The accuracy of the predicted suspension density profile is approximately ± 20% and was based on comparisons with experimental data, obtained from the UBC pilot CFB and the Studsvik CFB. For the UBC CFB, experimental data were measured for superficial gas velocities of 6 m/s to 10 m/s, solids recirculation rates of 20 kg/m^{2}s to 170 kg/m^{2}s and for various primary/secondary air splits. For the Studsvik CFB, experimental data were collected for superficial gas velocities of 4 m/s to 8 m/s, solids recirculation rates of 40 kg/m^{2}s to 90 kg/m^{2}s and for various air splits.

Although solids flow in a two-dimensional or a three-dimensional model will be more representative of an actual CFB riser, than a simple core/annulus model, increased dimensional models are more complex, significantly more difficult to solve and may not necessarily give more accurate results than a lower dimensional model. It was found that a model where the riser was split into a one-dimensional core and an annulus region, which is called the two-zone, core/annulus approach, gave reasonable trends. The two zones interact with one another by radial interchange of solids across the zone boundary, see Figure 2.2.

Axially, Senior's CFB model was divided into 20 core cells and 20 annulus cells along the height of the riser, above the secondary air. The primary zone is represented as a single cell. The hydrodynamic results from Senior's models show that fewer cells can be used near the middle section of the riser, where suspension densities are quite uniform; however, the top and the bottom of the riser may be regions of steep suspension density gradients and more cells may be needed to accurately predict the densities. Comparing this model to the overall models shows that the overall models had different number of cells along the height of the riser. Some models divided the riser into 2, 3 or many cells, and one model (IEA) took the entire riser as being one cell. Some of the model differences result from different number of cells being needed to predict different phenomena. For example, a riser where the solids are well mixed will require only a single cell to sufficiently predict the overall solids mixing. However, to understand the details of the density profile, more axial cells may be needed.

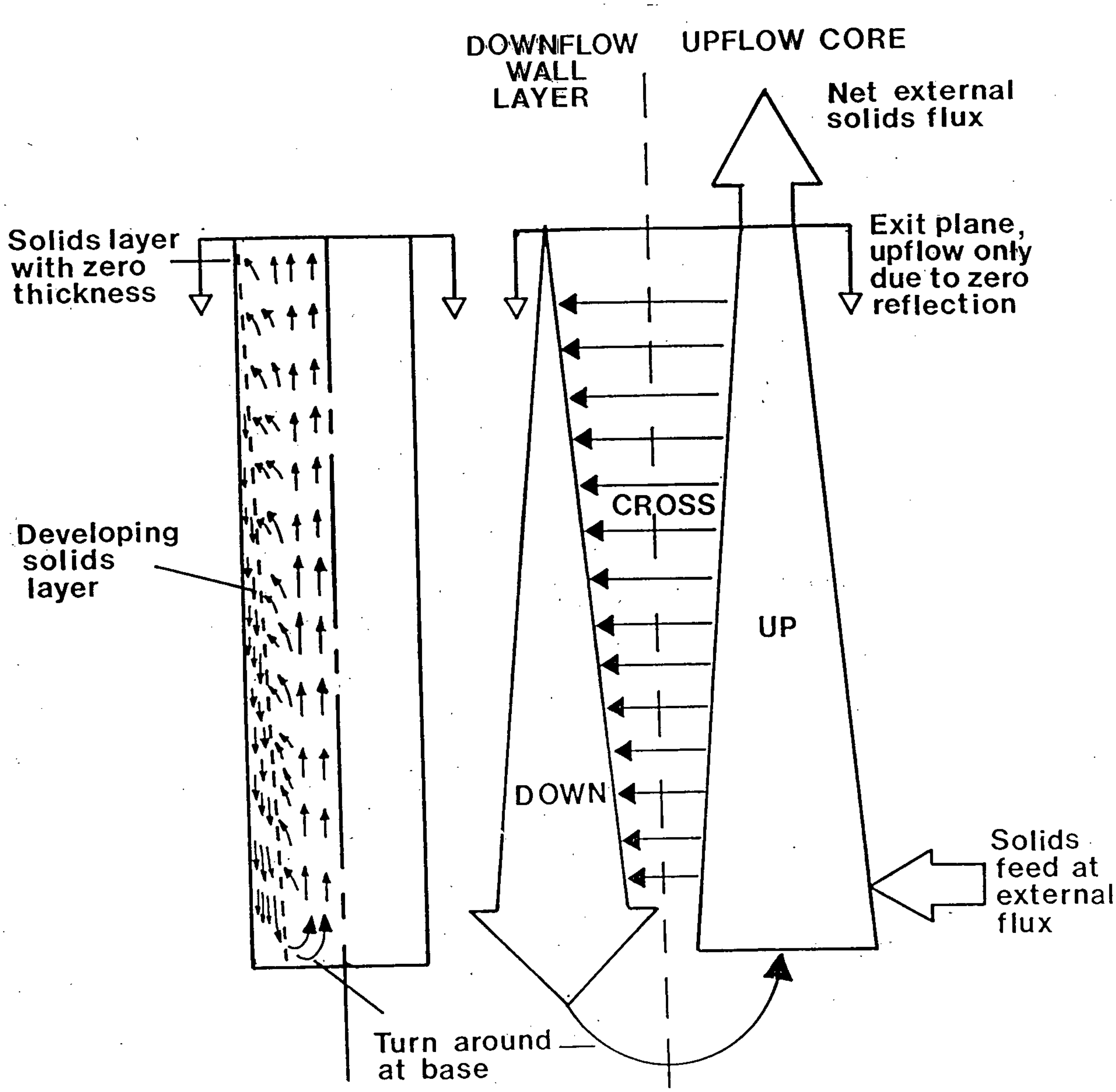
2.3.1.1 Assumptions

The assumptions made in Senior's model are:

(i) The hydrodynamics is represented by a two-zone, core/annulus flow structure, which is described above.

(ii) The riser is isothermal. Typically, a riser's temperature ranges from 850 °C to 1000 °C, and is not isothermal in practice; however, these temperature variations will not significantly affect the hydrodynamics but will affect heat release and heat transfer in the riser. Test runs conducted using Senior's model and varying bed temperatures from 850 °C to 1000 °C show less than a 10%

Figure 2.2 Regions and Flow Patterns Assumed by a 2-Zone Core/Annulus Modelling Approach in a CFB [Brereton, 1987]



difference in the mass flowrate of air; therefore, the hydrodynamic results are almost the same.

(iii) Gas and solid densities are constant. The solid suspension densities, however, vary along the height of the riser and in each zone.

(iv) The behavior of the particles is represented by particles with the sauter mean particle size.

(v) The particles in the fully-developed region in the core travel up the riser at a constant velocity. This velocity is equal to the superficial gas velocity minus the sauter mean particle terminal velocity. This assumption is valid for dilute systems.

(vi) There are no clusters in the core above the secondary air feed ports.

(vii) The primary zone is in the developing flow region near the bottom of the riser, and the assumptions on the behavior of the particles, listed above, do not apply in this region; therefore, only the bulk density was predicted in the primary zone.

(viii) For simplicity, the height of the top of the developing flow region is also the secondary air feed port height. In reality, the top of the developing flow region is usually 0.5 m to 1.5 m above the secondary air.

The region above the secondary air is in fully-developed flow. The developing flow region is the region near the bottom of the reactor, where there is a steep decline in the density profile and large core to wall flux of solids. In the fully developed region, there is less interchange of solids between the core and the annulus. The interface between these two regions are described in more detail in Senior's thesis.

(ix) In the developing flow region, an exponential decaying profile is assumed for the bulk suspension density.

(x) The average streamer velocity in the annulus is assumed to be -1.1 m/s. The average velocity of the falling streamer usually ranges from -0.5 m/s to -1.8 m/s, and this velocity is dependent on the suspension density. This range of streamer velocity was found experimentally using high speed cinematography by Wu [Wu et al., 1990], and is the same order of magnitude as suggested by other researchers such as Glicksman [1988].

Another observation that was included in Senior's model is the non-homogeneous nature of the annulus. Some wall sections contain streamers and others are exposed to the dilute upwards flow of particle suspension in the core. Both of these conditions were modeled in the annulus, by computing the thickness of the streamer and the fraction of the wall coverage by the streamers as a function of riser height.

Some limitations in Senior's model include the assumptions made in the developing flow region or the primary zone, and the assigned reflection coefficient, which is presently modeled as not a function of solids recirculation rate, superficial gas velocity, gas viscosity, gas density, particle density, particle size distribution and exit geometry. The reflection coefficient is defined as the fraction of solids traveling upwards at the exit height that are returned down the walls of the riser. Figure 2.3 shows the gas and solids flow patterns at a sharp riser exit [Brereton, 1987] and Figure 2.4 shows the effects of riser exit smoothness on a suspension density profile [Senior, 1992]

Figure 2.3 Observed Gas and Solid Flow Patterns in a Sharp CFB Riser Exit [Brereton, 1987]

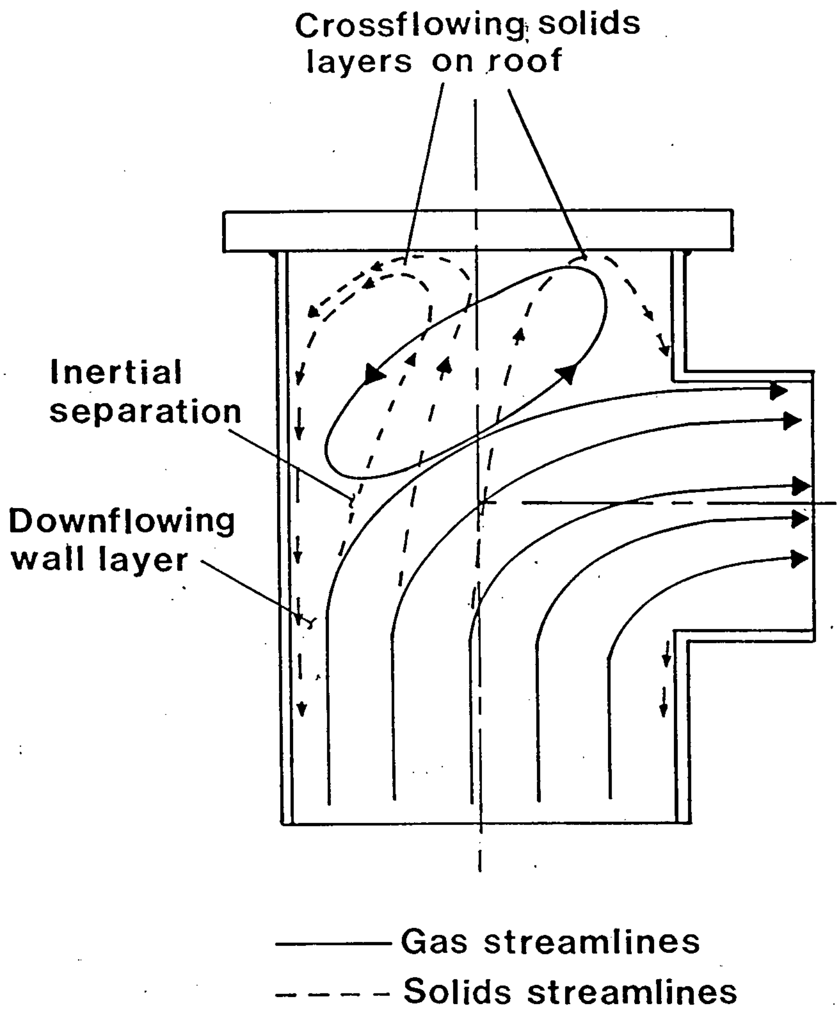
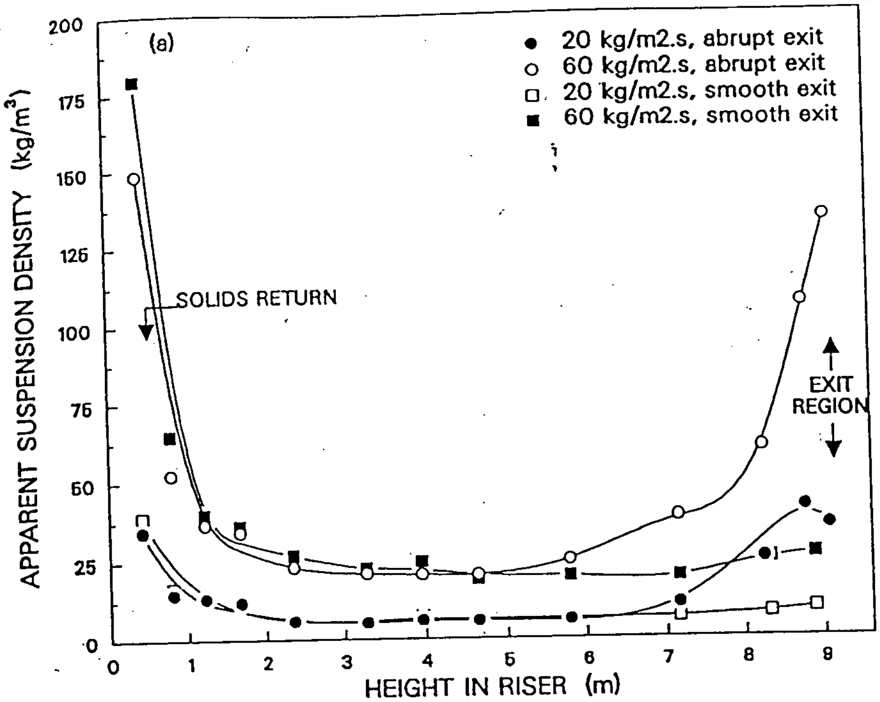
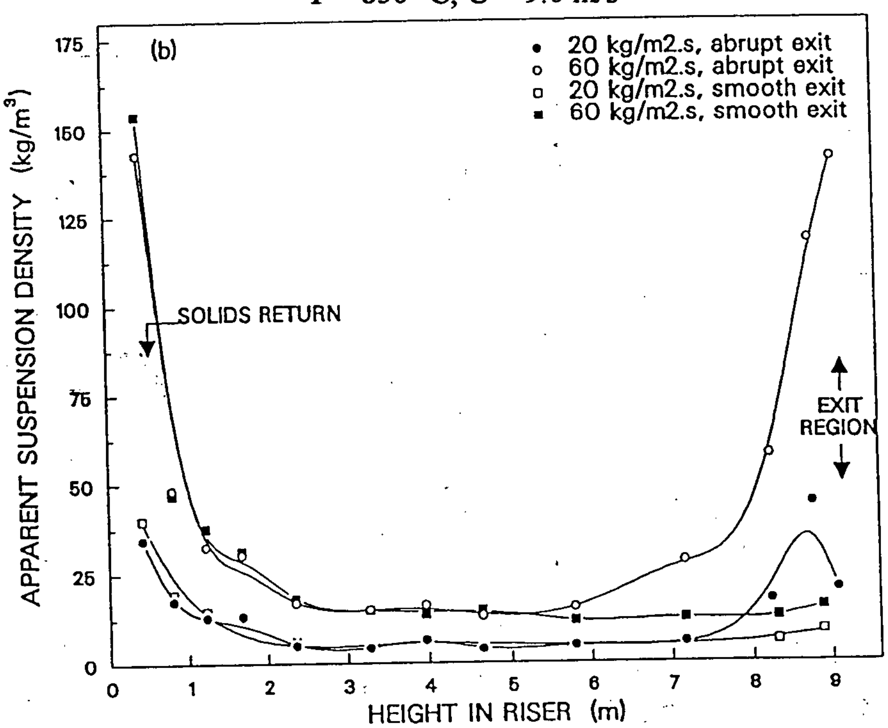


Figure 2.4 Apparent Suspension Density Profile as a Function of Riser Exit Geometries [Senior, 1992]

T = 850 °C, U = 6.5 m/s



T = 850 °C, U = 9.0 m/s



2.4 HEAT TRANSFER

Presently, there is a lack of experimental data from commercial operating CFBs that is not considered proprietary; however, a few researchers have made their data available [Werdermann et al., 1993], [Couturier et al., 1991] and [Leckner et al., 1992]. The majority of other CFB data that are available are for CFBs with either small heat transfer surfaces, small diameter CFBs or for CFBs operating at room temperatures, for example [Bi et al., 1990] and [Furchi et al., 1988]. In addition, most experimental data do not include radiative heat transfer and when compared with each other are often scattered.

Generally speaking, heat transfer models fall into three categories depending on how they treat the solid suspension near the riser wall. Theses categories are as follows:

(1) Film theory

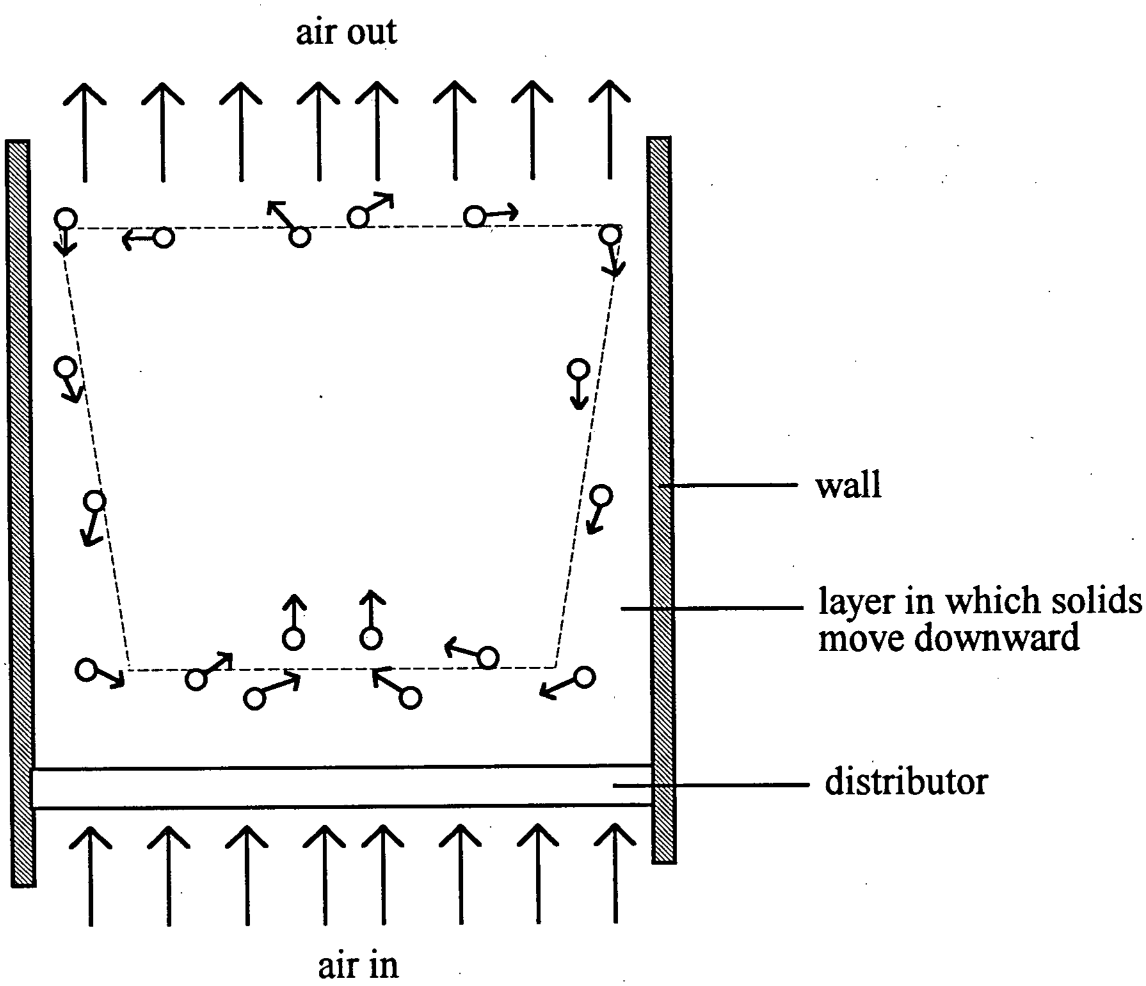
(2) Penetration theory

(3) Gas film-emulsion packet theory

2.4.1 Film Theory

The film theory was first proposed by Dow and Jacob [Dow et al., 1951]. They conducted experiments with various particle sizes and column diameters to study the heat transfer mechanism between a fluidized bed and a heat transfer surface. In their model there is an air film between the downward moving solids and the wall of the riser. Adjacent to this air film, the solid suspension is treated as discrete particles that move down the film, and discrete hot particles move up through the center of the bed. See Figure 2.5. The particle to surface contact is assumed to be negligible and heat is transferred through this film, which may be as thin as 0.01 mm thick. As expected, there is a temperature gradient across the film, and there is also a temperature gradient near the distributor as the cold primary air mixes with the hot particles in the bed; however, the rest of the bed is at a uniform temperature. In reality, this film layer is not continuous, but it is scoured by particles at irregular intervals.

Figure 2.5 Film Theory



Leva [1952] used the same model as Dow and Jacob, but assumed that the air film thickness is strongly dependent on the gas viscosity. In addition, as the particles scour the air film, the film's resistance decreases; therefore, the particle's velocity should also be included in the heat transfer equation. Leva, derived an equation that contains the thermal conductivity and the viscosity of the gas as well as the mass and velocity of the particles, and a new dimensionless variable called the "fluidization efficiency" was defined. The fluidization efficiency value was determined by fitting a derived bed to wall heat transfer coefficient with experimental data.

Levenspiel and Walton [Levenspiel et al., 1954] also used the film theory, but did not assume that the air film was continuous along the wall. They assumed that a fresh film starts at every point on the heat transfer wall where a solid particle touches the surface; thereby, producing several films and predicting a smaller total resistance to heat transfer. The total resistance is expressed as an "equivalent film thickness".

2.4.2 General Comments on the Film Theory

The film theory emphasizes the role of thermal conductivity of the gas and neglects thermal capacity of the solid particles. Also, the air film is scoured by solids which decreases the thickness of the film. The results of this theory may appear reasonable; however, the assumption that the role of the solid particles in heat transfer are insignificant is not seen experimentally.

This model wrongly suggests that at minimum fluidization the heat transfer is zero, because an anomaly in the derived equation at minimum fluidization gives zero equivalent film thickness, which leads to zero heat transfer. Therefore, the heat transfer value at minimum fluidization must be extrapolated from a higher value. In addition, extrapolation of heat transfer values for higher fluidization ranges must also be done.

Most models using the film theory predicts that radiation heat transfer is insignificant at temperatures less than 1000 °C. Radiation heat transfer was shown, by subsequent researchers [Szekely et al., 1969], [Botterill et al., 1970], [Baskakov, 1985] and [Han et al., 1992], to be significant at much lower operating temperatures.

2.4.3 Penetration Theory

Mickley and Trilling [Mickley et al., 1949] were first to develop the penetration theory for fluid bed heat transfer. Emphasis was placed on the transport of heat by the solid particles, which suggests that because the heat transport by the solids is fast, the temperature gradient is present only in a thin layer near the heat transfer surface. In addition, the effective thickness of this layer is reduced by the motion of the particles and heat flows by conduction and convection.

Mickley and Fairbanks [Mickley et al., 1955] were the first to represent the solid suspension as a packet. They recognized the heat transfer mechanism to be unsteady conduction and they researched the role of heat capacity of solid particles. The packet resides within a thin layer near the wall and the physical properties of the packet are the same as that of the bed. The packet has a finite life span before it is re-entrained into the core of the riser, and is replaced by a fresh packet. A continuous flow of such packets is the chief mechanism of heat exchange. See Figure 2.6.

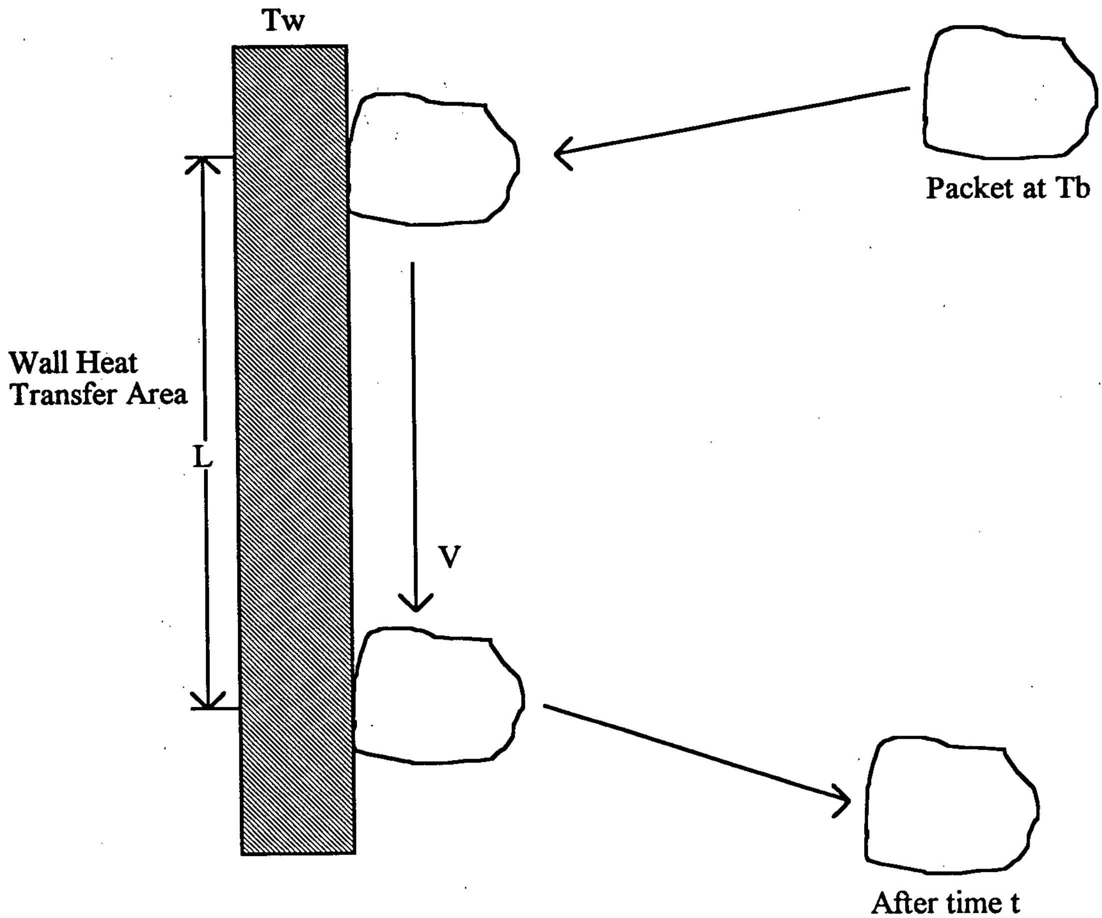
The boundary conditions are such that the packet instantaneously attains the temperature of the wall when it comes into contact with it, i.e., there is zero resistance or an infinite heat transfer coefficient between the packet and the wall.

Mickley and Fairbanks considered two models for bed dynamics.

(i) Slug model - all the packets move down the wall at a uniform velocity. They all have the same residence time and behave alike.

(ii) Side mixing model - there is a radial exchange of packets between the surface and the bed.

Figure 2.6 Penetration Theory



From their experiments, they showed that the heat transfer coefficient was proportional to the square root of the thermal conductivity of the packet, assuming constant packet density and heat capacity. Their model also explained how heat transfer increases due to a decrease in the particle size, because smaller particles circulate at surfaces more rapidly than larger particles.

The disadvantage of this model is that it predicts infinite heat transfer coefficients as the contact time approaches zero. The model also assumes that the bed is homogenous, which is not the case, since there are porosity changes.

Baskakov [1964] used the packet model of Mickley and Fairbanks, but he included addition thermal resistance between the wall and the packet to account for changes in porosity. His model is essentially a combination of the film theory and the penetration theory. Changes in porosity are significant near walls where gas layer thicknesses are approximately one particle radius.

Baskakov's model gives finite values of the heat transfer coefficient as the contact time approaches zero, as compared to Mickley and Fairbanks model. In addition, this additional thermal resistance seems to suggest a gap between the fluidized bed and the membrane wall.

Gorelik [1967] used a model similar to Baskakov's except the packet that reaches the wall is divided into a higher and a lower porosity zone. The higher porosity zone is close to the wall, and the lower one is equal to the bed porosity. However, the heat transfer problem becomes the unsteady heating of two zones, each having different thermal properties due to different porosities. Two zones with different thermal conductivities causes a temperature gradient at their interface. The difficulty then is to determine the thermal properties of the two zones.

2.4.4 Gas Film - Emulsion Packet Theory

The gas film-emulsion packet theory, also called the "alternate-slab model", proposed by Gabor [1970], assumes that the solid suspension near the riser wall is made up of alternate slabs of gas and solid. See Figure 2.7. Many investigators [Vedamurthy et al., 1974], [Bhattacharya et al., 1977] and [Kolar et al., 1979], using this theory assume that radiation only occurs between adjacent plates along with conduction through the gas film between the plates. The bed and heat transfer surface are considered grey and the gas is assumed to be transparent [Kolar, 1979]. The properties are evaluated at an average temperature equal to the mean of the temperature of the two bounding slab surfaces.

The radiation incident on each slab is assumed to undergo reflection, radiation, and scattering. The limiting values of these parameters as the number of slabs approaches infinity are considered to be the effective bed values.

The predictions from this model over predicts the heat transfer coefficient values at high temperatures; however, the maximum prediction error using this model is less than $\pm$35%, which is remarkably good considering its simplifying assumptions.

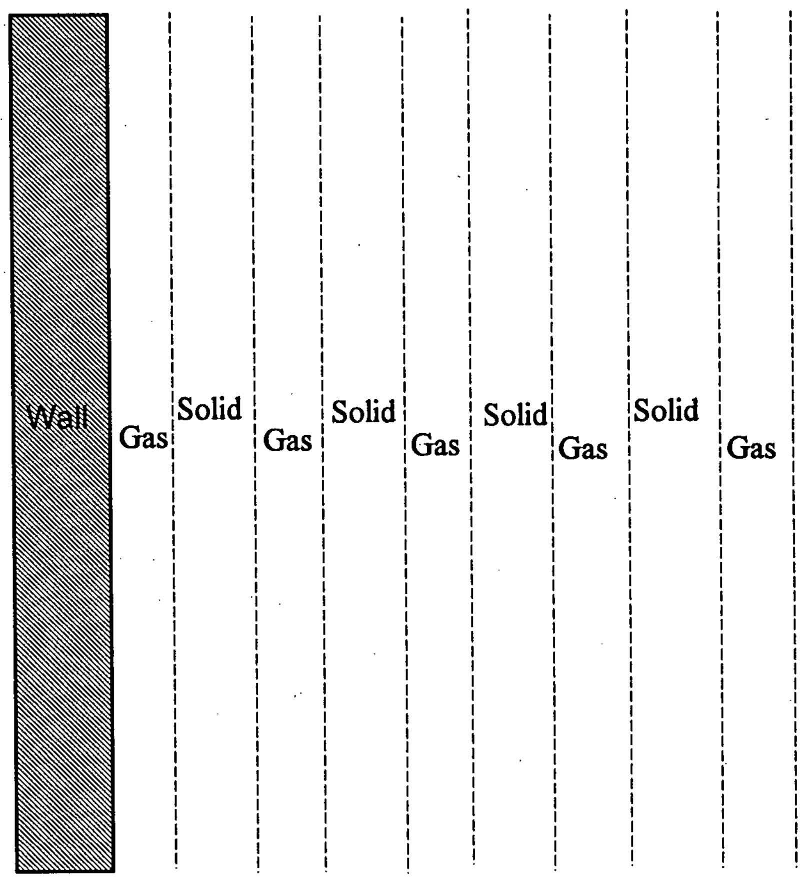
All of the above models were initially developed for bubbling beds. Many have subsequently been adapted for CFBs.

2.4.5 Radiative Heat Transfer

Most studies on heat transfer in CFBs only deal with particle convective heat transfer or overall heat transfer. Although an investigation by Jolley [1949] showed that radiative heat transfer term is significant at operating temperature of 1000 °C, experimental measurements of the radiative heat transfer contribution is difficult.

There are many views as to the contribution of radiation to the overall heat transfer in a CFB. One point of agreement is that it is insignificant at low temperatures; however, there is no agreement as to what temperatures are considered "low" and what are

Figure 2.7 Gas Film - Emulsion Packet Theory



considered "high" temperatures. According to Han's experimental measurements [Han et al., 1992], the contribution of radiative heat transfer to the total heat flux can range from 5% to 50% for suspension temperatures from 200 °C to 600 °C. In addition, there is uncertainty as to how other variables, such as particle diameter, particle surface temperature, fluidizing velocity, and effective bed and surface emissivities, affect the radiative heat transfer term. It is therefore necessary for a model of heat transfer in CFB to predict the radiative contribution in high temperature beds as a function of various parameters and operating conditions.

The additional heat transfer in the packet due to radiation using the penetration theory was studied by several researchers, such as work done in model 3. Another more complex model, by Chen [1988], involves developing a model of the heat transfer process by a non-linear differential formulation of the simultaneous radiative-conductive flux in the packet. In Chen's model, the radiative flux is split into an absorption and a scattering flux in both the forward and backward directions.

The general limitation of the penetration theory is that a number of the mean packet properties must be known, such as effective packet thermal conductivity, packet residence time and bubble fraction. In addition, for Chen's model, the packet's absorption and scattering cross-sections must also be known, which are difficult to evaluate. One assumption in the penetration theory is the packet's surface adjacent to the wall is assumed to immediately attain the wall temperature; in other words, there is zero resistance. Other assumptions include the packet leaves the wall before the thermal wave penetrates the packet, and the packet and the bed are assumed to have the same thermal properties.

The penetration theory gives predictions that are only accurate for long contact times. As time approaches zero, the heat transfer coefficient predicted approaches infinity.

2.4.5.1 Chen's Model

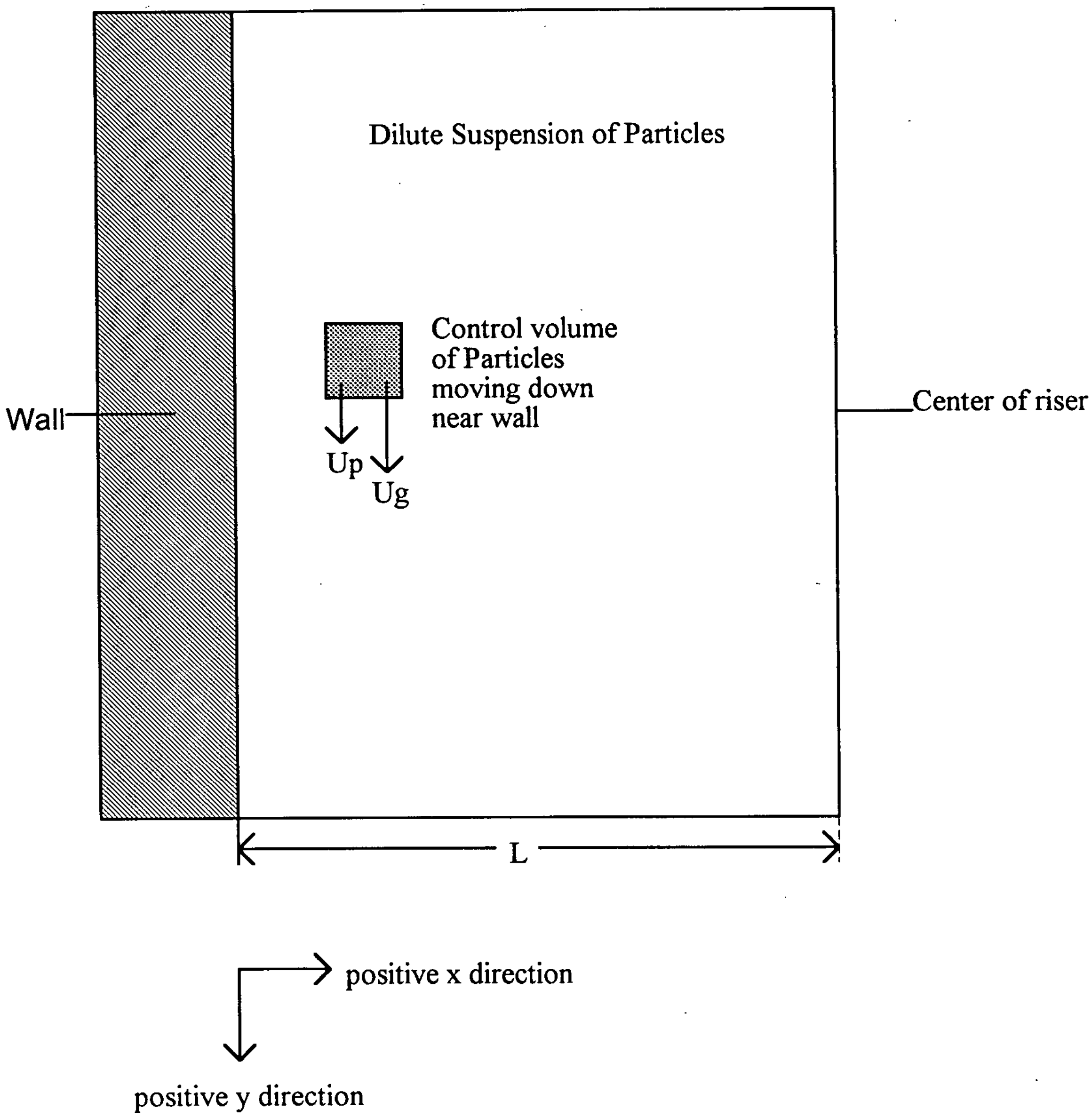
Chen developed a model that represents the interactive convective and radiative heat transfer process in a CFB. In the past, radiative heat transfer models usually treat the two-phase suspension as an opaque grey body with an effective suspension emissivity. The radiative heat transfer coefficient is then added to the convective heat transfer coefficient to obtain the overall heat transfer coefficient. In reality, radiative and convective heat transfer occur simultaneously throughout the suspension and are non-linear. The resulting equation is non-linear and has not been solved analytically. Numerical methods were used to solve the general case.

Chen's model considers an axial segment of the riser from the wall to the center of the riser. See Figure 2.8. Solid suspension is characterized by local parameters such as volume fraction of solid particles, temperature, heat generation rate, effective thermal conductivity, absorption cross-section, back-scattering cross-section, axial particle velocity and axial gas velocity.

For steady-state conditions, an energy balance can be made for the control volume. The general formulation is given in Equation 2.1.

$$\frac{\partial}{\partial x}\left(k_{eff}\frac{\partial T}{\partial x}\right)-\left[\left(\alpha_p\rho_p c_p u_p\right)+\left(1-\alpha_p\right)\rho_g c_g u_g\right]\frac{\partial T}{\partial y}-\frac{\partial}{\partial x}(I-J)=-G_v \qquad \text{.........(2.1)}$$

Figure 2.8 Radiative Heat Transfer Model [Chen, 1988]



where, y distance in the axial direction (m)
x distance in the transverse direction (m)
k_{eff} effective thermal conductivity (W/m·K)
T absolute temperature (K)
α_p volume fraction of the particle
ρ_p density of the particle (kg/m^3)
c_p specific heat of the particle (J/kg·K)
u_p velocity of the particle (m/s)
ρ_g density of the gas (kg/m^3)
c_g specific heat of the gas (J/kg·K)
u_g velocity of the gas (m/s)
I radiative flux in the positive y direction (W/m^2)
J radiative flux in the negative y direction (W/m^2)
G_v heat source intensity per unit volume (W/m^3)

From the energy balance equation, Chen's model ignores the axial conductive and axial radiative fluxes as well as radial convection of the particles and gas.

The photon transport equations for the radiant energy passing through the solid suspension by absorption and back-scattering are given below.

$$\frac{\partial I}{\partial x} = -(A_r + S_r)I + S_r J + A_r \sigma T^4 \qquad ....(2.2)$$

$$\frac{\partial J}{\partial x} = (A_r + S_r)J - S_r I - A_r \sigma T^4 \qquad ....(2.3)$$

where, A_r radiation absorption cross-section / unit volume
S_r back-scattering cross-section / unit volume
σ Stefan-Boltzman constant (W/m^{2}K^4)

and A_r and S_r are calculated by:

$$A_r = CL\frac{3\alpha_p \varepsilon_p}{d_p} \qquad ....(2.4)$$

$$S_r = CL\frac{3b\alpha_p(1-\varepsilon_p)}{d_p} \qquad ....(2.5)$$

where, CL dimensionless proportionality factor
ε_p emissivity of the particles
d_p diameter of the particles (m)
b back-scattering coefficient

The boundary conditions used are:

$$T(0,y) = T_w$$
$$\frac{\partial T}{\partial x}(L,y) = 0$$
$$T(x,0) = T_i$$
$$I_w(0,y) = \varepsilon_w \sigma T_w^4 + (1-\varepsilon_w)J_w$$
$$J_L(L,y) = I_L$$

where the subscripts representation are,
w wall condition
i initial condition
L condition at the center of the reactor column

2.4.5.2 Radiative Contribution in Heat Transfer Model

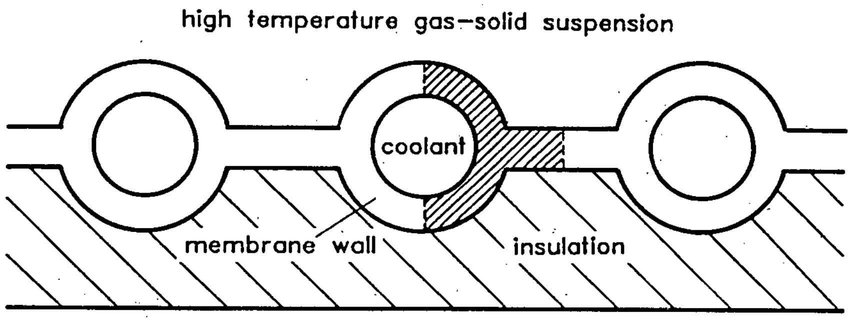
The convective and radiative heat transfer process in a CFB in reality is interactive. The equations are highly non-linear and difficult to solve numerically. Initially, Chen's equations were used in the heat transfer model developed in this work. The riser was divided into 20 axial cells and 2 radial cells. The annulus cell and the core cell were separated as individual control volumes, and the finite difference method was used to solve Equation 2.1. Temperature convergence was difficult to achieve; therefore, a less sophisticated non-interactive convective and radiative heat transfer equation was used to solve for the temperature profile in this thesis work. Due to the modular nature of the program developed, the heat transfer subroutine can be replaced with a more sophisticated heat transfer equation at a later date.

2.4.6 Heat Transfer in Overall Model

There are various models developed to describe high temperature heat transfer processes in CFBs and all of them use the penetration theory. Models 2, 3, 5, 6, 7, 8 and 10, listed previously include a heat transfer model. Model 2 uses a heat transfer model according to Nag [Nag et al., 1991], which includes particle and gas convection to all of the neighboring cells. Model 3 uses a more complex heat transfer model that includes conduction, convection and radiative heat transfer. The overall heat transfer in this model is determined by a mass and energy balance on all solid and gas phases. Model 5 uses an enthalpy balance on each chemical species and a constant wall heat transfer coefficient to determine the heat transfer in the CFB. Models 6 and 8 are similar to model 5's treatment of heat transfer; however, the wall heat transfer rates are determined by energy balances at the furnace wall. Model 7 calculates the amount of chemical heat generated using the Delft SURE Model [Lin et al., 1989]; however, this model does not include bed to wall heat transfer to be implemented into an overall model. Finally, model 10 determines the amount of chemical heat generated by solving a mass balance for each gas species and assuming a constant wall temperature, a heat balance is done according to a model by Martin [1980].

None of the overall models look at heat transfer to a membrane waterwall surface, which consists of tubes connected by longitudinal fins [Bowen et al., 1991], see Figure 2.9.

Figure 2.9 Schematic Cross-Section of a Membrane Waterwall Surface [Bowen et al, 1991]



CHAPTER 3

MODELLING OF HEAT RELEASE, OXYGEN PROFILES AND TEMPERATURE PROFILES OF CFBs

In this chapter, a detailed description of the model, developed in this thesis work, to predict heat release, oxygen and temperature distributions in CFB combustors will be discussed. The equations used are simple exponential equations for devolatilization and char combustion. The oxygen partial pressure profile is determined by a mass balance for each cell, given the initial oxygen pressure, and the temperature is determined by solving a nonlinear partial differential equation with the temperature term to the 4th power.

The program code is modular, so that each subroutine can be easily replaced by other equations. The heat release and heat transfer subroutines are coupled, which is required to solve for the temperature distribution.

3.1 MODEL ASSUMPTIONS

The assumptions used in the heat release and heat transfer subroutines are as follows.

(i) The heat capacity of the gas is assumed to be constant and equal to the heat capacity of the gas at a temperature of 850 °C.

The heat capacity of the gas is recognized to be a function of temperature. However, this assumption was made to simplify the heat transfer equation to show, at this initial stage, that the program gives reasonable predictions. The program can be easily modified to include more sophisticated energy balances, including a heat capacity term that is a function of temperature.

(ii) The heat capacity of the particle is assumed to be constant.

(iii) The density of the particle is assumed to be constant.

(iv) The density of the gas is assumed to be constant.

(v) Velocity changes of the gas due to combustion are neglected.

Realistically, the variables in assumptions (iv) and (v) are both a function of temperature and gas velocity does change as more combustion gas is produced. However, this assumption is consistent with the hydrodynamics model used. In Senior's model, the mass flux of the gas is assumed to be constant. Since the mass flux of the gas is the product of gas density and gas velocity, both of these values were taken as constants. In the absence of a hydrodynamic model that is a function of temperature, these assumptions were made.

(vi) Fragmentation and attrition of coal particles were assumed to be insignificant. In practice, the reaction of coal in CFBs, namely devolatilization and char combustion where heat is released, may be complicated by fragmentation that typically occurs near the end of devolatilization and by attrition, which occurs throughout char burning.

(vii) The mass transfer rates of oxygen to the char particle and carbon dioxide away from the particle are assumed to be rapid [Howard, 1983]. Therefore, the limiting step is the kinetic rate of char combustion.

This assumption is valid for high gas velocities or good gas-solid mixing, which is a characteristic of CFBs [Basu and Yan, 1993].

(viii) The char is assumed to be completely burned to form carbon dioxide, i.e., no carbon monoxide present.

(ix) No heat release occurs in the standpipe, since there is very little oxygen present to support combustion.

(x) The gas and particles in each cell are well mixed and at the same temperature.

(xi) The higher heating value of the fuel was used for both the volatile and the char combustion.

This neglects some of the complexities at the local heat balance, and more detailed balances are needed for further development of the work.

(xii) The model first calculates the enthalpy needed to dry all the moisture from the fuel before the coal undergoes combustion. The amount of moisture in each cell is calculated based on the fractional heat released within the cell.

(xiii) The particle heat up rate is assumed to be infinite. In other words, the volatiles immediately start being released from the coal particles upon entering the primary zone.

(xiv) There is 100% combustion of the coal particles. This is easily modified.

3.2 DESCRIPTION OF MODEL APPROACH AND SUBROUTINE EQUATIONS

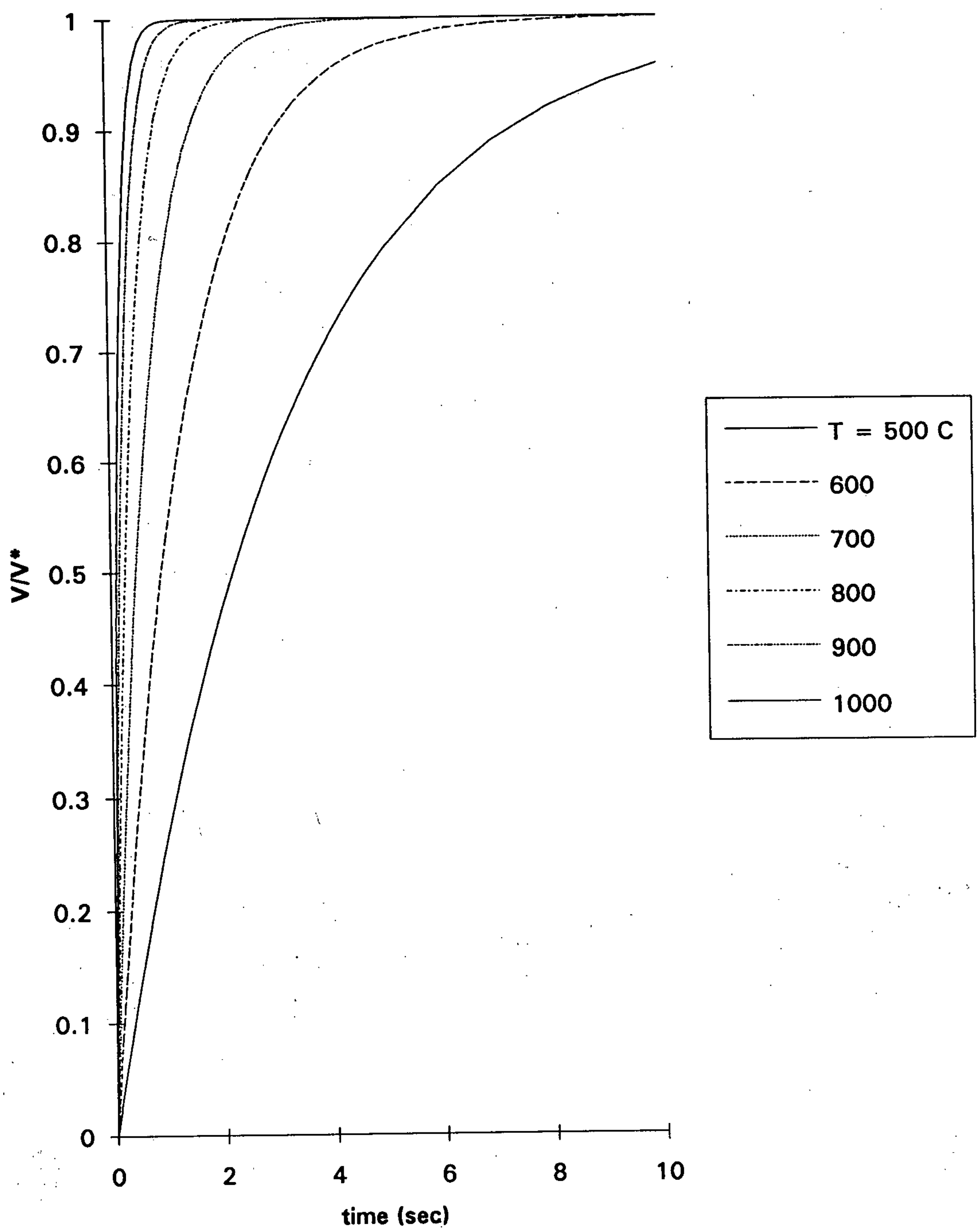
3.2.1 Devolatilization

Several devolatilization expressions were considered. These expressions were developed by Jia [Jia et al., 1993], Anthony [Anthony et al., 1975], and a combined devolatilization expression by Agarwal [1986] and Davidson [Davidson et al., 1985].

The devolatilization expression by Anthony, shown in Equation 3.1, was determined by heating up to 950 °C, in a helium environment, monolayer samples of lignite and bituminous coal supported on wire mesh. Devolatilization was found to be a function of time and temperature and not a function of particle diameter. For bituminous coal, the correlation was found to have a standard deviation of approximately 3 wt%. Figure 3.1 shows how the correlation predicts the time to devolatilize as a function of temperature.

$$V = V^{*}\left(1 - \exp\left[-k_0 t \exp\left\{\frac{-E_0}{RT}\right\}\right]\right) \qquad \text{.........(3.1)}$$

Figure 3.1 Devolatilization Time as a Function of Temperature Predicted by Equation 3.1



where,

where,	V	fraction of volatiles released at time t
	V^*	initial fraction of volatiles in coal (from proximate analysis)
	t	time (s)
	T	temperature (K)
	k_o	= 706 s
	E_o	= 11.8 kcal/mol
	R	= 1.978×10^{-3} kcal/mol.K

The devolatilization expression by Jia, shown in Equation 3.2, is a function of particle diameter; however, it is not a function of time.

$$t_d = 5.10x10^{10} T_b^{-1.95} d_p^{1.6} P_0^{-0.086} \qquad \text{.........(3.2)}$$

where,	t_d	devolatilization time (s)
	T_b	bed temperature (K)
	d_p	particle diameter (m)
	P_o	partial pressure of oxygen (atm.) must be within the range 0.01 atm. to 0.14 atm.

Very recently, a third devolatilization expression, which is a combination of the expressions by Agarwal and Davidson, was used. This devolatilization expression is both a function of particle diameter and time. The equations and results are listed and compared in the following chapter.

Although for all of the test cases, the devolatilization expression by Anthony was used, due to the modular nature of the program, Equation 3.1 can be easily replaced by another equation which may incorporate pressure, heating rate and particle size.

3.2.2 Plume Model

Experimentally, in both large and small CFBs, volatile plumes are found. These plumes are caused by poor radial mixing of gas, and the effect of the plume is that volatiles are not necessarily burned at the location where they are released. Clearly, as shown in Figure 3.2, this is a 2 or 3 dimensional mixing problem; however, the core/annulus model is only 1 dimensional. In order to superimpose the 2 dimensional phenomenon upon the 1 dimensional model, it is necessary to perform separate computations and then transfer the results into the 1 dimensional case.

In this model, the volatiles are assumed to burn at their point of release; therefore, the plume phenomena was handled by looking at the volatiles release as a function of height, and then transferring some fraction of the volatiles to the cell above. This transfer simulates the poor mixing, which prevents volatiles from releasing their heat of combustion at their point of evolution.

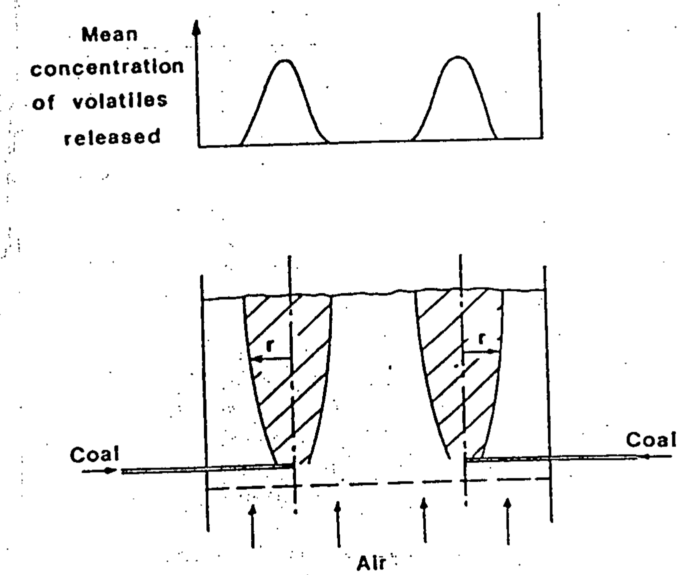
Devolatilization is rapid and generally takes place 3 to 20 seconds after the coal is fed into a CFB. Since the volatile matter will disperse from the fuel feed point rapidly in the axial direction, but only slowly in the radial direction, the volatiles evolution region forms an axial symmetric region centered on the fuel feed point [Stubington, 1980] and [Park et al., 1981]. If the fuel feed point is located at the wall, then the evolution region's axis of symmetry will be centered at the wall.

The volatiles must mix with oxygen for combustion to occur. Therefore, oxygen availability can be the limiting factor in volatile combustion, if the oxygen concentration is less than stoichiometric in the region near the fuel feed. This is more prevalent in large CFBs, where the volatiles burn higher up the riser.

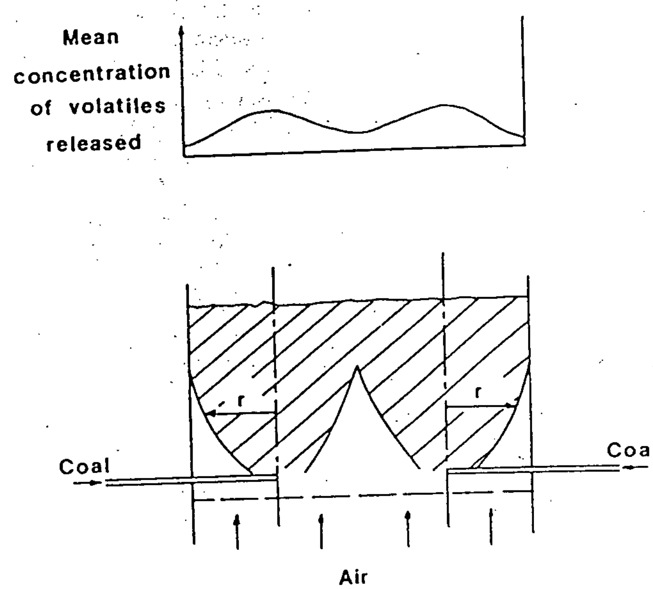
As the volatiles travel up the height of the bed, they also diffuse a significant radial distance, which is given by Einstein's diffusion equation [Stubington, 1980].

$$x^2 = 2D_{rv}t \qquad \text{.........(3.3)}$$

Figure 3.2 Plume Model of Volatiles Dispersion [Stubington, 1980]



Volatiles evolution region for short devolatilization time



Volatiles evolution region for long devolatilization time

where, x^2 average displacement squared
D_{rv} radial volatile diffusion coefficient
$= 0.01\ m^2/s$
t time (s)

To correct for the volatile dispersion, the above equation was solved for t, then knowing the velocity of the gas in the axial direction, the height h above the coal feed point where we observe fully radial mixing of volatiles is calculated. Fully radial mixing is achieved when the volatile evolution region spans the full cross-sectional area of the riser. For any cells below this height h, the amount of volatiles released is corrected for by transferring a fraction of the total volatiles to the cell above. This fraction is called the volatiles transfer fraction and is set at 0.3, which seemed to produce reasonable results.

The current volatiles release rate, calculated from Equation 3.1, is very fast and mainly occurs in the primary zone. The effects of using the plume model is not clearly seen, including the effect of various volatile transfer fraction values.

3.2.3 Char Combustion

After devolatilization, the char particle that remains may take several minutes to burn out, depending on the size of the particle. Since the mass transfer rate of oxygen to the coal particle was assumed to be rapid and the limiting step is char combustion, the Arrhenius equation was used to express char combustion. Assuming a first-order reaction, the following equation was used [Howard, 1983].

$$k_R = A_C \exp\left[-\frac{E_A}{RT_S}\right] \qquad \text{.........(3.4)}$$

where, k_R reaction rate ($kg/m^2 \cdot s \cdot atm$)
T_S surface temperature (K)
E_A = 150,000 kJ/kg
A_C = 7260 $kg/m^2 \cdot s \cdot atm$
R = 8.314 $kJ/kg \cdot K$

The char combustion equation was also included in a separate subroutine within the program; thereby, making replacement expressions of the char combustion rate an easy task. The time for burnout of a particle is given by:

$$\tau = \frac{\rho_C d_C}{24 k_R P_O} \qquad \text{.........(3.5)}$$

where, d_c diameter of the char particle (m)
k_R reaction rate ($kg/m^2 \cdot s \cdot atm$)
P_o partial pressure of oxygen (atm)
ρ_C density of the char particle (kg/m^3)
τ burn-out time (s)

From Table 3.1, we can compare the predicted burnout times and riser residence times for various particle diameters. It should be noted that the devolatilization time, calculated from Equation 3.1 [Anthony et al., 1975], is not a function of particle diameter. Also, the average particle residence times, given in Table 3.1, are determined based on a single pass.

Table 3.1 Comparison of Predicted Burnout Times with Particle Diameters

Studsvik CFB Bed Temperature = 850 °C Particle Surface Temperature = 900 °C Partial Pressure of O_2 = 0.05 atm Particle Density = 1400 kg/m^3 Superficial Gas Velocity = 7 m/s				
Time (s)	dp = 100 µm	dp = 1 mm	dp = 3 mm	dp = 1 cm
Devolatilization [Anthony et al., 1975]]	4			
Devolatilization [Jia et al., 1993]	1.8×10^{-5}	1.1	6.5	44.9
Devolatilization [Agarwal, 1986]	0.047	1.5	7.8	47.4
Char burnout	0.784	784	2352	7840
Average single pass particle residence in the riser above the secondary air	30			
Average single pass particle residence in the primary zone	10			

Comparing the devolatilization time prediction by Anthony with Jia shows that Anthony's formulation over predicts the devolatilization time for small particle diameters and under predicts the time for large particles. Therefore, there is a limited range of particle size (approximately 2 mm) where this correlation is valid.

The model assumes that the fuel particle travels through the bed in the same way as the bed particles. Then the single pass residence time for the primary and secondary zone is independent of the particle diameter. This assumption is valid for small diameter particles that are approximately the same size or smaller than the bed particles. For larger diameter particles, this assumption breaks down. However, typical coal particle diameters in CFBs are no more than approximately 4 mm, compared to an average bed particle of 0.5 mm [Senior, 1992].

By comparing the char combustion time with the single pass residence time in the secondary zone, for large diameter particles, we can conclude that the coal particle will pass through the riser many times before it is completely burnt out. The heat release distribution for large particles will then be similar to the density distribution. Therefore, there is a potential for simplification in the heat release model for large particles, by setting the heat release distribution to equal the density distribution.

Finally, by comparing the devolatilization time with the single pass residence time, for small diameter particles, we can conclude that if the devolatilization time is much less that the residence time in the primary zone, then most of the volatiles will be released in this zone. In addition, from Figure 3.1, most of the volatiles are released within the first few seconds from when the fuel enters the riser; therefore, most of the volatiles will be released in the primary zone, according to Anthony's correlation.

3.2.4 Monte Carlo Approach

The Monte Carlo Method is a class of mathematical methods first used by scientists in the 1940s. The essence of this method is the use of random or pseudo random numbers to study some phenomena. Although the problem may be non-probabilistic, an individual event that makes up the problem has the structure of a stochastic process, a sequence of states determined by random events. Therefore, although the answers obtained are statistical in nature and subject to the laws of chance, the average value of the answer isn't. In order to determine how accurate the answer is or to obtain a more accurate answer more experiments can be conducted. In this program approximately 100 particles will give reasonable heat release distributions due to char combustion.

Many people use the Monte Carlo Method and it has become an accepted part of scientific practice in many fields. Some advantages are convenience, ease and directness of the method. In addition, Monte Carlo Methods are computationally effective, compared with deterministic methods when treating many dimensional problems.

For the Monte Carlo method to be effective, a source of randomness is needed. Unfortunately, the random functions supplied with different computers are pseudo random, which is to say that they are deterministic but mimic the properties of independent uniformly distributed random variables.

3.2.5 Comparison of Monte Carlo Approach with Analytic Technique

An alternative method to the Monte Carlo Approach is to solve the heat release and the heat transfer equations simultaneously by formulating mass and energy balance equations for each particle size within each cell. There are approximately 40 cells and the greater the number of particle sizes considered in the mass and energy balances the more accurate the final result. Assuming that there are 20 particle sieve sizes considered, which is the number in the fuel feed's particle size distribution, there would be over 800 simultaneous non-linear equations that must be solved for each time step. This very large and sparse matrix must then be iterated until a final converged value is reached. Such an approach will be time consuming, and due to the nonlinear nature of the energy balance equation, the solution may be difficult to converge.

The Monte Carlo approach was chosen because it seems to be a simpler method to program than the analytic technique method. In addition, using the Monte Carlo method, CFB systems of hundreds or thousands of particles can be treated quite routinely.

3.2.6 Monte Carlo Approach within the Program

In this program a large number of coal particles are individually traced throughout the bed riser and solids recirculation system. In each cell, the coal particle's probability of being transferred to the wall, from the wall, up the riser or down the riser is simply the ratio of the flow of particles out of the cell in a given direction, to the cell mass. The time steps were selected such that at any given time step, the probability of the coal particle leaving the cell is set at 10%. See Figure 3.3. This probability value of 10% was chosen after initial experiments, using various probability values, showed that at higher probability values the accuracy of representing particle movement within the riser decreased. At lower probability values, accuracy increased; however, total run time also increased. A probability value of 10% seemed to be the optimum value.

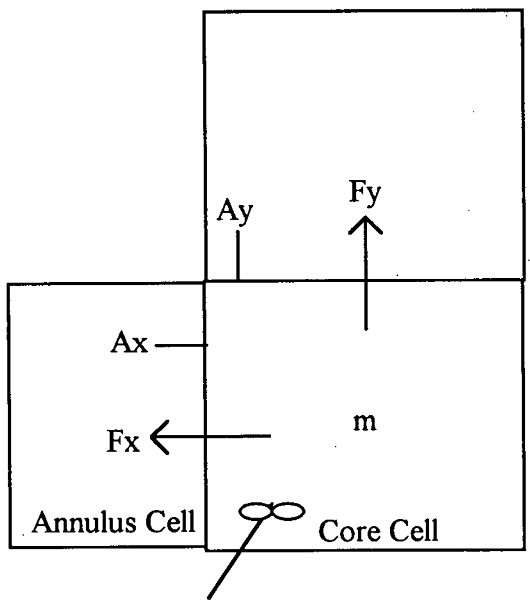
Several hydrodynamic assumptions were made in this program. The particles in the core were assumed to move only up the riser or to the streamer, and the particles in the streamer were assumed to only move down the streamer or to the core. See Figure 3.4. This assumption is the same as in Senior's hydrodynamic model. In addition, the coal particles were assumed to move in the same way as the bulk ash and sand particles.

A fraction of the particles that hit the top of the riser is reflected back into the streamer, based on a given reflection coefficient in the CFB. The rest of the coal particles that leave the top of the riser enter the cyclone, which is treated as a CSTR with a residence time of 0.3 seconds. This cyclone model can be replaced by alternative models. The coal particles less than 50 μm exit with the flue gas while larger particles leaving the cyclone are returned to the CFB's primary zone through the standpipe.

As the coal particle move throughout the riser, it first undergoes devolatilization then char combustion. In addition, to tracking the path of the particle, the Monte Carlo method also follows in which cell and at what time heat is released. Ultimately, this form of "bookkeeping" produces a heat release distribution.

The resultant heat release distribution is a function of temperature and partial pressure of oxygen, which must be initially guessed. However, once the heat release distribution is determined a new partial pressure of oxygen profile can be calculated and then a new temperature profile. The Monte Carlo method is repeated until a converged heat release distribution, partial pressure of oxygen profile and temperature profiles are obtained.

Figure 3.3 Probability of a Particle Leaving a Cell



Variables:

m mass of particles in cell (kg)
Fy flow across Ay (kg/s)
Fx flow across Ax (kg/s)
t time step (s)

0

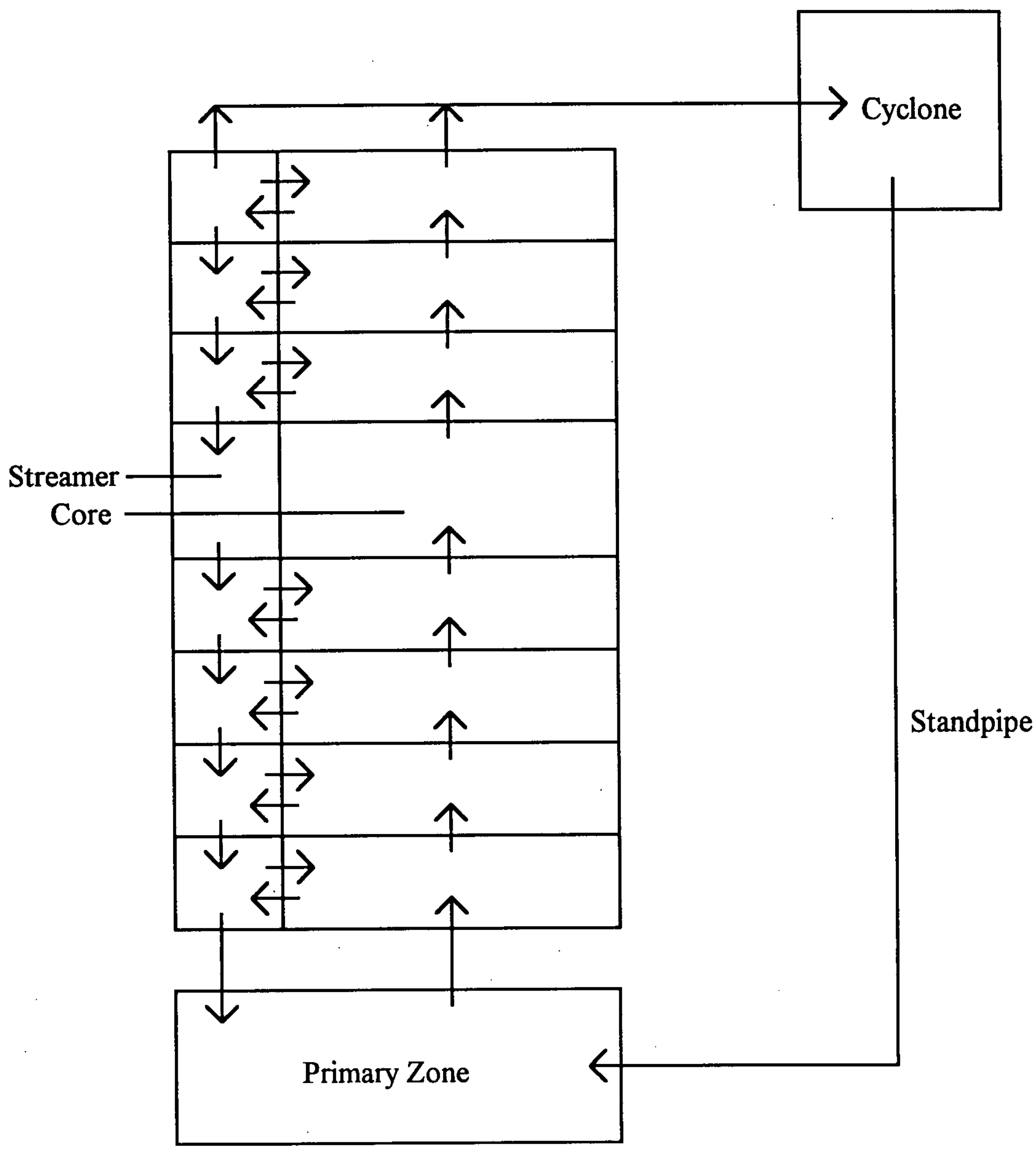
Probability of a particle moving vertically: $Py = Fy \, . \, t / m$

Probability of a particle moving horizontally: $Px = Fx \, . \, t / m$

Probability of a particle staying within the cell: $Pm = 1 - Py - Px$

1

Figure 3.4 Solid Particle Paths in the Riser



In order to validate the predicted particle paths throughout the riser, based on the Monte Carlo method, a test run was conducted. In this experiment one large "theoretical" particle, with a diameter of 1 m, was introduced into the primary zone and was traced as it underwent devolatilization and char combustion. The large size of the particle ensures that it will move through all of the cells many times before it is finally consumed. If the particles that hit the top of the riser are assumed to all reflect back down the streamer and the riser's temperature and oxygen concentration are constant, then the resultant heat release distribution should equal to the density distribution of the CFB.

The expression for devolatilization time chosen for this test is from Jia [Jia et al, 1993], since the time for volatiles release in this expression is given as a function of bed temperature and particle diameter. However, the devolatilization rate was assumed to be constant. The devolatilization time expression for Highvale coal is shown in Equation 3.2. The char combustion rate used is from Howard [1993] and was shown previously in Equations 3.4 and 3.5.

The results from this test, assuming a constant riser temperature of 850 °C, is that the heat release distribution due to volatiles and char combustion was indeed found to be the same shape as the density distribution.

3.2.7 Heat Transfer Model

Two types of heat transfer were considered in the model; cell to cell heat transfer and cell to wall heat transfer.

3.2.7.1 Cell to Cell Heat transfer

The overall cell to cell heat transfer equation, given below, includes conduction, convection and radiative heat transfer of both particles and gases.

$$-\frac{kA_W}{(\delta x)_W}(T_P - T_E) - \frac{kA_E}{(\delta x)_E}(T_P - T_E) - \frac{kA_N}{(\delta y)_N}(T_P - T_N) - \frac{kA_S}{(\delta y)_S}(T_P - T_S)$$

$$-(F_x c_p + \rho_g c_g v_g)A_W(T_W - T^0) - (F_x c_p + \rho_g c_g v_g)A_E(T_E - T^0)$$

$$-(F_y c_p + \rho_g c_g u_g)A_N(T_N - T^0) - (F_y c_p + \rho_g c_g u_g)A_S(T_S - T^0)$$

$$-\varepsilon\sigma A_P T_P^4 + \varepsilon\sigma A_W T_W^4 + \varepsilon\sigma A_E T_E^4 + \varepsilon\sigma A_N T_N^4 + \varepsilon\sigma A_S T_S^4 + G = 0$$

.........(3.6)

where,	k	thermal conductivity of the cell (W/m·K)
	A	surface area of one side of the cell (m^2)
	T	temperature (K)
	x	distance in the transverse direction (m)
	y	distance in the axial direction (m)
	F_x	mass flux of particles in the transverse direction (kg/m^2·s)
	F_y	mass flux of particles in the axial direction (kg/m^2·s)
	c_p	heat capacity of particles (J/kg·K)
	ρ_g	density of gas (kg/m^3)
	c_g	heat capacity of gas (J/kg·K)
	v_g	represents the mass exchange of gas in the transverse direction due to turbulent mixing (m/s)
	u_g	velocity of the gas in the axial direction (m/s)
	ε	emissivity of the cell
	σ	Stefan-Boltzman constant (W/m^2·K^4)
	G	source term in the cell (W/m)
subscripts,	W	west
	E	east
	N	north
	S	south
	P	control volume
superscripts,	0	reference

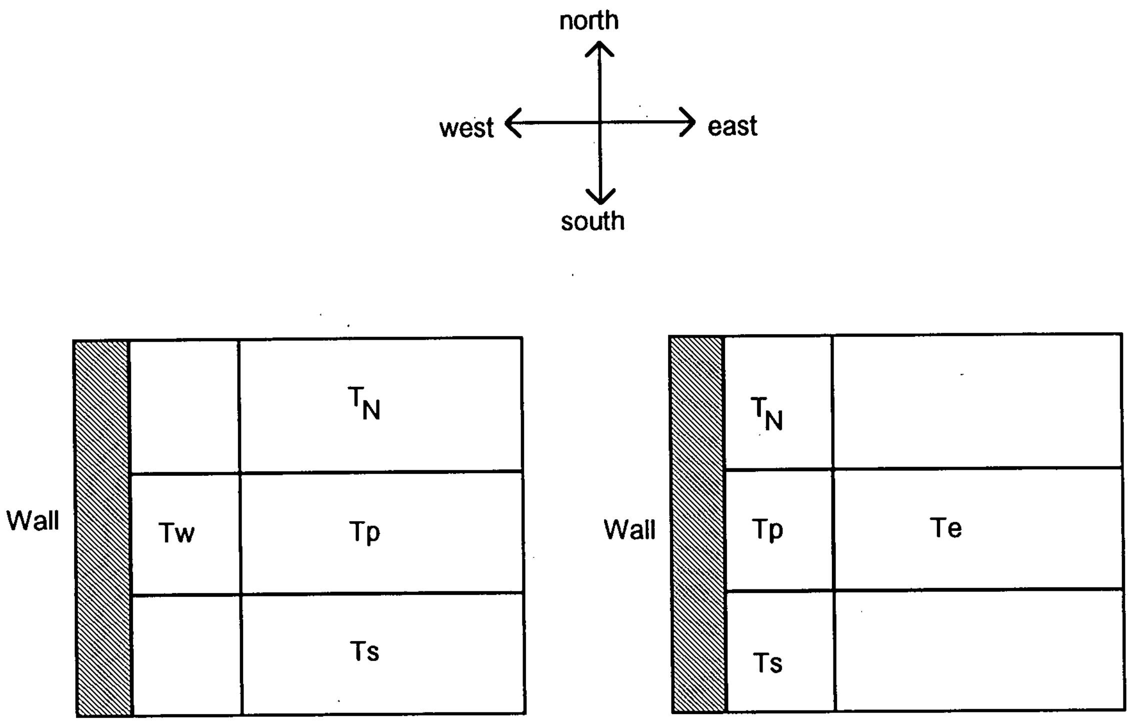
Figure 3.5 shows an enlarged riser cell cross-section, to indicate the direction convention used in the overall cell to cell heat transfer equation.

3.2.7.2 Differences with Chen's Model

The differences between the above heat transfer equation and the one used by Chen, besides the fact that the above equation does not couple the radiative and the conductive heat transfer terms are, the equation above includes heat conduction not only in the radial direction but also in the axial direction. Secondly, in Chen's model only convective heat transfer in the axial direction is considered; whereas, the above equation includes convection in the radial direction.

In Chen's model, the entire riser width is treated as a uniform gas solid suspension. The average suspension properties must be known to solve the steady-state finite differences formulation. However, in this model, the properties of the annulus and the core sections have different properties; therefore, the riser is split into a number of core and annulus cells along the riser height.

Figure 3.5 Direction Convention used in Cell to Cell Heat Transfer Equation



(a) Core Cell as Control Volume

(b) Annulus Cell as Control Volume

3.2.7.3 Finite Difference Formulation

Since the heat transfer equation is not conducive to analytical solution, numerical methods were used to solve the equation. More specifically, finite differences with the control volume method was used. The width of the riser was divided into four cells: the wall cell, the annulus, the core and the axis of symmetry of the riser. Each cell had different boundary conditions and had to be treated separately. The finite difference formulation of the heat transfer equation for each cell is given below.

For the wall cell, a constant temperature boundary condition was used. The wall temperature was set at 250°C. This assumes that the limiting rate of heat transfer is on the hot gas side, so that the cooling water temperature is equal to the wall temperature.

The annulus cell had the following finite difference formulation.

$$
\begin{aligned}
& -hA_W\left(\frac{T_P A_N + T_E A_{ne}}{at} - T_W\right) - \frac{kA_E}{(\delta x)_E}(T_P - T_E) - \frac{kA_N}{(\delta y)_N}(T_P - T_N) - \frac{kA_S}{(\delta y)_S}(T_P - T_S) \\
& -\left(F_x c_p + \rho_g c_g v_g\right)A_E\left(T_P - T^0\right) + \left(F_{xe} c_p + \rho_g c_g v_g\right)A_E\left(T_E - T^0\right) \\
& +F_{yn} c_p A_N\left(T_N - T^0\right) - \rho_g c_g u_s A_N\left(T_P - T^0\right) \\
& -F_{ys} c_P A_S\left(T_P - T^0\right) + \rho_g c_g u_s A_S\left(T_S - T^0\right) \\
& -\varepsilon\sigma A_P T_P^4 + \varepsilon\sigma A_W T_W^4 + \varepsilon\sigma A_E T_E^4 + \varepsilon\sigma A_N T_N^4 + \varepsilon\sigma A_S T_S^4 + G = 0
\end{aligned}
\tag{3.7}
$$

where,	h	cell to wall heat transfer coefficient ($W/m^2 \cdot K$)
subscripts,	ne	north face of the cell to the east of the control volume
	xe	transverse direction of the cell to the east of the control volume (m)
	yn	axial direction of the cell to the north of the control volume (m)
	ys	axial direction of the cell to the south of the control volume (m)

For the core cells, the finite difference formulation is as follows.

$$-\frac{kA_W}{(\delta x)_W}(T_P - T_W) - \frac{kA_N}{(\delta y)_N}(T_P - T_N) - \frac{kA_S}{(\delta y)_S}(T_P - T_S)$$

$$-(F_x c_p + \rho_g c_g v_g)A_W(T_P - T^0) + (F_{xw} c_p + \rho_g c_g v_g)A_W(T_W - T^0)$$

$$-(F_{yn} c_p + \rho_g c_g u_g)A_N(T_P - T^0) + (F_{ys} c_p + \rho_g c_g u_g)A_S(T_S - T^0)$$

$$-\varepsilon\sigma A_P T_P^4 + \varepsilon\sigma A_W T_W^4 + \varepsilon\sigma A_N T_N^4 + \varepsilon\sigma A_S T_S^4 + G = 0$$

.........(3.8)

The finite difference formulation for the core to annulus conduction terms, in Equations 3.7 and 3.8, estimates the temperature gradient as the difference in the core and annulus temperatures divided by their distance apart. This estimation is more valid for small CFB risers, where the distance between the core and annulus is much smaller. In larger CFB units, this estimation assumes that there is a constant gradual temperature gradient between the core and the annulus, when in actuality, the temperature gradient in a CFB is very steep in the annulus and becomes less steep near the core and annulus boundary.

The center of the riser symmetry is handled by setting the temperature gradient across the symmetry point to zero. The temperature of the center symmetry point, within the finite difference formulation, is set to equal to the core temperature at the same riser height. This boundary condition becomes less valid near the top and bottom of the riser, where the solids exit and entry points are not symmetric.

Using the given equation and boundary conditions, a temperature profile of the riser was obtained.

3.2.7.4 Wall to Cell Heat Transfer Equation

The wall heat transfer coefficient term used is from a Studsvik report [Morris, 1988]. This term was obtained by fitting experimental data on the Studsvik CFB unit. A linear relationship between the furnace side heat transfer coefficient and the furnace solids bulk density was observed to be the following.

$$h_f = 1.8\rho_b \qquad \text{.........(3.9)}$$

where, h_f furnace side heat transfer coefficient ($W/m^2{\cdot}K$)
ρ_b furnace solids bulk density (kg/m^3)

3.2.7.5 Cyclone and Standpipe

The cyclone is treated as adiabatic. The total amount of devolatilization and char combustion is recorded and an overall heat balance is calculated. There are two possible selections for the solids return particle temperature. The first selection is assuming that a heat exchanger is placed between the cyclone and the standpipe, the solids return particles are assumed to re-enter the riser at a constant temperature, set by the user. The second selection is to set the temperature of the solids return equal to the operating temperature of the cyclone. The second selection was chosen in the sensitivity analysis cases.

The solids return particles are initially mixed with the combustion air and the fuel feed. The initial temperature of this mixture is used as the boundary condition of the surface temperature of the south face of the primary zone. Since this surface temperature is usually not equal to the temperature of the primary zone, there is heat loss due to conduction and radiative heat transfer through this surface. The magnitude of the heat loss is less than 0.5% of the total heat transfer through the membrane wall; therefore, this loss does not affect the accuracy of the heat balance equation and the final temperature results. However, better alternative to this boundary condition, is to set the boundary condition as being an adiabatic surface. In this way, there would be no heat loss through this surface.

3.3 DESCRIPTION OF MODEL PROGRAM

3.3.1 Input and Output Files

The model's algorithm is seen in Figure 3.6, a description of the convergence loops and tolerances used are listed in Table 3.2, and the program listing is included in appendix A. Initially, input and output files are assigned. There are 2 input files included in appendix B; one containing the CFB initial conditions and specifications, most of which are output values obtained from Senior's CFB model. The other input file includes the fuel specifications, the relaxation parameters used in the specific case and the number of particles in the Monte Carlo method. The four output files generated by the program are listed below.

(i) A final output file included in appendix C

(ii) A file that contains the temperature distributions at every iteration

(iii) A file that contains information used in the enthalpy balance check

(iv) A file that contains the temperature of one cell at every iteration, which show whether of not convergence has been achieved.

A description of the input and output variables used in the program are listed in appendix D.

Figure 3.6 Model Algorithm

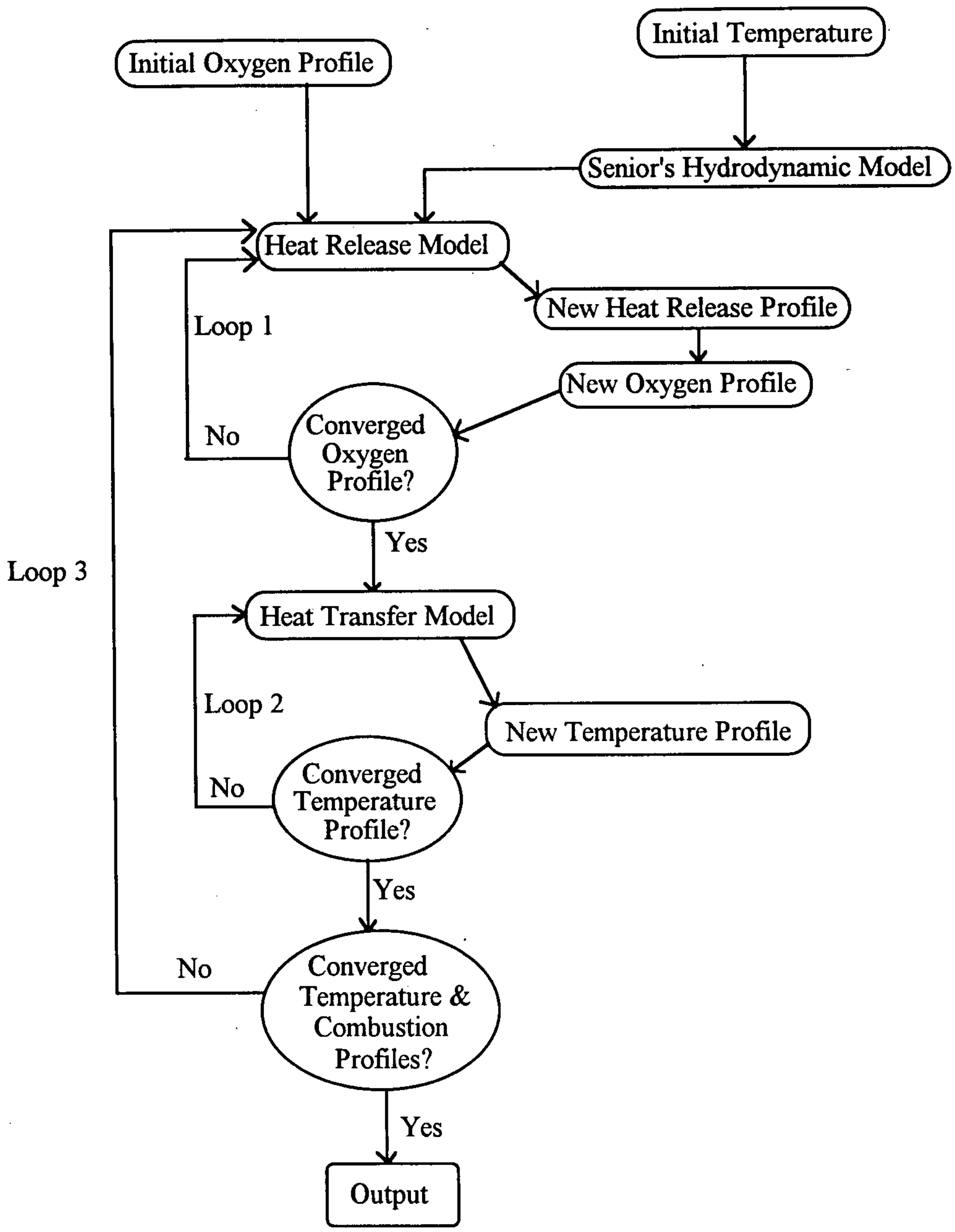


Table 3.2 Description of Convergence Loops and Tolerances used in Program

Convergence Loop	Description	Tolerance	Relaxation
1	Partial pressure of oxygen profile convergence for the core cells only	Absolute 0.001 atm.	0.7
2	Temperature profile convergence	Relative 1%	0.7
3	Heat Transfer Subroutine convergence is met by monitoring the convergence of 1 core cell's temperature at every call to the heat transfer subroutine calculation, or comparing the temperature profile with the previous iteration's profile, until the absolute error is less than the set tolerance.	Absolute approx. 0.01 °C	--

3.3.2 Program Steps

(i) The program initially reads the input files and creates the output files.

(ii) The riser is divided into core and annulus cells, and cell dimensions are then determined. For all the test cases, the riser was divided into 20 core cells and 20 annulus cells, which have equal height and corresponds to the cell divisions used in Senior's model. Also there is a cell that represents the primary zone and a cell that represents the cyclone.

(iii) Given the gas velocities, the combustion efficiency and the excess oxygen value of the gas and the ultimate analysis of the fuel, the air and fuel feedrates are calculated.

(iv) The transverse and radial mass fluxes for all the cells are converted into mass flowrates.

(v) The mass flowrate values are used in a mass balance where the axial mass flowrates of particles in the core cells were changed to ensure conservation of mass throughout the riser. Due to the nature of Senior's mass fluxes output values, the mass balance for each cell in the riser was not entirely balanced. The error in the mass balance varies from + 4% near the bottom of the riser to - 5% at the top of the riser. Although this did not pose problems to Senior's hydrodynamic model, the enthalpy balance is very sensitive to the mass balance. A mass balance was needed to solve the temperature distribution in this model.

(vi) Next a uniform initial value of 21% partial pressure of oxygen was set for the riser, and a uniform temperature of 850 °C was guessed for the bed. In addition, the user was prompted by the program to specify whether the solids return temperature will be equal to the cyclone temperature or a set temperature, specified by the user.

(vii) A probability matrix is then set up using the mass flowrate information. This matrix is used to determine how a coal particle will travel within the CFB riser during devolatilization and char combustion.

(viii) Next the total membrane surface area is determined if a CFB design approach is used. Given an initial operating temperature of the bed, the program will calculate the fractional heat transfer area needed to achieve that temperature. If a rating approach is used, the user can specify the heat transfer area and the program will then calculate the operating temperature. Presently, the program sets the heat transfer surface as evenly distributed on all sides and along the full height of the riser above the secondary zone. The location of the heat transfer surface can be easily set at specific locations, at a later date.

(ix) The devolatilization subroutine is called.

(x) This heat release profile due to devolatilization is corrected by using a volatile transfer fraction term, which assumes that the unburnt volatiles travel up the riser in a plume until they reach a cell with more oxygen, or until the volatiles are radially fully mixed with other gases. This phenomena is discussed in more detail in Section 3.2.2.

(xi) The heat release due to devolatilization is determined, by summing up the total volatiles released in each cell and assuming the volatiles have the same higher heating value as for char.

(xii) The subroutine to determine the partial pressure of oxygen profile is called. A mass balance is done to determine the oxygen profile. The secondary air is introduced into both the core and the annulus cells just above the primary zone. The split is determined on the core and the annulus cross-sectional area. In this way, the mean gas velocities in the core and annulus will be constant and equal to the gas velocities set in the user input file.

(xiii) This updated partial pressure profile of oxygen is compared with the previous iteration's profile to determine if convergence has been met. If convergence has not been met, the heat release due to char combustion is recalculated using the updated partial pressure of oxygen profile.

(xiv) The subroutine to calculate the temperature profile of the CFB riser is called. Finite differences with a control volume formulation was used to conduct an enthalpy balance around each cell to determine the temperature profile.

(xv) The updated temperature profile is determined.

(xvi) The temperatures for the core and annulus cells at a height that corresponds to the beginning of the developing zone are altered to smooth the temperature profile. The other cell's temperatures were not altered. This discontinuity in the temperature profile is discussed in the Section 3.3.4.

(xvii) The updated temperature profile is compared to the previous iteration to ensure convergence is reached. If convergence has not been achieved, the heat release due to devolatilization and char combustion and the partial pressure of oxygen subroutines are recalculated.

(xviii) A printout of the output is generated.

3.3.3 Model Tuning

The major parameters in the user input file, found in appendix B, that can be varied for convergence reasons are listed below.

(i) Number of particles in the Monte Carlo method.

The greater the number of particles used, the heat release distribution, the oxygen partial pressure profile and the temperature profile will be more smooth. The errors associated with not enough particles become more evident in the oxygen partial pressure profile in the annulus. A coal particle does not travel through many annulus cells, especially near the bottom of the riser; therefore, as the number of particles increases, more particles will travel though any given cell.

Initial tests of the Monte Carlo method showed that approximately 100 particles are needed for reproducible results, in the core cells, which do not significantly change as more particles in the Monte Carlo method are used. More than 400 particles are needed to produce smooth profiles in the annulus cells. However, as more particles are used, the total run time increases linearly.

(ii) Tolerance used in the partial pressure of oxygen profile calculation.

This value is used in convergence loop 1, which is shown in Figure 3.6 and Table 3.2. The tolerance is an absolute tolerance, set at 0.001 atmospheres, which corresponds to a relative tolerance of 1% to 2.5%, and is based on the partial pressure of oxygen in the core. The change in the partial pressure of oxygen in the core was used as the basis, because there is very little oxygen in some parts of the annulus and its' absolute and relative tolerance errors would be too small to be meaningful. Conversely, the absolute and relative variations in the partial pressure of oxygen in the core is not large, and this iterative calculation converges steadily, normally within 10 iterations if an under relaxation factor of 0.7 is used.

(iii) Tolerance used in the temperature profile calculation

This is a relative tolerance, used in convergence loop 2 which is shown in Figure 3.6 and Table 3.2, and is set at 1% of any cell's temperature compared to the cell's temperature in the previous iteration. This calculation is very rapid, using an under relaxation factor of 0.7.

(iv) Tolerance in the heat transfer subroutine.

This value is used in convergence loop 3, which is shown in Figure 3.6 and Table 3.2. Normally, the temperature for 1 core cell was monitored to determine whether a steady-state temperature had been reached; however, the user may also specify a temperature tolerance to determine whether convergence is achieved.

For the test runs conducted, by monitoring the temperature of 1 core cell until convergence has been achieved, the final absolute temperature tolerance was less than 0.01 °C.

(v) Relaxation parameter in the partial pressure of oxygen calculation.

This under relaxation factor is set to 0.7.

(vi) Relaxation parameter in temperature profile calculation.

This under relaxation factor is set at 0.7 and prevents this subroutine from diverging.

The relaxation parameters used in the partial pressure of oxygen and the temperature calculations are used to prevent the profile predictions from diverging. Even if increasing the relaxation parameters does not cause the profile predictions to diverge, this will not significantly decrease the program's computation time, since the limiting calculation is the Monte Carlo method.

(vii) Residence time of the cyclone.

This value is set at 0.3 seconds, and can be easily replaced with a more sophisticated cyclone model, if necessary.

3.3.4 Discontinuity of Temperature Profile

There is a discontinuity in the temperature profile calculated by this model, which varies for different CFBs and initial conditions. The position and magnitude of the discontinuity coincides with the boundary between the developing and the fully-developed zone. The discontinuity results from the hydrodynamic model, which uses different equations to predict the mass fluxes for the developing and the fully-developed zones.

Figure 3.7, shows a plot of mass flowrate versus height for the UBC CFB, and the discontinuity can be seen clearly. Since the discontinuity does not significantly affect the hydrodynamic code, but affects the temperature profile, and since only 1 cell is affected, namely the boundary cell, a curve smoothing subroutine was used to correct for this one point. From Figure 3.8, it can be seen that the curve smoothing subroutine does not change the results of the other points or affect the temperature prediction in subsequent iterations.

Several other methods to correct for the discontinuity were considered. Initially, subdividing the riser into more cells in the axial direction was tested. The result of this test is shown in Figure 3.7. By increasing the number of axial cells, the bounds of the discontinuity location were constricted and the magnitude of the discontinuity was reduced; however, by increasing the number of cells, the run time increased. Secondly, the tolerance in the hydrodynamics code that controls the convergence of the boundary mass fluxes prediction was decreased. This caused the discontinuity to decrease, but not to an extent that the temperature profile would be continuous. In fact, if the tolerance was decreased too much, the hydrodynamic code would not converge.

Figure 3.7 Net Mass Flowrate From the Core to the Streamer versus Height for the UBC CFB

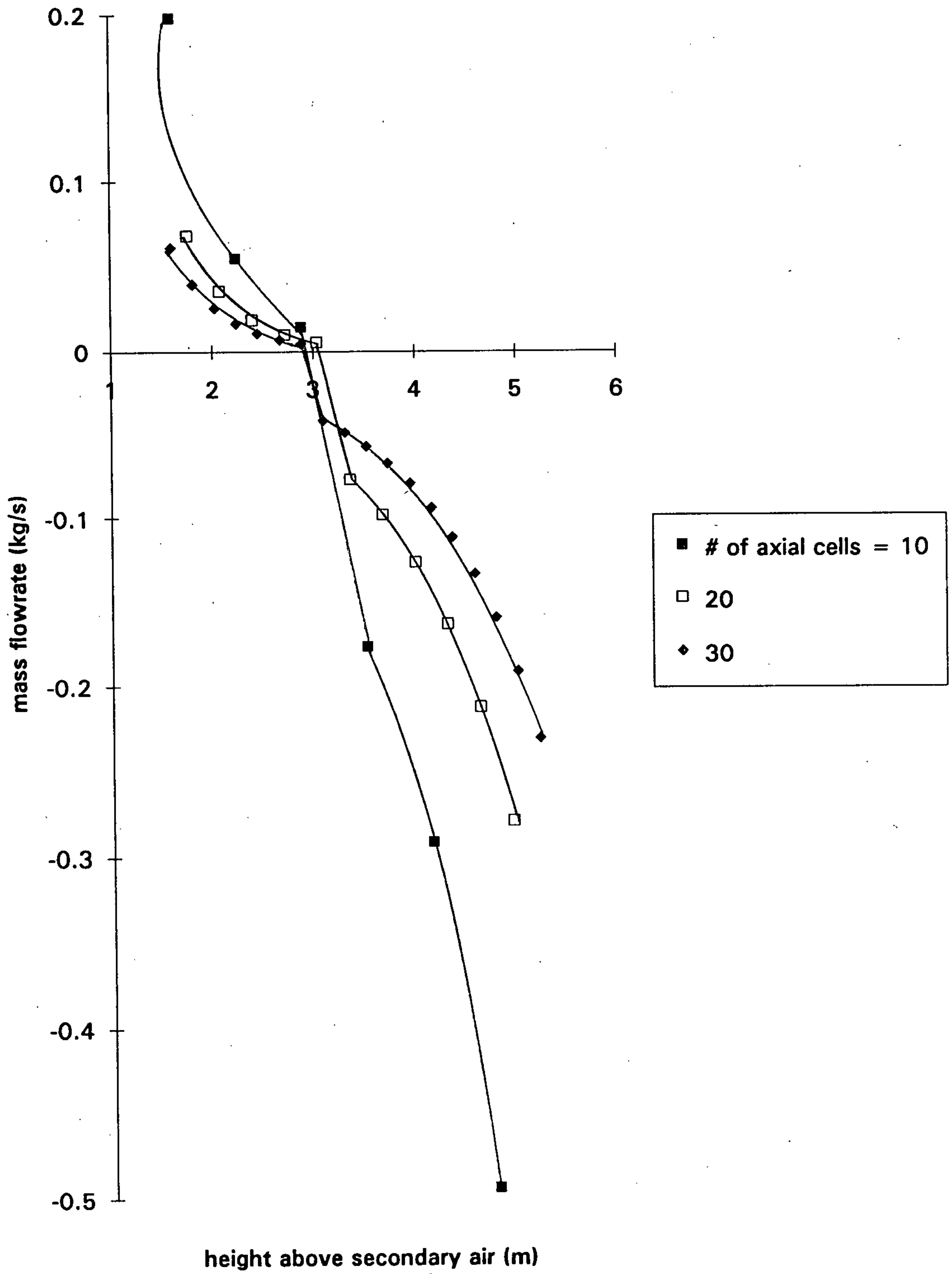
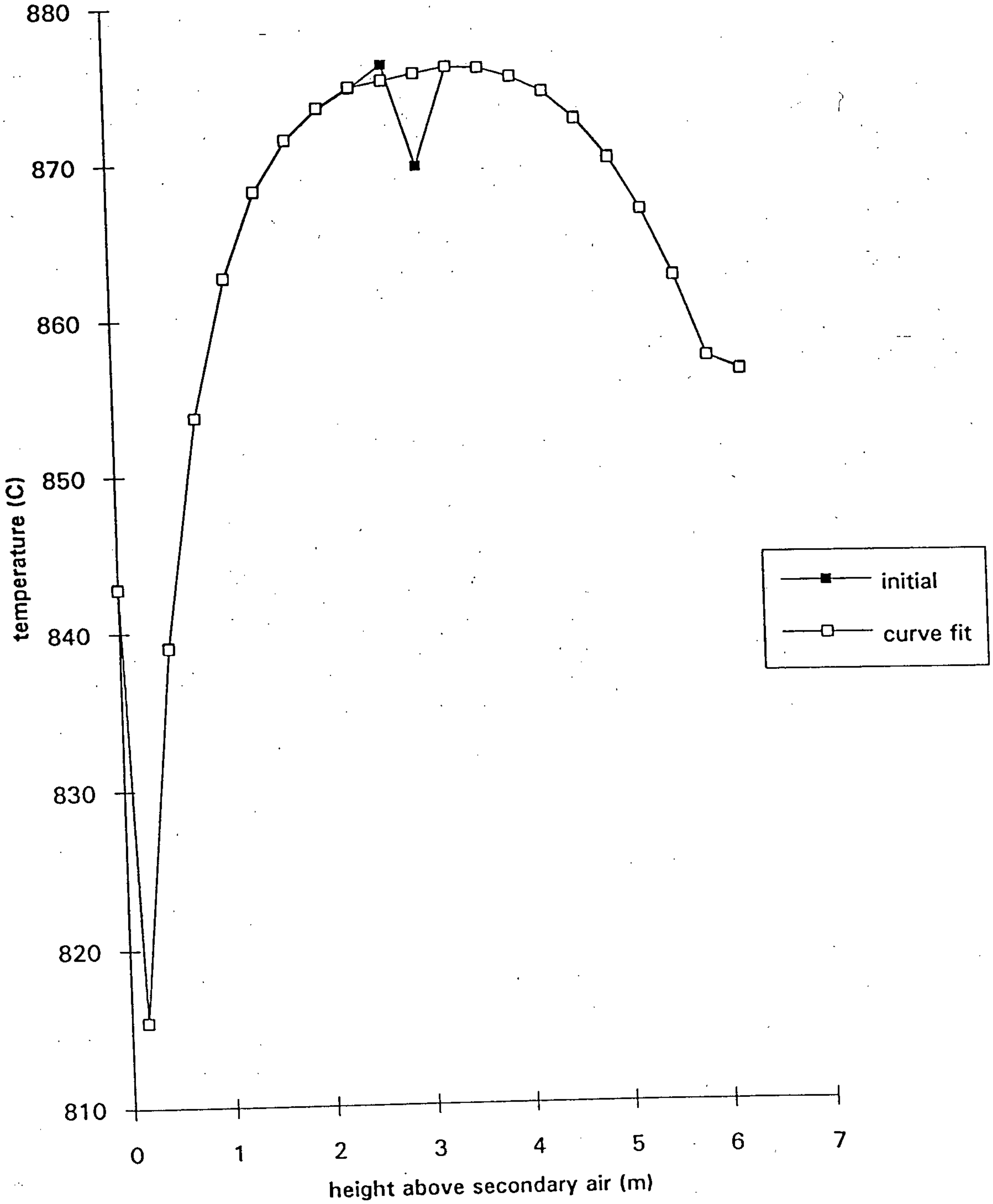


Figure 3.8 Temperature Distribution of Core Cells (before and after curve smoothing)



Since this discontinuity also affected the heat generation profile slightly, smoothing the heat generation profile was considered. This reduced the magnitude of the discontinuity; however, it was still present.

The best method found to date to deal with the discontinuity is to smooth the temperature profile directly, at every iteration.

3.3.5 Convergence

Due to the non-linear nature of the equations, it takes several hundred iterations until a final converged solution is obtained. In practice, several test runs were first conducted at different initial temperature guesses, to determine the bounds of the final temperature solution. These bounds, within $\pm$ 20 °C were then used in the final run. In this way, the initial guess of the temperatures is close to the final solution, so that convergence is achieved in less than 100 iterations. If the test runs were not conducted, it may take more than 600 hundred iterations to obtain the final converged result.

Figure 3.9 shows that there is indeed a final temperature solution, since a higher or a lower initial temperature guess will still converge on the same final value.

Repeatability of the results was also studied by running the same conditions several times, starting with different initial temperature profiles. The results, shown in Figure 3.10, were such that each run produced effectively identical profiles, provided that sufficient time was given for convergence; therefore, the repeatability of the program is good.

3.3.6 Numerical Stability of Partial Pressure of Oxygen Profile

An analysis was done to determine if and when instabilities arose in the partial pressure of oxygen profile iteration and in the temperature profile iteration. For the partial pressure of oxygen profile, it was shown that the greatest relative variation in the amount

Figure 3.9 Temperature Convergence for Various Initial Temp. Guesses (Studsvik CFB, case sh0)

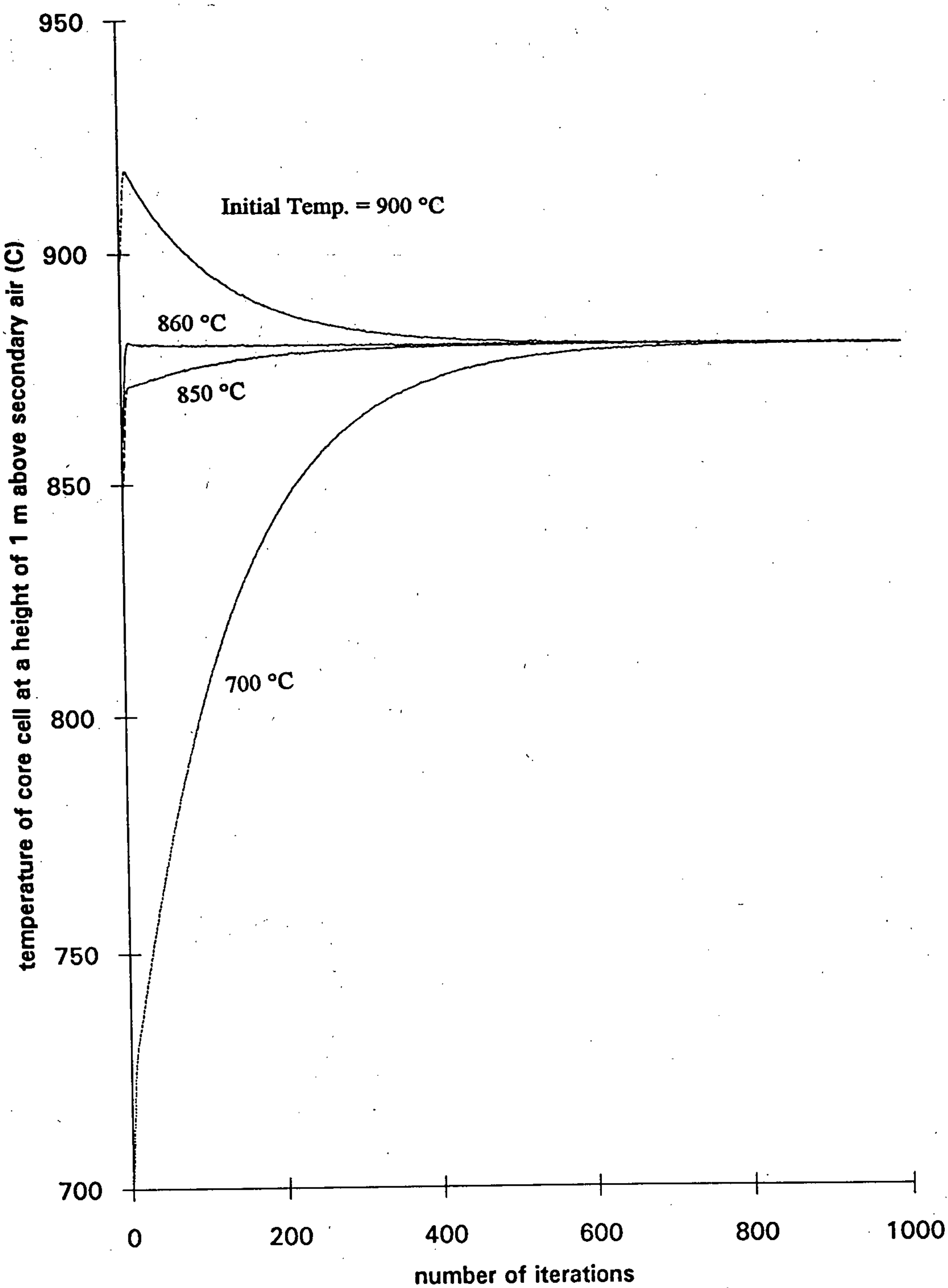
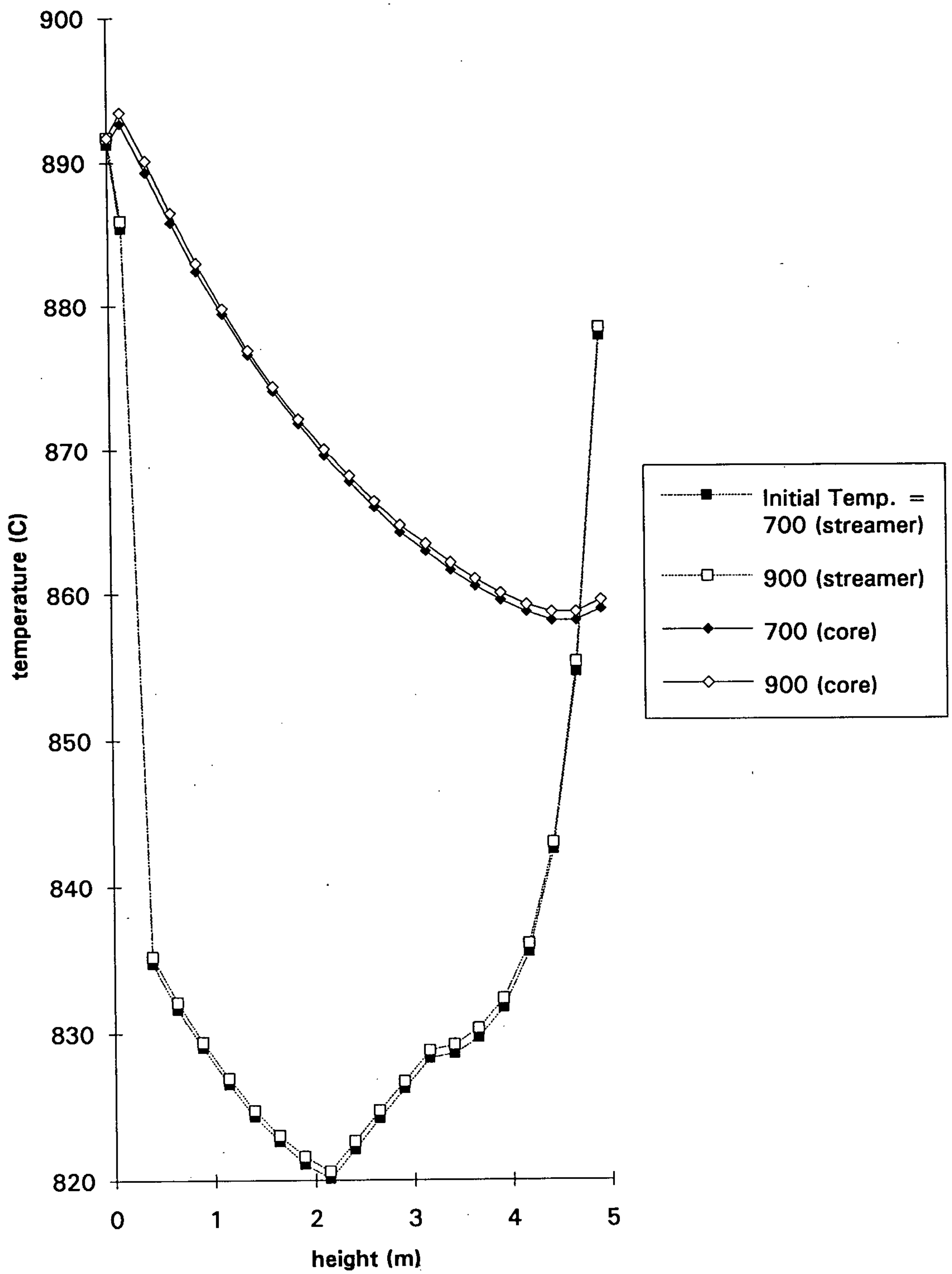


Figure 3.10 Temperature Profiles of Case sh0
(for various initial temperature guesses)



of oxygen was in the annulus cells. This suggests that because only 100 particles were used in the Monte Carlo method, and the volume and residence time in the annulus is small compared to the core cells, if one extra coal particle enters an annulus cell, the oxygen partial pressure profile can be significantly different. A test run was conducted for the Studsvik CFB, in which the number of particles in the Monte Carlo method was increased from 100 particles to 400 particles, see Figure 3.11. From this figure we see that with 400 particles the partial pressure profile in the annulus is more smooth, but clearly more particles are needed to obtain a final converged annulus profile.

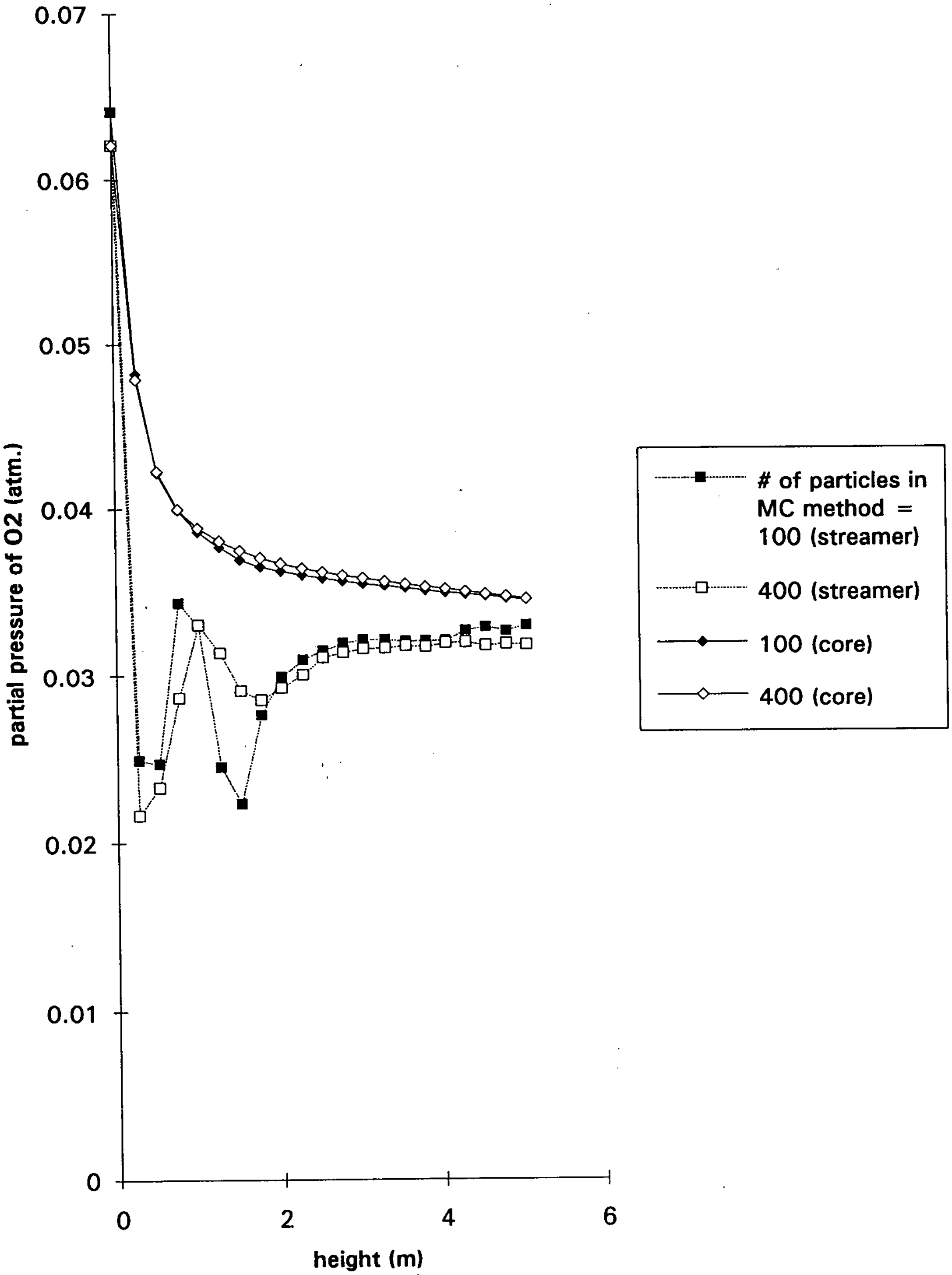
This error in the partial pressure of oxygen in the core cells was small compared to the streamer and seemed to reach a converged value quickly, as will be shown in the next chapter, Figure 4.1.

3.3.7 Run Time

The run time required for convergence could be slightly improved by varying the relaxation parameters and the convergence tolerance values. However, as mentioned previously, the limiting subroutine in the program was generating the heat release distribution using the Monte Carlo method. Decreasing the minimum number of particles needed in the Monte Carlo method, can significantly decrease the overall run time of the program.

For the test cases studied, which are rating problems, initially several quick runs of approximately 10 minutes each were conducted using only 10 particles in the Monte Carlo method and starting each run at a different initial temperature guess, to determine the range of the final converged temperate profile. Then using relaxation parameters of 0.7 for both the partial pressure of oxygen profile and the temperature profile calculations, setting 0.001 atmospheres for the absolute tolerance value of the partial pressure of oxygen and 0.01 °C for the absolute tolerance of the heat transfer subroutine, and using

Figure 3.11 Partial Pressure of O2 vs Height
(Studsvik CFB, Combustion of Highvale Coal with U = 7m/s and Gs = 15 kg/m^{2}s)



100 particles in the Monte Carlo method, the program took approximately 2.5 minutes per iteration. With a initial guess of the final temperature of the riser, which is close to the final converged temperature, program convergence can be obtained within 20 iterations; however, with most of the test runs, the program was allowed to run for 200 iterations to ensure that convergence has been met. The total run time for 200 iterations was approximately 8 hours. If more particles are used in the Monte Carlo method, then the total run time of the program would increase linearly in proportion to the number of particles.

For a design problem, where we wish to find the total heat transfer area needed to achieve a given average operating bed temperature, initial quick test runs were also conducted using a different heat transfer area for each test. The design problem was found to take just as long to run as a rating problem.

The program was executed on Sun workstations, which is approximately 3 to 4 times as fast as a 33 MHz 486 PC.

CHAPTER 4

DISCUSSION OF RESULTS AND VALIDATION

4.1 INTRODUCTION

The goal of a Circulating Fluidized Bed Boiler's operation is to generate steam for energy production. In a typical day, the demand for energy varies, with a higher demand early mornings and early evenings. Since the CFB boiler is unable to store any energy, the operation of the CFB will have to be changed to meet the various steam demands throughout the day.

The basic strategy for meeting varying steam demands is to vary the heat flux from the boiler The basic heat flux equation is given below.

$$Q = UA\Delta T \qquad ....(4.1)$$

Since the heat transfer area, A, is constant and the temperature difference, ΔT, cannot change significantly, this implies that the heat transfer coefficient, U, must be varied.

Some parameters must be kept within certain operating ranges. One of these parameters is the percentage of air leaving with the flue gas. Ideally, this value is kept at a minimum, usually between 10% and 30% excess air, or just enough air is added for complete combustion; thereby, minimizing heat loss by heating the excess air. Secondly, the average temperature of the bed is kept within the operating range of 750 °C to 900 °C. A temperature greater than this range will cause more NOx to be generated, decrease sulphur capture and cause other operating problems. Operating temperatures considerably less than 750 °C will hinder coal combustion.

The exact temperature will depend upon fuel reactivity. The above arguments assume that the reactor is approximately isothermal. At low load, the gas velocity may be low and the circulation rate may drop correspondingly. In this case, the primary zone must be held at the desired operating temperature; therefore, there may be a significant drop in the upper furnace temperatures.

In order to change the heat transfer coefficient to meet the steam demands, the suspension density profile of the CFB must be varied. There are several parameters that can be changed to achieve the desired heat transfer coefficient. The typical parameters include air feedrate, solids recirculation rate and flue gas recycle rate.

To verify that CFB control can be effectively modeled using the program developed here, results were obtained for both the Studsvik CFB and for the UBC CFB using various superficial gas velocities and solids recirculation rate inputs. The model does not consider flue gas recirculation; therefore, the effects of this parameter on a CFB's operations were not studied.

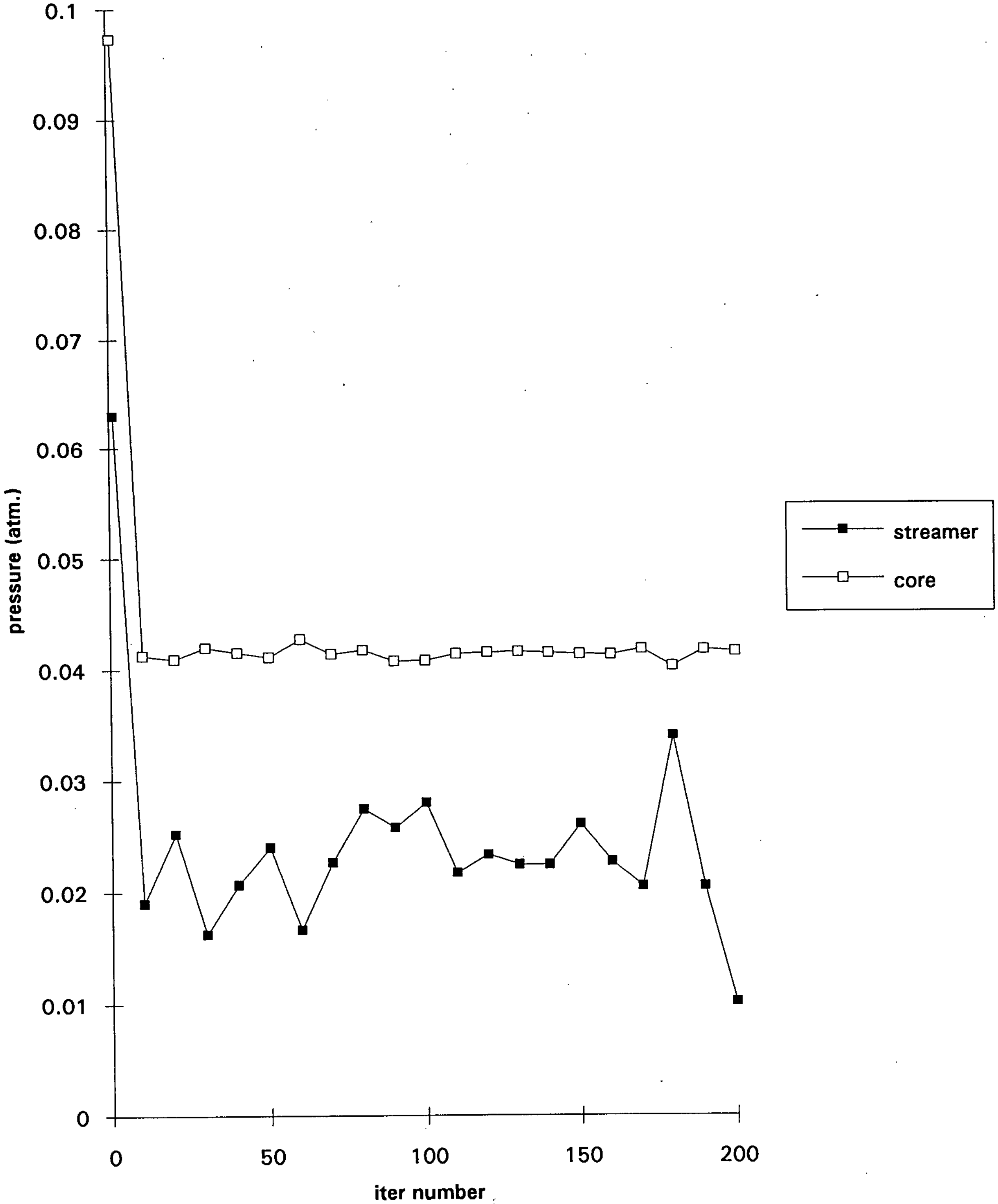
4.1.1 Initial Test Runs

To ensure that a random number was generated with each call to the random number generator, when the program was executed on a 486 PC, a new seed was selected with each call for a random number. The results of several Studsvik CFB runs, sh0, with the same initial inputs were conducted with similar, but not identical results. When this program was executed on the Sun Workstation, it was not possible to generate a random seed with each call to the random number generator; however, the random numbers generated are sufficiently random, such that different initial starting points of the same test case gave the same, but not identical profile predictions.

From previous testing of the model, it is clear that the temperature profile changes affect the pressure profile to a larger extent than the pressure profile causing changes in the temperature profile calculations. The reason for this is that the high solids recirculation rates tend to smooth out the temperature profile, making the temperature more uniform throughout the riser. This effect masks changes in the heat release and partial pressure of oxygen profiles under the conditions studied. Therefore, test runs were conducted to ensure that the CFB's partial pressure of oxygen profile had indeed converged before the program called the subroutine to predict the temperature profile. On average, the program conducted 10 to 20 iterations of the partial pressure of oxygen profile before the tolerance was met and the temperature profile could then be predicted. There was some concern that the tolerance was not tight enough for the pressure convergence. In one test, the partial pressure of oxygen calculation was allowed to continue for 200 iterations, tracking the pressure of oxygen in a core and streamer cell at a height which shows the greatest pressure variations. The height chosen, based on behaviour in previous runs, was 1 m above the secondary air. Figure 4.1 shows that the partial pressure of oxygen in the core cell quickly reached a steady value of approximately 0.04 atm. within the first 10 iterations, while the streamer cell's partial pressure of oxygen did not converge but varied around an average value of 0.02 atm. The reason, which was previously mentioned, is that the number of Monte Carlo particles used may not be large enough so that if one extra particle enters an annulus cell, its oxygen partial pressure profile can be significantly changed. Therefore, more particles in the Monte Carlo method will be needed. This will cause the total run time to increase.

A third test run was conducted to show that the Monte Carlo Method was simulating the path of the coal particle as it traveled throughout the CFB, based on the CFB's hydrodynamics. For this test, a very large "theoretical" particle with a diameter of 1 m was introduced into the primary zone of the CFB and tracked throughout its devolatilization and combustion. The riser was assumed to be at a constant temperature and partial pressure of oxygen. In addition, the devolatilization expression used was from Jia, which is a function of particle diameter. Since the primary zone is normally much larger and denser than a core or streamer cell, a small coal particle will devolatilize and combust before it has the chance to travel up the riser. A large coal particle should have a long enough combustion time for it to travel through all of the cells many times over. In these circumstances, the percentage of the total heat release in each cell should be the

Figure 4.1 Oxygen Partial Pressure of Cells at a Height of 1m Above Secondary Air (Studsvik CFB; case sh0)



same as the cell's percentage suspension density. This was indeed found to be the case; thereby, showing that the Monte Carlo Method was working as the program intended.

4.2 STUDSVIK CFB

4.2.1 General Description

The Studsvik 2.5 MW thermal prototype CFB is a boiler that is 6.1 m tall with a square cross-sectional area of 0.65 m by 0.65 m. There are membrane surfaces on all four sides of the riser. The riser has a smooth exit geometry with a riser top reflection coefficient of 0.1 [Senior, 1992]. A schematic of the Studsvik CFB is shown in Figure 4.2.

4.2.2 Sensitivity Analysis

A set of sensitivity analysis was conducted for the Studsvik CFB to study the effects of varying superficial gas velocity and solid recirculation rates, while combusting Highvale coal. An analyses of Highvale coal is given in Table 4.1, and the particles size distribution of the Highvale coal and the bed are given in Table 4.2. The inputs and the operating conditions of the six cases studied in the sensitivity analysis are listed in Table 4.3. The three different solids recirculation rates studied were 15 kg/m^2s, 30 kg/m^2s and 50 kg/m^2s. In addition, two superficial gas velocities cases of approximately 7 m/s and 6m/s were also studied.

In practice, a commercial CFB may have a "turndown", a reduction in the load, as low as 3:1, or a corresponding decrease in the superficial gas velocity from a full load value of 7m/s to as low as 2.5 m/s. It would be useful to model a case where the superficial gas velocity is 2.5 m/s, to observe changes in the temperature distribution. However, it was found that at superficial gas velocities less than approximately 5 m/s, the hydrodynamic model breaks down. Low gas velocities in the hydrodynamic model, coupled with the existing "wall disturbance factor", which is a value fitted to experimental

Figure 4.2 Schematic of the Studsvik CFB [Kobro, 1984]

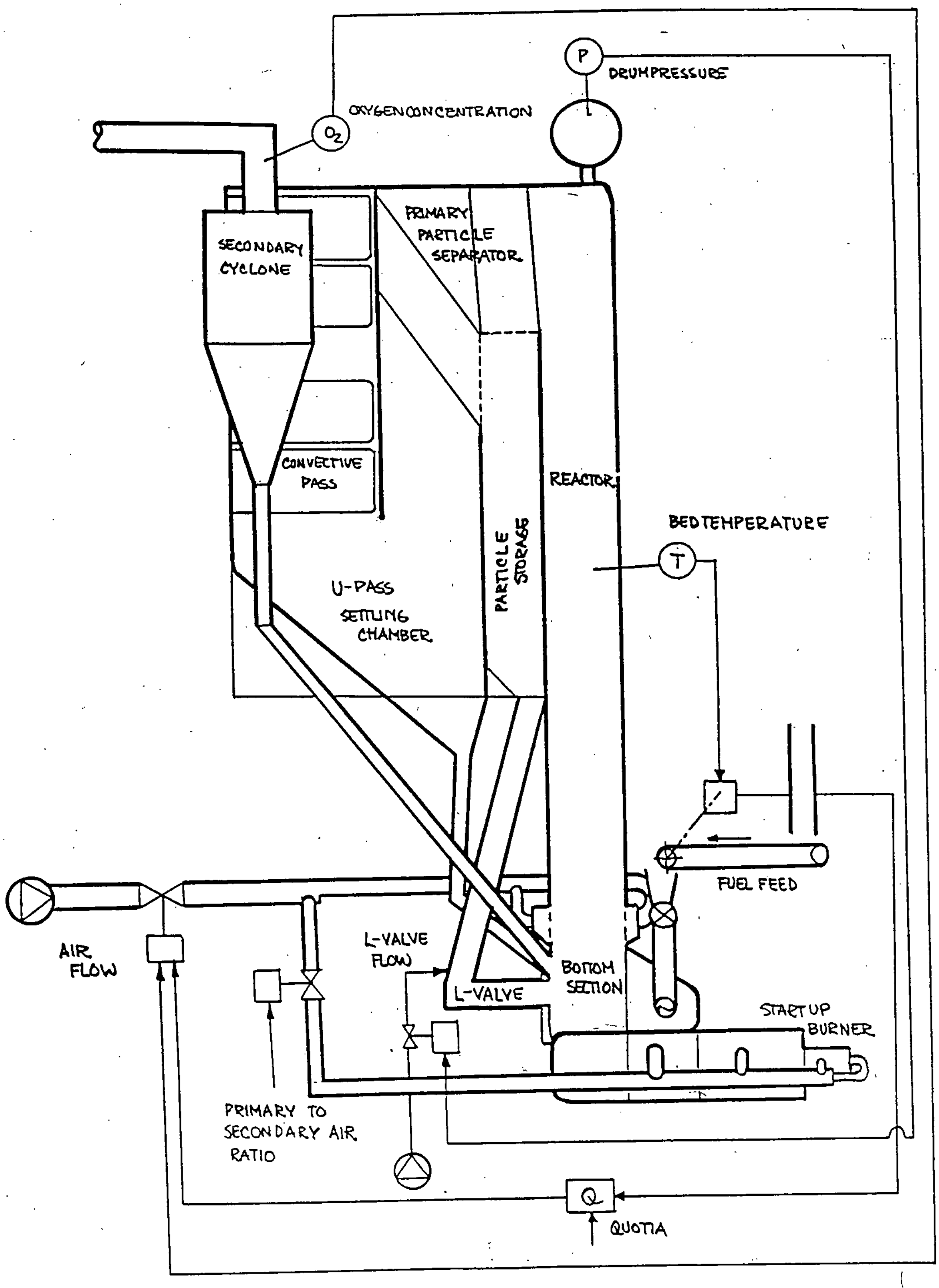


Table 4.1 Characteristics of Highvale Coal [Grace et al, 1989]

Proximate Analysis	(%)
Volatile Matter	30.5
Fixed Carbon	42.1
Ash	12.2
Moisture	15.2
Ultimate Analysis - Dry Basis (%)	
Carbon	62.4
Hydrogen	3.6
Nitrogen	0.8
Sulphur	0.2
Oxygen	18.7
Ash	14.3
Higher Heating Value (MJ/kg)	24

Table 4.2 Particle Size Distribution of Highvale Coal and Bed

Particle Size (mm)	Highvale Coal (%)	Lime (%)	Bed (%)
7.925	9.25	0	0
5.613	10.92	0	0
3.962	13.18	0	0
2.794	12.11	0.34	0
1.981	11.09	0.61	0
1.397	8.73	1.36	2.0
0.991	7.75	0.95	4.44
0.701	5.48	4.33	3.7
0.495	4.75	14.06	3.27
0.351	3.74	13.33	10.78
0.246	3.41	13.19	28.29
0.175	3.99	20.54	23.72
0.124	1.29	19.76	14.33
0.088	0	7.02	5.95
0.053	0	2.91	1.54
0.045	0	1.51	0.66
0.038	0	0	0.57
0	0	0	0.75

Table 4.3 Major Parameters in the Sensitivity Analysis Cases (Studsvik CFB, base case sh0)

cases:	sh0	sh1	sh2	sh3	sh4	sh5
superficial gas velocity (m/s)	7	7	7	6	6	6
solids recirculation rate (kg/m^2s)	30	50	15	30	50	15
solids return temperature (°C)	859	835	898	812	764	852
fuel feedrate (kg/hr)	396	389	403	341	335	347
air feedrate (kg/hr)	3070	3018	3129	2644	2599	2694
height of developed zone (m)	2.8	2.5	3.3	2.5	2.5	3.0
Highvale coal	yes	yes	yes	yes	yes	yes
Fuel density (kg/m^3)	1400	1400	1400	1400	1400	1400
bed density (kg/m^3)	2800	2800	2800	2800	2800	2800
average particle size (mm)	2.89	2.89	2.89	2.89	2.89	2.89
excess air (%)	20	20	20	20	20	20
number of particles used in the Monte Carlo Method	100	100	100	100	100	100

data over a limited range, produced unreasonable core-wall flux calculations. Therefore, only a 15% reduction in the maximum load has been studied to this point.

In order to study the effects of turndown by decreasing the superficial gas velocity to a value of 3.3 m/s, the wall disturbance factor was increased from 310 to 470. However, there is insufficient experimental hydrodynamic data to validate this modification. The results from this low superficial gas velocity test, sh6, for the Studsvik CFB, is presented at the end of appendix C. Clearly, further work is needed to extend the hydrodynamic model to cover a greater operating range.

Initially, the heat transfer area needed to give an average operating temperature of 850 °C was calculated. The heat transfer area calculated was approximately 70 % of the total wall area. This percentage wall area was used for all the runs in the sensitivity analysis. The actual heat transfer area of the CFB can be modified depending on the type of fuel combusted by installing refractory, but is approximately 50% of the total wall area.

As expected, the heat transfer area calculated using the model was larger than the actual heat transfer area. This is a result of two major reasons.

The model assumes that the membrane surfaces are smooth and not made up of membranes, or parallel tubes connected longitudinally by fins. Therefore, the actual total membrane surface area is greater than the area calculated in the model. The model corrects for this inconsistency by calculating the total heat transfer area based on the steady state bed temperature one would like the model to operate at. In this way, the total heat transfer area would be equivalent to the actual heat transfer area of a membrane surface. Further work on the details of the membrane wall heat transfer would aid in the calculation of the cell to wall heat transfer rate. The performance of the membrane surface should include an effectiveness factor.

Secondly, the model does not include heat loss from the riser. However, based on a rough overall energy balance on the Studsvik CFB, assuming 50% heat transfer area, the surface of the CFB is at 35 °C, the heat transfer coefficient from the CFB surface to the surrounding air is 15 W/m^2C, the surrounding air is at 20 °C and a coal feedrate of 400 kg/hr, the heat loss from the riser is less than 10 % of the total heat generated.

4.2.3 Results

The following figures of heat release, oxygen partial pressure and temperature profiles are for conditions above the secondary air. At a height of 0 m, this point indicates the condition in the primary zone.

4.2.3.1 Heat Release Profiles

The results from the sensitivity analysis, Figures 4.3, 4.4 and 4.5, show that the volatiles and char heat release is mainly in the primary zone. This is because the devolatilization expression used releases the volatiles quickly from the coal upon entry into the primary zone. In addition, the density and size of the primary zone is large compared

Figure 4.3 Volatiles Heat Release vs Height
(Combustion of Highvale Coal with U = 7 m/s; Studsvik CFB; cases sh0, sh1 & sh2)

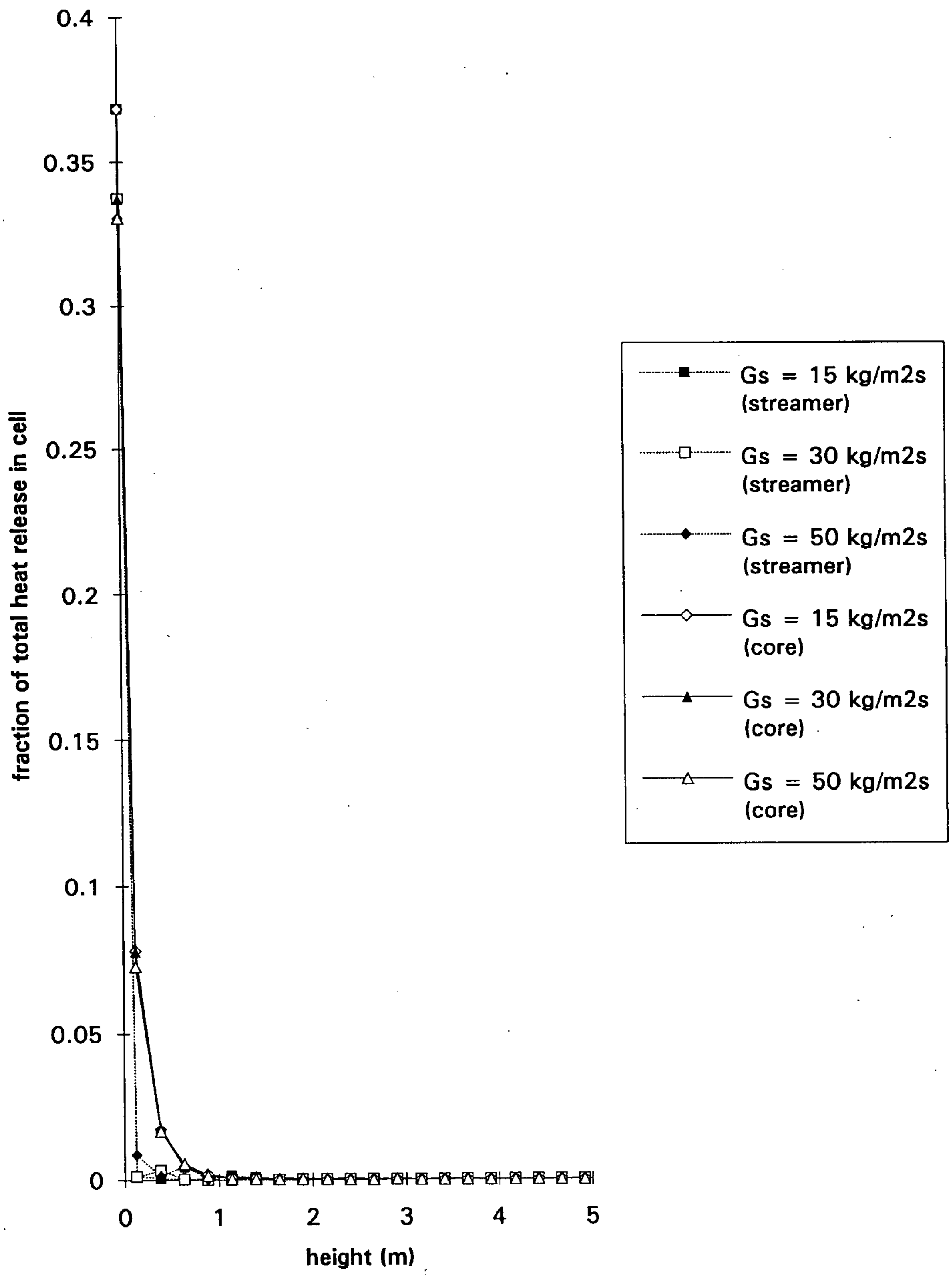


Figure 4.4 Char Heat Release vs Height
(Combustion of Highvale Coal with U = 7 m/s; Studsvik CFB; cases sh0, sh1 & sh2)

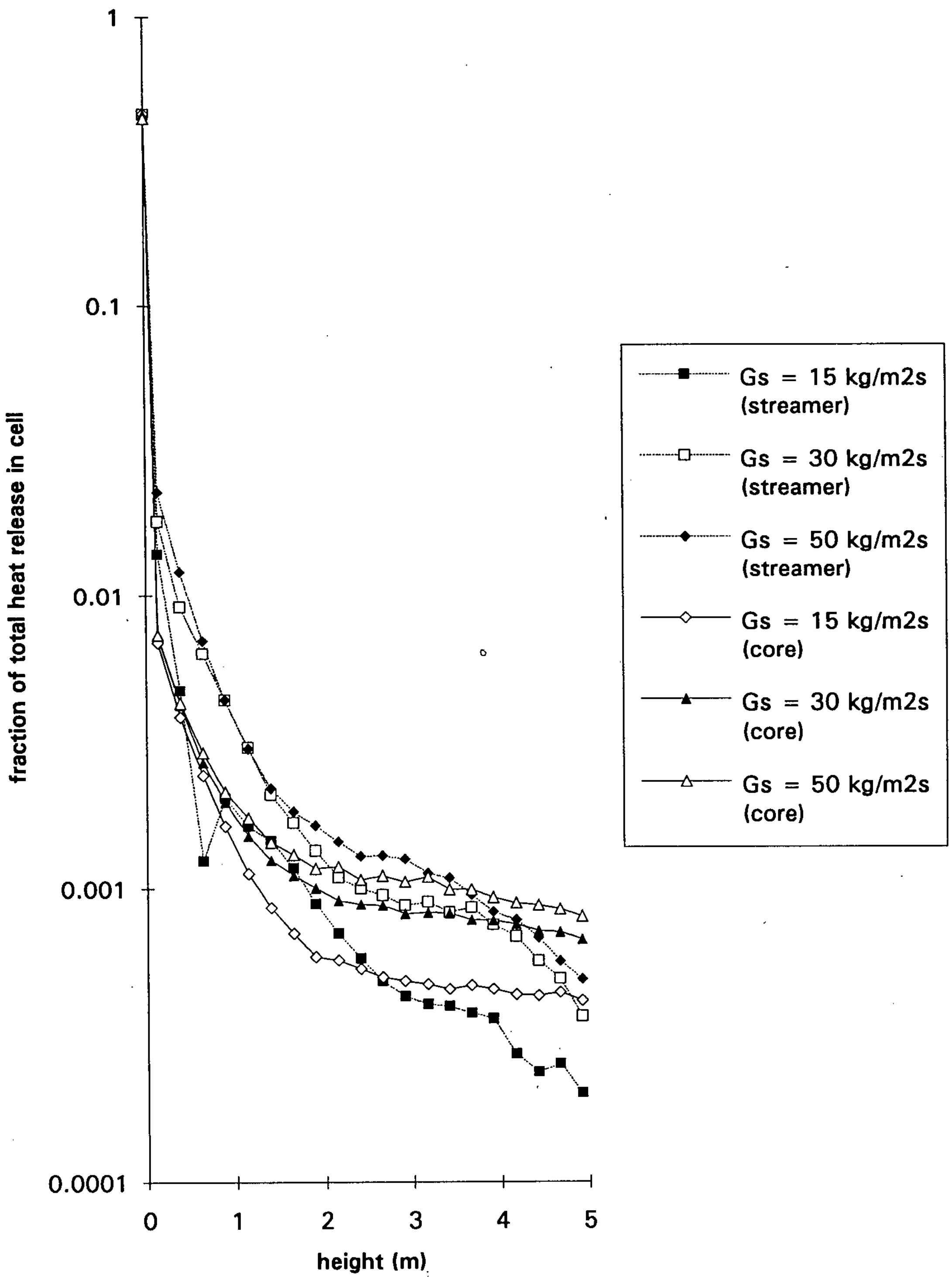
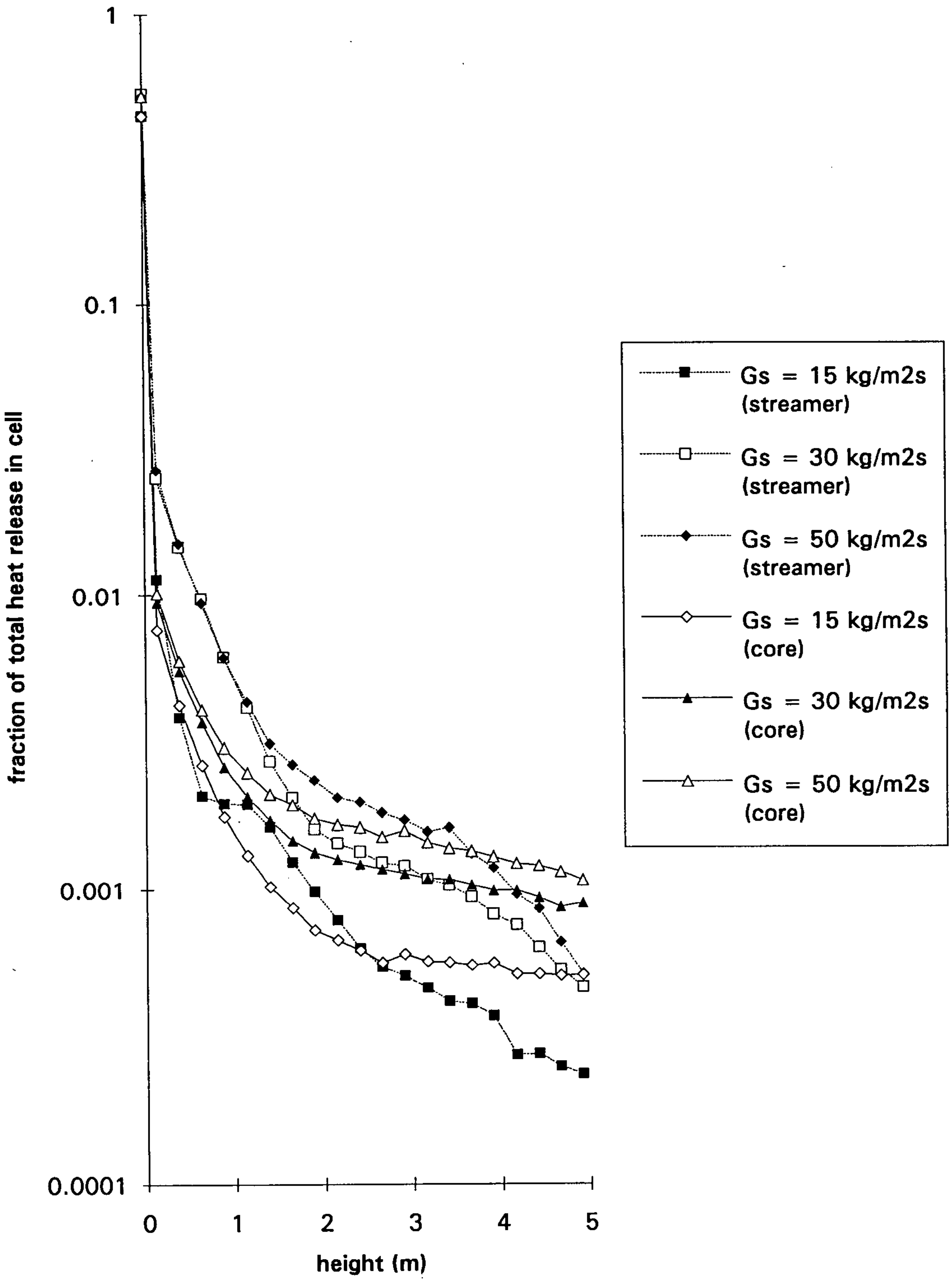


Figure 4.5 Char Heat Release vs Height
(Combustion of Highvale Coal with U = 6 m/s; Studsvik CFB; cases sh3, sh4 & sh5)



to other cells in the riser, and the residence time in the primary zone compared to other cells is considerably larger. The primary zone is approximately 6 to 8 times larger than a core cell and 6 to 50 times as dense.

The second observation from these figures is that the char heat release profiles for various solid recirculation rates are almost the same; however for higher solid recirculation rates, the fraction of heat release in the primary zone is less; thereby, a larger percentage of heat is released in the riser and cyclone. This is because as more solids are being added to the riser, the primary zone begins to become saturated with solids, and the percentage density increase in that zone is not great. The density of the primary zone stays almost constant at approximately 315 kg/m^3. Instead, the solids are transferred up the riser and the percentage density change of the riser in the secondary zone is significantly increased, causing more heat to be released further up the riser. The density changes can be seen in Figure 4.6.

In addition, the case with a higher superficial gas velocity show a slightly lower fraction of heat release near the bottom the riser. The higher gas velocity seem to contribute to carrying the particles from the primary zone up the riser, consequently releasing the heat in the secondary zone. This can be seen by comparing the heat release results from runs sh0 and sh3, shown in Figure 4.7.

4.2.3.2 Partial Pressure Profiles

From the partial pressure of oxygen profiles, shown in Figures 4.8 and 4.9, a higher partial pressure of oxygen was shown for higher solid recirculation rates and for higher gas velocities. However, the higher oxygen concentration in the core meant fewer oxygen in the streamer cells. The total amount of oxygen in the streamer is very small, approximately 1.5% of the total oxygen in the riser. In addition, the oxygen profile in the streamer varied from iteration to iteration. It is difficult to obtain a converged oxygen profile, as can be seen in Figure 4.1.

Figure 4.6 Changes in Core Density in Secondary Zone for Various Solids Recirculation Rates - Primary Zone Density = 315 kg/m^3
(Combustion of Highvale Coal with U = 7 m/s; Studsvik CFB; cases sh0, sh1 & sh2)

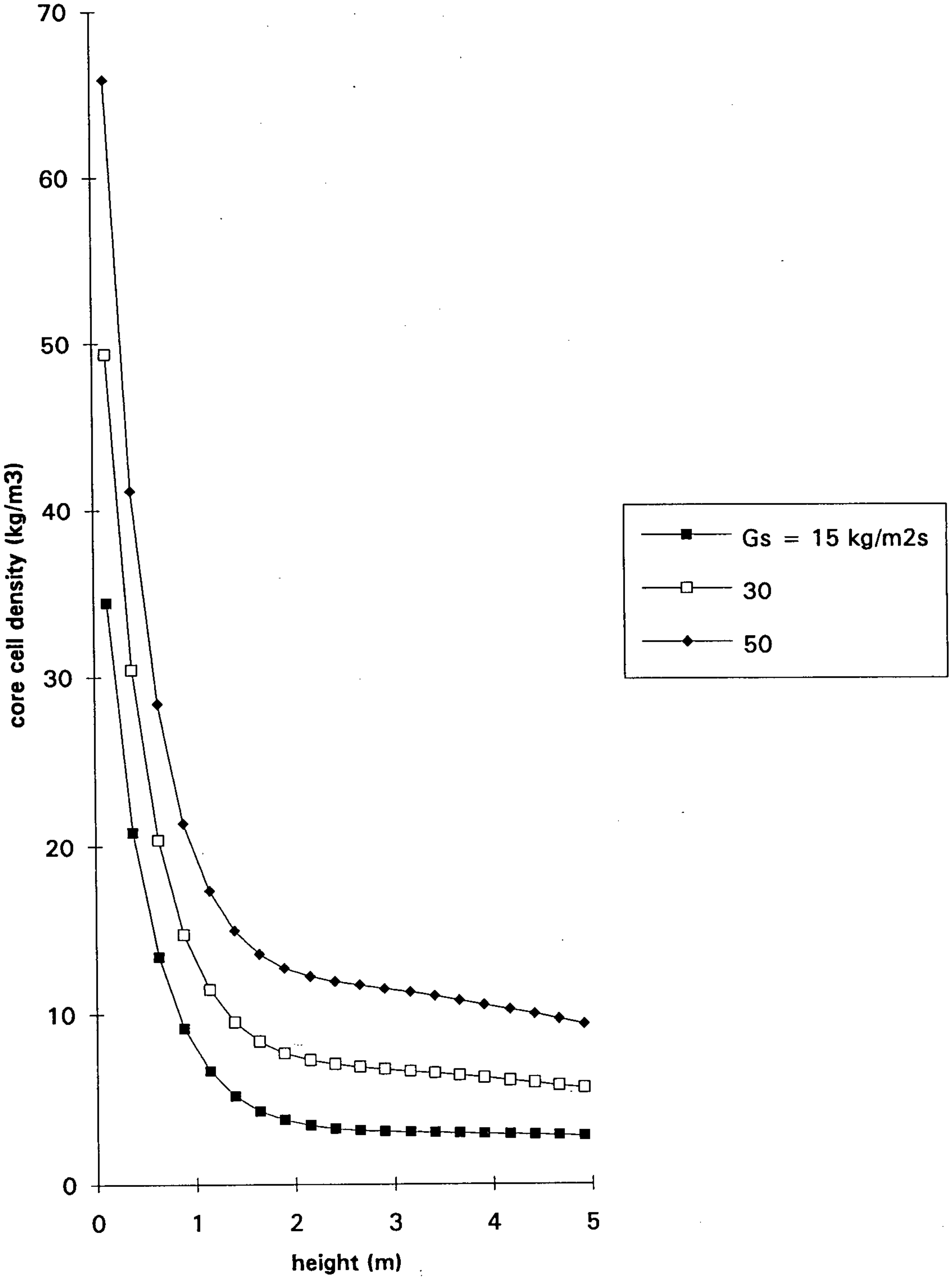


Figure 4.7 Char Heat Release Distribution vs Height
(Combustion of Highvale Coal, Studsvik CFB; cases sh0 and sh3)

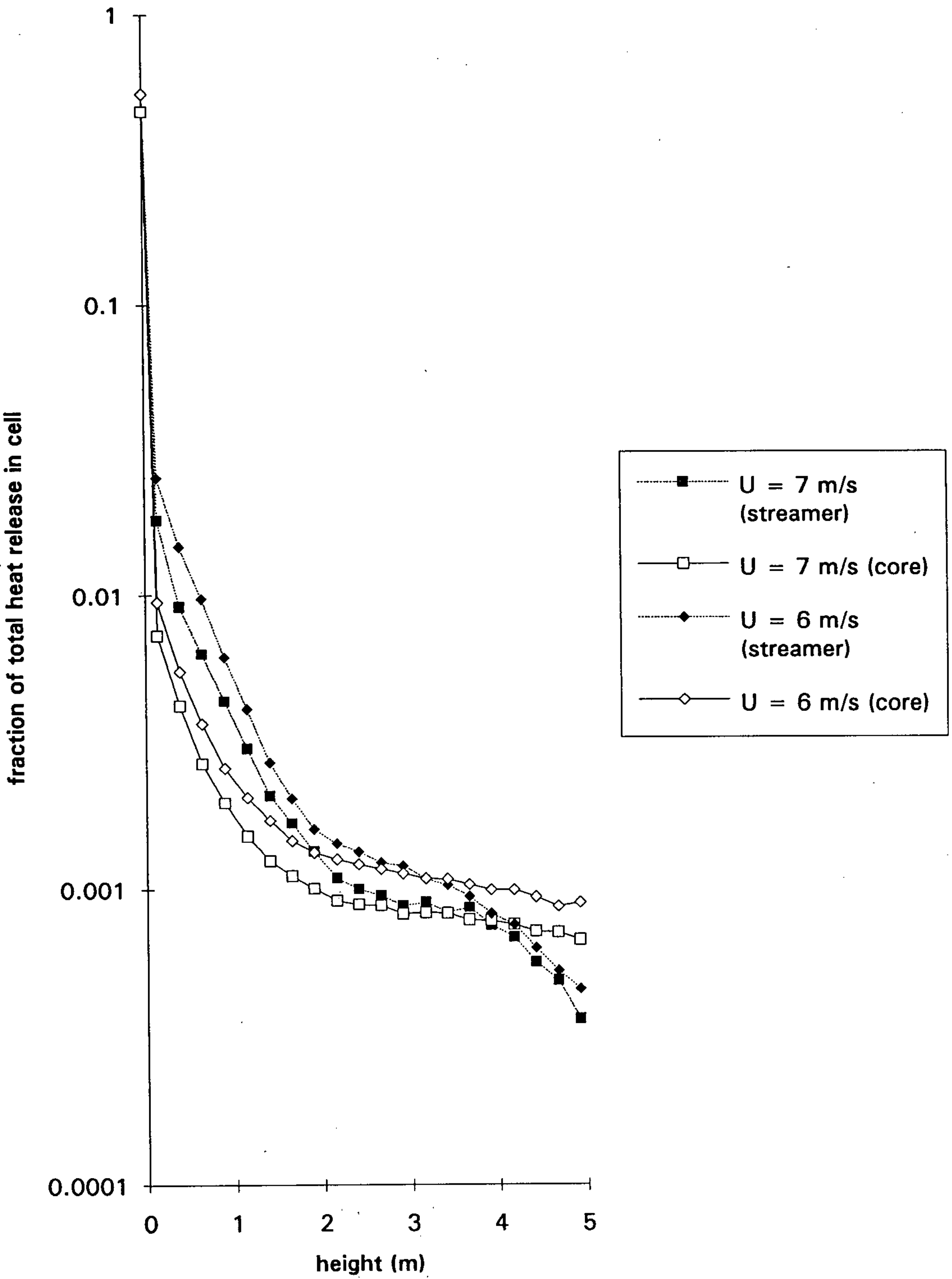


Figure 4.8 Partial Pressure of O2 vs Height
(Combustion of Highvale Coal with U = 7 m/s; Studsvik CFB; cases sh0, sh1 & sh2)

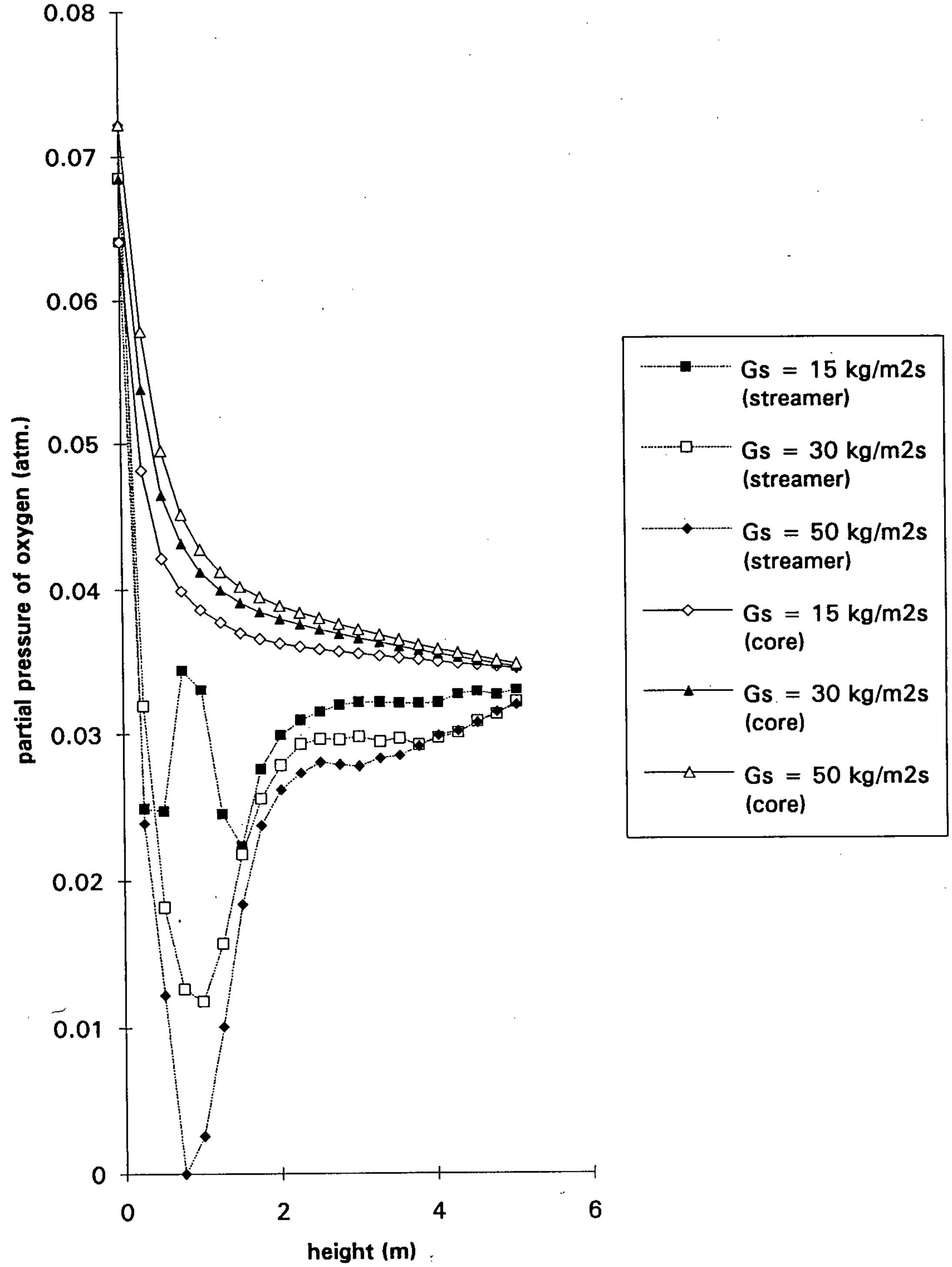
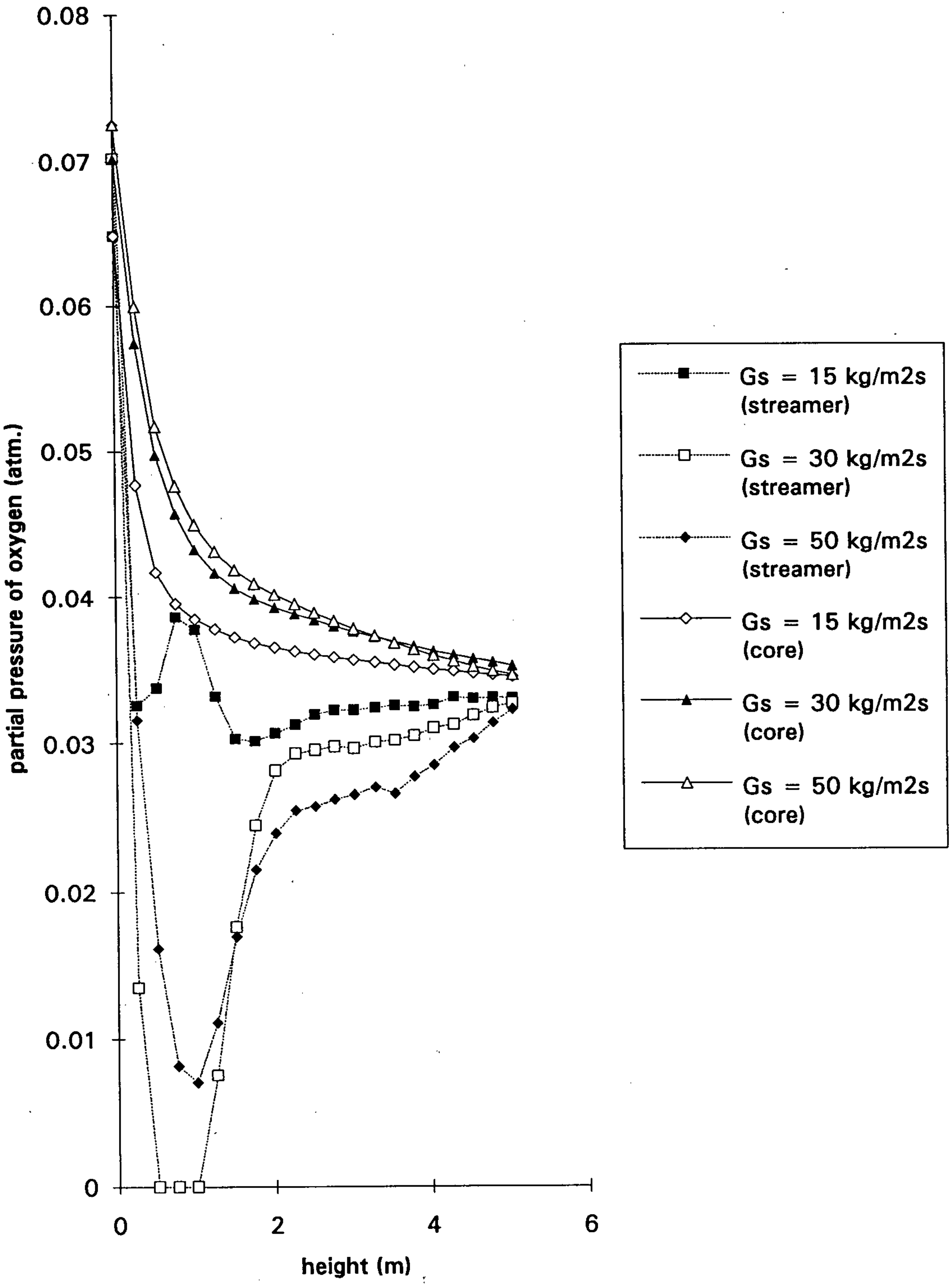


Figure 4.9 Partial Pressure of O2 vs Height
(Combustion of Highvale Coal with U = 6 m/s; Studsvik CFB; cases sh3, sh4 & sh5)



As the superficial gas velocity decreased, there seems to be even less oxygen in the annulus cells. In fact, there are cells where there is no oxygen, near the bottom of the riser. The partial pressure of oxygen in the core cells, however, seems to change very little.

The variation in the partial pressure of oxygen in the streamer cells is due to the insufficient number of particles used in the Monte Carlo method. From Figure 3.11, when more particles are used, we see less fluctuations in the partial pressure predictions.

4.2.3.3 Temperature Profiles

From the temperature profiles, Figures 4.10 and 4.11, we see that although various solids recirculation rates and superficial gas velocities were used in these test cases, the temperature profiles were similarly shaped and uniform; however, they are displaced by approximately 50 °C. This is due to the significant contribution of the heat release distribution to the overall temperature distribution. However, the high internal circulation rates tends to smooth out huge maldistributions in the heat release distribution. Although approximately 80% of the heat release occurs in the primary zone, there are sufficient recirculating solids that there is still only a 50 °C temperature change throughout the riser. It is then understandable that the heat release distributions are similar, and subsequently the temperature profiles will also be similar although the pressure profiles may not be. Pressure has less of an affect on temperature as the reverse situation.

Another interesting phenomena is that the temperature of the streamer increases near the top of the riser, which is due to the nature of the energy balance. The volume of the streamer at the top of the riser is small; approximately 0.0003 m^3, or 0.3% of the core volume at the top. Therefore, hot particles from the core and particles that are reflected off the top of the riser cause the streamer cells to heat up to temperatures that are greater than the core temperatures.

Figure 4.10 Temperature vs Height
(Combustion of Highvale Coal with U = 7 m/s; Studsvik CFB; cases sh0, sh1 & sh2)

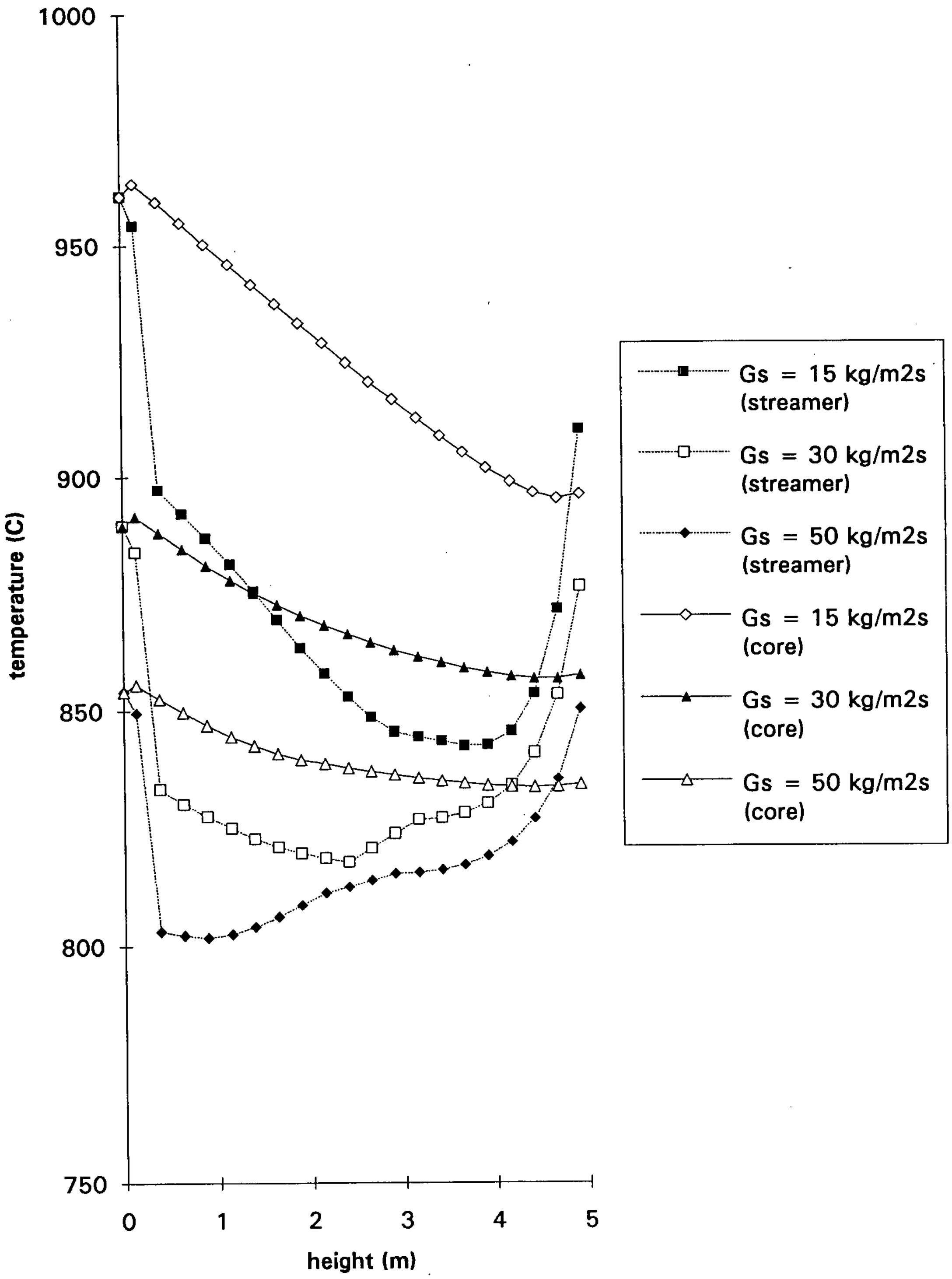
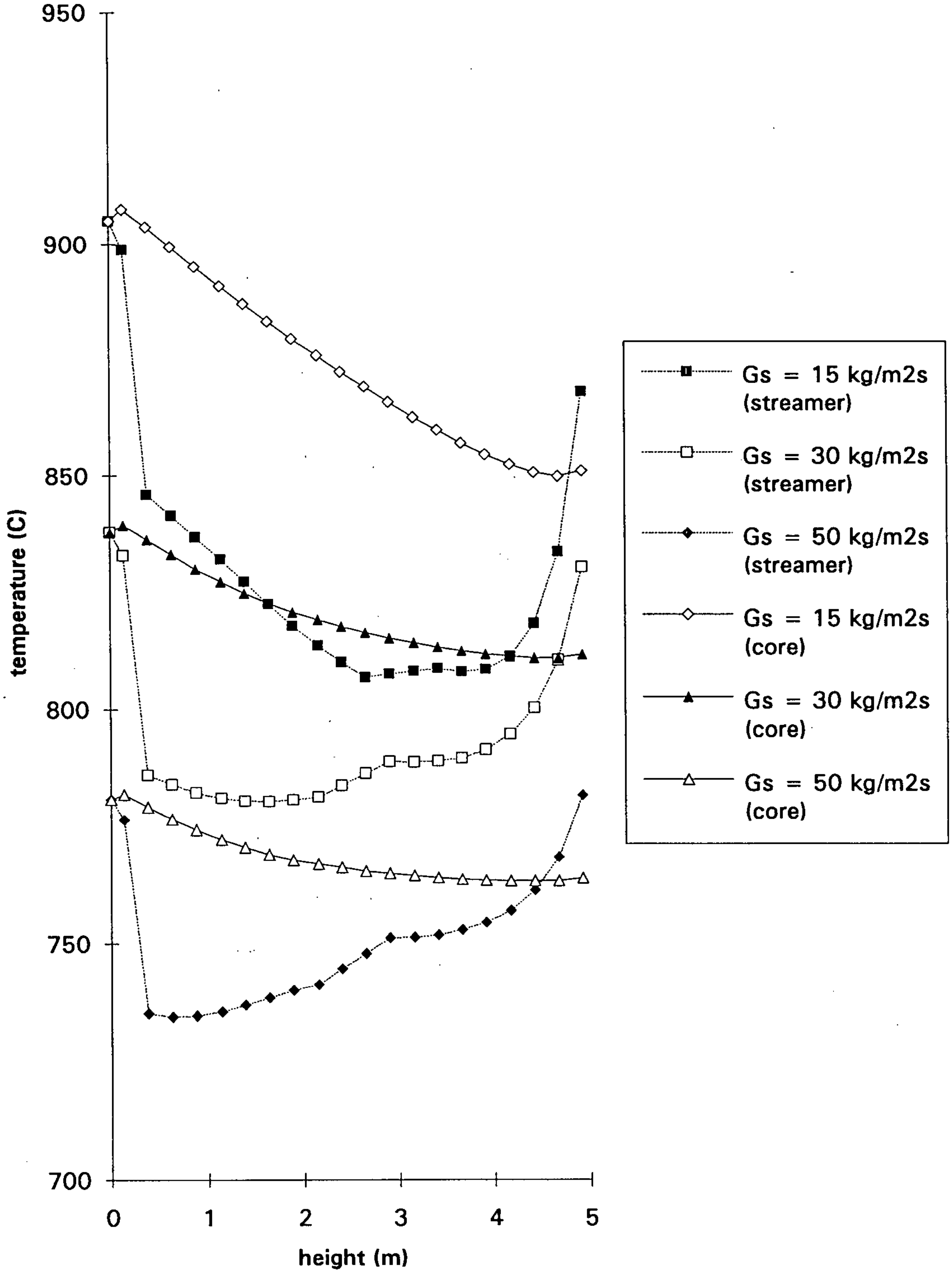


Figure 4.11 Temperature vs Height
(Combustion of Highvale Coal with U = 6 m/s; Studsvik CFB; cases sh3, sh4 & sh5)



The temperature of the core cells is a steady decreasing curve, but the streamer cells have temperatures approximately 50 °C less than the core. This thermal boundary layer near the wall follow the same trends as experimental measurements [Leckner, 1991] and theoretical equations [Brewster, 1984], shown in Figure 4.12.

Although the model's temperature gradient predictions matches Leckner's experimental measurements very well, this is not an indication of the sophistication of the heat transfer model, since a number of simplifying assumptions have been made. However, this does indicate that the average temperature predictions of the model can be used as a starting point to predict combustion and heat transfer rates in the streamer and might be extended to predict the production of certain flue gases such as NOx and SO_2.

4.3 UBC PILOT CFB

4.3.1 Description

The detailed description of the UBC pilot-scale circulating fluidized bed combustion facility can be found in Grace [Grace et al, 1989]. A schematic of the major components can be seen in Figure 4.13.

The reactor column is 7.32 m high and has a cross-section of 152 mm by 152 mm. Primary air flows through the bottom of the CFB, through a distributor plate into a tapered primary zone. The secondary air enters the CFB through 2 opposed air ports located 0.9 m above the distributor plate. The solids and gas leaving the top of the CFB are separated in a refractory lined primary cyclone with 0.31 m ID, and finer particles are captured in a secondary cyclone with a 0.2 m ID. The solids from the primary cyclone are returned through the standpipe located 0.4 m above the distributor.

Figure 4.12 Comparison of Wall Temperature Gradient at a Height of 2.4 m Above Secondary Air with Other Experimental and Theoretical Works

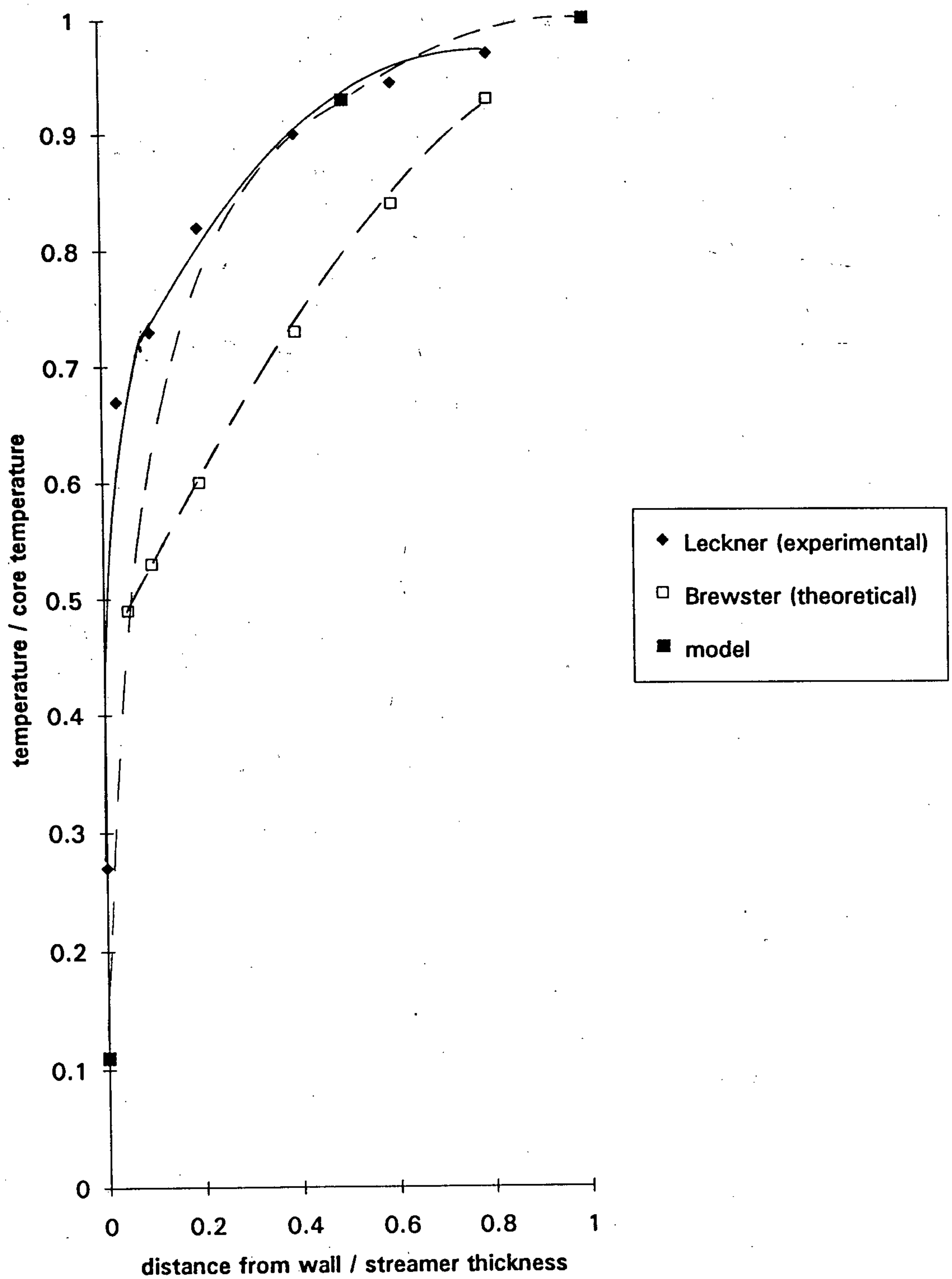
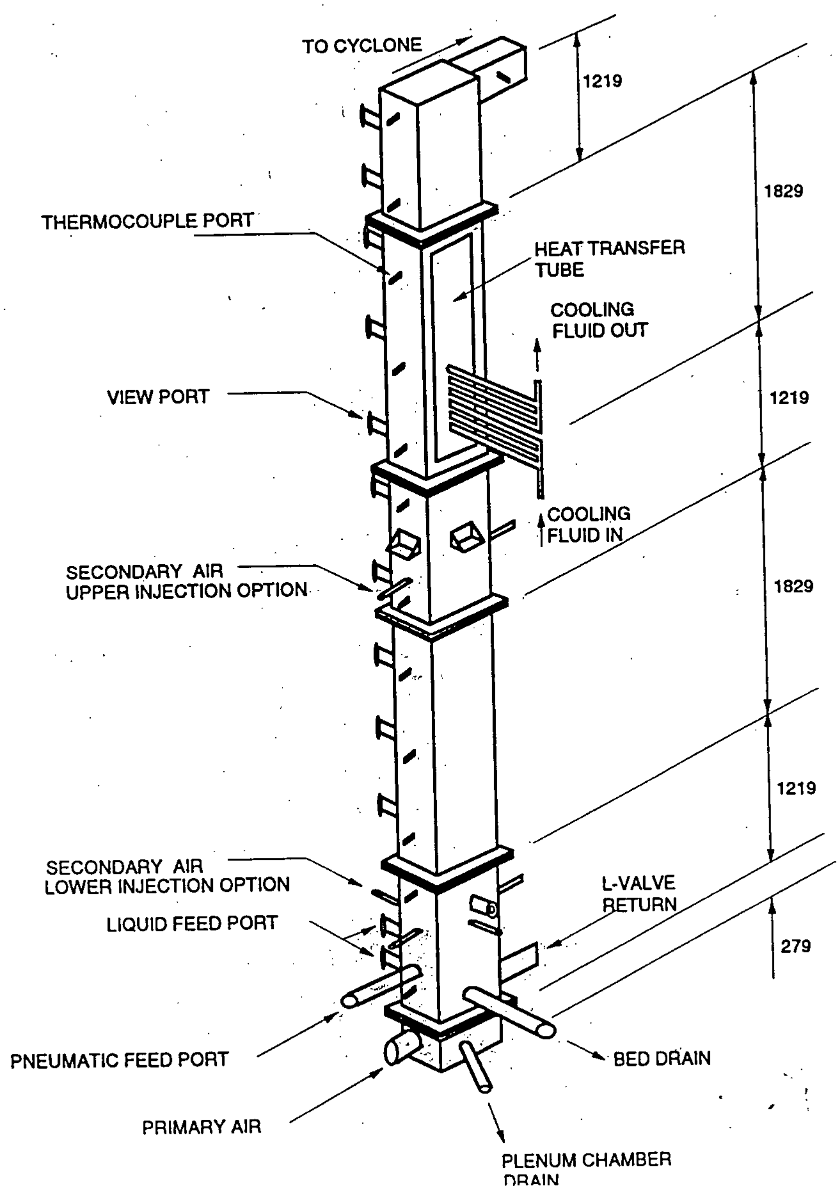


Figure 4.13 Simplified Schematic Diagram of UBC Pilot-Scale CFB



4.3.2 Test Run

A test case, uh0, was conducted using the model of the UBC CFB, to see how well the model predicts operating parameters in a pilot-scale CFB as compared to a commercial CFB. In addition, experimental data are available for the UBC CFB for various load control parameters. These data can be used to qualitatively validate the model.

The baseline conditions for case uh0 are superficial gas velocity of 7.03 m/s and a solids recirculation rate of 30 kg/m2s.

The heat transfer area calculated by the model, which gave a corresponding CFB operating temperature of 850 °C is 35% of the total wall area. The model assumes that the heat transfer area is evenly distributed on all four sides of the CFB riser and no heat transfer or heat loss from the primary cyclone and standpipe.

The UBC CFB's actual heat transfer area is only approximately 5% of the total wall area located in a small section near the top of the riser. However, the UBC CFB has high heat loss from all four sides of the riser and from the primary cyclone and standpipe. The heat loss from the riser is evenly distributed throughout the full height of the riser, and as much as 50% of the heat loss is from the primary cyclone and standpipe. For this CFB, the heat transfer assumptions made in the model, would reasonably represent the actual heat transfer and heat loss from the CFB, except that the high capacitance of the refractory and the axial heat transfer through the refractory would tend to make experimental temperature results more uniform.

4.3.3 Results

The heat release results from run uh0 compared to that from case sh0 of the Studsvik CFB, listed in Table 4.4 of baseline conditions, shows the volatiles completely devolatilizing in the bottom 3 m of the riser in the UBC CFB; whereas, in the Studsvik

CFB, the volatiles are released within the first meter upon entering the riser. The volatiles and char heat release profiles are shown in Figures 4.14 and 4.15.

From Figures 4.14 and 4.15, we can see that the fraction of heat released in the streamer is higher than in the core for UBC's CFB, but in the Studsvik CFB the reverse is seen.

In the Studsvik CFB, the annulus region's average cross-sectional area is approximately 0.9 % of the total cross-sectional area; whereas in the UBC CFB, the average annulus region is approximately 3 % of the total cross-sectional area. While even 3% may not seem significant in terms of total cross-sectional area occupied, the annulus region contains approximately 80% of the total solids in the cross-section. Therefore, the streamer is much more significant in terms of its effect upon combustion and pollutant formation behaviour in small cross-sectional CFB risers.

Table 4.4 Parameters in Baseline Test

cases:	uh0 (UBC)	sh0 (Studsvik)
superficial gas velocity (m/s)	7	7
solids recirculation rate (kg/m^2s)	30	30
solids return temperature (°C)	793	859
fuel feedrate (kg/hr)	23	396
air feedrate (kg/hr)	177	3070
height of developed zone (m)	3.2	2.8
Highvale coal	yes	yes
fuel density (kg/m^3)	880	1400
bed density (kg/m^3)	2650	2700
average particle size (mm)	2.89	2.89
excess air (%)	20	20
number of particles used in the Monte Carlo Method	100	100

Figure 4.14 Volatile Heat Release
(Combustion of Highvale Coal with U = 7 m/s and Gs = 30 kg/m^{2}s)

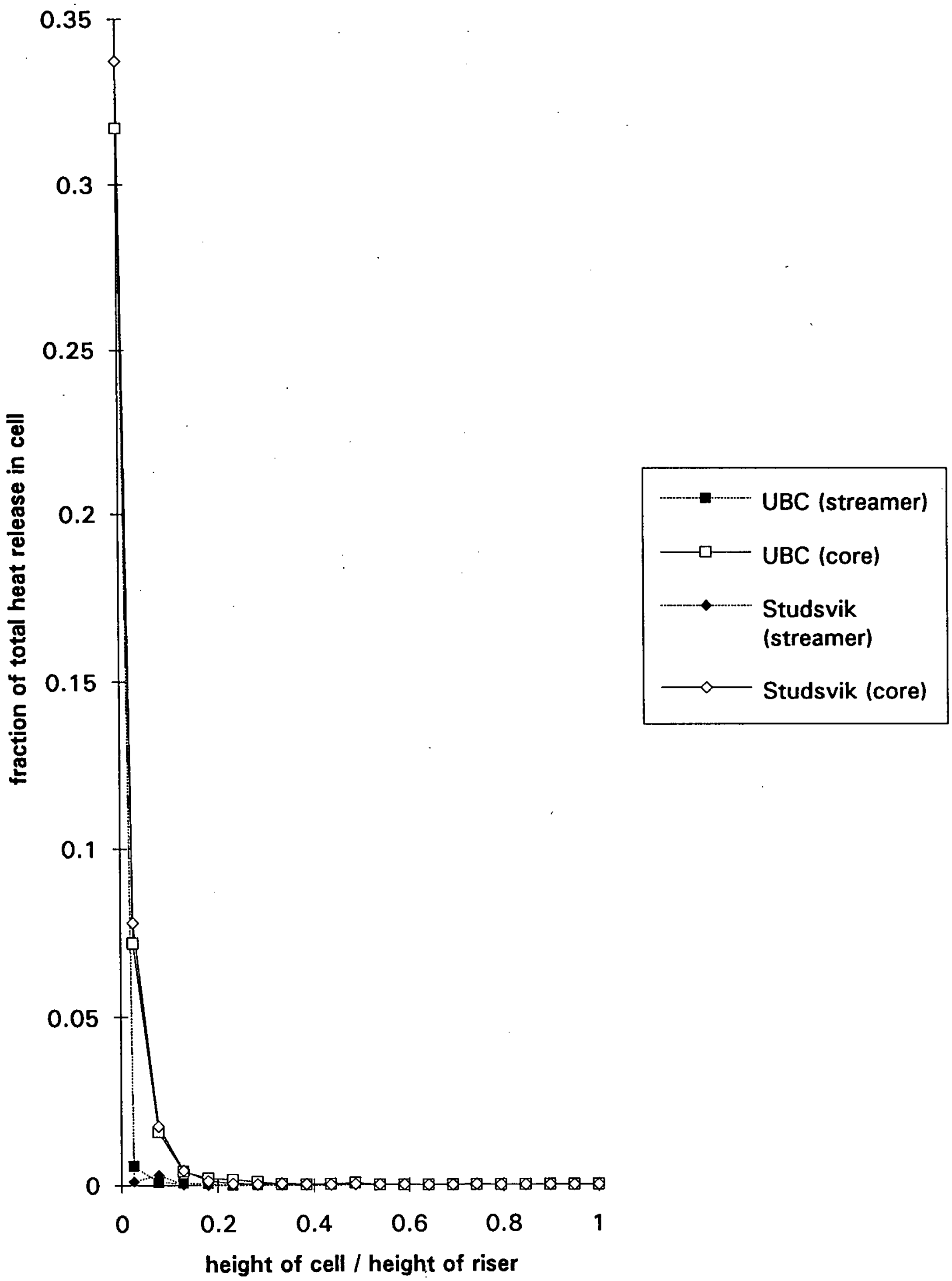
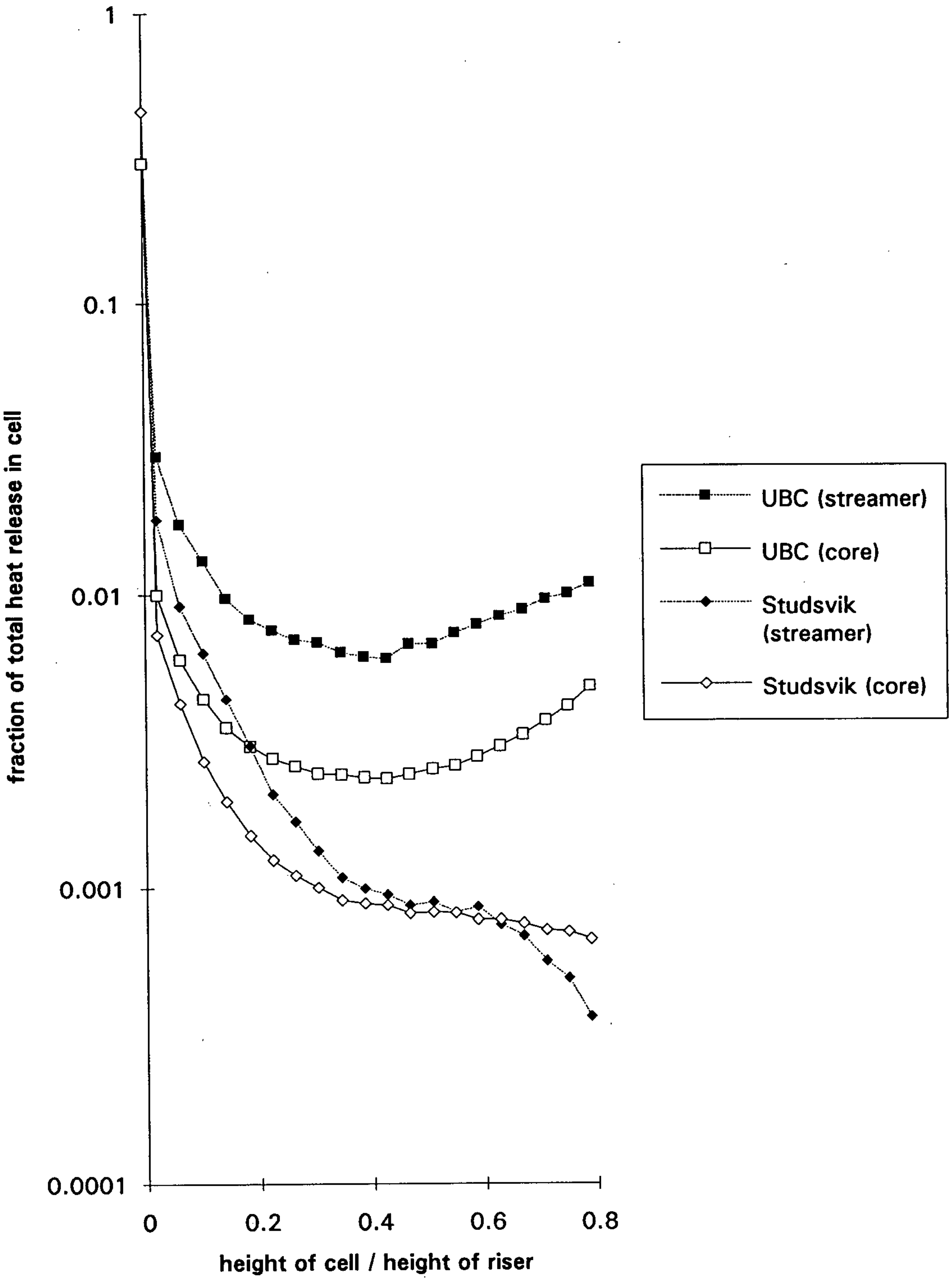


Figure 4.15 Char Heat Release
(Combustion of Highvale Coal with U = 7 m/s and Gs = 30 kg/m^{2}s)



In terms of modelling, because the streamer's influence on combustion and emissions is less for a large cross-sectional CFB riser, a one dimensional combustion/pollutant model that considers the core cells only will be faster to converge, and properly applied, the temperature and pressure profile results may still be valid. A core annulus model for heat transfer is still vital, since heat transfer occurs in the wall layer.

For this test run, most of the volatiles are released in the primary zone, because the primary zone in the UBC CFB is approximately 2.3 times as large as a core cell and 12 to 35 times as dense. Therefore, the residence time in this zone is more than 10 times aslong as any other cell in the riser. From Figure 4.14, we see that for the UBC CFB, the fraction of volatiles released near the bottom of the riser is greater than in the Studsvik CFB. This may be due to the smaller riser diameter of the UBC CFB. In the UBC CFB, the volatile plume that forms, quickly spans the full diameter of the riser; therefore, there is enough oxygen present, near the bottom of the riser, for volatiles combustion.

The char heat release profiles with various particle diameters, at a constant temperature profile, can be seen in Figures 4.16. This figure shows that the solids in the UBC CFB is well mixed; therefore causing the char heat release profiles to stay the same regardless of particle diameter. If larger particles are combusted, not only would the devolatilization expression used be invalid, but the assumption that the fuel particle behave in the same way as the bed particles would also be invalid. The heat release profiles would then be different.

Comparing UBC's partial pressure of oxygen profiles with the profile from case sh0, Figure 4.17, shows that for UBC's CFB, the pressure profile in the streamer cells is more smooth and uniform. Again, this is due to the streamer's significance in a smaller cross-sectional CFB. The amount of oxygen present in the annulus is approximately 5% of the total oxygen in the UBC CFB; whereas in the Studsvik CFB, there is only 1.5% oxygen in the annulus. If additional coal particles were to combust in the Studsvik CFB's

Figure 4.16 Char Heat Release for Various Mean Particle Diameters
(UBC CFB, Combustion of Highvale Coal with U = 7 m/s)

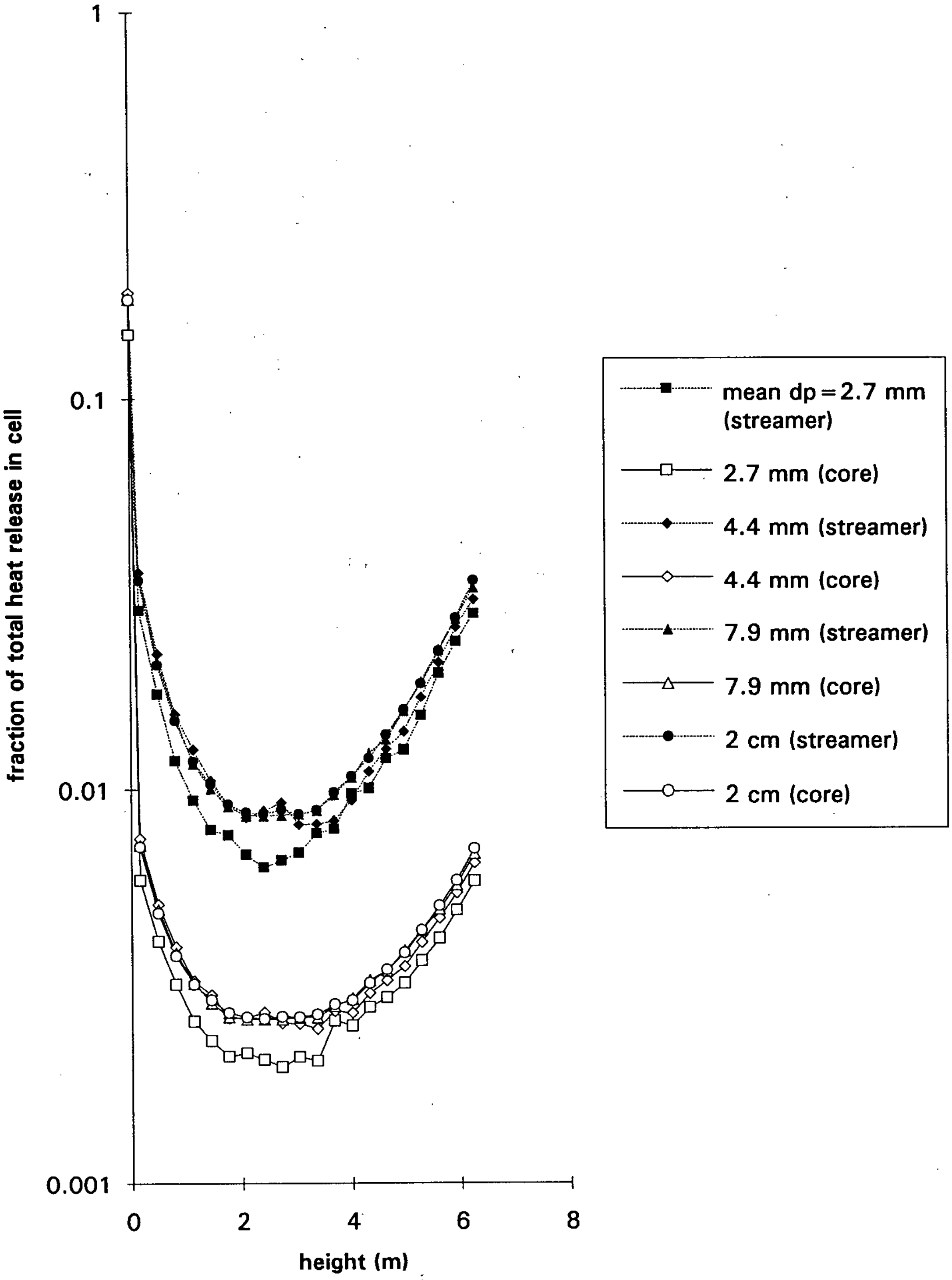
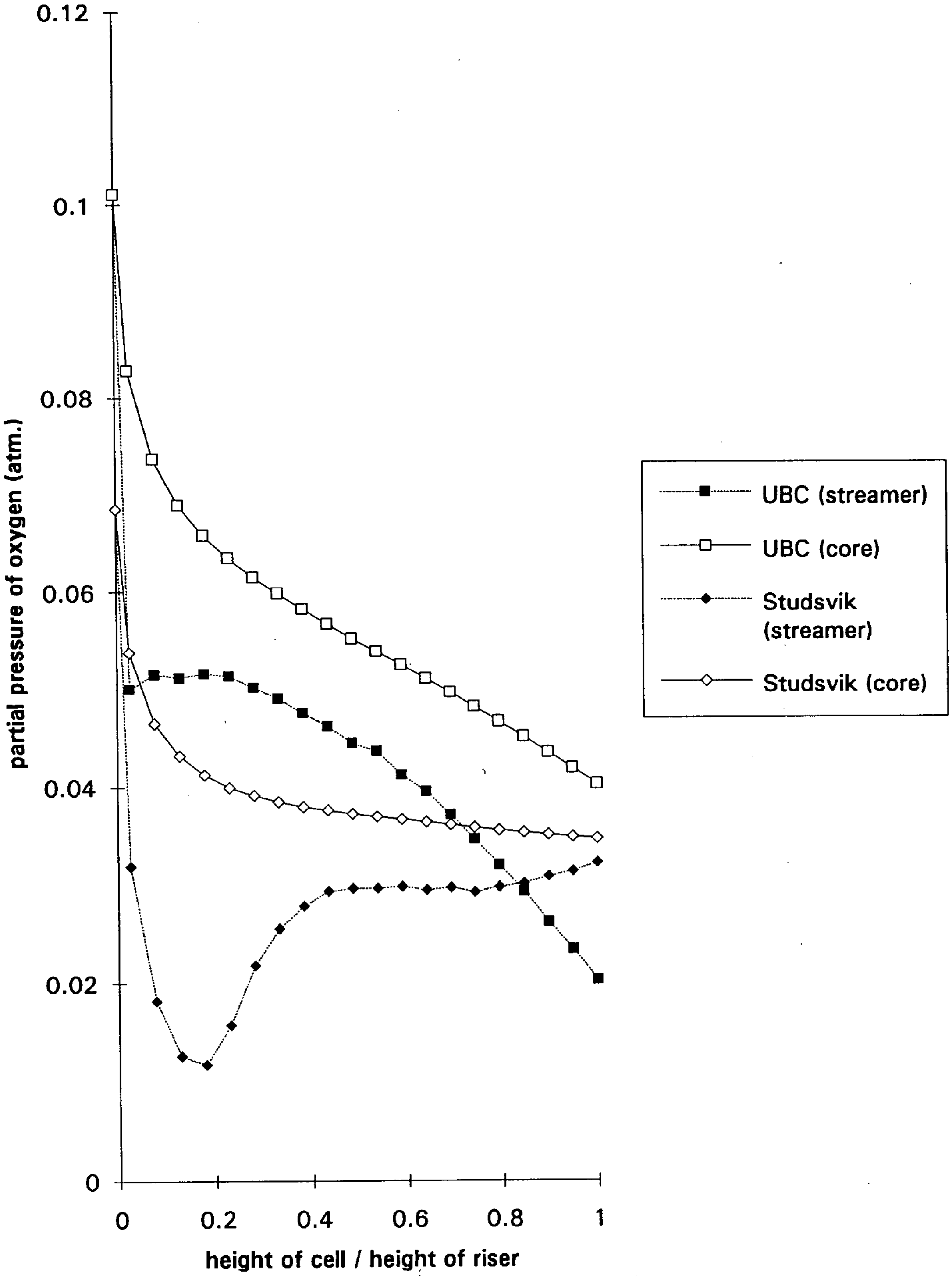


Figure 4.17 Partial Pressure of O2 vs Height
(Combustion of Highvale Coal with U = 7 m/s and Gs = 30 kg/m^2s)



annulus, the oxygen partial pressure profile results can be quite different. Combustion in the cyclone for both the UBC CFB and the Studsvik CFB are insignificant, less than 0.5% of the total heat release, in this model.

The temperature profile, Figure 4.18, shows the UBC's CFB to give temperature in the streamer and core that are 50 °C apart near the bottom of the riser, but quickly become only 10 °C apart further up the riser. In the Studsvik CFB, the streamer's temperature is much less than the core's temperature. In addition, for UBC's CFB, we do not observe the temperature of the streamer heating up near the top of the riser.

The "kink" in the temperature profile of the streamer is due to the discontinuity in the temperature profile prediction, as discussed in Section 3.5. Although the temperature at the discontinuity point has been smoothed, by just averaging the temperatures in the adjacent cells, at times the streamer temperature profile is not as smooth as is desirable. Finally, similarly to the Studsvik CFB, there is a high solids recirculation rate in the CFB, which causes the temperature profile to become more uniform; however, for the UBC CFB, the dense annulus region, causes the average bed density for a given riser height to be greater than for the Studsvik CFB and therefore, the heat transfer coefficient is also greater. As more heat leaves through the heat transfer surface, the CFB temperature cools considerably. Figure 4.19 shows the magnitude of the particle convective term compared to the conduction and radiative terms.

Figure 4.18 Temperature vs Height
(Combustion of Highvale Coal with U = 7 m/s; UBC CFB; case uh0)

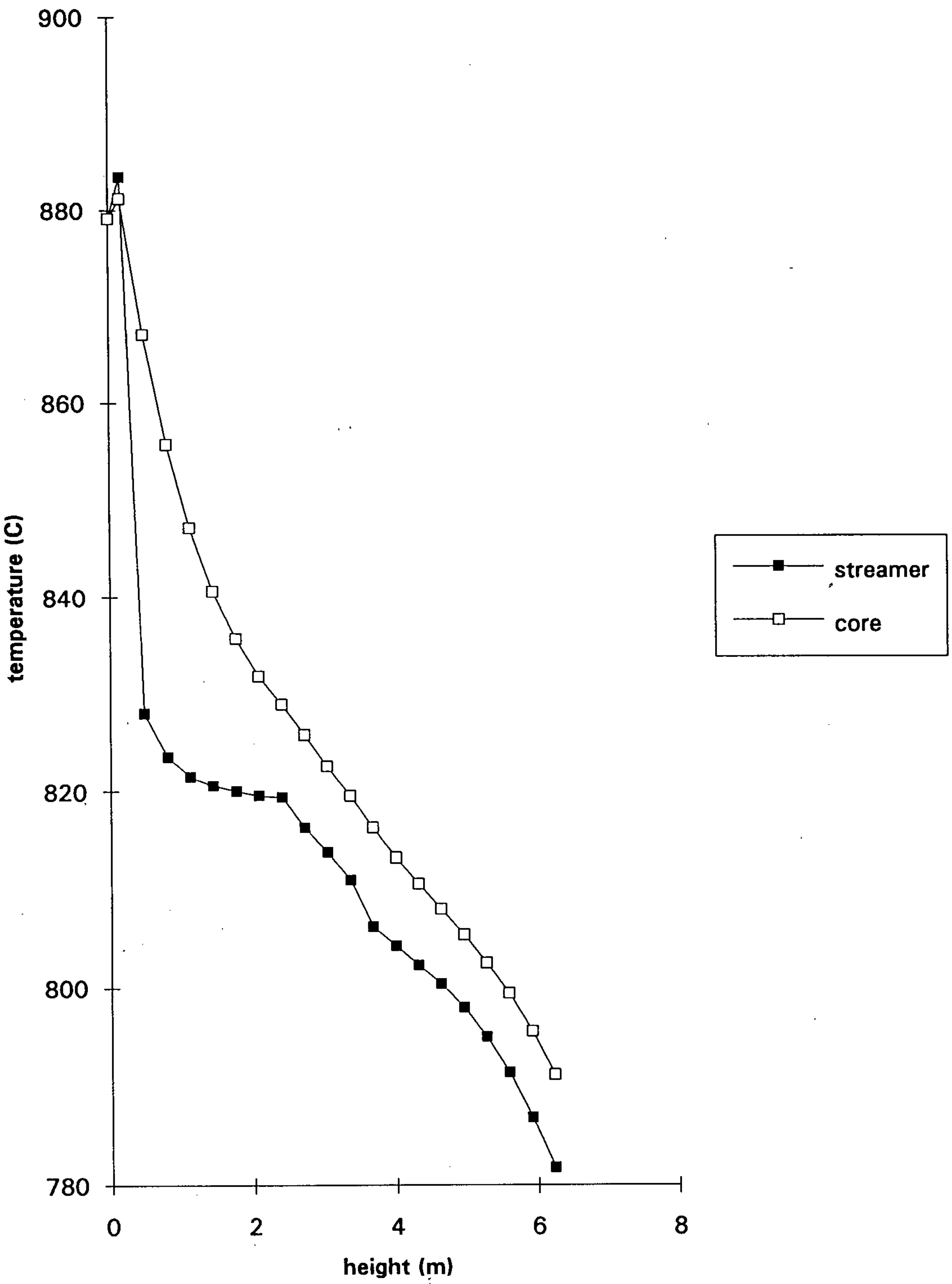
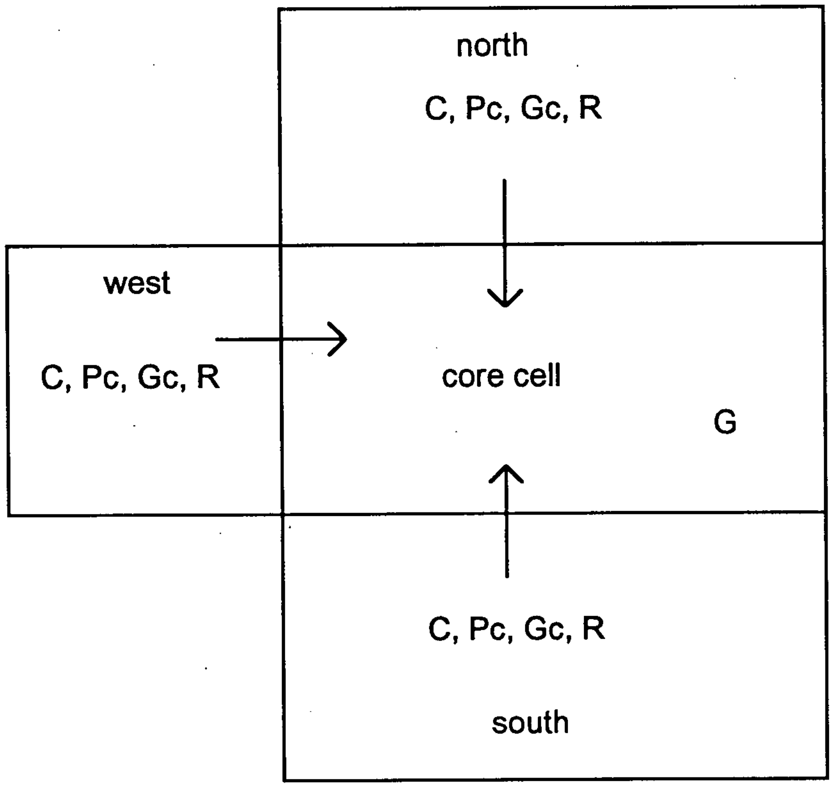


Figure 4.19 Enthapy Balance for Core Cell at Height = 3.36 m (UBC CFB, case uh0)



Heat Transfer (W)	core cell	west	north	south
Temperature (C)	826			
G : heat generation	447			
C : conduction		-2	0	0
Pc : particle convection		-5681	-1016630	1022077
Gc : gas convection		-37	-46664	46779
R : radiation		-263	-35	8
Total Enthapy Balance	-1			

4.4 VALIDATION

The oxygen partial pressure profiles for the UBC CFB were computed using two different devolatilization expressions. The first expression of Anthony et. al. was shown in Equation 3.1, and the second expression is a combination of expressions by Agarwal [1986] and Davidson et. al. [1985], which are shown below. The expression by Anthony, is not a function of particle diameter and is valid for small particles with diameters less than 2 mm. This expression is not valid for larger particles; therefore, the second expression by Agarwal and Davidson was also looked at to observed the differences. The results were compared with experimental partial pressure of oxygen values measured by Zhao [1992]. Experimental and predicted profiles are shown in Figure 4.20.

The devolatilization time and rate are given by the following expressions by Agarwal and Davidson, respectively. The equation presented by Davidson is the prediction of a shrinking core model with diffusion control.

$$\tau_d = k_v d_p^{\,n} \qquad \text{.........(4.2)}$$

where,

	τ_d	devolatilization time (s)
	d_p	particle diameter (mm)
	kv	constant (s/mm^n)
		= 1.5
	n	constant
		= 1.5

$$\frac{t}{\tau_d} = 1 - 3(1-f)^{\frac{2}{3}} + 2(1-f) \qquad \text{.........(4.3)}$$

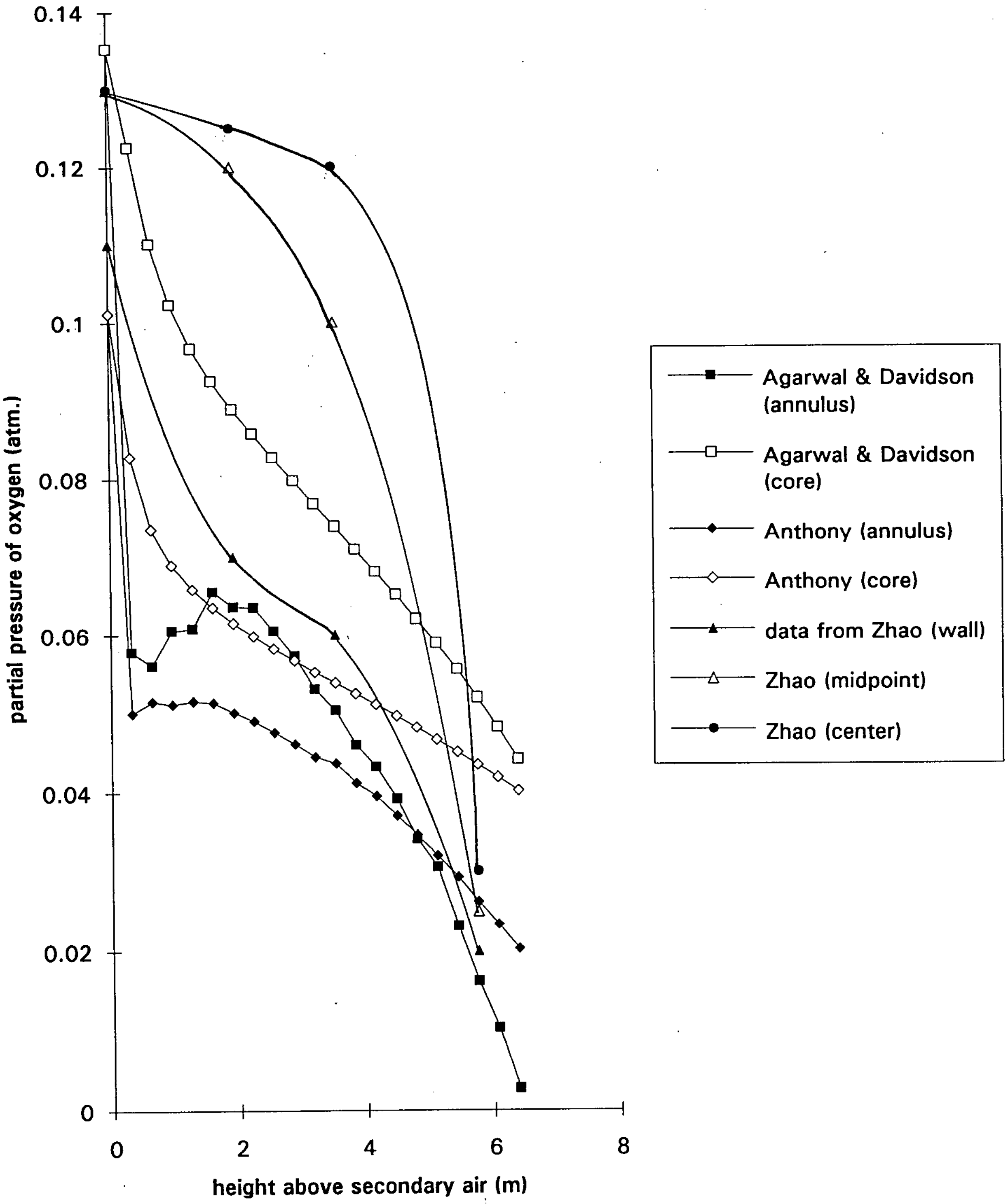
where,

	t	time (s)
	τ_d	devolatilization time (s)
	f	fractional yield of volatiles

Differences in the predicted partial pressure of oxygen profiles and experimental data may be due to several reasons. The combustion conditions used in the model and by Zhao are not identical. In addition, the devolatilization expression by Anthony is not a

Figure 4.20 Oxygen Concentration Profiles for Highvale Coal

Conditions: Zhao (T=891 °C, U = 8.26 m/s, O_2 in flue gas = 2.9%)
Anthony (T=830 °C, U = 7 m/s, O_2 in flue gas = 3.7%)
Agarwal & Davidson (T=830 °C, U = 7 m/s, O_2 in flue gas = 3.8%)



function of particle diameter. Results using Anthony's expression shows most of the volatiles being released in the primary zone and not further up the riser. This is reflected in less oxygen near the bottom of the riser. The devolatilization expression by Agarwal is a function of particle diameter. This expression shifts the volatiles release further up the riser and also causes the oxygen partial pressure profile to be shifted up. This prediction is closer to the experimentally measured results. The oxygen profile in the annulus is also predicted better in this case.

In addition, accurate experimental oxygen measurements are extremely difficult to obtain, and the experimental measurements show oxygen concentrations at the wall, the center and a point midway between the wall and the center of the riser. These measurements were conducted on a square cross-sectional area riser with entrance/exit effects. In this model, oxygen profiles are calculated for the core and annulus of an equivalent circular cross-sectional riser, without considering entrance/exit effects. Therefore, only a qualitative comparison can be done.

Figure 4.20 does show the effects of a core/annulus structure in a CFB. Secondly, the expression by Agarwal and Davidson predicts approximately the correct combustion in the primary zone. The shape of the partial pressure of oxygen curve in the annulus was also correctly predicted by Agarwal and Davidson. There are some differences in the partial pressure of oxygen curves in the core; however, these differences may be due to the reasons stated above or due to experimental errors.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 CONCLUSION

In this thesis, a computer model was developed to predict heat release partial pressure of oxygen profiles and temperature profiles in a CFB combustor, given the geometry, hydrodynamic properties of the CFB and the physical properties of the fuel. This model can be used for designing purposes to predict the heat transfer area needed to operate at a given temperature or it can be used in a rating problem to predict the temperature profile given the heat transfer area of the CFB. The program structure is modular, with separate subroutines for devolatilization, plume model, char combustion, oxygen profile and temperature calculations.

Several test cases were conducted to observe how the model predictions change with various inputs of superficial gas velocities and solid recirculation rates. In addition, comparisons were made between the UBC CFB, a pilot scale CFB with a cross-sectional area of 0.15 m by 0.15 m, and the Studsvik CFB, a 2.5 MW thermal prototype CFB with a cross-sectional area of 0.65 m by 0.65 m. A qualitative validation was made between the model predictions of the UBC CFB and experimental data. The results from this validation seems to suggest that the model can predict the correct trends, with a more representative devolatilization model.

There are some limitations to the operating cases the model can predict and the accuracy of the predictions. They are listed below.

(i) The primary zone and the cyclone are both treated as CSTRs (Continuous Stirred Tank Reactors).

(ii) Superficial gas velocities below 5 m/s were not studied. Due to the limitations in the hydrodynamic code as discussed in Section 4.2.2, hydrodynamic predictions for low velocity cases were not possible.

(iii) Combustion air was not recycled back into the riser.

(iv) Incomplete combustion to for CO was not looked at.

(v) The devolatilization equation used is not a function of particle diameter.

(vi) A simplified energy equation was used, where the radiative and convective heat transfer terms are not coupled. Due to the highly non-linear nature of the energy balance equation, convergence was extremely difficult to achieve and it took many iterations to arrive at the final output, even with a good initial guess of the temperature. In addition, the particle convective term is orders of magnitude larger than the other terms, see Figure 4.19. Therefore, any changes in heat release, oxygen profile or temperature within a cell will take many iterations for that disturbance to affect the whole riser. An attempt to converge an equation where the convective and radiative heat transfer terms are coupled was unsuccessful.

(vii) Radiative heat transfer from one cell was assumed to affect its adjacent cells or surface only. This assumption is valid for a annulus cell, where there are dense particles; however, for the dilute core cells, this assumption may not be valid.

5.2 RECOMMENDATIONS FOR FUTURE WORK

Future work can be done on the model to remove the limitations listed in the previous section. Some of the limitations to the devolatilization and char combustion equation can be easily programmed due to the modular nature of the program. In addition, incorporating this model as a subroutine to Senior's hydrodynamic model, and changing the hydrodynamics code so that the temperature profile output from the model can be placed back into the hydrodynamics code and iterated until a final converged solution is achieved. Finally, the addition of a NOx and SO_2 emissions model would make the overall CFB program complete.

NOMENCLATURE

Variables

		Units
y	distance in axial direction	m
x	distance in radial direction	m
k_{eff}	effective thermal conductivity	W/m·K
T	absolute temperature	K
α_p	volume fraction of particles	
ρ_p	density of particle	kg/m^3
c_p	specific heat of particle	J/kg.K
u_p	velocity of particle	m/s
ρ_g	density of gas	kg/m^3
c_g	specific heat of gas	J/kg·K
u_g	velocity of gas in the axial direction	m/s
I	radiative flux in the positive x direction	W/m^2
J	radiative flux in the negative x direction	W/m^2
G_v	heat source intensity per unit volume	W/m^3
A_r	radiative absorption cross-section per unit volume	
S_r	back-scattering cross-section per unit volume	
σ	Stefan-Boltzman constant	$W/m^2 \cdot K^4$
CL	dimensionless proportionality factor	
ε_p	emissivity of the particles	
d_p	diameter of the particles	m
b	back-scattering coefficient	
V	fraction of volatiles released at time t	
V^*	initial fraction of volatiles in coal (from proximate analysis)	
t	time	s
R	gas constant	kJ/kg·K kcal/mol·K
t_d	devolatilization time	s
T_b	bed temperature	K
P_0	partial pressure of oxygen	atm.
x^2	average displacement squared	
D_{rv}	radial volatile diffusion coefficient	
k_R	reaction rate	$kg/m^2 \cdot s \cdot atm$
T_s	surface temperature	K
d_c	diameter of char particle	m
ρ_c	density of char particle	kg/m^3
τ	burnout time	s
k	thermal conductivity of the cell	W/m·K
A	surface area of one side of the cell	m2
F_x	mass flux of particles in the transverse direction	$kg/m^2 \cdot s$

F_y	mass flux of particles in the axial direction	$kg/m^2 \cdot s$
V_g	represents the mass exchange of gas in the transverse direction due to turbulent mixing	m/s
ε	emissivity of the cell	
G	source term in the cell	W/m
h	cell to wall heat transfer coefficient	W/m2·K
h_f	furnace side heat transfer coefficient	W/m2·K
ρ_b	furnace solids bulk density	kg/m^3
U	overall heat transfer coefficient	W/m·K
Q	heat transfer	W
f	fractional yield of volatiles	

Subscripts

w	wall	
i	initial	
L	condition at the center of the reactor column	
W	west	
E	east	
N	north	
S	south	
P	control volume	
NE	north face of the cell to the east of the control volume	
xE	transverse direction of the cell to the east of the control volume	m
yN	axial direction of the cell to the north of the control volume	m
yS	axial direction of the cell to the south of the control volume	m

Superscripts

0	reference

REFERENCES

Agarwal, P.K., *"A Single Particle Model for the Evolution and Combustion of Coal Volatiles"*, Fuel, Vol. 65, p. 803-810, June 1986.

Anthony, D.B., Howard, J.B., Hottel, H.C. and Meissner, H.P., *"Rapid Devolatilization of Pulverized Coal"*, Symp. Int. Combust. Proc., 15, p. 1303-1317, 1975.

Baskakov, A.P., *"The Mechanism of Heat Transfer Between a Fluidized Bed and a Surface"*, Int. Chem. Eng., 4(2), p. 320-323, 1964.

Baskakov, A.P., *"Radiative Heat Transfer in Fluidized Beds"*, Fluidization, 2nd ed., Academic Press, London, Ch. 13B, p. 465-472, 1985.

Basu, P. and Fraser, S.A., Circulating Fluidized Bed Boilers: Design and Operations, Butterworth-Heinemann, 1991.

Basu, P. and Yan, J., *"Characterization of the Fine Char Particle Combustion in CFBs"*, Fluidized Bed Combustion, Volume 1, ASME 1993.

Bhattacharya, S.C. and Harrison, D., *"Heat Transfer in High Temperature Fluidized Beds"*, European Congress on Particle Technology, Nuremburg, p. 23, session K2, 1977.

Bi, H., Jin, Y., Yu, Z. and Bai, D., *"An Investigation on Heat Transfer in CFB"*, Circulating Fluidized Bed Technology III, 1990.

Botterill, J.S.M. and Sealey, C.J., *"Radiative Heat Transfer Between a Gas-Fluidized Bed and an Exchange Surface"*, British Chem. Eng., Vol. 15, No. 9, p. 1167, 1970.

Bowen, B.D., Fournier, N. and Grace, J.R., *"Heat Transfer in Membrane Waterwalls"*, Int. J. Heat Mass Transfer, Vol. 34, No. 4/5, p. 1043-1057, 1991.

Brereton, C. and Stromber, L., *"Some Aspects of the Fluid Dynamic Behavior of Fast Fluidized Beds"*, CFB Technology, Pergamon Press, Toronto, 1986.

Brereton, C., *"Fluid Mechanics of High Velocity Fluidized Beds"*, Ph.D. Dissertation, Department of Chemical Engineering, U.B.C., 1987.

Brewster, M.Q., *"Effective Emissivity of Fluidized Bed"*, ASME Heat Transfer Division, Vol. 40, p.7-13, 1984.

Chen, J.C., Cimini, R.J. and Dou, S., *"A Theoretical Model for Simultaneous Convective and Radiative Heat Transfer in Circulating Fluidized Beds"*, Circulating Fluidized Bed Technology II, p. 255-262, 1988.

Couturier, M.F. and Stevens, D., *"Measurements of Heat Transfer, Temperature, Solids Mass Flux, Gas Concentration and Cyclone Capture Efficiency in the Chatham CFB Unit"*, Energy Conversion Engineering Group, University of New Brunswick, 1991.

Davidson, J.F., Cliff, R. and Harrison, D., Fluidization, 2nd ed., Academic Press, 1985, p. 642.

Dow, W.M. and Jakob, M., *"Heat Transfer Between a Vertical Tube and a Fluidized Air-Solid Mixture"*, Chem. Eng. Prog., 47(12), p. 637-648, 1951.

Energy, Mines and Resources Canada, Energy in Canada : A Background Paper, November 1987.

Furchi, J.C.L., Golstein Jr., L., Lombardi, G. and Mohseni, M., *"Experimental Local Heat Transfer in a CFB"*, Circulating Fluidized Bed Technology II, 1988.

Gabor, J.D., *"Wall-to-Bed Heat Transfer in Fluidized and Packed Beds"*, Chem. Eng. Progress Sym. Series, 66(105), p. 76-86, 1970.

Glicksman, L.R., *"CFB Heat Transfer"*, CFB Technology II, 1988.

Gorelik, A.G., *"Mechanism of Heat Exchange Between Surfaces and a Fluidized Bed"*, J. Eng. Phys., 13(6), p. 495-498, 1967.

Grace, J.R., Brereton, C., Lim, C.J., Legros, R., Zhao, J., Senior, R.C., Wu, R.L., Muir, J.R. and Engman, R., *"Circulating Fluidized Bed Combustion of Western Canadian Fuels"*, Final Report Prepared for Energy, Mines and Resources Canada under contract 52SS.23440-7-9136, 1989.

Han, G.Y., Tuzla, K. and Chen, J.C., *"Radiative Heat Transfer from High Temperature Suspended Flows"*, Institute of Thermo-Fluid Engineering and Science, 1992.

Howard, J.R., Fluidized Beds, London: Applied Science, p. 62, 1983.

Jia, L., Becker, H.A. and Code, R.K., *"Devolatilization and Char Burning of Coal Particles in a Fluidized Bed Combustor"*, The Canadian Journal of Chemical Engineering, Vol. 71, Feb. 1993.

Jolley, L.J., *"Heat Transfer in Beds of Fluidized Solids"*, Fuel Research 28(5), p. 114-115, 1949.

Kobro, H. *"Description of Studsvik's Fast Fluidized Bed Prototype"*, Studsvik Report, Studsvik/EM-84/3, 1984.

Kolar, A.K., Grewal, N.S. and Saxena, S.C., *"Investigation of Radiative Contribution in a High Temperature Fluidized-Bed Using the Alternate-Slab Model"*, Int. J. Heat Mass Transfer, Vol. 22, p. 1695-1703, 1979.

Leckner, B., *"Heat Transfer in Circulating Fluidized Bed Boilers"*, Circulating Fluidized Bed Technology III, p. 27-37, 1991.

Leckner, B. and Andersson, B.A. *"Characteristic Features of Heat Transfer in CFB Boilers"*, Powder Technology, 70, p. 303-314, 1992.

Leva, M., and Grummer, M., *"A Correlation of Solids Turnover in Fluidized Systems - Its Relation to Heat Transfer"*, Chem. Eng. Prog. 48(6), p.307-313, 1952.

Levenspiel, O., and Walton, J.S., *"Bed-Wall Heat Transfer in Fluidized Systems"*, Chem. Eng. Prog. Symp. Ser. 50(9), p. 1-13, 1954.

Lin, W., and Van den Bleek, C.M., *"The SOx/NOx Emissions in CFB Combustion of Coal"*, Proc. of the 3rd Int. Conf. on CFB, p. 545-550, 1989.

Martin, H., *"Warme-und Stoffubertragung in der Wirbelschicht"*, Chem-Ing-Tech, 52, nr 3, s.199/209, 1980.

Mickley, H.S. and Fairbanks, D.F., *"Mechanism of Heat Transfer to Fluidized Beds"*, A.I.Ch.E. Journal, 1(3), p. 374-384, 1955.

Mickley, H.S. and Trilling, C.A., *"Heat Transfer Characteristics of Fluidized Beds"*, Ind. Eng. Chem. 41(6), p. 1135-1147, 1949.

Morris, M., *"Furnace-Side Heat Transfer Coefficient Within Circulating Fluidized Beds"*, Studsvik Report, p. 110, 1988.

Nag, P.K. and Moran, M.N., *"Prediction of Heat Transfer in Circulating Fluidized Beds"*, Proc. of the 3rd Int. Conf. on CFB, 1991.

Park, D., Levenspiel, O. and Fitzgerald, T.J., *"A Model for Large Scale Atmospheric Fluidized Bed Combustors"*, The American Institute of Chemical Engineers Symp. Series, 77(205), p. 116-126, 1981.

Sanderson, W.E., *"A Review of Overall Models of Circulating Fluidized Bed Combustors - A Literature Study"*, Technische Universiteit Delft, September 1993.

Saxena, S.C. and Gabor, J.D., *"Mechanisms of Heat Transfer Between a Surface and a Gas-Fluidized Bed for Combustion Application"*, Prog. Energy Combust. Sci., Vol. 7, p. 73-102, 1981.

Senior, R., *"Circulating Fluidized Bed Fluid and Particle Mechanics: Modeling and Experimental Studies with Application to Combustion"*, Ph.D Dissertation, Department of Chemical Engineering, U.B.C., 1992.

Stubington, J.F., *"The Role of Coal Volatiles in Fluidized Bed Combustion"*, Journal of the Institute of Energy, p. 191-195, 1980.

Szekely, J. and Fisher, R.J., *"Bed to Wall Radiative Heat Transfer in a Gas-Solid Fluidized Bed"*, Chemical Engineering Science, Vol. 24, p. 833-849, 1969.

Vedamurthy, V.N. and Sastri, V.M.K., *"An Analysis of the Conductive and Radiative Heat Transfer to the Walls of Fluidized Bed Combustors"*, Int. J. Heat Mass Transfer, 17, p.1-9, 1974.

Werdermann, C.C. and Werther, J., *"Heat Transfer in Large-Scale CFB Combustors of Different Sizes"*, Technical University Hamburg, 1993.

Wu, R.L., *"Heat Transfer in Circulating Fluidized Beds"*, Ph.D. Dissertation, Department of Chemical Engineering, U.B.C., August 1989.

Wu, R.L., Grace, J.R., and Lim, C.J., *"A Model for Heat Transfer in Circulating Fluidized Beds"*, Chemical Engineering Science, Vol. 45, No. 12, p. 3389-3398, 1990.

Yang, W., *"The Hydrodynamics of CFBs"*, Encyclopedia of Fluid Mechanics Supplements, Gulf Publishing, 1992.

Yang, Y., Jin, Y., Yu, Z., Wang, Z. and Bai, D., *"The Radial Distribution of Local Particle Velocity in a Dilute Circulating Fluidized Bed"*, CFB Technology III, Pergamon Press, Oxford, 1991.

Yerushalmi, J., Cankurt, N.T., Geldart, D. and Liss, B., *"Flow Regimes in Vertical Gas-Solid Contact Systems"*, A.I.Ch.E. Symp., Series No. 176, Vol. 74, 1, 1978.

Zhao, J., *"Nitrogen Oxide Emissions from Circulating Fluidized Bed Combustion"*, Ph.D. Dissertation, Department of Chemical Engineering, U.B.C., 1992.

APPENDIX A

PROGRAM LISTING

```
c              *************** HEAT.F ******************
c              *                                       *
c              *          HEAT GENERATION and          *
c              *        HEAT TRANSFER PROBLEM          *
c              *                                       *
c              *          rev. 8.1, 1995 Feb. 8        *
c              *             by: D.W. Ju               *
c              *                                       *
c              *****************************************
c
c This program uses the Monte Carlo Method to compute the heat
c release, oxygen and temperature profile in a CFB riser.  Initially,
c the y-dir flux of the core cells had to be recalculated to force a
c mass balance.  The devolatilization rate is calculated as a function of
c bed temperature.  The program also incorporates char combustion assuming
c only kinetic rates and a first order reaction.  It calculates the partial
c pressure of oxygen along the streamer and core by assuming air enters at
c 21% O2.  Dispersion of air in the radial direction has been corrected
c for using the plume model.  Some of the particles that leave the top of
c the riser is returned to the CFB after passing through a  cyclone with a
c residence time of RT sec.  The streamer cross-sectional area varies along the
c CFB riser.  The heat transfer subroutine uses a simplified radiation heat
c transfer term.  The temperature profile was smoothed for 1 point at every
c iteration.  The control-volume method was also used.
c
c*****************************************************************

      implicit real*8(a-h,o-z)
      real*8 mcyc,k
      character*65 title1,title2,cyclon
      common/blka/acell(300),o2feed,x,fuel,uc,us
      common/blkb/cycv,npart,dt(300),pmatt(300),pmat1(300),rc,
     1 volf,valh,rt,distv(300),siv(20),pdist(20)
      common/blkc/heatc(300),dpcut,presc(300),press(300),denp,coeff
      common/blkd/heat(300),total,dycell,cross,presc2(300),press2(300),con0,
     1 oxyclc,mcyc,pair
      common/blke/vtf,nfeed
      common/blkf/to(5,300),k,at,twall,tair,vg,tref,cp,cg,afeed,fin
      common/blkg/flux(300,5),dx(5,300),dy(5,300),f,emiss,denb(300)
      common/blkh/acinit,asinit,acfin,asfin
```

```
      common/blki/areaw(5,300),areae(5,300),arean(5,300),
     1 areas(5,300),areat(5,300),effh(300),deng,sbc,const1,effc(300),effr(300),v2,
     2 v5,v6,cyc,gcyc
      dimension fluxc(300,5),heatv(300),ult(7)
      dimension pmat2(300),tempo(300),temp(300)

c Unit 1 and 2 are input files, and 3,7,8,9 are output files.

      open(unit=1,file='sh0.dat')
      open(unit=2,file='h14.inp')
      open(unit=3,file='sh0.plt')
      open(unit=7,file='sh0.xls')
      open(unit=8,file='sh0.out')
      open(unit=9,file='sh0.txt',form='print')

      data nx,dpcut/2,5.d-5/
      data po2,cp,cg/0.21d0,800.d0,1172.d0/
      data deng,sbc/0.3d0,5.67d-8/

      pi=4.d0*datan(1.d0)

c Error handler during generation of the executable file.

      ieeer=ieee_handler('set', 'common', SIGFPE_DEFAULT)
      if (ieeer.ne.0) print *, 'could not establish fp signal handler'

c Read input file 1.

      read(1,900) title1,title2
900   format(1x,a65,/1x,a65,/)
      read(1,910) ny,at,rc,per,primev,dbavg,devh,pair,tb,twall
910   format(1x,i3,/1x,8(f10.6,/1x),f10.6)

      tinit=855.d0

      read(1,*)
      read(1,*)
      read(1,*)

      primeh=primev/at
      ncell=ny*nx+1

      do i=1,ncell
         read(1,920) (flux(i,j),j=1,4)
920      format(8x,f6.2,3f11.4)
```

```
      enddo

      read(1,*)
      read(1,*)
      read(1,*)
      read(1,930) asinit
      acinit=at-asinit
      do i=1,ny
         read(1,930) acell(ny+i)
930      format(14x,f10.6)
      enddo
      read (1,930) asfin
      acfin=at-asfin
      do i=1,ny
         acell(i)=at-acell(ny+i)
      enddo
      acell(ncell)=at

      read(1,*)
      read(1,*)
      read(1,*)
      do i=1,7
         read(1,940) ult(i)
940      format(1x,f10.3)
      enddo
      read(1,*)
      read(1,941) volf,denp
941   format(1x,f10.3,/1x,f10.3)
      volf=volf/100.d0
      read(1,*)
      read(1,941) uc,us
      read(1,942) sug,fluxr,k,emiss
942   format(1x,f10.5,3(/1x,f10.5),///)
      do i=1,18
         read(1,943) siv(i),pdist(i)
943      format(1x,f10.3,5x,f10.3)
      enddo
      close(1)

      recirc=fluxr*at

c Calculate the furnace solids bulk density as a function of height.

      do i=1,ny+2
         denb(i+2)=(flux(i,4)*acell(i)+flux(i+ny,4)*acell(i+ny))/at
```

```
      enddo
      denb(2)=flux(ncell,4)


c Read input file 2.

      read(2,945) c1,c2,valh
 945  format(//1x,f8.2,5x,f8.2,/1x,f8.1)
      read(2,946) npart,perc,nfeed,eps,eps2,eps3,rf2,rf,cross,vtf,rt,exair,ceff,tsp,
     1 tair,tref,const1
 946  format(/1x,i10,/1x,f10.6,/1x,i10,14(/1x,f10.6))
      close(2)

      vg=cross

c Set dx and dy values for each cell.

      dycell=flux(2,1)-flux(1,1)
      r=dsqrt(at/pi)
      do j=1,ny+3
         dx(1,j)=0.d0
         dx(4,j)=0.d0
      enddo
      do j=3,ny+2
         rcore=dsqrt(acell(j-2)/pi)
         ra=r-rcore
         dx(2,j)=ra
         dx(3,j)=rcore
      enddo
      rcore=dsqrt(acinit/pi)
      ra=r-rcore
      do i=1,2
         dx(2,i)=ra
         dx(3,i)=rc
      enddo
      rcore=dsqrt(acfin/pi)
      ra=r-rcore
      dx(2,ny+3)=ra
      dx(3,ny+3)=rc

      do i=1,4
         dy(i,1)=0.d0
         dy(i,2)=primeh
         do j=3,ny+2
            dy(i,j)=dycell
```

```
            enddo
            dy(i,ny+3)=0.d0
         enddo

c  Call subroutine to determine air and fuel feedrates.

         call feed(tb,po2,ceff,exair,ult)

c  Multiply the mass flux matrix (FLUX) by the dimensions of the riser and store
c  in the mass flowrate matrix (FLUXC).

         do i=1,ny-1
            fluxc(i,1)=flux(i,1)
            fluxc(i,2)=flux(i,2)*dycell*per
            fluxc(i,4)=flux(i,4)*dycell*acell(i)
         enddo
         fluxc(ny,1)=flux(ny,1)
         fluxc(ny,2)=flux(ny,2)*dycell*per
         fluxc(ny,4)=flux(ny,4)*dycell*acell(ny)
         fluxc(ny+1,1)=flux(ny+1,1)
         fluxc(ny+1,2)=flux(ny+1,2)*dycell*per
         fluxc(ny+1,3)=flux(ny+1,3)*asinit
         fluxc(ny+1,4)=flux(ny+1,4)*dycell*acell(ny+1)
         do i=ny+2,ncell-1
            fluxc(i,1)=flux(i,1)
            fluxc(i,2)=flux(i,2)*dycell*per
            fluxc(i,3)=flux(i,3)*(acell(i)+acell(i-1))/2.d0
            fluxc(i,4)=flux(i,4)*dycell*acell(i)
         enddo
         fluxc(ncell,1)=flux(ncell,1)
         fluxc(ncell,2)=0.d0
         fluxc(ncell,4)=flux(ncell,4)*primeh*at

c  calculate axial flux of the core cells to ensure a mass balance.

         fluxc(ncell,3)=recirc+fluxc(ny+1,3)
         fluxc(1,3)=fluxc(ncell,3)-fluxc(1,2)+fluxc(ny+1,2)
         do i=2,ny
            fluxc(i,3)=fluxc(i-1,3)-fluxc(i,2)+fluxc(ny+i,2)
         enddo

         flux(ncell,3)=fluxc(ncell,3)/acinit
         do i=1,ny-1
            flux(i,3)=fluxc(i,3)/((acell(i)+acell(i+1))/2.d0)
         enddo
```

```
      flux(ny,3)=fluxc(ny,3)/acfin
      afeed=o2feed/32.d0/.21d0*29.d0

c Set initial guess of pressure and temperature.

      do i=1,ny+2
         press(i)=0.21d0
         presc(i)=0.21d0
      enddo

      do i=1,ncell
         temp(i)=tinit
         tempo(i)=temp(i)
      enddo
      do j=2,ny+3
         to(1,j)=twall
         do i=2,4
            to(i,j)=tinit
         enddo
      enddo

c Input solids return temperature.  It can be set to equal the cyclone
c temperature, calculated by the program, or set at a bed temp. set
c by the user (normally 850C).

 2    print*, 'Select solids return temperature. (C=cyclone,
     1 B=temperature selected by user)'
      read(*,950) cyclon
 950  format(a3)

      if(cyclon.ne.'C'.and. cyclon.ne.'B') goto 2

      if(cyclon.eq.'B') then
         print*, 'Enter temperature of inlet particles (C)'
         read(*,*) tp
      endif
      tcyc=tp
      fin=fuel/at

c Determine the time step and the probabilities of how the particle
c will move, depending on the location of the particle.

      do i=1,ncell
         pmat1(i)=fluxc(i,2)/fluxc(i,4)
         pmat2(i)=fluxc(i,3)/fluxc(i,4)
```

```
                pmatt(i)=pmat1(i)+pmat2(i)
                dt(i)=perc/pmatt(i)

                pmat1(i)=pmat1(i)*dt(i)
                pmat2(i)=pmat2(i)*dt(i)
                pmatt(i)=pmat1(i)+pmat2(i)
             enddo

c  Calculate the fraction of the wall covered by membrane tubes (f), or
c  set it at a specified wall area.

c     htarea=(fuel*valh*1000.d0/2.5d0)/(const1*dbavg*(tinit-twall)
c    2+emiss*sbc*((tinit+273.15d0)**4-(twall+273.15d0)**4))
c     rarea=per*(primeh+flux(ny,1)+dycell/2.d0)
c     if(htarea.le.0.d0) htarea=0.d0
c     f=htarea/rarea

      f=0.7d0

c  Initialize heat distribution terms

      iter2=0
 5    iter2=iter2+1

c  Determine the areas.

      do j=1,ny+3
         do i=1,4
            areaw(i,j)=0.d0
            areae(i,j)=0.d0
            arean(i,j)=0.d0
            areas(i,j)=0.d0
            areat(i,j)=0.d0
         enddo
      enddo

      areaw(1,2)=primeh*per*f
      areae(1,2)=primeh*per*f
      areaw(2,2)=primeh*per*f
      areae(2,2)=primeh*per
      do i=3,4
         areaw(i,2)=primeh*per
         areae(i,2)=primeh*per
      enddo
      do j=3,ny+2
```

```
          areaw(1,j)=dycell*per*f
          areae(1,j)=dycell*per*f
          areaw(2,j)=dycell*per*f
          areae(2,j)=dycell*per
          do i=3,4
             areaw(i,j)=dycell*per
             areae(i,j)=dycell*per
          enddo
       enddo
       do j=3,ny+1
          arean(3,j)=(acell(j-2)+acell(j-1))/2.d0
          arean(2,j)=(acell(j-2+ny)+acell(j-1+ny))/2.d0
          areas(3,j+1)=arean(3,j)
          areas(2,j+1)=arean(2,j)
       enddo
       arean(3,ny+2)=acfin
       arean(2,ny+2)=asfin
       arean(3,ny+3)=acfin
       arean(2,ny+3)=asfin
       arean(3,1)=acinit
       arean(2,1)=asinit
       arean(3,2)=acinit
       arean(2,2)=asinit
       areas(3,3)=acinit
       areas(2,3)=asinit
       areas(3,2)=acinit
       areas(2,2)=asinit
       areas(3,1)=acinit
       areas(2,1)=asinit
       areas(3,ny+3)=acfin
       areas(2,ny+3)=asfin
       do j=2,ny+2
          areat(1,j)=areaw(1,j)
          areat(2,j)=areae(2,j)+areaw(2,j)+arean(2,j)+areas(2,j)
          areat(3,j)=areaw(3,j)+arean(3,j)+areas(3,j)
       enddo
       areat(2,1)=areas(2,1)
       areat(3,1)=areas(3,1)
       areat(2,ny+3)=arean(2,ny+3)
       areat(3,ny+3)=arean(3,ny+3)

       cycv=0.d0

c Call subroutine to calculate volatilization heat distribution

```

```
      call volat(ny,heatv,tdvol,totv,ncell,c1,c2,temp,pi)

      coeff=7.26d3*exp(-1.5d5/(8.314d0*(tsp+273)))

c Call subroutine to correct for volatile dispersion

      call vdisp(heatv,ncell,ny,pi,flux)

c Count the number of iterations and call subroutine to calculate
c the char heat distribution

      iter=0
 10   iter=iter+1

      call char(ny,cyc,pi,ncell,ult)

      cycc=cyc-cycv

c Calculate fraction of the total heat generated in each cell.

      do i=1,nmax
         heat(i)=0.d0
      enddo

      total=0.d0
      do i=1,ncell
         heat(i)=heatv(i)+heatc(i)
         total=total+heat(i)
      enddo
      total=total+cyc

      do i=1,ncell
         heat(i)=heat(i)/total
      enddo

c Call subroutine to calculate the O2 partial pressure profile

      call pres(ny,cyc,pi,po2,ncell)

c Check that the errors in the pressure of the core cells are less than EPS.

      ermax=0.d0
      do i=1,ny+2
         errorc=abs(presc(i)-presc2(i))
         if(errorc.gt.ermax) then
```

```
                    ermax=errorc
                    ic=i
                 endif
              enddo

c Print the error and the iteration number.

              print*,'iter,error',iter,ermax

c Update the pressures.

              do i=1,ny+2
                 press(i)=press(i)+rf*(press2(i)-press(i))
                 presc(i)=presc(i)+rf*(presc2(i)-presc(i))
              enddo

c Decide whether convergence has been met.  If not, go back
c to statement number 10.

              if(ermax.gt.eps) goto 10
              er1=ermax

c Set the temperature of the solids return.

              if(cyclon.eq.'C') then
                 trec=tcyc
              else
                 trec=tp
              endif

              tin=(afeed*cg*tair+fuel*cp*tref+recirc*cp*trec)/(afeed*cg+fuel*cp+
     1        recirc*cp)
              do i=1,4
                 to(i,1)=tin
              enddo

c Call subroutine heat to determine temperature profile.

              call htrans(ncell,ny,eps3,per,rf2,recirc,ult)

              print*, 'No. of iterations in htrans=', iter2
              write(8,*) 'No. of iterations in htrans=', iter2

c New temperatures

```

```
          do j=ny+2,3,-1
             temp(j-2+ny)=to(2,j)
             temp(j-2)=to(3,j)
          enddo
          temp(ncell)=to(3,2)*acinit/at+to(2,2)*asinit/at

c Smooth temperature profile for 1 point (at the boundary between
c developing and fully developed region).

          do i=1,ny
             if(devh.le.flux(i,1)) then
                i=i-1
                ratio=(temp(i+1)-temp(i-2))/(flux(i+1,1)-flux(i-2,1))
                temp(i)=ratio*(flux(i,1)-flux(i-2,1))+temp(i-2)
                temp(i-1)=ratio*(flux(i-1,1)-flux(i-2,1))+temp(i-2)
                i=i+1+ny
                ratio=(temp(i+1)-temp(i-3))/(flux(i+1,1)-flux(i-3,1))
                temp(i)=ratio*(flux(i,1)-flux(i-3,1))+temp(i-3)
                temp(i-1)=ratio*(flux(i-1,1)-flux(i-3,1))+temp(i-3)
                temp(i-2)=ratio*(flux(i-2,1)-flux(i-3,1))+temp(i-3)
                goto 20
             endif
          enddo

c Write the temperature to output file.

 20       write(8,960) (to(i,ny+3),i=1,3)
 960      format(3(1x,f10.2))
          do j=ny+2,3,-1
             write(8,965) twall,temp(j+ny-2),temp(j-2),effh(j)
 965         format(4(1x,f10.2))
             if(j.eq.7) then
                write(3,*) temp(j-2)
             endif
          enddo
          write(8,965) (to(i,2),i=1,3),effh(2)
          write(8,960) (to(i,1),i=1,3)
          call flush(3)
          call flush(7)
          call flush(8)

c Calculate the temperature of the cyclone.

          tcycn=temp(ny)+gcyc/(afeed*cg+recirc*cp)

```

```
c Set the number of iterations in the temperature profile subroutine to
c ensure that a converged solution is obtained.

      if(iter2.ge.200) goto 50

c Check the convergence of the temperature.

      error=0.d0
      ermax=0.d0
      ierr=0
      do i=1,ncell
         error=dabs(temp(i)-tempo(i))
         if(error.gt.ermax) then
            ermax=error
            ierr=i
         endif
      enddo
      error=dabs(tcycn-tcyc)
      if(error.gt.ermax) then
         ermax=error
         ierr=ncell+1
      endif

      print*,'eps2,ermax,cell',eps2,ermax,ierr
      write(8,*) 'eps2,ermax,cell',eps2,ermax,ierr
      if(ierr.eq.(ncell+1)) then
         print*, 'tempo,temp',tcyc,tcycn
         write(8,*) 'tempo,temp',tcyc,tcycn
      else
         print*, 'tempo,temp',tempo(ierr),temp(ierr)
         write(8,*) 'tempo,temp',tempo(ierr),temp(ierr)
      endif
      write(8,*)

c Update temperature and check that convergence has been met.
c If not, go back to statement number 5.

      if(ermax.gt.eps2) then
         rf3=1.d0
         do i=1,ncell
            tempo(i)=tempo(i)-rf3*(tempo(i)-temp(i))
            tcyc=tcyc-rf3*(tcyc-tcycn)
         enddo
         goto 5
      endif
```

```
c Calculate average partial pressure of O2 leaving riser and cyclone (atm).

 50     pout=presc(ny+2)*acfin/at+press(ny+2)*asfin/at
        pcyc=(oxyclc-mcyc*x)/(uc*acfin+us*asfin)*po2/con0

c Print output results to unit 9.

        write(9,800) title1,title2
800     format(45x,'page 1 of 6',//////15x,
   1    'CFB HEAT RELEASE AND HEAT TRANSFER MODEL',/15x,
   2    '---------------------------------------',//15x,
   3    'RUN RESULTS FROM HEAT TRANSFER ROUTINE HEAT.F,
   4    VERSION 1.1',/15X,
   5    'WRITTEN BY: DALE W.C. JU',///15x,a65,/15x,a65,///15x,
   6    'FUEL PHYSICAL PROPERTIES AND COMPOSITION',/15X,
   7    '---------------------------------------',//15x,
   8    'PROXIMATE ANALYSIS',//15x,'Weight %')
        write(9,802) (ult(i),i=1,7)
802     format(15x,f8.3,5x,'Ash',/15x,f8.3,5x,'Moisture',/15x,f8.3,5x,
   1    'Sulphur',/15x,f8.3,5x,'Hydrogen',/15x,f8.3,5x,'Carbon',/15x,
   2    f8.3,5x,'Nitrogen',/15x,f8.3,5x,'Oxygen',//15x,
   3    'PARTICLE SIZE DISTRIBUTION',//15x,5x,'mm',13x,'wt %')
        do i=1,18
            write(9,804) siv(i),pdist(i)
804         format(15x,f10.3,5x,f10.3)
        enddo

        write(9,806) npart,f*100.d0
806     format(("1"),45x,'page 2 of 6',//////15x,
   1    'COMBUSTION CONDITIONS',/15x,'--------------------',//15x,
   2    '# of particles in Monte Carlo Method',4x,i10,/15x,
   3    '% of total wall area with membranes',5x,f10.1,' %')

        if(cyclon.eq.'C') then
            write(9,808) trec
808         format(15x,'Solids return temp. equals cyclone temp.',f10.1,' C')
        else
            write(9,810) trec
810         format(15x,'Solids return temp. set at',14x,f10.1,' C')
        endif

        write(9,812) recirc,fluxr,cross,ceff*100.d0,exair*100.d0,vtf,
   1    nfeed,fuel*3600.d0,afeed*3600.d0,pair*100.d0,rt,rc,devh
812     format(15x,'Solids recirculation rate',16x,f10.3,' kg/s',/15x,
```

```
     1 'Solids recirculation flux',15x,f10.3,' kg/m2s',/15x,
     2 'Gas cross-flow coefficient',14x,f10.3,' m/s',/15x,
     3 'Combustion efficiency',19x,f10.1,' %',/15x,'Excess air',30x,f10.3,' %',/15x,
     4 'Volatile transfer fraction',14x,f10.3,/15x,'Number of fuel feed points',
     5 14x,i10,/15x,'Fuel feedrate',27x,f10.3,' kg/hr',/15x,'Air feedrate',28x,
     6 f10.3,' kg/hr',/15x,'% of total air that is primary',10x,f10.1,' %',/15x
     7 'Residence time of particles in cyclone',2x,f10.3,' sec.',/15x,
     8 'Reflection coefficient',18x,f10.3,/15x,
     9 'Height at which developed zone begins',3x,f10.3,' m')

       write(9,814) uc,us,sug,tb
 814   format(//15x,'GAS VELOCITIES',/15x,'--------------',//15x,
     1 'Core insterstitial gas velocity',9x,f10.3,' m/s',/15x,
     2 'Streamer interstitial gas velocity',6x,f10.3,' m/s',/15x,
     3 'Superficial gas velocity',16x,f10.3,' m/s',//15x,
     4 'Bed temperature used in calculating',/17x,
     5 'heat transfer area and gas velocities',3x,f10.1,' C')

       write(9,816)
 816   format(("1"),45x,'page 3 of 6',//////15x,
     1 'HEAT RELEASE DISTRIBUTION',/15x,
     2 '-------------------------',//15x,'Height',8x,
     3 'Fraction of Total Heat Release',/34x,'Volatiles',16x,
     4 'Char',/17x,'(m)',9x,'Streamer',4x,'Core',6x,'Streamer',4x,'Core',/)

       write(9,818) fluxc(ncell,1),heatv(ncell)/total,heatc(ncell)/total
 818   format(15x,f5.2,12x,f10.6,12x,f10.6)
       do i=1,ny
          write(9,820) fluxc(i,1),heatv(i+ny)/total,heatv(i)/total,heatc(i+ny)/total,
     1    heatc(i)/total
 820      format(15x,f5.2,6x,3(1x,f10.6),2x,f10.6)
       enddo
       write(9,822) cycv/total,cycc/total,totv/total,(total-totv)/total
 822   format(15x,'Cyclone',10x,f10.6,12x,f10.6,//15x,'TOTAL',12x,f10.6,12x,
     1 f10.6)

       write(9,824) fluxc(ncell,1),press(2)
 824   format(("1"),45x,'page 4 of 6',//////15x,
     1 'OXYGEN PARTIAL PRESSSURE DISTRIBUTION',
     2 /15X,'-------------------------------------',//15x,'Height',8x,
     3 'Partial Pressure of Oxygen (atm.)',/17x,'(m)',9x,
     4 'Streamer',4x,'Core',//15x,f5.2,12x,f10.6)
       do i=1,ny
          write(9,826) fluxc(i,1)+dycell/2.d0,press2(i+2),presc2(i+2)
 826      format(15x,f5.2,6x,2(1x,f10.6))
```

```
      enddo
      write(9,828) er1,po2,pout,pcyc
 828  format(//15x,'Pressure convergence tolerance',10x,f10.4,' atm.',
     1 /15x,'Partial pressure of oxygen entering',5x,f10.6,' atm.',/15x,
     2 'Partial pressure of oxygen leaving riser',f10.3,' atm.',/15x,
     3 'Partial pressure of oxygen leaving cyclone',f8.3,' atm.')

      write(9,830) fluxc(ncell,1),temp(ncell)
 830  format(("1"),45x,'page 5 of 6',//////15x,
     1 'TEMPERATURE DISTRIBUTION',/15x,
     2 '------------------------',//15x,'Height',8x,'Temperature (C)',
     3 /17x,'(m)',9x,'Streamer',4x,'Core',//15x,f5.2,11x,f10.1)
      do i=1,ny
         write(9,832) fluxc(i,1),temp(i+ny),temp(i)
 832     format(15x,f5.2,4x,2(1x,f10.1))
      enddo
      write(9,834) trec,ermax,tcyc,twall
 834  format(//15x,'Solids return temperature',15x,f10.1,' C',/15x,
     1 'Temperature convergence tolerance',7x,f10.3,' C',/15x,
     2 'Cyclone temperature',21x,f10.1,' C',/15x,'Wall temperature',24x,f10.1,' C')

      write(9,836)
 836  format(("1"),45x,'page 6 of 6',//////15x,
     1 'HEAT TRANSFER COEFFICIENTS',/15x,
     2 '--------------------------',//15x,'Height',2x,'Density',
     3 2x,'Core Temp.',2x,'Heat Transfer Coefficient (W/m2C)',
     4 /17x,'(m)',3x,'(kg/m3)',5x,'(C)',6x,'Radiative',2x,'Convective',3x,'Overall',/)
      write(9,838) fluxc(ncell,1),flux(ncell,4),temp(ncell),effr(2),effc(2),effh(2)
      do i=1,ny
      denav=(flux(i,4)*acell(i)+flux(i+ny,4)*acell(i+ny))/at
         write(9,838) fluxc(i,1),denav,temp(i),effr(i+2),effc(i+2),effh(i+2)
 838     format(15x,f5.2,2x,f8.3,2x,f7.1,3(2x,f10.1))
      enddo

 100  close(9)
      close(3)
      close(7)
      close(8)
      stop
      end

c********************** subroutine feed *************************
      subroutine feed(tb,po2,ceff,exair,ult)
c Subroutine to calculate the coal feedrate (fuel), given
c the ultimate analysis of the coal and the gas velocity in the
```

```
c streamer and the core (us and uc).
c
c Variables are:
c
c fuel        coal feedrate (kg/s)
c o2feed oxygen feedrate (kg/s)
c o2need oxygen feedrate needed for every 1 kg/s of coal feed
c             (kg/s)
c ult         ultimate analysis of coal
c uc          gas velocity in the core (m/s)
c us          gas velocity in the streamer (m/s)
c*************************************************************

      implicit real*8(a-h,o-z)
      common/blka/acell(300),o2feed,x,fuel,uc,us
      common/blkh/acinit,asinit,acfin,asfin
      dimension ult(7)

c Calculate the O2 feedrate (kg/s)

      o2feed=101.325d0*(uc*acinit+us*asinit)/8.314d0/(273.15d0+tb)*
     1 po2*32.d0

c Calculate the O2 feedrate needed for 1 kg/s fuel (kg/s)

      x=(ceff*(ult(3)/32.d0+ult(4)/4.d0+ult(5)/12.d0)*32.d0-ult(7))/100.d0
      o2need=exair*x+x

c Calculate the fuel feedrate (kg/s)

      fuel=o2feed/o2need
      return
      end

c********************** subroutine volat ************************
      subroutine volat(ny,heatv,tdvol,totv,ncell,c1,c2,temp,pi)
c Subroutine to determine the heat release distribution due to
c devolatilization (heatv).
c***************************************************************

      implicit real*8(a-h,o-z)
      common/blkb/cycv,npart,dt(300),pmatt(300),
     1 pmat1(300),rc,volf,valh,rt,distv(300),siv(20),pdist(20)
      common/blkc/heatc(300),dpcut,presc(300),press(300),denp,coeff
      dimension heatv(300),temp(300)
```

```
c Intialize heatv.

      voli=0.d0
      do i=1,ncell
        heatv(i)=0.d0
      enddo

c Main loop over the number of particles.

      do 30 ii=1,npart

c Determine the initial size of the particle based on the particle
c size distribution.

        rval=d_lcran()
        totwt=0.d0
        do i=1,18
          totwt=totwt+pdist(i)/100.d0
          if(rval.le.totwt) then
            dpinit=siv(i)/1000.d0
            goto 5
          endif
        enddo

 5      volp=pi*dpinit**3/6.d0
        pmas=denp*volp

        vol=voli
        voldif=1.d0
        time=0.d0
        icell=ncell
        icello=icell

c Generate a random real number between [0,1] to determine the position
c of the particle.

 10     time=time+dt(icell)

        if(voldif.le.1.d-6) then
          tdvol=time-dt(icell)
          goto 30
        endif

        rval=d_lcran()
```

```

              if(icell.eq.ncell) then
                 if(rval.le.pmatt(icell)) icell=1
                 goto 20
              endif

              if(rval.le.pmat1(icell)) then
                 if(icell.le.ny) then
                    icell=icell+ny
                 else
                    icell=icell-ny
                 endif
              elseif(rval.le.pmatt(icell)) then
                 if(icell.eq.ny) then

c If the particle exits the top of the riser, another random number
c is generated to determine whether the particle is transferred to
c the streamer or is removed to the cyclone.

                    rval=d_lcran()
                    if(rval.le.rc) then
                       icell=ncell-1
                       goto 20
                    else
                       voldif=volf*(1.d0-dexp(-c1*time*dexp(-c2/
     1                 (1.987d-3*(273.15d0+temp(icello))))))-vol
                       vol=vol+voldif
                       heatv(icello)=heatv(icello)+valh*voldif*pmas
                        time=time+rt
                       voldif=volf*(1.d0-dexp(-c1*time*dexp(-c2/
     1                 (1.987d-3*(273.15d0+temp(icello))))))-vol
                       vol=vol+voldif
                       cycv=cycv+valh*voldif*pmas
                       icell=ncell
                       icello=icell
                       goto 10
                    endif
                 elseif(icell.lt.ny) then
                    icell=icell+1
                 elseif(icell.eq.ny+1) then
                    icell=ncell
                 else
                    icell=icell-1
                 endif
              endif
```

```
c  Add the heat generation due to volatiles to each cell.

 20         voldif=volf*(1.d0-dexp(-c1*time*dexp(-c2/
   1        (1.987d-3*(273.15d0+temp(icello))))))-vol
            vol=vol+voldif
            heatv(icello)=heatv(icello)+valh*voldif*pmas
            icello=icell
            goto 10
 30     continue

c  Calculate the heat distribution.

        totv=0.d0
        do 40 i=1,ncell
            totv=totv+heatv(i)
 40     continue
        distv(1)=heatv(1)/totv
        do 50 i=2,ncell
            sum=0.d0
            do j=1,i
                sum=sum+heatv(j)
            enddo
            distv(i)=sum/totv
 50     continue
        return
        end

c********************** subroutine vdisp ***********************
        subroutine vdisp(heatv,ncell,ny,pi,flux)
c  Subroutine which uses the plume model to correct for volatile
c  dispersion
c.
c  Variables are:
c
c  nfeed  Number of feed points.
c  height Height above the feed where there is full radial mixing
c  sdisp  Average displacement in the radial direction (m)
c  tdisp  Time (sec.)
c  r      Radius (m)
c*****************************************************************

        implicit real*8(a-h,o-z)
        common/blka/acell(300),o2feed,x,fuel,uc,us
        common/blkb/cycv,npart,dt(300),pmatt(300),
```

```
     1    pmat1(300),rc,volf,valh,rt,distv(300),siv(20),pdist(20)
          common/blke/vtf,nfeed
          dimension r(300),heatv(300),flux(300,5)
          data drp/0.015d0/

          r(ncell)=dsqrt(acell(ncell)/pi)
          ndiv=1
          if(nfeed.ne.1) ndiv=(nfeed-2)*2+2

          sdisp=r(ncell)/ndiv
          tdisp=sdisp**2/(2.d0*drp)

c Calculate the height where the volatiles are fully mixed in the
c radial direction.

          height=uc*tdisp

c Transfer a fraction (vtf) of the volatiles to the cell above where
c the volatiles are released.

          heatv(ncell)=heatv(ncell)-vtf*heatv(ncell)
          if(flux(1,1).ge.height) return
          heatv(1)=heatv(1)+vtf*heatv(ncell)
          heatv(1)=heatv(1)-vtf*heatv(1)
          do i=2,ny-1
            if(flux(i,1).ge.height) return
            heatv(i)=heatv(i)+vtf*heatv(i-1)
            heatv(i)=heatv(i)-vtf*heatv(i)
          enddo

          if(flux(ny,1).ge.height) return
          heatv(ny)=heatv(ny)+vtf*heatv(ny-1)
          heatv(ny)=heatv(ny)-vtf*heatv(ny)
          cycv=cycv+vtf*heatv(ny)
          return
          end

c*********************** subroutine char *************************
          subroutine char(ny,cyc,pi,ncell,ult)
c Subroutine to determine the char heat release distribution.
c
c Variables are:
c
c cmass  Mass of char particle
c cyc    Total heat released in the cyclone
```

```
c dp    Particle diameter (m)
c icell Position of the particle at a given time
c volmas Mass of volatiles
c*****************************************************************

      implicit real*8(a-h,o-z)
      common/blkb/cycv,npart,dt(300),pmatt(300),
     1 pmat1(300),rc,volf,valh,rt,distv(300),siv(20),pdist(20)
      common/blkc/heatc(300),dpcut,presc(300),press(300),denp,coeff
      dimension ult(7)

c Intialize the heat due to char combustion vector to zero, and the
c heat released in the cyclone to equal the heat released due to
c devolatilization.

      do i=1,ncell
         heatc(i)=0.d0
      enddo
      cyc=cycv

c Main loop over the number the particles.

      do 30 ii=1,npart

c Determine the initial size of the particle based on the particle
c size distribution.

         rval=d_lcran()
         totwt=0.d0
         do i=1,18
            totwt=totwt+pdist(i)/100.d0
            if(rval.le.totwt) then
               dpinit=siv(i)/1000.d0
               goto 5
            endif
         enddo

 5       volp=pi*dpinit**3/6.d0
         pmas=denp*volp
         volmas=pmas*volf
         ashmas=pmas*ult(1)/100.d0
         cmas=pmas-volmas-ashmas

c Determine diameter of a particle of fixed carbon only.

```

```
            dp=(6.d0*cmas/(denp*pi))**(1.d0/3.d0)

c  Generate a random real number between [0,1] to determine the initial
c  position of the char particle based on the devolatilization heat
c  released distribution.

            rval=d_lcran()
             icell=1
            do i=1,ncell-1
                if(rval.ge.distv(i)) icell=i+1
            enddo
            icello=icell

            time=0.d0
   10       time=time+dt(icell)

            rval=d_lcran()
            if(icell.eq.ncell) then
                if(rval.lt.pmatt(icell)) icell=1
                goto 20
             endif

            if(rval.le.pmat1(icell)) then
                if(icell.le.ny) then
                    icell=icell+ny
                else
                    icell=icell-ny
                endif
            elseif(rval.le.pmatt(icell)) then
                if(icell.eq.ny) then

c  If the particle exits the top of the riser, another random number
c  is generated to determine whether the particle is transferred to
c  the streamer or is removed to the cyclone.

                    rval=d_lcran()
                    if(rval.lt.rc) then
                        icell=ncell-1
                    else
                        if(dp.gt.dpcut) then
                            fi=coeff*pi*(dp**2)*presc(icello+2)*dt(icello)*12.d0
                            cmas2=cmas-fi
                            if(cmas2.le.0.d0) then
                                heatc(icello)=heatc(icello)+cmas2*valh
                                goto 30
```

```
                  endif
                  heatc(icello)=heatc(icello)+fi*valh
                  cmas=cmas-fi

                  time=time+rt
                  fi=coeff*pi*(dp**2)*presc(ny)*rt*12.d0
                  cmas2=cmas-fi
                  if(cmas2.le.0.d0) then
                     cyc=cyc+cmas2*valh
                     goto 30
                  endif
                  cyc=cyc+fi*valh
                  cmas=cmas-fi
                  dp=(6.d0*cmas/(denp*pi))**(1.d0/3.d0)
                  icell=ncell
                  icello=icell
                  goto 10
                else
                  goto 30
                endif
              endif

           elseif(icell.lt.ny) then
              icell=icell+1
           elseif(icell.eq.ny+1) then
              icell=ncell
           else
              icell=icell-1
           endif
         endif

c  Calculate the heat generation due to char combustion, assuming first
c  order reaction.  From: Howard, J.R.

 20      if(icello.le.ny) then
            fi=coeff*pi*(dp**2)*presc(icello+2)*dt(icello)*12.d0
         elseif(icello.eq.ncell) then
            fi=coeff*pi*(dp**2)*presc(2)*dt(icello)*12.d0
         else
             fi=coeff*pi*(dp**2)*press(icello-ny+2)*dt(icello)*12.d0
         endif
          heatc(icello)=heatc(icello)+fi*valh
          icello=icell

c  Mass balance to determine the new particle diameter, DP.
```

```

            cmas=cmas-fi
            if(cmas.lt.0.d0) goto 30
            dp=(6.d0*cmas/(denp*pi))**(1.d0/3.d0)
            goto 10
 30     continue
        return
        end

c********************** subroutine pres **************************
        subroutine pres(ny,cyc,pi,po2,ncell)
c Subroutine to determine the partial pressure of oxygen profile.
c Secondary in injected into the core and the streamer cells to
c keep the gas velocities in the streamer and core at a constant
c value.
c
c Variables are:
c
c cc      Concentration of oxygen in the core
c cs      Concentration of oxygen in the streamer
c mcyc    Mass of fuel in the cyclone (kg)
c mfuel   Mass of fuel in each cell (kg)
c o2prim  Oxygen feed in the primary air
c rcore   Radius of the core
c*****************************************************************

        implicit real*8(a-h,o-z)
        real*8 mfuel,mcyc
        common/blka/acell(300),o2feed,x,fuel,uc,us
        common/blkd/heat(300),total,dycell,cross,presc2(300),
     1  press2(300),con0,oxyclc,mcyc,pair
        common/blkh/acinit,asinit,acfin,asfin
        dimension mfuel(300),conc(300)

c Assume time duration is 1 sec.
c Calculate the mass of fuel in each cell (kg) based on the fraction
c of heat released.

        do i=1,ncell
           mfuel(i)=heat(i)*fuel
        enddo
         mcyc=cyc/total*fuel

c Calculate the concentration of O2 in each cell (kg/m3)

```

```
      con0=o2feed/(uc*acinit+us*asinit)
      cprim=o2feed*pair-mfuel(ncell)*x

c Addition of secondary air, in both the streamer and core,
c after the primary zone.

      if(cprim.le.0.d0) then
         conin=(o2feed*(1.d0-pair))/(uc*acinit+us*asinit)
      else
         conin=(o2feed-mfuel(ncell)*x)/(uc*acinit+us*asinit)
      endif

      conc(ncell)=conin
      oxyc=conin*uc*(acell(1)+acell(2))/2.d0
      oxys=conin*us*(acell(ny+1)+acell(ny+2))/2.d0

      do i=1,ny-1
         rcore=dsqrt(acell(i)/pi)
         frac=cross*2.d0*pi*rcore*dycell
         cc=(acell(i)+acell(i+1))/2.d0*uc
         cs=(acell(ny+i)+acell(ny+i+1))/2.d0*us

         oxys=(oxys-mfuel(ny+i)*x+frac*(oxyc-mfuel(i)*x)/
     1   (cc+frac))/(1.d0+frac/cs-frac**2/cs/(cc+frac))
         oxyc=(oxyc-mfuel(i)*x+frac*oxys/cs)/(1.d0+frac/cc)
         if(oxys.lt.0.d0) oxys=0.d0
         if(oxyc.lt.0.d0) oxyc=0.d0
         conc(i)=oxyc/cc
         conc(ny+i)=oxys/cs
      enddo
      rcore=dsqrt(acell(ny)/pi)
      frac=cross*2.d0*pi*rcore*dycell
      cc=acfin*uc
      cs=asfin*us

      oxys=(oxys-mfuel(ny+ny)*x+frac*(oxyc-mfuel(ny)*x)/
     1 (cc+frac))/(1.d0+frac/cs-frac**2/cs/(cc+frac))
      oxyc=(oxyc-mfuel(ny)*x+frac*oxys/cs)/(1.d0+frac/cc)
      if(oxys.lt.0.d0) oxys=0.d0
      if(oxyc.lt.0.d0) oxyc=0.d0
      oxyclc=oxys+oxyc
      conc(ny)=oxyc/cc
      conc(2*ny)=oxys/cs

c Calculate the partial pressure of O2 in each cell
```

```
      press2(1)=po2
      presc2(1)=po2
      press2(2)=conc(ncell)*po2/con0
      presc2(2)=press2(2)

      do i=3,ny+2
          presc2(i)=conc(i-2)*po2/con0
          press2(i)=conc(ny+i-2)*po2/con0
       enddo

      return
      end

c************************ subroutine htrans ************************
      subroutine htrans(ncell,nycell,eps,per,rf2,recirc,ult)
c Subroutine to calculate the temperature profile given the partial
c pressure of oxygen profile and heat release distribution.
c To aid convergence, the particle convective term entering the riser
c is set to equal the term leaving the riser.
c
c Variables are:
c
c a,b,c,r   Entries in the tridiagonal matrix
c cg        Heat capacity of the gas (J/kgK)
c cp        Heat capacity of the particles (J/kgK)
c deng      Density of the gas (kg/m3)
c emiss     Emissivity
c f     Fraction of the wall covered by membrane
c fx        Matrix of mass flux in the radial direction (kg/m2s)
c fyn       Matrix of mass flux in the north direction (kg/m2s)
c fys       Matrix of mass flux in the south direction (kg/m2s)
c g         Matrix of source term for each cell (W)
c heatev Heat of evaporation of water at 25 C (J/kg)
c sbc       Stefan-Boltzmann constant (W/m2K4)
c t     Temperature matrix for present iteration
c to        Temperature matrix for previous iteration
c u         Solution vector from subroutine tridag
c******************************************************************
      implicit real*8(a-h,o-z)
      real*8 k
      common/blka/acell(300),o2feed,x,fuel,uc,us
      common/blkb/cycv,npart,dt(300),pmatt(300),
     1 pmat1(300),rc,volf,valh,rt,distv(300),siv(20),pdist(20)
      common/blkd/heat(300),total,dycell,cross,presc2(300),
```

```
     1    press2(300),con0,oxyclc,mcyc,pair
          common/blkf/to(5,300),k,at,twall,tair,vg,tref,cp,cg,afeed,fin
          common/blkg/flux(300,5),dx(5,300),dy(5,300),f,emiss,denb(300)
          common/blkh/acinit,asinit,acfin,asfin
          common/blki/areaw(5,300),areae(5,300),arean(5,300),
     1    areas(5,300),areat(5,300),effh(300),deng,sbc,const1,
     2    effc(300),effr(300),v2,v5,v6,cyc,gcyc
          dimension t(5,300),fyn(5,300),fys(5,300),fx(5,300)
          dimension a(300),b(300),c(300),r(300),u(300),heat(300)
          dimension g(5,300),ult(7)
          data heatev/2.44d6/

          ny=nycell+3
          nx=4

c Convert temperatures from C to K

          do i=1,nx
              do j=1,ny
                  to(i,j)=to(i,j)+273.15d0
                  t(i,j)=to(i,j)
              enddo
          enddo

c Determine fx, fyn and fys values.

          do j=1,ny
              do i=1,nx
                  fx(i,j)=0.d0
                  fyn(i,j)=0.d0
                  fys(i,j)=0.d0
              enddo
          enddo

          do j=3,ny-1
              fx(3,j)=flux(j-2,2)
              fx(2,j)=flux(j-2+nycell,2)
          enddo
          fx(2,2)=flux(nycell+1,3)*asinit/(dy(2,2)*per)
          fx(3,2)=0.d0
          do j=4,ny-2
              fyn(3,j)=flux(j-2,3)
              fys(3,j)=flux(j-3,3)
              fys(2,j)=flux(j-2+nycell,3)
              fyn(2,j)=flux(j-1+nycell,3)
```

```
          enddo
          fys(2,3)=flux(nycell+1,3)
          fyn(2,3)=flux(nycell+2,3)
          fyn(2,2)=flux(nycell+1,3)
          fyn(3,3)=flux(1,3)
          fys(3,3)=flux(ncell,3)
          fyn(3,2)=flux(ncell,3)
          fys(3,2)=(recirc+fuel)/acinit
          fyn(3,ny-1)=flux(nycell,3)
          fys(3,ny-1)=flux(nycell-1,3)
          fys(2,ny-1)=flux(ncell-1,3)
          fyn(2,ny-1)=flux(nycell,3)*acfin*rc/asfin

c Calculate heat generation term (W), subtracting the heat loss due
c to the evaporation of water at (25 C).

          g(2,2)=heat(ncell)*(fuel*valh*1000.d0-
     1    (fuel*ult(2)+fuel*ult(4)/2.d0*18.d0)/100.d0*heatev)*asinit/at
          g(3,2)=heat(ncell)*(fuel*valh*1000.d0-
     1    (fuel*ult(2)+fuel*ult(4)/2.d0*18.d0)/100.d0*heatev)*acinit/at
          do j=3,ny-1
             g(2,j)=heat(j-2+nycell)*(fuel*valh*1000.d0-
     1       (fuel*ult(2)+fuel*ult(4)/2.d0*18.d0)/100.d0*heatev)
             g(3,j)=heat(j-2)*(fuel*valh*1000.d0-
     1       (fuel*ult(2)+fuel*ult(4)/2.d0*18.d0)/100.d0*heatev)
          enddo
          gcyc=cyc/total*fuel*valh*1000.d0

c Start N-S sweep

          iter=0
 10       iter=iter+1

          do 100 j=2,ny

C Calculate A,B,C and R.

             a(1)=0.d0
             b(1)=1.d0
             c(1)=0.d0
             r(1)=twall+273.15d0

             if(j.eq.ny) then
                do i=2,4
                   a(i)=0.d0
```

```
                 b(i)=1.d0
                 c(i)=0.d0
                 r(i)=t(3,j-1)
              enddo
              goto 50
           endif

c  Set an upper limit of the heat transfer coefficientto 100.

           h=cons1*denb(j)

           if(h.ge.100.d0) h=100.d0

           i=2
           t1=(fx(2,j)*cp+deng*cg*vg)*areae(i,j)
           t2=(fx(3,j)*cp+deng*cg*vg)*areae(i,j)
           t3=fyn(i,j)*cp*arean(i,j)
           t4=deng*cg*us*arean(i,j)
           t5=fys(i,j)*cp*areas(i,j)
           t6=deng*cg*us*areas(i,j)

           ae=-k*areae(i,j)/((dx(i,j)+dx(i+1,j))/2.d0)
           an=-k*arean(i,j)/((dy(i,j)+dy(i,j+1))/2.d0)
           as=-k*areas(i,j)/((dy(i,j)+dy(i,j-1))/2.d0)
           s=-g(i,j)
           ap=ae+an+as
           a(i)=h*areaw(i,j)+emiss*sbc*areaw(i,j)*to(i-1,j)**3
           b(i)=ap-h*areaw(i,j)*arean(i,j)/at-emiss*sbc*areat(i,j)*to(i,j)**3-
     1     t1-t4-t5
           c(i)=-ae-h*areaw(i,j)*arean(i+1,j)/at+emiss*sbc*areae(i,j)*to(i+1,j)
     1     **3+t2
           r(i)=an*to(i,j+1)+as*to(i,j-1)+s-emiss*sbc*arean(i,j)*
     1     to(i,j+1)**4-emiss*sbc*areas(i,j)*to(i,j-1)**4+
     2     (-t1+t2-t4-t5)*(tref+273.15d0)-t3*(to(i,j+1)-(tref+273.15d0))
     3     -t6*(to(i,j-1)-(tref+273.15d0))

           i=3
           t1=(fx(3,j)*cp+deng*cg*vg)*areaw(i,j)
           t2=(fx(2,j)*cp+deng*cg*vg)*areaw(i,j)
           t3=(fyn(i,j)*cp+deng*cg*uc)*arean(i,j)
           t4=(fys(i,j)*cp+deng*cg*uc)*areas(i,j)

           aw=-k*areaw(i,j)/((dx(i,j)+dx(i-1,j))/2.d0)
           an=-k*arean(i,j)/((dy(i,j)+dy(i,j+1))/2.d0)
           as=-k*areas(i,j)/((dy(i,j)+dy(i,j-1))/2.d0)
```

```
          s=-g(i,j)
          ap=aw+an+as
          a(i)=-aw+emiss*sbc*areaw(i,j)*to(i-1,j)**3+t2
          b(i)=ap-emiss*sbc*areat(i,j)*to(i,j)**3-t1-t3
          c(i)=0.d0
          r(i)=an*to(i,j+1)+as*to(i,j-1)+s-emiss*sbc*arean(i,j)*
     1    to(i,j+1)**4-emiss*sbc*areas(i,j)*to(i,j-1)**4+
     1    (-t1+t2-t3)*(tref+273.15d0)-t4*(to(i,j-1)-(tref+273.15d0))

          if(j.eq.2) r(i)=r(i)+gcyc

          i=4
          aw=1.d0
          ap=aw
          a(i)=-aw
          b(i)=ap
          c(i)=0.d0
          r(i)=0.d0

 50       call tridag(a,b,c,r,u,nx)

          do i=1,nx
             t(i,j)=u(i)
          enddo

c Update temperature solution.

 90       do i=1,4
             to(i,j)=to(i,j)-rf2*(to(i,j)-t(i,j))
          enddo

 100    continue

c Calculate the temperature of the cyclone.

        tcyc=to(3,ny)+gcyc/(afeed*cg+recirc*cp)

        error=0.d0
        ermax=0.d0
        itab=0
        jtab=0
        do j=2,ny
           do i=1,nx
              error=dabs(t(i,j)-to(i,j))/t(i,j)
              if(error.gt.ermax) then
```

```
                ermax=error
                itab=i
                jtab=j
              endif
            enddo
          enddo
          print*, 'i,j,iter,error',itab,jtab,iter,ermax

c  Calculate the new mixing temperature.

          tmix=(afeed*cg*(tair+273.15d0)+fuel*cp*(tref+273.15d0)+
     1    recirc*cp*tcyc)/(afeed*cg+fuel*cp+recirc*cp)
          do i=1,4
            to(i,1)=tmix
          enddo

          if(ermax.gt.eps) goto 10

c-----------------------------------------------------
c  Check the energy balance (for debugging purposes).

          v1=0.d0
          v2=0.d0
          v3=0.d0
          v4=0.d0

          do j=ny-1,2,-1
            do i=2,3
              gen=g(i,j)
              v1=v1+gen
              write(7,900) i,j,t(i,j),gen
 900          format(i15,2x,i15,2x,f15.4,2x,f15.4)

c  Set upper limit of the heat transfer coefficient.

              h=const1*denb(j)

              if(h.ge.100.d0) h=100.d0

              if(i.eq.2) then
                condw=-h*areaw(i,j)*((t(i,j)*arean(i,j)+t(i+1,j)*
     1          arean(i+1,j))/at-t(i-1,j))
                conde=-k*areae(i,j)/((dx(i,j)+dx(i+1,j))/2.d0)*(t(i,j)-t(i+1,j))
                v2=v2+condw
              else
```

```
            condw=-k*areaw(i,j)/((dx(i,j)+dx(i-1,j))/2.d0)*
     1      (t(i,j)-t(i-1,j))
            conde=0.d0
         endif
         condn=-k*arean(i,j)/((dy(i,j)+dy(i,j+1))/2.d0)*(t(i,j)-to(i,j+1))
         conds=-k*areas(i,j)/((dy(i,j)+dy(i,j-1))/2.d0)*(t(i,j)-to(i,j-1))
         if(j.eq.ny-1) v3=v3+condn
         if(j.eq.2) v4=v4+conds
         write(7,910) condw,conde,condn,conds
910      format(4(f15.4,2x))

         if(i.eq.2) then
            convwp=0.d0
            convwg=0.d0
            convep=-fx(2,j)*cp*areae(i,j)*(t(i,j)-298.15d0)+
     1      fx(3,j)*cp*areae(i,j)*(t(i+1,j)-298.15d0)
            conveg=-deng*cg*vg*areae(i,j)*
     1      (t(i,j)-298.15d0)+deng*cg*vg*areae(i,j)*(t(i+1,j)-298.15d0)
            convnp=fyn(i,j)*cp*arean(i,j)*(to(i,j+1)-298.15d0)
            convng=-deng*cg*us*arean(i,j)*(t(i,j)-298.15d0)
            convsp=-fys(i,j)*cp*areas(i,j)*(t(i,j)-298.15d0)
            convsg=deng*cg*us*areas(i,j)*(to(i,j-1)-298.15d0)
            if(j.eq.ny-1) htop=convng+convnp
            if(j.eq.2) then
               convsg=0.d0
               convsp=0.d0
            endif
         else
            convwp=-fx(3,j)*cp*areaw(i,j)*(t(i,j)-298.15d0)+
     1      fx(2,j)*cp*areaw(i,j)*(t(i-1,j)-298.15d0)
            convwg=-deng*cg*vg*areaw(i,j)*
     1      (t(i,j)-298.15d0)+deng*cg*vg*areaw(i,j)*
     2      (t(i-1,j)-298.15d0)
            convep=0.d0
            conveg=0.d0
            convnp=-fyn(i,j)*cp*arean(i,j)*(t(i,j)-298.15d0)
            convng=-deng*cg*uc*arean(i,j)*(t(i,j)-298.15d0)
            convsp=fys(i,j)*cp*areas(i,j)*(to(i,j-1)-298.15d0)
            convsg=deng*cg*uc*areas(i,j)*(to(i,j-1)-298.15d0)
            if(j.eq.ny-1) htop=htop+convng+convnp
            if(j.eq.2) then
               convsg=0.d0
               convsp=-htop-(v1+v2)+gcyc
            endif
         endif
```

```
            if(j.eq.ny-1) v3=v3+convnp+convng
            if(j.eq.2) v4=v4+convsp+convsg
            write(7,910) convwp,convep,convnp,convsp
            write(7,910) convwg,conveg,convng,convsg

            radw=-emiss*sbc*areaw(i,j)*(to(i,j)**3*t(i,j)-to(i-1,j)**3*t(i-1,j))
            radn=-emiss*sbc*arean(i,j)*(to(i,j)**3*t(i,j)-to(i,j+1)**4)
            rads=-emiss*sbc*areas(i,j)*(to(i,j)**3*t(i,j)-to(i,j-1)**4)
            if(i.eq.2) then
                rade=-emiss*sbc*areae(i,j)*(to(i,j)**3*t(i,j)-
                to(i+1,j)**3*t(i+1,j))
                v2=v2+radw
            else
                rade=0.d0
            endif
            if(j.eq.ny-1) v2=v2+radn
            if(j.eq.2) v2=v2+rads
            write(7,910) radw,rade,radn,rads

            if(i.eq.2) then
                effc(j)=-condw/areaw(i,j)/(to(i,j)-to(i-1,j))
                effr(j)=-radw/areaw(i,j)/(to(i,j)-to(i-1,j))
                effh(j)=effc(j)+effr(j)
            endif
        enddo
    enddo

    v5=v1+v2+v3+v4
    v6=v5/v1*100.d0
    print*, v1,v2,v3,v4,v5
    write(8,*) 'v1 - v5',v1,v2,v3,v4,v5

    print*, 'heat balance % diff. of heat gen. = ',v6
    write(8,*) 'heat balance % diff. of heat gen. = ',v6
    z1=v1
    z2=v2
    z3=v3

c-----------------------------------------------------------

c Convert the temperatures back from K to C.

    do j=1,ny
        do i=1,nx
            to(i,j)=to(i,j)-273.15d0
```

```
          enddo
        enddo
        return
        end

c************************* subroutine tridag*************
        subroutine tridag(a,b,c,r,u,n)
c Subroutine to solve a nxn tridiagonal matrix.
c*******************************************************

        implicit real*8(a-h,o-z)
        dimension gam(300),a(300),b(300),c(300),r(300),u(300)
        bet=b(1)
        u(1)=r(1)/bet

c Decomposition and forward substitution.

        do j=2,n
          gam(j)=c(j-1)/bet
          bet=b(j)-a(j)*gam(j)
          u(j)=(r(j)-a(j)*u(j-1))/bet
        enddo

c Backsubstitution.

        do j=n-1,1,-1
          u(j)=u(j)-gam(j+1)*u(j+1)
        enddo
        return
        end

c******** IEEE error handling routine ************
        integer function common_handler (sig, sip, uap)
        integer sig

c define the structure siginfo, as in < sys/siginfo.h>

        structure /fault/
          integer address
        end structure
        structure /siginfo/
          integer si_signo
          integer si_code
          integer si_errno
          record /fault/ fault
```

```
      end structure
      record /siginfo/ sip

c  for error codes see p 89 numerical computation guide

      write (0,10) sip.si_code, sip.fault.address
 10   format('ieee exception ', i1,' occurred at address ', z8 )
      end
```

APPENDIX B

SAMPLE INPUT FILES

B.1 HYDRODYNAMIC INPUT FILE LISTING

COMBUSTOR: Studsvik Prototype
CASE: sh0

20	---- no. of cells in y-dir
425000	---- x-sectional area (m2)
0.100000	---- reflection coeff.
2.607681	---- perimeter of riser (m)
0.680000	---- primary zone volume (m3)
107.334949	---- average bed density (kg/m3)
2.777500	---- height of start of dev. zone (m)
0.719603	---- frac. of total air that is primary
849.850000	---- bed temperature (C)
106.850000	---- wall temperature (C)

cell#	height(m)	flux out X-dir.	flux out Y-dir.	densities
1	.13	76.6772	238.1944	49.3334
2	.38	46.5892	151.6668	30.4128
3	.63	28.5548	104.8062	20.3644
4	.88	17.6849	78.2123	14.7241
5	1.14	11.0329	62.7280	11.4609
6	1.39	6.9686	53.5793	9.5401
7	1.64	4.5322	48.1274	8.3980
8	1.89	3.0692	44.8620	7.7148
9	2.15	2.1894	42.9003	7.3047
10	2.40	1.6597	41.7035	7.0580
11	2.65	1.3395	40.8774	6.9041
12	2.90	1.3410	40.1386	6.7814
13	3.16	1.3169	39.3816	6.6567
14	3.41	1.2920	38.6006	6.5280
15	3.66	1.2663	37.7956	6.3953
16	3.91	1.2398	36.9665	6.2585
17	4.17	1.2126	36.1136	6.1177
18	4.42	1.1847	35.2373	5.9729
19	4.67	1.1560	34.3383	5.8243
20	4.92	1.1266	33.4162	5.6720
21	.13	12.1690	1247.4000	1134.0000

22	.38	7.6581	1247.4000	1134.0000
23	.63	5.0597	1247.4000	1134.0000
24	.88	3.5054	1247.4000	1134.0000
25	1.14	2.4755	1247.4000	1134.0000
26	1.39	1.8042	1247.4000	1134.0000
27	1.64	1.4154	1247.4000	1134.0000
28	1.89	1.1882	1247.4000	1134.0000
29	2.15	1.0542	1247.4000	1134.0000
30	2.40	.9746	1247.4000	1134.0000
31	2.65	.9262	1247.4000	1134.0000
32	2.90	.8862	1247.4000	1134.0000
33	3.16	.8467	1247.4000	1134.0000
34	3.41	.8063	1247.4000	1134.0000
35	3.66	.7650	1247.4000	1134.0000
36	3.91	.7229	1247.4000	1134.0000
37	4.17	.6801	1247.4000	1134.0000
38	4.42	.6367	1247.4000	1134.0000
39	4.67	.5929	1247.4000	1134.0000
40	4.92	.5489	1247.4000	1134.0000
41	.00	.0000	369.1127	316.9441

height (m)	Aa (m2)
.00	.089157
.13	.072131
.38	.044831
.63	.028355
.88	.018412
1.14	.012411
1.39	.008790
1.64	.006604
1.89	.005285
2.15	.004489
2.40	.004009
2.65	.003708
2.90	.003469
3.16	.003225
3.41	.002972
3.66	.002712
3.91	.002444
4.17	.002167
4.42	.001882
4.67	.001589
4.92	.001288

5.05	.001136

Particle Physical Properties and Composition

Fuel	Weight %
12.200	ash
15.200	moisture
.170	sulphur
3.050	hydrogen
52.900	carbon
.680	nitrogen
15.800	oxygen
40.000	% volatiles yield
1400.000	particle density (kg/m3)
7.122	mean core gas velocity (m/s)
3.567	mean streamer gas velocity (m/s)
6.95850	superficial gas velocity (m/s)
30.00000	solids recirc. flux (kg/m2s)
.07921	thermal conductivity of gas
.85000	particle radiation emissivity

Particle Sieve Sizing

mm	wt%
7.925	9.250
5.613	10.920
3.962	13.180
2.794	12.110
1.981	11.090
1.397	8.730
.991	7.750
.701	5.480
.495	4.750
.351	3.740
.246	3.410
.175	3.990
.124	1.290
.088	.000
.053	.000
.045	.000
.038	.000
.000	.000

B.2 USER INPUT FILE LISTING

INPUT FILE FOR HEAT.F
Constants Used With the Devolatilization Rate Equation

11.8	706.0	bituminous coal
24000.0		higher heating value (kJ/kg)
100		number of particles in the Monte Carlo method
0.1		frac. of particles that exit a cell within dt
1		number of feed points
0.001		tolerance for partial pressure of O2 (atm)
1.0		tolerance for bed temperature (C)
0.01		convergence tolerance in subroutine heat
0.7		relaxation factor in subroutine heat
0.7		relaxation factor for partial pressure of O2
0.1		mass transfer crossflow coefficient
0.3		volatile transfer fraction
0.3		residence time in the cyclone (sec.)
0.2		excess air
1.0		combustion efficiency
900.0		particle surface temperature (C)
25.0		temperature of inlet air (C)
25.0		reference temperature (C)
1.0		const. in wall convective heat transfer coeff. term

APPENDIX C

OUTPUT FILES

CFB HEAT RELEASE AND HEAT TRANSFER MODEL

RUN RESULTS FROM HEAT TRANSFER ROUTINE HEAT.F, VERSION 8.1
WRITTEN BY: DALE W.C. JU

COMBUSTOR: Studsvik Prototype
CASE: Sardinian Coal
Case : sh0 (base case)
Superficial gas velocity = 6.96 m/s
Solids reciculation rate = 30 kg/m2s
Highvale coal(mean dp = 2.89 mm)

FUEL PHYSICAL PROPERTIES AND COMPOSITION

PROXIMATE ANALYSIS

Weight %	
12.200	Ash
15.200	Moisture
0.170	Sulphur
3.050	Hydrogen
52.900	Carbon
0.680	Nitrogen
15.800	Oxygen

PARTICLE SIZE DISTRIBUTION

mm	wt %
7.925	9.250
5.613	10.920
3.962	13.180
2.794	12.110
1.981	11.090
1.397	8.730
0.991	7.750
0.701	5.480
0.495	4.750
0.351	3.740
0.246	3.410
0.175	3.990
0.124	1.290
0.088	0.000
0.053	0.000
0.045	0.000
0.038	0.000
0.000	0.000

COMBUSTION CONDITIONS

# of particles in Monte Carlo Method	100
% of total wall area with membranes	70.0 %
Solids return temp. equals cyclone temp.	858.6 C
Solids recirculation rate	12.750 kg/s
Solids recirculation flux	30.000 kg/m2s
Gas cross-flow coefficient	0.100 m/s
Combustion efficiency	100.0 %
Excess air	20.000 %
Volatile transfer fraction	0.300
Number of fuel feed points	1
Fuel feedrate	395.687 kg/hr
Air feedrate	3070.295 kg/hr
% of total air that is primary	72.0 %
Residence time of particles in cyclone	0.300 sec.
Reflection coefficient	0.100
Height at which developed zone begins	2.777 m

GAS VELOCITIES

Core insterstitial gas velocity	7.122 m/s
Streamer interstitial gas velocity	3.567 m/s
Superficial gas velocity	6.958 m/s
Bed temperature used in calculating heat transfer area and gas velocities	849.9 C

HEAT RELEASE DISTRIBUTION

Height	Fraction of Total Heat Release			
	Volatiles		Char	
(m)	Streamer	Core	Streamer	Core
0.00	0.337328		0.464242	
0.13	0.001086	0.077952	0.017981	0.007278
0.38	0.003157	0.017585	0.009128	0.004215
0.63	0.000082	0.004516	0.006292	0.002686
0.88	0.000003	0.001274	0.004353	0.001962
1.14	0.000000	0.000414	0.003025	0.001509
1.39	0.000004	0.000233	0.002080	0.001248
1.64	0.000001	0.000448	0.001675	0.001108
1.89	0.000007	0.000271	0.001341	0.001003
2.15	0.000001	0.000200	0.001087	0.000910
2.40	0.000000	0.000257	0.000996	0.000883
2.65	0.000000	0.000123	0.000947	0.000874
2.90	0.000000	0.000076	0.000874	0.000818
3.16	0.000000	0.000039	0.000898	0.000825
3.41	0.000000	0.000063	0.000825	0.000822
3.66	0.000000	0.000079	0.000860	0.000781
3.91	0.000000	0.000027	0.000751	0.000779
4.17	0.000000	0.000017	0.000686	0.000754
4.42	0.000000	0.000007	0.000564	0.000716
4.67	0.000000	0.000007	0.000491	0.000709
4.92	0.000000	0.000051	0.000364	0.000670
Cyclone	0.000037		0.004644	
TOTAL	0.502019		0.497981	

OXYGEN PARTIAL PRESSSURE DISTRIBUTION

Height (m)	Partial Pressure of Oxygen (atm.) Streamer	Core
0.00	0.068524	
0.26	0.031904	0.053800
0.51	0.018193	0.046472
0.76	0.012646	0.043154
1.00	0.011824	0.041219
1.26	0.015730	0.039964
1.51	0.021778	0.039116
1.76	0.025567	0.038457
2.01	0.027828	0.037964
2.27	0.029310	0.037572
2.52	0.029630	0.037212
2.77	0.029585	0.036890
3.02	0.029795	0.036598
3.29	0.029436	0.036308
3.54	0.029658	0.036025
3.79	0.029217	0.035742
4.04	0.029720	0.035482
4.29	0.030067	0.035238
4.54	0.030834	0.035020
4.79	0.031302	0.034815
5.04	0.032164	0.034630

Pressure convergence tolerance	0.0040 atm.
Partial pressure of oxygen entering	0.210000 atm.
Partial pressure of oxygen leaving riser	0.035 atm.
Partial pressure of oxygen leaving cyclone	0.034 atm.

TEMPERATURE DISTRIBUTION

Height (m)	Temperature (C) Streamer	Core
0.00	889.4	
0.13	883.8	891.4
0.38	833.4	888.0
0.63	830.3	884.5
0.88	827.6	881.0
1.14	825.1	877.8
1.39	822.9	875.0
1.64	821.1	872.5
1.89	819.8	870.2
2.15	818.7	868.1
2.40	817.9	866.3
2.65	820.9	864.5
2.90	823.9	862.8
3.16	826.9	861.4
3.41	827.3	860.2
3.66	828.4	859.0
3.91	830.4	858.0
4.17	834.2	857.2
4.42	841.1	856.7
4.67	853.3	856.7
4.92	876.3	857.4

Solids return temperature	858.6 C
Temperature convergence tolerance	0.004 C
Cyclone temperature	858.6 C
Wall temperature	106.8 C

HEAT TRANSFER COEFFICIENTS

Height (m)	Density (kg/m3)	Core Temp. (C)	Heat Transfer Coefficient (W/m2C) Radiative	Convective	Overall
0.00	316.944	889.4	110.3	100.5	210.8
0.13	233.423	891.4	109.9	100.8	210.7
0.38	146.824	888.0	98.1	106.9	205.0
0.63	94.664	884.5	97.4	101.4	198.7
0.88	63.214	881.0	96.8	67.7	164.5
1.14	44.242	877.8	96.2	47.4	143.6
1.39	32.797	875.0	95.7	35.1	130.9
1.64	25.889	872.5	95.3	27.7	123.1
1.89	21.720	870.2	95.0	23.2	118.3
2.15	19.205	868.1	94.8	20.5	115.3
2.40	17.688	866.3	94.6	18.9	113.5
2.65	16.738	864.5	94.8	17.8	112.6
2.90	15.982	862.8	96.6	16.8	113.4
3.16	15.211	861.4	96.6	15.9	112.6
3.41	14.412	860.2	96.7	15.1	111.8
3.66	13.591	859.0	97.0	14.2	111.1
3.91	12.744	858.0	97.4	13.2	110.6
4.17	11.869	857.2	98.3	12.2	110.5
4.42	10.968	856.7	99.8	11.2	111.0
4.67	10.042	856.7	102.6	10.1	112.7
4.92	9.091	857.4	108.0	8.9	116.9

CFB HEAT RELEASE AND HEAT TRANSFER MODEL

RUN RESULTS FROM HEAT TRANSFER ROUTINE HEAT.F, VERSION 8.1
WRITTEN BY: DALE W.C. JU

COMBUSTOR: Studsvik Prototype
CASE: Sardinian Coal
Case : sh1
Superficial gas velocity = 6.96 m/s
Solids reciculation rate = 50 kg/m2s
Highvale coal(mean dp = 2.89 mm)

FUEL PHYSICAL PROPERTIES AND COMPOSITION

PROXIMATE ANALYSIS

Weight %	
12.200	Ash
15.200	Moisture
0.170	Sulphur
3.050	Hydrogen
52.900	Carbon
0.680	Nitrogen
15.800	Oxygen

PARTICLE SIZE DISTRIBUTION

mm	wt %
7.925	9.250
5.613	10.920
3.962	13.180
2.794	12.110
1.981	11.090
1.397	8.730
0.991	7.750
0.701	5.480
0.495	4.750
0.351	3.740
0.246	3.410
0.175	3.990
0.124	1.290
0.088	0.000
0.053	0.000
0.045	0.000
0.038	0.000
0.000	0.000

COMBUSTION CONDITIONS

# of particles in Monte Carlo Method	100
% of total wall area with membranes	70.0 %
Solids return temp. equals cyclone temp.	835.1 C
Solids recirculation rate	21.250 kg/s
Solids recirculation flux	50.000 kg/m2s
Gas cross-flow coefficient	0.100 m/s
Combustion efficiency	100.0 %
Excess air	20.000 %
Volatile transfer fraction	0.300
Number of fuel feed points	1
Fuel feedrate	388.886 kg/hr
Air feedrate	3017.519 kg/hr
% of total air that is primary	72.0 %
Residence time of particles in cyclone	0.300 sec.
Reflection coefficient	0.100
Height at which developed zone begins	2.525 m

GAS VELOCITIES

Core insterstitial gas velocity	7.187 m/s
Streamer interstitial gas velocity	3.600 m/s
Superficial gas velocity	6.958 m/s
Bed temperature used in calculating heat transfer area and gas velocities	849.9 C

HEAT RELEASE DISTRIBUTION

Height (m)	Fraction of Total Heat Release Volatiles Streamer	Volatiles Core	Char Streamer	Char Core
0.00	0.330548		0.451193	
0.13	0.008532	0.072786	0.022746	0.007294
0.38	0.001237	0.016510	0.012063	0.004265
0.63	0.004695	0.005423	0.006954	0.002901
0.88	0.000078	0.001387	0.004356	0.002131
1.14	0.000033	0.000365	0.002992	0.001742
1.39	0.000000	0.000267	0.002187	0.001434
1.64	0.000010	0.000123	0.001822	0.001301
1.89	0.000000	0.000287	0.001637	0.001168
2.15	0.000000	0.000080	0.001444	0.001182
2.40	0.000000	0.000029	0.001286	0.001070
2.65	0.000000	0.000027	0.001289	0.001105
2.90	0.000000	0.000054	0.001260	0.001052
3.16	0.000000	0.000017	0.001123	0.001092
3.41	0.000000	0.000013	0.001082	0.000990
3.66	0.000000	0.000005	0.000949	0.000990
3.91	0.000000	0.000036	0.000831	0.000929
4.17	0.000000	0.000022	0.000781	0.000890
4.42	0.000000	0.000006	0.000678	0.000875
4.67	0.000000	0.000005	0.000565	0.000847
4.92	0.000000	0.000006	0.000489	0.000803
Cyclone	0.000012		0.005618	
TOTAL	0.497612		0.502388	

OXYGEN PARTIAL PRESSSURE DISTRIBUTION

Height (m)	Partial Pressure of Oxygen (atm.) Streamer	Core
0.00	0.072215	
0.26	0.023893	0.057783
0.51	0.012219	0.049493
0.76	0.000000	0.045156
1.00	0.002534	0.042749
1.26	0.010056	0.041216
1.51	0.018399	0.040186
1.76	0.023755	0.039461
2.01	0.026177	0.038872
2.27	0.027334	0.038395
2.52	0.028038	0.037992
2.77	0.027895	0.037594
3.02	0.027771	0.037204
3.29	0.028304	0.036830
3.54	0.028480	0.036482
3.79	0.029135	0.036152
4.04	0.029855	0.035846
4.29	0.030160	0.035557
4.54	0.030736	0.035289
4.79	0.031467	0.035042
5.04	0.031969	0.034815

Pressure convergence tolerance	0.0039 atm.
Partial pressure of oxygen entering	0.210000 atm.
Partial pressure of oxygen leaving riser	0.035 atm.
Partial pressure of oxygen leaving cyclone	0.034 atm.

TEMPERATURE DISTRIBUTION

Height (m)	Temperature (C) Streamer	Core
0.00	854.0	
0.13	849.5	855.4
0.38	803.1	852.4
0.63	802.2	849.6
0.88	801.8	846.9
1.14	802.5	844.5
1.39	804.0	842.6
1.64	806.1	841.0
1.89	808.6	839.7
2.15	811.2	838.8
2.40	812.6	837.9
2.65	814.0	837.1
2.90	815.4	836.4
3.16	815.6	835.7
3.41	816.2	835.1
3.66	817.3	834.6
3.91	819.2	834.2
4.17	822.2	833.9
4.42	827.2	833.8
4.67	835.5	833.9
4.92	850.3	834.4

Solids return temperature	835.1 C
Temperature convergence tolerance	0.004 C
Cyclone temperature	835.1 C
Wall temperature	106.8 C

HEAT TRANSFER COEFFICIENTS

Height (m)	Density (kg/m3)	Core Temp. (C)	Heat Transfer Coefficient (W/m2C) Radiative	Convective	Overall
0.00	383.621	854.0	102.3	100.3	202.6
0.13	288.739	855.4	101.7	100.6	202.4
0.38	185.084	852.4	91.4	106.3	197.7
0.63	122.702	849.6	91.2	106.3	197.6
0.88	85.097	846.9	91.2	90.3	181.5
1.14	62.419	844.5	91.3	66.1	157.4
1.39	48.736	842.6	91.6	51.4	143.0
1.64	40.479	841.0	92.1	42.5	134.5
1.89	35.495	839.7	92.6	37.0	129.7
2.15	32.488	838.8	93.2	33.7	126.9
2.40	30.757	837.9	93.4	31.8	125.3
2.65	29.504	837.1	94.2	30.4	124.6
2.90	28.167	836.4	94.1	29.0	123.1
3.16	26.773	835.7	94.1	27.5	121.7
3.41	25.316	835.1	94.3	26.0	120.2
3.66	23.795	834.6	94.5	24.4	118.9
3.91	22.212	834.2	94.9	22.7	117.6
4.17	20.559	833.9	95.6	20.9	116.5
4.42	18.840	833.8	96.7	19.0	115.7
4.67	17.052	833.9	98.5	17.0	115.6
4.92	15.196	834.4	101.9	14.9	116.8

CFB HEAT RELEASE AND HEAT TRANSFER MODEL

RUN RESULTS FROM HEAT TRANSFER ROUTINE HEAT.F, VERSION 8.1
WRITTEN BY: DALE W.C. JU

COMBUSTOR: Studsvik Prototype
CASE: Sardinian Coal
Case : sh2
Superficial gas velocity = 6.96 m/s
Solids reciculation rate = 15 kg/m2s
Highvale coal(mean dp = 2.89 mm)

<u>FUEL PHYSICAL PROPERTIES AND COMPOSITION</u>

PROXIMATE ANALYSIS

Weight %	
12.200	Ash
15.200	Moisture
0.170	Sulphur
3.050	Hydrogen
52.900	Carbon
0.680	Nitrogen
15.800	Oxygen

PARTICLE SIZE DISTRIBUTION

mm	wt %
7.925	9.250
5.613	10.920
3.962	13.180
2.794	12.110
1.981	11.090
1.397	8.730
0.991	7.750
0.701	5.480
0.495	4.750
0.351	3.740
0.246	3.410
0.175	3.990
0.124	1.290
0.088	0.000
0.053	0.000
0.045	0.000
0.038	0.000
0.000	0.000

COMBUSTION CONDITIONS

# of particles in Monte Carlo Method	100
% of total wall area with membranes	70.0 %
Solids return temp. equals cyclone temp.	897.8 C
Solids recirculation rate	6.375 kg/s
Solids recirculation flux	15.000 kg/m2s
Gas cross-flow coefficient	0.100 m/s
Combustion efficiency	100.0 %
Excess air	20.000 %
Volatile transfer fraction	0.300
Number of fuel feed points	1
Fuel feedrate	403.300 kg/hr
Air feedrate	3129.367 kg/hr
% of total air that is primary	72.0 %
Residence time of particles in cyclone	0.300 sec.
Reflection coefficient	0.100
Height at which developed zone begins	3.283 m

GAS VELOCITIES

Core insterstitial gas velocity	7.064 m/s
Streamer interstitial gas velocity	3.536 m/s
Superficial gas velocity	6.958 m/s
Bed temperature used in calculating heat transfer area and gas velocities	849.9 C

HEAT RELEASE DISTRIBUTION

Height	Fraction of Total Heat Release			
	Volatiles		Char	
(m)	Streamer	Core	Streamer	Core
0.00	0.368394		0.466610	
0.13	0.001269	0.078107	0.013888	0.006876
0.38	0.000458	0.017016	0.004697	0.003829
0.63	0.000093	0.004032	0.001244	0.002424
0.88	0.000300	0.001880	0.002026	0.001628
1.14	0.001258	0.000603	0.001626	0.001121
1.39	0.000767	0.000655	0.001453	0.000861
1.64	0.000000	0.000138	0.001174	0.000704
1.89	0.000000	0.000029	0.000887	0.000586
2.15	0.000000	0.000006	0.000704	0.000569
2.40	0.000000	0.000001	0.000578	0.000531
2.65	0.000000	0.000000	0.000482	0.000497
2.90	0.000000	0.000000	0.000427	0.000482
3.16	0.000000	0.000000	0.000402	0.000471
3.41	0.000000	0.000000	0.000394	0.000451
3.66	0.000000	0.000000	0.000375	0.000466
3.91	0.000000	0.000000	0.000358	0.000451
4.17	0.000000	0.000000	0.000272	0.000433
4.42	0.000000	0.000000	0.000236	0.000428
4.67	0.000000	0.000000	0.000252	0.000440
4.92	0.000000	0.000000	0.000199	0.000413
Cyclone	0.000000		0.003048	
TOTAL	0.535547		0.464453	

OXYGEN PARTIAL PRESSSURE DISTRIBUTION

Height (m)	Partial Pressure of Oxygen (atm.) Streamer	Core
0.00	0.064113	
0.26	0.024916	0.048143
0.51	0.024727	0.042146
0.76	0.034367	0.039890
1.00	0.033023	0.038603
1.26	0.024529	0.037719
1.51	0.022326	0.036985
1.76	0.027596	0.036556
2.01	0.029910	0.036262
2.27	0.030934	0.036028
2.52	0.031514	0.035833
2.77	0.031949	0.035666
3.02	0.032133	0.035514
3.29	0.032136	0.035370
3.54	0.032060	0.035230
3.79	0.032083	0.035092
4.04	0.032094	0.034959
4.29	0.032669	0.034841
4.54	0.032881	0.034731
4.79	0.032650	0.034617
5.04	0.032975	0.034515

Pressure convergence tolerance	0.0020 atm.
Partial pressure of oxygen entering	0.210000 atm.
Partial pressure of oxygen leaving riser	0.035 atm.
Partial pressure of oxygen leaving cyclone	0.034 atm.

TEMPERATURE DISTRIBUTION

Height (m)	Temperature (C) Streamer	Core
0.00	960.6	
0.13	954.2	963.3
0.38	897.2	959.3
0.63	892.0	954.8
0.88	886.8	950.2
1.14	881.2	945.9
1.39	875.4	941.6
1.64	869.3	937.4
1.89	863.3	933.2
2.15	857.8	929.0
2.40	852.8	924.7
2.65	848.5	920.5
2.90	845.4	916.7
3.16	844.4	912.7
3.41	843.5	908.8
3.66	842.5	905.2
3.91	842.7	901.9
4.17	845.6	898.9
4.42	853.5	896.5
4.67	871.4	895.2
4.92	910.2	896.2

Solids return temperature	897.8 C
Temperature convergence tolerance	0.002 C
Cyclone temperature	897.8 C
Wall temperature	106.8 C

HEAT TRANSFER COEFFICIENTS

Height (m)	Density (kg/m3)	Core Temp. (C)	Heat Transfer Coefficient (W/m2C) Radiative	Convective	Overall
0.00	244.887	960.6	127.9	100.7	228.7
0.13	176.105	963.3	127.9	101.0	228.8
0.38	108.381	959.3	113.1	107.4	220.5
0.63	67.562	954.8	111.8	72.8	184.6
0.88	42.946	950.2	110.6	46.4	156.9
1.14	28.095	945.9	109.2	30.4	139.6
1.39	19.131	941.6	107.8	20.8	128.6
1.64	13.725	937.4	106.4	14.9	121.3
1.89	10.462	933.2	104.9	11.4	116.4
2.15	8.491	929.0	103.6	9.3	112.9
2.40	7.304	924.7	102.5	8.0	110.5
2.65	6.586	920.5	101.5	7.2	108.7
2.90	6.153	916.7	100.8	6.7	107.5
3.16	5.899	912.7	100.2	6.5	106.6
3.41	5.709	908.8	100.7	6.2	106.9
3.66	5.503	905.2	100.1	6.0	106.1
3.91	5.295	901.9	100.2	5.7	105.9
4.17	5.083	898.9	100.8	5.4	106.3
4.42	4.871	896.5	102.6	5.2	107.8
4.67	4.656	895.2	106.9	4.8	111.7
4.92	4.440	896.2	116.4	4.4	120.7

CFB HEAT RELEASE AND HEAT TRANSFER MODEL

RUN RESULTS FROM HEAT TRANSFER ROUTINE HEAT.F, VERSION 8.1
WRITTEN BY: DALE W.C. JU

COMBUSTOR: Studsvik Prototype
CASE: Sardinian Coal
Case : sh3
Superficial gas velocity = 5.99 m/s
Solids reciculation rate = 30 kg/m2s
Highvale coal(mean dp = 2.89 mm)

<u>FUEL PHYSICAL PROPERTIES AND COMPOSITION</u>

PROXIMATE ANALYSIS

Weight %	
12.200	Ash
15.200	Moisture
0.170	Sulphur
3.050	Hydrogen
52.900	Carbon
0.680	Nitrogen
15.800	Oxygen

PARTICLE SIZE DISTRIBUTION

mm	wt %
7.925	9.250
5.613	10.920
3.962	13.180
2.794	12.110
1.981	11.090
1.397	8.730
0.991	7.750
0.701	5.480
0.495	4.750
0.351	3.740
0.246	3.410
0.175	3.990
0.124	1.290
0.088	0.000
0.053	0.000
0.045	0.000
0.038	0.000
0.000	0.000

COMBUSTION CONDITIONS

# of particles in Monte Carlo Method	100
% of total wall area with membranes	70.0 %
Solids return temp. equals cyclone temp.	812.3 C
Solids recirculation rate	12.750 kg/s
Solids recirculation flux	30.000 kg/m2s
Gas cross-flow coefficient	0.100 m/s
Combustion efficiency	100.0 %
Excess air	20.000 %
Volatile transfer fraction	0.300
Number of fuel feed points	1
Fuel feedrate	340.730 kg/hr
Air feedrate	2643.858 kg/hr
% of total air that is primary	72.0 %
Residence time of particles in cyclone	0.300 sec.
Reflection coefficient	0.100
Height at which developed zone begins	2.525 m

GAS VELOCITIES

Core insterstitial gas velocity	6.147 m/s
Streamer interstitial gas velocity	3.077 m/s
Superficial gas velocity	5.992 m/s
Bed temperature used in calculating heat transfer area and gas velocities	849.9 C

HEAT RELEASE DISTRIBUTION

Height	Fraction of Total Heat Release			
	Volatiles		Char	
(m)	Streamer	Core	Streamer	Core
0.00	0.258625		0.534937	
0.13	0.006435	0.060164	0.025247	0.009468
0.38	0.000144	0.012962	0.014644	0.005495
0.63	0.000058	0.002760	0.009723	0.003660
0.88	0.000027	0.000635	0.006133	0.002588
1.14	0.000002	0.000137	0.004100	0.002051
1.39	0.000000	0.000031	0.002707	0.001709
1.64	0.000001	0.000013	0.002032	0.001462
1.89	0.000000	0.000003	0.001593	0.001332
2.15	0.000000	0.000001	0.001429	0.001263
2.40	0.000000	0.000000	0.001335	0.001217
2.65	0.000000	0.000000	0.001232	0.001170
2.90	0.000000	0.000000	0.001201	0.001126
3.16	0.000000	0.000000	0.001078	0.001083
3.41	0.000000	0.000000	0.001027	0.001080
3.66	0.000000	0.000000	0.000939	0.001031
3.91	0.000000	0.000000	0.000818	0.000989
4.17	0.000000	0.000000	0.000755	0.000988
4.42	0.000000	0.000000	0.000629	0.000936
4.67	0.000000	0.000000	0.000528	0.000868
4.92	0.000000	0.000000	0.000459	0.000893
Cyclone	0.000000		0.005050	
TOTAL	0.385113		0.614887	

OXYGEN PARTIAL PRESSSURE DISTRIBUTION

Height (m)	Partial Pressure of Oxygen (atm.) Streamer	Core
0.00	0.070199	
0.26	0.013500	0.057427
0.51	0.000000	0.049735
0.76	0.000000	0.045732
1.00	0.000000	0.043320
1.26	0.007485	0.041694
1.51	0.017631	0.040611
1.76	0.024464	0.039862
2.01	0.028172	0.039301
2.27	0.029309	0.038829
2.52	0.029512	0.038400
2.77	0.029735	0.038000
3.02	0.029642	0.037614
3.29	0.030066	0.037253
3.54	0.030170	0.036901
3.79	0.030455	0.036571
4.04	0.031002	0.036266
4.29	0.031235	0.035972
4.54	0.031846	0.035706
4.79	0.032373	0.035467
5.04	0.032682	0.035236

Pressure convergence tolerance	0.0054 atm.
Partial pressure of oxygen entering	0.210000 atm.
Partial pressure of oxygen leaving riser	0.035 atm.
Partial pressure of oxygen leaving cyclone	0.034 atm.

TEMPERATURE DISTRIBUTION

Height (m)	Temperature (C) Streamer	Core
0.00	837.8	
0.13	832.7	839.3
0.38	786.1	836.2
0.63	784.0	833.0
0.88	782.3	829.8
1.14	781.1	827.0
1.39	780.5	824.5
1.64	780.4	822.4
1.89	780.7	820.5
2.15	781.3	819.0
2.40	783.8	817.6
2.65	786.4	816.2
2.90	788.9	815.1
3.16	788.8	814.1
3.41	789.0	813.2
3.66	789.7	812.3
3.91	791.4	811.6
4.17	794.6	811.1
4.42	800.2	810.8
4.67	810.3	810.8
4.92	830.1	811.5

Solids return temperature	812.3 C
Temperature convergence tolerance	0.005 C
Cyclone temperature	812.3 C
Wall temperature	106.8 C

HEAT TRANSFER COEFFICIENTS

Height (m)	Density (kg/m3)	Core Temp. (C)	Heat Transfer Coefficient (W/m2C) Radiative	Convective	Overall
0.00	331.166	837.8	98.3	100.4	198.7
0.13	246.560	839.3	97.9	100.8	198.7
0.38	156.579	836.2	87.9	106.7	194.6
0.63	102.403	833.0	87.4	106.8	194.2
0.88	69.743	829.8	87.1	74.5	161.5
1.14	50.044	827.0	86.8	53.4	140.2
1.39	38.157	824.5	86.7	40.6	127.3
1.64	30.984	822.4	86.7	32.9	119.6
1.89	26.657	820.5	86.7	28.2	114.9
2.15	24.045	819.0	86.8	25.4	112.2
2.40	22.460	817.6	87.0	23.6	110.6
2.65	21.317	816.2	88.2	22.2	110.4
2.90	20.224	815.1	88.4	21.0	109.4
3.16	19.101	814.1	88.4	19.8	108.2
3.41	17.948	813.2	88.4	18.6	107.0
3.66	16.760	812.3	88.6	17.3	105.9
3.91	15.542	811.6	89.0	16.0	105.0
4.17	14.292	811.1	89.6	14.6	104.3
4.42	13.013	810.8	90.8	13.2	104.0
4.67	11.707	810.8	93.0	11.7	104.7
4.92	10.373	811.5	97.3	10.1	107.4

CFB HEAT RELEASE AND HEAT TRANSFER MODEL

RUN RESULTS FROM HEAT TRANSFER ROUTINE HEAT.F, VERSION 8.1
WRITTEN BY: DALE W.C. JU

COMBUSTOR: Studsvik Prototype
CASE: Sardinian Coal
Case : sh4
Superficial gas velocity = 5.99 m/s
Solids reciculation rate = 50 kg/m2s
Highvale coal(mean dp = 2.89 mm)

FUEL PHYSICAL PROPERTIES AND COMPOSITION

PROXIMATE ANALYSIS

Weight %	
12.200	Ash
15.200	Moisture
0.170	Sulphur
3.050	Hydrogen
52.900	Carbon
0.680	Nitrogen
15.800	Oxygen

PARTICLE SIZE DISTRIBUTION

mm	wt %
7.925	9.250
5.613	10.920
3.962	13.180
2.794	12.110
1.981	11.090
1.397	8.730
0.991	7.750
0.701	5.480
0.495	4.750
0.351	3.740
0.246	3.410
0.175	3.990
0.124	1.290
0.088	0.000
0.053	0.000
0.045	0.000
0.038	0.000
0.000	0.000

COMBUSTION CONDITIONS

# of particles in Monte Carlo Method	100
% of total wall area with membranes	70.0 %
Solids return temp. equals cyclone temp.	764.4 C
Solids recirculation rate	21.250 kg/s
Solids recirculation flux	50.000 kg/m2s
Gas cross-flow coefficient	0.100 m/s
Combustion efficiency	100.0 %
Excess air	20.000 %
Volatile transfer fraction	0.300
Number of fuel feed points	1
Fuel feedrate	334.951 kg/hr
Air feedrate	2599.018 kg/hr
% of total air that is primary	72.0 %
Residence time of particles in cyclone	0.300 sec.
Reflection coefficient	0.100
Height at which developed zone begins	2.525 m

GAS VELOCITIES

Core insterstitial gas velocity	6.212 m/s
Streamer interstitial gas velocity	3.107 m/s
Superficial gas velocity	5.992 m/s
Bed temperature used in calculating heat transfer area and gas velocities	849.9 C

HEAT RELEASE DISTRIBUTION

Height	Fraction of Total Heat Release			
	Volatiles		Char	
(m)	Streamer	Core	Streamer	Core
0.00	0.257134		0.527291	
0.13	0.000530	0.055538	0.026825	0.010168
0.38	0.001910	0.012797	0.015019	0.005935
0.63	0.000014	0.002853	0.009405	0.004031
0.88	0.000013	0.001002	0.006096	0.003002
1.14	0.000003	0.000353	0.004286	0.002480
1.39	0.000113	0.000254	0.003105	0.002090
1.64	0.000001	0.000081	0.002637	0.001927
1.89	0.000000	0.000065	0.002335	0.001734
2.15	0.000004	0.000021	0.002037	0.001652
2.40	0.000004	0.000031	0.001967	0.001618
2.65	0.000003	0.000014	0.001808	0.001501
2.90	0.000004	0.000008	0.001710	0.001572
3.16	0.000006	0.000007	0.001558	0.001435
3.41	0.000004	0.000018	0.001604	0.001371
3.66	0.000000	0.000005	0.001320	0.001343
3.91	0.000001	0.000002	0.001180	0.001287
4.17	0.000000	0.000001	0.000960	0.001219
4.42	0.000000	0.000000	0.000857	0.001197
4.67	0.000000	0.000000	0.000659	0.001142
4.92	0.000000	0.000000	0.000511	0.001071
Cyclone	0.000001		0.006260	
TOTAL	0.375245		0.624755	

OXYGEN PARTIAL PRESSSURE DISTRIBUTION

Height (m)	Partial Pressure of Oxygen (atm.) Streamer	Core
0.00	0.072593	
0.26	0.031569	0.059943
0.51	0.016184	0.051720
0.76	0.008136	0.047600
1.00	0.006963	0.044969
1.26	0.011088	0.043167
1.51	0.016966	0.041880
1.76	0.021508	0.040922
2.01	0.023921	0.040157
2.27	0.025435	0.039510
2.52	0.025717	0.038910
2.77	0.026202	0.038355
3.02	0.026501	0.037807
3.29	0.027027	0.037303
3.54	0.026612	0.036807
3.79	0.027727	0.036352
4.04	0.028494	0.035931
4.29	0.029672	0.035555
4.54	0.030273	0.035201
4.79	0.031363	0.034886
5.04	0.032257	0.034608

Pressure convergence tolerance	0.0042 atm.
Partial pressure of oxygen entering	0.210000 atm.
Partial pressure of oxygen leaving riser	0.035 atm.
Partial pressure of oxygen leaving cyclone	0.034 atm.

TEMPERATURE DISTRIBUTION

Height (m)	Temperature (C) Streamer	Core
0.00	780.8	
0.13	776.5	781.9
0.38	735.2	779.2
0.63	734.5	776.6
0.88	734.7	774.3
1.14	735.6	772.2
1.39	737.0	770.5
1.64	738.6	769.0
1.89	740.1	767.8
2.15	741.3	767.0
2.40	744.6	766.2
2.65	747.8	765.4
2.90	751.1	764.9
3.16	751.3	764.4
3.41	751.8	764.0
3.66	752.8	763.6
3.91	754.3	763.4
4.17	756.9	763.2
4.42	761.2	763.2
4.67	768.4	763.3
4.92	781.7	763.8

Solids return temperature	764.4 C
Temperature convergence tolerance	0.004 C
Cyclone temperature	764.4 C
Wall temperature	106.8 C

HEAT TRANSFER COEFFICIENTS

Height (m)	Density (kg/m3)	Core Temp. (C)	Heat Transfer Coefficient (W/m2C) Radiative	Convective	Overall
0.00	401.087	780.8	86.4	100.3	186.6
0.13	306.273	781.9	85.9	100.7	186.5
0.38	198.719	779.2	77.7	106.2	183.9
0.63	134.022	776.6	77.6	106.2	183.8
0.88	95.034	774.3	77.6	100.7	178.3
1.14	71.518	772.2	77.8	75.5	153.3
1.39	57.334	770.5	78.0	60.3	138.3
1.64	48.776	769.0	78.4	51.1	129.4
1.89	43.612	767.8	78.6	45.5	124.1
2.15	40.494	767.0	78.9	42.1	121.0
2.40	38.535	766.2	79.2	39.9	119.1
2.65	36.836	765.4	81.0	37.6	118.6
2.90	34.966	764.9	80.8	35.7	116.5
3.16	33.027	764.4	80.8	33.7	114.5
3.41	31.010	764.0	80.9	31.6	112.5
3.66	28.918	763.6	81.1	29.4	110.5
3.91	26.748	763.4	81.4	27.1	108.5
4.17	24.498	763.2	81.9	24.7	106.7
4.42	22.173	763.2	82.8	22.2	105.0
4.67	19.766	763.3	84.2	19.6	103.8
4.92	17.282	763.8	86.9	16.8	103.8

CFB HEAT RELEASE AND HEAT TRANSFER MODEL

RUN RESULTS FROM HEAT TRANSFER ROUTINE HEAT.F, VERSION 8.1
WRITTEN BY: DALE W.C. JU

COMBUSTOR: Studsvik Prototype
CASE: Sardinian Coal
Case : sh5
Superficial gas velocity = 5.99 m/s
Solids reciculation rate = 15 kg/m2s
Highvale coal(mean dp = 2.89 mm)

<u>FUEL PHYSICAL PROPERTIES AND COMPOSITION</u>

PROXIMATE ANALYSIS

Weight %	
12.200	Ash
15.200	Moisture
0.170	Sulphur
3.050	Hydrogen
52.900	Carbon
0.680	Nitrogen
15.800	Oxygen

PARTICLE SIZE DISTRIBUTION

mm	wt %
7.925	9.250
5.613	10.920
3.962	13.180
2.794	12.110
1.981	11.090
1.397	8.730
0.991	7.750
0.701	5.480
0.495	4.750
0.351	3.740
0.246	3.410
0.175	3.990
0.124	1.290
0.088	0.000
0.053	0.000
0.045	0.000
0.038	0.000
0.000	0.000

COMBUSTION CONDITIONS

# of particles in Monte Carlo Method	100
% of total wall area with membranes	70.0 %
Solids return temp. equals cyclone temp.	852.1 C
Solids recirculation rate	6.375 kg/s
Solids recirculation flux	15.000 kg/m2s
Gas cross-flow coefficient	0.100 m/s
Combustion efficiency	100.0 %
Excess air	20.000 %
Volatile transfer fraction	0.300
Number of fuel feed points	1
Fuel feedrate	347.226 kg/hr
Air feedrate	2694.266 kg/hr
% of total air that is primary	72.0 %
Residence time of particles in cyclone	0.300 sec.
Reflection coefficient	0.100
Height at which developed zone begins	3.030 m

GAS VELOCITIES

Core insterstitial gas velocity	6.090 m/s
Streamer interstitial gas velocity	3.049 m/s
Superficial gas velocity	5.992 m/s
Bed temperature used in calculating heat transfer area and gas velocities	849.9 C

HEAT RELEASE DISTRIBUTION

Height	Fraction of Total Heat Release			
	Volatiles		Char	
(m)	Streamer	Core	Streamer	Core
0.00	0.384113		0.449719	
0.13	0.000993	0.081644	0.011341	0.007597
0.38	0.001149	0.017436	0.003789	0.004170
0.63	0.000019	0.003700	0.002066	0.002620
0.88	0.000010	0.000954	0.001942	0.001758
1.14	0.000000	0.000240	0.001930	0.001303
1.39	0.000001	0.000103	0.001620	0.001022
1.64	0.000001	0.000047	0.001235	0.000863
1.89	0.000001	0.000034	0.000981	0.000724
2.15	0.000016	0.000018	0.000784	0.000671
2.40	0.000001	0.000027	0.000627	0.000617
2.65	0.000000	0.000006	0.000540	0.000561
2.90	0.000000	0.000001	0.000505	0.000598
3.16	0.000000	0.000000	0.000458	0.000566
3.41	0.000000	0.000000	0.000413	0.000559
3.66	0.000000	0.000000	0.000406	0.000549
3.91	0.000000	0.000000	0.000368	0.000557
4.17	0.000000	0.000000	0.000271	0.000510
4.42	0.000000	0.000000	0.000273	0.000511
4.67	0.000000	0.000000	0.000247	0.000504
4.92	0.000000	0.000000	0.000232	0.000507
Cyclone	0.000000		0.002974	
TOTAL	0.553297		0.446703	

OXYGEN PARTIAL PRESSSURE DISTRIBUTION

Height (m)	Partial Pressure of Oxygen (atm.) Streamer	Core
0.00	0.064817	
0.26	0.032562	0.047682
0.51	0.033750	0.041712
0.76	0.038638	0.039566
1.00	0.037759	0.038501
1.26	0.033150	0.037794
1.51	0.030272	0.037249
1.76	0.030134	0.036829
2.01	0.030661	0.036503
2.27	0.031216	0.036236
2.52	0.031911	0.036014
2.77	0.032211	0.035826
3.02	0.032213	0.035642
3.29	0.032355	0.035472
3.54	0.032526	0.035309
3.79	0.032435	0.035150
4.04	0.032545	0.034995
4.29	0.033092	0.034863
4.54	0.032986	0.034731
4.79	0.033042	0.034605
5.04	0.033026	0.034481

Pressure convergence tolerance	0.0031 atm.
Partial pressure of oxygen entering	0.210000 atm.
Partial pressure of oxygen leaving riser	0.035 atm.
Partial pressure of oxygen leaving cyclone	0.034 atm.

TEMPERATURE DISTRIBUTION

Height (m)	Temperature (C) Streamer	Core
0.00	905.0	
0.13	898.8	907.5
0.38	845.8	903.7
0.63	841.3	899.4
0.88	836.7	895.1
1.14	831.9	891.0
1.39	827.0	887.1
1.64	822.2	883.3
1.89	817.7	879.6
2.15	813.5	876.0
2.40	809.9	872.4
2.65	806.7	869.2
2.90	807.4	865.9
3.16	808.0	862.6
3.41	808.7	859.8
3.66	807.9	857.0
3.91	808.4	854.5
4.17	811.2	852.3
4.42	818.2	850.6
4.67	833.5	849.8
4.92	868.0	850.9

Solids return temperature	852.1 C
Temperature convergence tolerance	0.003 C
Cyclone temperature	852.1 C
Wall temperature	106.8 C

HEAT TRANSFER COEFFICIENTS

Height (m)	Density (kg/m3)	Core Temp. (C)	Heat Transfer Coefficient (W/m2C) Radiative	Convective	Overall
0.00	255.628	905.0	113.6	100.7	214.4
0.13	185.093	907.5	113.5	101.0	214.5
0.38	114.618	903.7	100.9	107.3	208.2
0.63	72.151	899.4	99.9	77.6	177.5
0.88	46.542	895.1	98.8	50.2	149.0
1.14	31.091	891.0	97.7	33.6	131.3
1.39	21.771	887.1	96.6	23.6	120.2
1.64	16.146	883.3	95.6	17.5	113.1
1.89	12.750	879.6	94.6	13.9	108.4
2.15	10.701	876.0	93.7	11.6	105.3
2.40	9.465	872.4	92.9	10.3	103.2
2.65	8.721	869.2	92.2	9.5	101.7
2.90	8.264	865.9	91.8	9.0	100.8
3.16	7.896	862.6	93.2	8.5	101.7
3.41	7.504	859.8	92.6	8.0	100.7
3.66	7.106	857.0	92.5	7.6	100.1
3.91	6.708	854.5	92.6	7.1	99.7
4.17	6.304	852.3	93.2	6.7	99.8
4.42	5.902	850.6	94.7	6.2	100.9
4.67	5.495	849.8	98.1	5.6	103.7
4.92	5.090	850.9	106.0	5.0	111.0

CFB HEAT RELEASE AND HEAT TRANSFER MODEL

RUN RESULTS FROM HEAT TRANSFER ROUTINE HEAT.F, VERSION 8.1
WRITTEN BY: DALE W.C. JU

COMBUSTOR: Studsvik Prototype
CASE: Sardinian Coal
Case : sh2b
Superficial gas velocity = 6.96 m/s
Solids reciculation rate = 15 kg/m2s
Highvale coal (mean dp = 2.89 mm)
# of particles in MC method = 400

FUEL PHYSICAL PROPERTIES AND COMPOSITION

PROXIMATE ANALYSIS

Weight %	
12.200	Ash
15.200	Moisture
0.170	Sulphur
3.050	Hydrogen
52.900	Carbon
0.680	Nitrogen
15.800	Oxygen

PARTICLE SIZE DISTRIBUTION

mm	wt %
7.925	9.250
5.613	10.920
3.962	13.180
2.794	12.110
1.981	11.090
1.397	8.730
0.991	7.750
0.701	5.480
0.495	4.750
0.351	3.740
0.246	3.410
0.175	3.990
0.124	1.290
0.088	0.000
0.053	0.000
0.045	0.000
0.038	0.000
0.000	0.000

COMBUSTION CONDITIONS

# of particles in Monte Carlo Method	400
% of total wall area with membranes	70.0 %
Solids return temp. equals cyclone temp.	898.9 C
Solids recirculation rate	6.375 kg/s
Solids recirculation flux	15.000 kg/m2s
Gas cross-flow coefficient	0.100 m/s
Combustion efficiency	100.0 %
Excess air	20.000 %
Volatile transfer fraction	0.300
Number of fuel feed points	1
Fuel feedrate	403.300 kg/hr
Air feedrate	3129.367 kg/hr
% of total air that is primary	72.0 %
Residence time of particles in cyclone	0.300 sec.
Reflection coefficient	0.100
Height at which developed zone begins	3.283 m

GAS VELOCITIES

Core insterstitial gas velocity	7.064 m/s
Streamer interstitial gas velocity	3.536 m/s
Superficial gas velocity	6.958 m/s

Bed temperature used in calculating heat transfer area and gas velocities	849.9 C

HEAT RELEASE DISTRIBUTION

Height	Fraction of Total Heat Release			
	Volatiles		Char	
(m)	Streamer	Core	Streamer	Core
0.00	0.296334		0.554419	
0.13	0.000769	0.062872	0.014896	0.008152
0.38	0.000290	0.013703	0.004266	0.004592
0.63	0.000306	0.003105	0.002118	0.002852
0.88	0.000135	0.000735	0.001509	0.001890
1.14	0.000084	0.000309	0.001702	0.001367
1.39	0.000002	0.000141	0.001592	0.001048
1.64	0.000001	0.000063	0.001323	0.000854
1.89	0.000000	0.000032	0.001051	0.000751
2.15	0.000000	0.000020	0.000860	0.000674
2.40	0.000000	0.000012	0.000671	0.000635
2.65	0.000000	0.000006	0.000591	0.000620
2.90	0.000000	0.000002	0.000526	0.000599
3.16	0.000000	0.000003	0.000493	0.000588
3.41	0.000000	0.000001	0.000455	0.000580
3.66	0.000000	0.000001	0.000445	0.000571
3.91	0.000000	0.000000	0.000395	0.000555
4.17	0.000000	0.000000	0.000378	0.000557
4.42	0.000000	0.000000	0.000384	0.000554
4.67	0.000000	0.000000	0.000351	0.000538
4.92	0.000000	0.000000	0.000342	0.000537
Cyclone	0.000001		0.003794	
TOTAL	0.427439		0.572561	

OXYGEN PARTIAL PRESSSURE DISTRIBUTION

Height (m)	Partial Pressure of Oxygen (atm.) Streamer	Core
0.00	0.062086	
0.26	0.021621	0.047834
0.51	0.023283	0.042258
0.76	0.028653	0.039970
1.00	0.033086	0.038825
1.26	0.031379	0.038072
1.51	0.029099	0.037510
1.76	0.028511	0.037075
2.01	0.029260	0.036731
2.27	0.030054	0.036453
2.52	0.031068	0.036223
2.77	0.031391	0.036017
3.02	0.031620	0.035830
3.29	0.031655	0.035652
3.54	0.031780	0.035481
3.79	0.031715	0.035314
4.04	0.031962	0.035158
4.29	0.031970	0.035004
4.54	0.031778	0.034850
4.79	0.031890	0.034703
5.04	0.031827	0.034558

Pressure convergence tolerance	0.0032 atm.
Partial pressure of oxygen entering	0.210000 atm.
Partial pressure of oxygen leaving riser	0.035 atm.
Partial pressure of oxygen leaving cyclone	0.034 atm.

TEMPERATURE DISTRIBUTION

Height (m)	Temperature (C) Streamer	Core
0.00	962.0	
0.13	955.2	964.3
0.38	898.1	960.2
0.63	893.0	955.7
0.88	887.6	951.1
1.14	882.0	946.7
1.39	876.2	942.4
1.64	870.3	938.3
1.89	864.3	934.1
2.15	858.8	929.9
2.40	853.8	925.7
2.65	849.5	921.6
2.90	848.1	917.7
3.16	846.5	913.7
3.41	845.0	909.9
3.66	843.6	906.3
3.91	843.6	903.0
4.17	846.7	900.0
4.42	854.7	897.6
4.67	872.5	896.4
4.92	911.5	897.4

Solids return temperature	898.9 C
Temperature convergence tolerance	0.003 C
Cyclone temperature	898.9 C
Wall temperature	106.8 C

HEAT TRANSFER COEFFICIENTS

Height (m)	Density (kg/m3)	Core Temp. (C)	Heat Transfer Coefficient (W/m2C) Radiative	Convective	Overall
0.00	244.887	962.0	128.2	100.8	229.0
0.13	176.105	964.3	128.1	101.0	229.1
0.38	108.381	960.2	113.3	107.4	220.7
0.63	67.562	955.7	112.1	72.7	184.8
0.88	42.946	951.1	110.8	46.3	157.1
1.14	28.095	946.7	109.4	30.4	139.8
1.39	19.131	942.4	108.0	20.8	128.8
1.64	13.725	938.3	106.6	14.9	121.5
1.89	10.462	934.1	105.2	11.4	116.6
2.15	8.491	929.9	103.9	9.3	113.2
2.40	7.304	925.7	102.7	8.0	110.7
2.65	6.586	921.6	101.7	7.2	109.0
2.90	6.153	917.7	101.1	6.7	107.8
3.16	5.899	913.7	100.4	6.5	106.9
3.41	5.709	909.9	100.9	6.2	107.1
3.66	5.503	906.3	100.4	6.0	106.3
3.91	5.295	903.0	100.4	5.7	106.1
4.17	5.083	900.0	101.1	5.4	106.5
4.42	4.871	897.6	102.9	5.2	108.1
4.67	4.656	896.4	107.1	4.8	111.9
4.92	4.440	897.4	116.7	4.4	121.1

CFB HEAT RELEASE AND HEAT TRANSFER MODEL

RUN RESULTS FROM HEAT TRANSFER ROUTINE HEAT.F, VERSION 8.1
WRITTEN BY: DALE W.C. JU

COMBUSTOR: Studsvik Prototype
CASE: Sardinian Coal
Case : sh700
Superficial gas velocity = 6.96 m/s
Solids reciculation rate = 30 kg/m2s
Highvale coal(mean dp = 2.89 mm)

FUEL PHYSICAL PROPERTIES AND COMPOSITION

PROXIMATE ANALYSIS

Weight %	
12.200	Ash
15.200	Moisture
0.170	Sulphur
3.050	Hydrogen
52.900	Carbon
0.680	Nitrogen
15.800	Oxygen

PARTICLE SIZE DISTRIBUTION

mm	wt %
7.925	9.250
5.613	10.920
3.962	13.180
2.794	12.110
1.981	11.090
1.397	8.730
0.991	7.750
0.701	5.480
0.495	4.750
0.351	3.740
0.246	3.410
0.175	3.990
0.124	1.290
0.088	0.000
0.053	0.000
0.045	0.000
0.038	0.000
0.000	0.000

COMBUSTION CONDITIONS

# of particles in Monte Carlo Method	100
% of total wall area with membranes	70.0 %
Solids return temp. equals cyclone temp.	859.9 C
Solids recirculation rate	12.750 kg/s
Solids recirculation flux	30.000 kg/m2s
Gas cross-flow coefficient	0.100 m/s
Combustion efficiency	100.0 %
Excess air	20.000 %
Volatile transfer fraction	0.300
Number of fuel feed points	1
Fuel feedrate	395.687 kg/hr
Air feedrate	3070.295 kg/hr
% of total air that is primary	72.0 %
Residence time of particles in cyclone	0.300 sec.
Reflection coefficient	0.100
Height at which developed zone begins	2.777 m

GAS VELOCITIES

Core insterstitial gas velocity	7.122 m/s
Streamer interstitial gas velocity	3.567 m/s
Superficial gas velocity	6.958 m/s
Bed temperature used in calculating heat transfer area and gas velocities	849.9 C

HEAT RELEASE DISTRIBUTION

Height	Fraction of Total Heat Release			
	Volatiles		Char	
(m)	Streamer	Core	Streamer	Core
0.00	0.258362		0.566111	
0.13	0.000590	0.055214	0.020026	0.008767
0.38	0.001039	0.013448	0.007124	0.005038
0.63	0.000117	0.003640	0.004689	0.003222
0.88	0.000399	0.001683	0.003693	0.002311
1.14	0.000008	0.001767	0.003065	0.001771
1.39	0.000002	0.000499	0.002469	0.001498
1.64	0.000000	0.000221	0.002033	0.001218
1.89	0.000000	0.000084	0.001562	0.001138
2.15	0.000000	0.000145	0.001418	0.001078
2.40	0.000000	0.000053	0.001351	0.001023
2.65	0.000000	0.000051	0.001158	0.000974
2.90	0.000000	0.000017	0.001013	0.000953
3.16	0.000000	0.000123	0.000976	0.000931
3.41	0.000000	0.000044	0.000852	0.000892
3.66	0.000000	0.000016	0.000808	0.000893
3.91	0.000000	0.000005	0.000753	0.000877
4.17	0.000000	0.000011	0.000636	0.000840
4.42	0.000000	0.000003	0.000645	0.000834
4.67	0.000000	0.000011	0.000479	0.000784
4.92	0.000000	0.000003	0.000433	0.000759
Cyclone	0.000011		0.005340	
TOTAL	0.380679		0.619321	

OXYGEN PARTIAL PRESSSURE DISTRIBUTION

Height (m)	Partial Pressure of Oxygen (atm.) Streamer	Core
0.00	0.066418	
0.26	0.025838	0.053535
0.51	0.022029	0.046858
0.76	0.021824	0.043752
1.00	0.020122	0.041830
1.26	0.020567	0.040394
1.51	0.021998	0.039458
1.76	0.023719	0.038775
2.01	0.026167	0.038252
2.27	0.026929	0.037792
2.52	0.026905	0.037386
2.77	0.027740	0.037022
3.02	0.028582	0.036693
3.29	0.028730	0.036359
3.54	0.029381	0.036061
3.79	0.029570	0.035776
4.04	0.029772	0.035505
4.29	0.030455	0.035255
4.54	0.030271	0.035009
4.79	0.031314	0.034793
5.04	0.031600	0.034591

Pressure convergence tolerance	0.0023 atm.
Partial pressure of oxygen entering	0.210000 atm.
Partial pressure of oxygen leaving riser	0.035 atm.
Partial pressure of oxygen leaving cyclone	0.034 atm.

TEMPERATURE DISTRIBUTION

Height (m)	Temperature (C) Streamer	Core
0.00	891.2	
0.13	885.4	892.7
0.38	834.7	889.3
0.63	831.6	885.8
0.88	829.0	882.4
1.14	826.5	879.4
1.39	824.3	876.6
1.64	822.6	874.1
1.89	821.1	871.8
2.15	820.1	869.6
2.40	822.1	867.8
2.65	824.2	866.0
2.90	826.2	864.2
3.16	828.3	862.9
3.41	828.6	861.6
3.66	829.7	860.5
3.91	831.7	859.5
4.17	835.5	858.7
4.42	842.5	858.1
4.67	854.6	858.1
4.92	877.8	858.9

Solids return temperature	859.9 C
Temperature convergence tolerance	0.002 C
Cyclone temperature	859.9 C
Wall temperature	106.8 C

HEAT TRANSFER COEFFICIENTS

Height (m)	Density (kg/m3)	Core Temp. (C)	Heat Transfer Coefficient (W/m2C) Radiative	Convective	Overall
0.00	316.944	891.2	110.7	100.5	211.2
0.13	233.423	892.7	110.2	100.8	211.0
0.38	146.824	889.3	98.4	106.8	205.2
0.63	94.664	885.8	97.7	101.3	199.0
0.88	63.214	882.4	97.1	67.7	164.8
1.14	44.242	879.4	96.5	47.4	143.9
1.39	32.797	876.6	96.1	35.1	131.2
1.64	25.889	874.1	95.7	27.7	123.4
1.89	21.720	871.8	95.3	23.2	118.6
2.15	19.205	869.6	95.1	20.5	115.6
2.40	17.688	867.8	95.0	18.9	113.8
2.65	16.738	866.0	95.1	17.8	112.9
2.90	15.982	864.2	96.9	16.8	113.7
3.16	15.211	862.9	96.9	15.9	112.9
3.41	14.412	861.6	97.0	15.1	112.1
3.66	13.591	860.5	97.2	14.2	111.4
3.91	12.744	859.5	97.7	13.2	110.9
4.17	11.869	858.7	98.5	12.2	110.8
4.42	10.968	858.1	100.1	11.2	111.3
4.67	10.042	858.1	102.9	10.1	113.0
4.92	9.091	858.9	108.4	8.9	117.3

CFB HEAT RELEASE AND HEAT TRANSFER MODEL

RUN RESULTS FROM HEAT TRANSFER ROUTINE HEAT.F, VERSION 8.1
WRITTEN BY: DALE W.C. JU

COMBUSTOR: Studsvik Prototype
CASE: Sardinian Coal
Case : sh900
Superficial gas velocity = 6.96 m/s
Solids reciculation rate = 30 kg/m2s
Highvale coal(mean dp = 2.89 mm)

FUEL PHYSICAL PROPERTIES AND COMPOSITION

PROXIMATE ANALYSIS

Weight %	
12.200	Ash
15.200	Moisture
0.170	Sulphur
3.050	Hydrogen
52.900	Carbon
0.680	Nitrogen
15.800	Oxygen

PARTICLE SIZE DISTRIBUTION

mm	wt %
7.925	9.250
5.613	10.920
3.962	13.180
2.794	12.110
1.981	11.090
1.397	8.730
0.991	7.750
0.701	5.480
0.495	4.750
0.351	3.740
0.246	3.410
0.175	3.990
0.124	1.290
0.088	0.000
0.053	0.000
0.045	0.000
0.038	0.000
0.000	0.000

COMBUSTION CONDITIONS

# of particles in Monte Carlo Method	100
% of total wall area with membranes	70.0 %
Solids return temp. equals cyclone temp.	860.5 C
Solids recirculation rate	12.750 kg/s
Solids recirculation flux	30.000 kg/m2s
Gas cross-flow coefficient	0.100 m/s
Combustion efficiency	100.0 %
Excess air	20.000 %
Volatile transfer fraction	0.300
Number of fuel feed points	1
Fuel feedrate	395.687 kg/hr
Air feedrate	3070.295 kg/hr
% of total air that is primary	72.0 %
Residence time of particles in cyclone	0.300 sec.
Reflection coefficient	0.100
Height at which developed zone begins	2.777 m

GAS VELOCITIES

Core insterstitial gas velocity	7.122 m/s
Streamer interstitial gas velocity	3.567 m/s
Superficial gas velocity	6.958 m/s
Bed temperature used in calculating heat transfer area and gas velocities	849.9 C

HEAT RELEASE DISTRIBUTION

Height (m)	Fraction of Total Heat Release: Volatiles Streamer	Volatiles Core	Char Streamer	Char Core
0.00	0.342553		0.477220	
0.13	0.004300	0.074679	0.013539	0.007436
0.38	0.000576	0.017038	0.004955	0.004236
0.63	0.000289	0.003826	0.003514	0.002766
0.88	0.000511	0.001003	0.003038	0.001992
1.14	0.000150	0.000253	0.002745	0.001493
1.39	0.000036	0.000126	0.002074	0.001223
1.64	0.000030	0.000031	0.001647	0.001082
1.89	0.000000	0.000007	0.001382	0.000982
2.15	0.000000	0.000002	0.001109	0.000928
2.40	0.000000	0.000000	0.001106	0.000922
2.65	0.000000	0.000002	0.000942	0.000848
2.90	0.000000	0.000000	0.000905	0.000853
3.16	0.000000	0.000001	0.000822	0.000836
3.41	0.000000	0.000000	0.000741	0.000802
3.66	0.000000	0.000000	0.000717	0.000775
3.91	0.000000	0.000000	0.000651	0.000743
4.17	0.000000	0.000000	0.000567	0.000729
4.42	0.000000	0.000000	0.000512	0.000737
4.67	0.000000	0.000000	0.000466	0.000692
4.92	0.000000	0.000000	0.000398	0.000691
Cyclone	0.000000		0.004768	
TOTAL	0.501927		0.498073	

OXYGEN PARTIAL PRESSSURE DISTRIBUTION

Height (m)	Partial Pressure of Oxygen (atm.) Streamer	Core
0.00	0.066846	
0.26	0.031068	0.051215
0.51	0.033960	0.044474
0.76	0.035640	0.041798
1.00	0.032011	0.040337
1.26	0.027738	0.039364
1.51	0.026677	0.038644
1.76	0.027007	0.038093
2.01	0.027774	0.037651
2.27	0.028930	0.037286
2.52	0.028606	0.036946
2.77	0.029225	0.036646
3.02	0.029315	0.036355
3.29	0.029683	0.036079
3.54	0.030116	0.035821
3.79	0.030156	0.035573
4.04	0.030445	0.035339
4.29	0.030921	0.035121
4.54	0.031221	0.034910
4.79	0.031434	0.034714
5.04	0.031819	0.034529

Pressure convergence tolerance	0.0010 atm.
Partial pressure of oxygen entering	0.210000 atm.
Partial pressure of oxygen leaving riser	0.035 atm.
Partial pressure of oxygen leaving cyclone	0.034 atm.

TEMPERATURE DISTRIBUTION

Height (m)	Temperature (C) Streamer	Core
0.00	891.7	
0.13	885.9	893.5
0.38	835.2	890.1
0.63	832.1	886.5
0.88	829.4	883.0
1.14	826.9	879.8
1.39	824.7	876.9
1.64	823.0	874.4
1.89	821.6	872.1
2.15	820.6	870.0
2.40	822.6	868.2
2.65	824.7	866.4
2.90	826.7	864.7
3.16	828.8	863.4
3.41	829.2	862.1
3.66	830.3	861.0
3.91	832.3	860.0
4.17	836.1	859.2
4.42	843.0	858.7
4.67	855.3	858.7
4.92	878.4	859.5

Solids return temperature	860.5 C
Temperature convergence tolerance	0.001 C
Cyclone temperature	860.5 C
Wall temperature	106.8 C

HEAT TRANSFER COEFFICIENTS

Height (m)	Density (kg/m3)	Core Temp. (C)	Heat Transfer Coefficient (W/m2C) Radiative	Convective	Overall
0.00	316.944	891.7	110.8	100.5	211.3
0.13	233.423	893.5	110.4	100.8	211.2
0.38	146.824	890.1	98.5	106.9	205.4
0.63	94.664	886.5	97.8	101.4	199.1
0.88	63.214	883.0	97.2	67.7	164.9
1.14	44.242	879.8	96.6	47.4	144.0
1.39	32.797	876.9	96.1	35.1	131.3
1.64	25.889	874.4	95.7	27.7	123.5
1.89	21.720	872.1	95.5	23.2	118.7
2.15	19.205	870.0	95.2	20.5	115.7
2.40	17.688	868.2	95.1	18.9	113.9
2.65	16.738	866.4	95.2	17.8	113.0
2.90	15.982	864.7	97.0	16.8	113.8
3.16	15.211	863.4	97.0	15.9	113.0
3.41	14.412	862.1	97.1	15.1	112.2
3.66	13.591	861.0	97.4	14.2	111.5
3.91	12.744	860.0	97.8	13.2	111.0
4.17	11.869	859.2	98.7	12.2	110.9
4.42	10.968	858.7	100.2	11.2	111.4
4.67	10.042	858.7	103.1	10.1	113.2
4.92	9.091	859.5	108.5	8.9	117.4

CFB HEAT RELEASE AND HEAT TRANSFER MODEL

RUN RESULTS FROM HEAT TRANSFER ROUTINE HEAT.F, VERSION 8.1
WRITTEN BY: DALE W.C. JU

COMBUSTOR: UBC COMBUSTOR
CASE: RUN NO. 21, APRIL 21 1988
Case : uh0
Superficial gas velocity = 7.03 m/s
Solids reciculation rate = 30 kg/m2s
Highvale coal(mean dp = 2.89 mm)

FUEL PHYSICAL PROPERTIES AND COMPOSITION

PROXIMATE ANALYSIS

Weight %	
12.200	Ash
15.200	Moisture
0.170	Sulphur
3.050	Hydrogen
52.900	Carbon
0.680	Nitrogen
15.800	Oxygen

PARTICLE SIZE DISTRIBUTION

mm	wt %
7.925	9.250
5.613	10.920
3.962	13.180
2.794	12.110
1.981	11.090
1.397	8.730
0.991	7.750
0.701	5.480
0.495	4.750
0.351	3.740
0.246	3.410
0.175	3.990
0.124	1.290
0.088	0.000
0.053	0.000
0.045	0.000
0.038	0.000
0.000	0.000

COMBUSTION CONDITIONS

# of particles in Monte Carlo Method	100
% of total wall area with membranes	35.0 %
Solids return temp. equals cyclone temp.	792.5 C
Solids recirculation rate	0.696 kg/s
Solids recirculation flux	30.000 kg/m2s
Gas cross-flow coefficient	0.100 m/s
Combustion efficiency	100.0 %
Excess air	20.000 %
Volatile transfer fraction	0.300
Number of fuel feed points	1
Fuel feedrate	22.863 kg/hr
Air feedrate	177.399 kg/hr
% of total air that is primary	50.4 %
Residence time of particles in cyclone	0.300 sec.
Reflection coefficient	0.860
Height at which developed zone begins	3.200 m

GAS VELOCITIES

Core insterstitial gas velocity	7.384 m/s
Streamer interstitial gas velocity	3.647 m/s
Superficial gas velocity	7.030 m/s
Bed temperature used in calculating heat transfer area and gas velocities	857.9 C

HEAT RELEASE DISTRIBUTION

Height	Fraction of Total Heat Release			
	Volatiles		Char	
(m)	Streamer	Core	Streamer	Core
0.00	0.317052		0.305613	
0.16	0.005887	0.071983	0.029671	0.009973
0.48	0.000893	0.015944	0.017396	0.005973
0.80	0.000692	0.004155	0.013057	0.004362
1.12	0.000459	0.002142	0.009720	0.003486
1.44	0.000052	0.001592	0.008220	0.003020
1.76	0.000021	0.000909	0.007529	0.002748
2.08	0.000002	0.000222	0.006999	0.002584
2.40	0.000012	0.000200	0.006848	0.002449
2.72	0.000383	0.000344	0.006309	0.002425
3.04	0.000548	0.000692	0.006106	0.002373
3.36	0.000000	0.000007	0.006034	0.002349
3.68	0.000000	0.000001	0.006743	0.002428
4.00	0.000000	0.000000	0.006760	0.002529
4.32	0.000000	0.000000	0.007350	0.002600
4.64	0.000000	0.000000	0.007849	0.002783
4.96	0.000000	0.000000	0.008391	0.003011
5.28	0.000000	0.000000	0.008868	0.003295
5.60	0.000000	0.000000	0.009645	0.003666
5.92	0.000000	0.000000	0.010064	0.004114
6.24	0.000000	0.000000	0.010948	0.004818
Cyclone	0.000000		0.004705	
TOTAL	0.477665		0.522335	

OXYGEN PARTIAL PRESSSURE DISTRIBUTION

Height (m)	Partial Pressure of Oxygen (atm.) Streamer	Core
0.00	0.101073	
0.32	0.050014	0.082836
0.64	0.051504	0.073647
0.96	0.051164	0.068944
1.28	0.051587	0.065837
1.60	0.051353	0.063474
1.92	0.050136	0.061521
2.24	0.049017	0.059852
2.56	0.047547	0.058266
2.88	0.046136	0.056704
3.20	0.044455	0.055137
3.52	0.043668	0.053828
3.84	0.041194	0.052458
4.16	0.039494	0.051084
4.48	0.037074	0.049655
4.80	0.034576	0.048167
5.12	0.031930	0.046627
5.44	0.029271	0.045058
5.76	0.026194	0.043449
6.08	0.023381	0.041871
6.40	0.020259	0.040204

Pressure convergence tolerance	0.0016 atm.
Partial pressure of oxygen entering	0.210000 atm.
Partial pressure of oxygen leaving riser	0.037 atm.
Partial pressure of oxygen leaving cyclone	0.037 atm.

TEMPERATURE DISTRIBUTION

Height (m)	Temperature (C) Streamer	Core
0.00	879.1	
0.16	883.4	881.2
0.48	828.0	867.1
0.80	823.6	855.7
1.12	821.5	847.1
1.44	820.6	840.6
1.76	820.0	835.7
2.08	819.4	831.8
2.40	819.6	828.9
2.72	820.6	825.8
3.04	815.8	822.6
3.36	811.0	819.5
3.68	806.2	816.3
4.00	804.3	813.3
4.32	802.3	810.6
4.64	800.4	808.0
4.96	798.0	805.4
5.28	795.0	802.5
5.60	791.4	799.4
5.92	786.9	795.6
6.24	781.8	791.2

Solids return temperature	792.5 C
Temperature convergence tolerance	0.002 C
Cyclone temperature	792.5 C
Wall temperature	106.8 C

HEAT TRANSFER COEFFICIENTS

Height (m)	Density (kg/m3)	Core Temp. (C)	Heat Transfer Coefficient (W/m2C) Radiative	Convective	Overall
0.00	394.263	879.1	109.9	99.4	209.2
0.16	171.130	881.2	109.7	99.8	209.5
0.48	111.608	867.1	96.9	105.0	201.9
0.80	80.285	855.7	95.9	83.7	179.6
1.12	63.788	847.1	95.4	66.0	161.4
1.44	55.069	840.6	95.2	56.6	151.8
1.76	50.507	835.7	95.1	51.6	146.7
2.08	48.088	831.8	95.0	48.9	143.9
2.40	46.797	828.9	95.0	47.4	142.4
2.72	46.122	825.8	95.2	46.5	141.7
3.04	46.005	822.6	95.2	46.3	141.5
3.36	47.861	819.5	90.9	49.1	140.0
3.68	51.859	816.3	92.1	52.6	144.7
4.00	57.031	813.3	91.7	57.7	149.4
4.32	63.672	810.6	91.3	64.4	155.7
4.64	72.284	808.0	90.8	73.0	163.9
4.96	83.593	805.4	90.3	84.4	174.8
5.28	98.506	802.5	89.7	99.5	189.2
5.60	118.322	799.4	88.9	101.1	190.0
5.92	144.943	795.6	88.0	101.1	189.1
6.24	180.706	791.2	87.0	101.2	188.1

CFB HEAT RELEASE AND HEAT TRANSFER MODEL

RUN RESULTS FROM HEAT TRANSFER ROUTINE HEAT.F, VERSION 8.1
WRITTEN BY: DALE W.C. JU

COMBUSTOR: Studsvik Prototype
CASE: Sardinian Coal
Case : low load test case, sh6
Wall disturbance factor changed from 310 to 470
Superficial gas velocity = 3.30 m/s
Solids reciculation rate = 30 kg/m2s
Highvale coal(mean dp = 2.89 mm)

FUEL PHYSICAL PROPERTIES AND COMPOSITION

PROXIMATE ANALYSIS

Weight %	
12.200	Ash
15.200	Moisture
0.170	Sulphur
3.050	Hydrogen
52.900	Carbon
0.680	Nitrogen
15.800	Oxygen

PARTICLE SIZE DISTRIBUTION

mm	wt %
7.925	9.250
5.613	10.920
3.962	13.180
2.794	12.110
1.981	11.090
1.397	8.730
0.991	7.750
0.701	5.480
0.495	4.750
0.351	3.740
0.246	3.410
0.175	3.990
0.124	1.290
0.088	0.000
0.053	0.000
0.045	0.000
0.038	0.000
0.000	0.000

COMBUSTION CONDITIONS

# of particles in Monte Carlo Method	100
% of total wall area with membranes	70.0 %
Solids return temp. equals cyclone temp.	604.5 C
Solids recirculation rate	12.750 kg/s
Solids recirculation flux	30.000 kg/m2s
Gas cross-flow coefficient	0.100 m/s
Combustion efficiency	100.0 %
Excess air	20.000 %
Volatile transfer fraction	0.300
Number of fuel feed points	1
Fuel feedrate	185.551 kg/hr
Air feedrate	1439.763 kg/hr
% of total air that is primary	67.8 %
Residence time of particles in cyclone	0.300 sec.
Reflection coefficient	0.100
Height at which developed zone begins	2.020 m

GAS VELOCITIES

Core insterstitial gas velocity	3.489 m/s
Streamer interstitial gas velocity	1.743 m/s
Superficial gas velocity	3.300 m/s

Bed temperature used in calculating heat transfer area and gas velocities	854.9 C

HEAT RELEASE DISTRIBUTION

Height	Fraction of Total Heat Release			
	Volatiles		Char	
(m)	Streamer	Core	Streamer	Core
0.00	0.376003		0.382288	
0.13	0.002162	0.082293	0.019153	0.013069
0.38	0.000125	0.017668	0.011832	0.007722
0.63	0.000042	0.003817	0.007813	0.005338
0.88	0.000002	0.000833	0.005403	0.004024
1.14	0.000001	0.000188	0.004050	0.003246
1.39	0.000000	0.000045	0.003218	0.002861
1.64	0.000000	0.000014	0.003026	0.002561
1.89	0.000000	0.000004	0.002623	0.002407
2.15	0.000000	0.000002	0.002475	0.002234
2.40	0.000000	0.000001	0.002254	0.002118
2.65	0.000000	0.000000	0.002127	0.001936
2.90	0.000000	0.000000	0.001974	0.001744
3.16	0.000000	0.000000	0.001693	0.001697
3.41	0.000000	0.000000	0.001582	0.001542
3.66	0.000000	0.000000	0.001299	0.001354
3.91	0.000000	0.000000	0.001118	0.001241
4.17	0.000000	0.000000	0.000804	0.001071
4.42	0.000000	0.000000	0.000626	0.000980
4.67	0.000000	0.000000	0.000439	0.000843
4.92	0.000000	0.000000	0.000265	0.000757
Cyclone	0.000000		0.001993	
TOTAL	0.545026		0.454974	

OXYGEN PARTIAL PRESSSURE DISTRIBUTION

Height (m)	Partial Pressure of Oxygen (atm.) Streamer	Core
0.00	0.077348	
0.26	0.048006	0.059016
0.51	0.045328	0.050294
0.76	0.041629	0.046541
1.00	0.038226	0.044397
1.26	0.035594	0.042924
1.51	0.033920	0.041784
1.76	0.032109	0.040819
2.01	0.031386	0.039957
2.27	0.030958	0.039141
2.52	0.030936	0.038368
2.77	0.030799	0.037649
3.02	0.030732	0.036987
3.29	0.031092	0.036373
3.54	0.031123	0.035810
3.79	0.031625	0.035319
4.04	0.031970	0.034881
4.29	0.032764	0.034519
4.54	0.033223	0.034208
4.79	0.033683	0.033951
5.04	0.034138	0.033739

Pressure convergence tolerance	0.0011 atm.
Partial pressure of oxygen entering	0.210000 atm.
Partial pressure of oxygen leaving riser	0.034 atm.
Partial pressure of oxygen leaving cyclone	0.033 atm.

TEMPERATURE DISTRIBUTION

Height (m)	Temperature (C) Streamer	Core
0.00	618.3	
0.13	615.6	619.0
0.38	587.4	615.3
0.63	587.4	612.4
0.88	588.8	610.2
1.14	591.1	608.6
1.39	593.7	607.4
1.64	595.3	606.9
1.89	596.8	606.4
2.15	598.4	605.8
2.40	599.9	605.4
2.65	599.8	605.1
2.90	599.7	604.8
3.16	599.6	604.5
3.41	599.7	604.3
3.66	599.9	604.1
3.91	600.4	604.0
4.17	601.5	603.9
4.42	603.4	603.9
4.67	607.2	604.0
4.92	615.9	604.2

Solids return temperature	604.5 C
Temperature convergence tolerance	0.001 C
Cyclone temperature	604.5 C
Wall temperature	106.8 C

HEAT TRANSFER COEFFICIENTS

Height (m)	Density (kg/m3)	Core Temp. (C)	Heat Transfer Coefficient (W/m2C) Radiative	Convective	Overall
0.00	490.237	618.3	57.3	100.3	157.6
0.13	400.288	619.0	57.1	100.5	157.7
0.38	273.636	615.3	52.9	105.0	158.0
0.63	197.644	612.4	52.9	104.7	157.6
0.88	151.900	610.2	53.1	104.1	157.2
1.14	124.329	608.6	53.5	103.4	156.8
1.39	107.699	607.4	53.8	102.7	156.5
1.64	97.668	606.9	54.2	99.7	153.8
1.89	91.803	606.4	54.4	93.3	147.7
2.15	86.734	605.8	55.2	87.2	142.4
2.40	80.762	605.4	54.7	81.6	136.4
2.65	74.758	605.1	54.7	75.5	130.3
2.90	68.662	604.8	54.7	69.3	124.1
3.16	62.458	604.5	54.7	63.1	117.8
3.41	56.192	604.3	54.7	56.7	111.4
3.66	49.906	604.1	54.8	50.3	105.1
3.91	43.656	604.0	54.8	44.0	98.8
4.17	37.489	603.9	55.0	37.7	92.7
4.42	31.461	603.9	55.3	31.5	86.8
4.67	25.619	604.0	55.8	25.5	81.3
4.92	20.007	604.2	57.2	19.6	76.7

APPENDIX D

LIST OF VARIABLES

D.1 INPUT FILE FROM HYDRODYNAMIC MODEL

Variable	Description	Variable Name in Senior's Model
acell(i)	cross-sectional area of core cells (m^2)	
acell(ncell)	primary zone cross-sectional area (m^2)	
acell(ny+i)	cross-sectional area of annulus cells (m^2)	
acfin	cross-sectional area of core at the top of the riser (m^2)	
acinit	core cross-sectional area at height = 0 m (m^2)	
asfin	cross-sectional area of annulus at the top of the riser (m^2)	
asinit	annulus cross-sectional area at height = 0 m (m^2)	
at	riser cross-sectional area (m^2)	bed(4)
dbavg	average density of the bed (kg/m^3)	dbav(3)
denp	particle density (kg/m^3)	pp(1,1)
devh	height of developing zone (m)	
emiss	particle radiation emissivity	pp(4,4)
flux(i,j)	i = cell number	
	j = 1 height of cell (m)	
	= 2 radial flux out of the cell (kg/m^2s)	
	= 3 axial flux out of the cell (kg/m^2s)	
	= 4 cell density (kg/m^3)	
fluxr	solids recirculation rate (kg/m^2s)	hydg(1)
k	thermal conductivity of gas	tcg
ny	number of cells along the riser, not including the primary zone	nzb
pair	fraction of the total combustion air that is primary air	
pdist(i)	weight percentage of particles at sieve size siv(i) (%)	
per	perimeter of riser (m)	peri
primev	volume of primary zone (m^3)	bed(1)
rc	reflection coefficient	hydz(5)
siv(i)	particle sieve sizing (mm)	
sug	superficial gas velocity (m/s)	ug(5)
tb	temperature of the bed (°C)	t
twall	temperature of the heat transfer surface (°C)	
uc	mean core gas velocity (m/s)	ug(1)

ult(i)	ultimate analysis of fuel (%)	
	i = 1 ash	pp(1,2)
	i = 2 moisture	pp(1,10)
	i = 3 sulphur	pp(1,6)
	i = 4 hydrogen	pp(1,4)
	i = 5 carbon	pp(1,3)
	i = 6 nitrogen	pp(1,9)
	i = 7 oxygen	pp(1,5)
us	mean annulus gas velocity (m/s)	ug(2)
volf	fractional volatiles yield	pp(1,7)

D.2 USER INPUT FILE

Variable	Description
c1, c2	constants used in the devolatilization equation
ceff	combustion efficiency
const1	constant in wall convective heat transfer coefficient calculation
cross	gas mass transfer crossflow coefficient
eps	tolerance of oxygen partial pressure calculation
eps2	tolerance of bed temperature calculation
eps3	tolerance of bed temperature within the energy balance subroutine "htrans"
exair	fractional excess air
nfeed	number of equally spaced feed points at the bottom of the primary zone
npart	number of particles used in the Monte Carlo method
perc	fraction of particles that will leave a cell during time step
rf	relaxation factor in oxygen partial pressure calculation
rf2	relaxation factor in temperature calculation
rt	residence time of the cyclone (s)
tair	combustion air inlet temperature (°C)
tref	reference temperature (°C)
tsp	particle surface temperature (°C)
vtf	volatile transfer fraction

D.3 PROGRAM VARIABLES

Variable	Description
afeed	air feedrate (kg/s)
areaw(i,j), areae(i,j), arean(i,j), areas(i,j)	cell area on west, east, north and south face
areat(i,j)	total surface area of cell (m^2)

cg	gas heat capacity
cp	particle heat capacity
denb(2)	primary zone bed density(kg/m^2)
denb(i+2)	bed density at a given height (kg/m^2)
deng	gas density (kg/m^3)
distv(i)	volatiles heat release distribution
dpcut	cut-off particle diameter in the cyclone (m)
dt	time step
dx(i,j), dy(i,j)	dimensions of the cell (m)
f	fraction of total wall area that is a heat transfer surface
fluxc(i,j)	i = cell number j = 1 height of cell (m) = 2 radial flowrate out of the cell (kg/s) = 3 axial florate out of the cell (kg/s) = 4 cell mass (kg)
fuel	fuel feedrate (kg/s)
heat (i)	heat release in cell
heatv(i)	heat release due to devolatilization
htarea	heat transfer area (m^2)
ncell	number of cells
nx	number of cells in the radial direction
o2feed	oxygen feedrate (kg/s)
o2need	oxygen feedrate needed per kg/s of fuel feedrate (kg/s)
pcyc	oxygen partial pressur in cyclone (atm)
pmat1(i), pmat2(i), pmatt(i)	probability of how a particle will move in a cell
po2	partial pressure of oxygen in the airfeed (atm)
presc(i)	core cell partial pressure of oxygen (atm)
press(i)	annulus cell partial pressure of oxygen (atm)
primeh	height of primary zone (m)
rarea	total wall area (m^2)
recirc	solids recirculation flowrate(kg/s)
sbc	Stefan-Boltzmann constant (W/m2k4)
tcyc	cyclone temperature (°C)
temp(i)	cell temperature (°C)
tempo(i)	cell temperature in previous iteration (°C)
tin	mixing temperature of fuel feed and combustion air (°C)
tinit	initial guess of bed temperature (°C)
volp	particle volume (m^3)

APPENDIX E

ENTHALPY BALANCE SPREADSHEETS

case: sh0

j	streamer temp (K and C)	q (W)		(W) west	east	north	south	core temp (K and C)	q (W)		(W) west	east	north	south
22	1149	918	cond	-3114	-5	0	0	1131	1820	cond	5	0	0	0
	876		p-conv	0	245405	1017426	-1222067	857		p-conv	-245405	0	-10174472	10415631
			g-conv	0	-433	-1213	1494			g-conv	433	0	-883550	882102
			rad	-37937	-3517	-6	-9			rad	3517	0	-1	-89
21	1127	1239	cond	-3436	1	0	0	1130	1809	cond	-1	0	0	0
	853		p-conv	0	245280	1222069	-1434616	857		p-conv	-245280	0	-10415856	10660502
			g-conv	0	76	-1494	1776			g-conv	-76	0	-882121	881536
			rad	-34956	604	9	-6			rad	-604	0	88	5
20	1114	1424	cond	-3753	4	0	0	1130	1825	cond	-4	0	0	0
	841		p-conv	0	242908	1434562	-1648749	857		p-conv	-242908	0	-10660754	10904993
			g-conv	0	359	-1776	2055			g-conv	-359	0	-881557	881482
			rad	-33441	2777	6	-4			rad	-2777	0	-6	60
19	1107	1731	cond	-4064	6	0	0	1130	1947	cond	-6	0	0	0
	834		p-conv	0	239286	1648716	-1861908	857		p-conv	-239286	0	-10905293	11146936
			g-conv	0	527	-2055	2329			g-conv	-527	0	-881506	881752
			rad	-32617	4049	4	-2			rad	-4049	0	-62	95
18	1104	1895	cond	-4368	8	0	0	1131	2033	cond	-8	0	0	0
	830		p-conv	0	234997	1861821	-2072113	858		p-conv	-234997	0	-11147254	11385213
			g-conv	0	633	-2329	2598			g-conv	-633	0	-881777	882245
			rad	-32162	4846	2	-1			rad	-4846	0	-96	118
17	1102	2170	cond	-4664	9	0	0	1132	2170	cond	-9	0	0	0
	828		p-conv	0	230276	2072030	-2278708	859		p-conv	-230276	0	-11385535	11619078
			g-conv	0	702	-2598	2860			g-conv	-702	0	-882270	882695
			rad	-31928	5363	1	-1			rad	-5363	0	-119	134
16	1100	2082	cond	-4953	9	0	0	1133	2233	cond	-9	0	0	0
	827		p-conv	0	225408	2278571	-2480731	860		p-conv	-225408	0	-11619385	11848309
			g-conv	0	754	-2860	3116			g-conv	-754	0	-882918	883677
			rad	-31793	5763	1	0			rad	-5763	0	-135	147
15	1100	2266	cond	-5236	10	0	0	1135	2180	cond	-10	0	0	0
	827		p-conv	0	220350	2480706	-2678609	861		p-conv	-220350	0	-11848632	12072762
			g-conv	0	790	-3116	3366			g-conv	-790	0	-883701	884573
			rad	-31754	6047	0	0			rad	-6047	0	-149	159
14	1100	2205	cond	-5511	10	0	0	1136	2256	cond	-10	0	0	0
	827		p-conv	0	216332	2678639	-2871501	863		p-conv	-216332	0	-12073137	12292363
			g-conv	0	824	-3366	3571			g-conv	-824	0	-884600	885571
			rad	-31744	6309	0	-8			rad	-6309	0	-160	169
13	1092	2391	cond	-5782	13	0	0	1137	2515	cond	-13	0	0	0
	819		p-conv	0	202981	2871512	-3055414	864		p-conv	-202981	0	-12292831	12500888
			g-conv	0	1048	-3571	3837			g-conv	-1048	0	-885605	886964
			rad	-30777	7954	8	-1			rad	-7954	0	-171	222
12	1091	2514	cond	-6125	14	0	0	1139	2877	cond	-14	0	0	0
	816		p-conv	0	325019	3055389	-3362060	866		p-conv	-325019	0	-12501389	12831774
			g-conv	0	1104	-3837	4229			g-conv	-1104	0	-887000	888244
			rad	-30707	8398	1	1			rad	-8398	0	-224	239
11	1092	2744	cond	-6667	14	0	0	1141	2801	cond	-14	0	0	0
	819		p-conv	0	526316	3362024	-3870626	868		p-conv	-526315	0	-12832252	13364660
			g-conv	0	1133	-4229	4871			g-conv	-1133	0	-888277	889143
			rad	-30796	8644	-1	1			rad	-8644	0	-241	257
10	1093	3400	cond	-7561	14	0	0	1143	3216	cond	-14	0	0	0
	820		p-conv	0	860443	3870625	-4714643	870		p-conv	-860443	0	-13365184	14232266
			g-conv	0	1157	-4871	5935			g-conv	-1157	0	-889178	889310
			rad	-30919	8867	-1	2			rad	-8867	0	-259	277
9	1094	4229	cond	-9037	14	0	0	1146	3929	cond	-14	0	0	0
	821		p-conv	0	1415577	4714575	-6115182	873		p-conv	-1415577	0	-14232838	15655867
			g-conv	0	1177	-5936	7702			g-conv	-1177	0	-889344	888199
			rad	-31077	9074	-2	3			rad	-9074	0	-279	302
8	1096	5258	cond	-11482	15	0	0	1148	3738	cond	-15	0	0	0
	823		p-conv	0	2338458	6114953	-8440266	875		p-conv	-2338458	0	-15656266	18004696
			g-conv	0	1195	-7702	10637			g-conv	-1195	0	-888222	884943
			rad	-31277	9260	-3	6			rad	-9260	0	-304	341
7	1098	7635	cond	-15539	15	0	0	1151	4853	cond	-15	0	0	0
	825		p-conv	0	3874176	8440036	-12305315	878		p-conv	-3874176	0	-18005204	21892169
			g-conv	0	1208	-10637	15512			g-conv	-1208	0	-884968	877935
			rad	-31536	9428	-6	10			rad	-9428	0	-343	384
6	1101	10993	cond	-22277	15	0	0	1154	8165	cond	-15	0	0	0
	828		p-conv	0	6427881	12304693	-18729275	881		p-conv	-6427881	0	-21892908	28337072
			g-conv	0	1224	-15514	23616			g-conv	-1224	0	-877965	864350
			rad	-31829	9623	-10	16			rad	-9623	0	-386	416
5	1103	16085	cond	-33465	15	0	0	1158	18176	cond	-15	0	0	0
	830		p-conv	0	10674755	18727945	-29408147	884		p-conv	-10674755	0	-28338043	39030695
			g-conv	0	1241	-23618	37100			g-conv	-1241	0	-864380	839408
			rad	-32147	9844	-16	30			rad	-9844	0	-417	418
4	1107	31001	cond	-35436	15	0	1	1161	55014	cond	-15	0	0	0
	833		p-conv	0	17741971	29406283	-47180374	888		p-conv	-17741971	0	-39031763	56774287
			g-conv	0	1252	-37102	62992			g-conv	-1252	0	-839431	795190
			rad	-32517	10017	-30	825			rad	-10017	0	-419	373
3	1157	48116	cond	-35765	2	-1	0	1165	215079	cond	-2	0	0	0
	884		p-conv	0	29196541	47177737	-76411429	891		p-conv	-29196541	0	-56773442	85824429
			g-conv	0	173	-62990	96252			g-conv	-173	0	-795178	727798
			rad	-38953	1486	-825	52			rad	-1486	0	-373	-101
2	1159	424343	cond	-228524	21	0	-1	1163	1598444	cond	-21	0	0	-4
	886		p-conv	0	-76582656	76413166	0	890		p-conv	76582656	0	-85807821	8903567
			g-conv	0	659	-96247	0			g-conv	-659	0	-727657	0
			rad	-250995	5774	-52	-2501			rad	-5774	0	106	-9887

heat generated in streamer	574639	
heat generated in core	1937081	
total heat generated		2611720
heat transferred to cooling wall		-1371007
heat leaving top of riser		-10041809
heat entering bottom of riser		8903554
	total	2457
	% diff. of heat gen.	0

case: eh1

i	streamer temp (K and C)	g (W)		(W) west	east	north	south	core temp (K and C)	g (W)		(W) west	east	north	south
22	1123	1212	cond	-5046	-4	0	0	1107	2006	cond	4	0	0	0
	850		p-conv	0	474162	1609953	-2048215	834		p-conv	-474162	0	-16099264	16570050
			g-conv	0	-365	-1977	2552			g-conv	365	0	-865327	863621
			rad	-34576	-2780	-8	-10			rad	2780	0	0	-52
21	1109	1401	cond	-5657	0	0	0	1107	2112	cond	0	0	0	0
	836		p-conv	0	461522	2048232	-2479666	834		p-conv	-461522	0	-16569810	17030137
			g-conv	0	-38	-2551	3112			g-conv	38	0	-863608	862332
			rad	-32770	-281	10	-7			rad	281	0	53	-11
20	1100	1681	cond	-6249	2	0	0	1107	2186	cond	-2	0	0	0
	827		p-conv	0	447784	2478703	-2898277	834		p-conv	-447784	0	-17029877	17477694
			g-conv	0	151	-3112	3653			g-conv	-151	0	-862319	861340
			rad	-31783	1112	7	-5			rad	-1112	0	12	15
19	1095	1936	cond	-6820	3	0	0	1107	2262	cond	-3	0	0	0
	822		p-conv	0	433520	2898321	-3306440	834		p-conv	-433520	0	-17477416	17911656
			g-conv	0	269	-3653	4177			g-conv	-269	0	-861326	860566
			rad	-31201	1966	5	-3			rad	-1966	0	-15	33
18	1092	2061	cond	-7371	4	0	0	1107	2394	cond	-4	0	0	0
	819		p-conv	0	419131	3306487	-3699311	834		p-conv	-419131	0	-17911386	18331570
			g-conv	0	345	-4177	4681			g-conv	-345	0	-860553	859962
			rad	-30850	2520	3	-2			rad	-2520	0	-33	46
17	1090	2355	cond	-7901	5	0	0	1108	2467	cond	-5	0	0	0
	817		p-conv	0	404767	3699384	-4079814	835		p-conv	-404767	0	-18331293	18737329
			g-conv	0	397	-4681	5168			g-conv	-397	0	-859949	859496
			rad	-30640	2890	2	-1			rad	-2890	0	-46	56
16	1089	2683	cond	-8411	5	0	0	1108	2488	cond	-5	0	0	0
	816		p-conv	0	390530	4079871	-4446774	835		p-conv	-390530	0	-18737068	19129035
			g-conv	0	434	-5168	5636			g-conv	-434	0	-859485	859152
			rad	-30513	3158	1	-1			rad	-3158	0	-56	65
15	1089	2786	cond	-8902	6	0	0	1109	2750	cond	-6	0	0	0
	816		p-conv	0	376814	4446796	-4800069	836		p-conv	-376814	0	-19128816	19506731
			g-conv	0	461	-5636	6087			g-conv	-461	0	-859142	858905
			rad	-30447	3354	1	0			rad	-3354	0	-64	71
14	1089	3124	cond	-9373	6	0	0	1110	2745	cond	-6	0	0	0
	815		p-conv	0	362938	4800142	-5140377	836		p-conv	-362938	0	-19506516	19870835
			g-conv	0	480	-6087	6523			g-conv	-480	0	-858896	858751
			rad	-30423	3498	0	1			rad	-3498	0	-70	77
13	1089	3197	cond	-9827	6	0	0	1110	2806	cond	-6	0	0	0
	816		p-conv	0	349370	5140387	-5466925	837		p-conv	-349370	0	-19870662	20221336
			g-conv	0	487	-6523	6904			g-conv	-487	0	-858744	858675
			rad	-30469	3552	-1	-6			rad	-3552	0	-76	80
12	1085	3188	cond	-10253	7	0	0	1111	2726	cond	-7	0	0	0
	812		p-conv	0	368964	5466986	-5814495	838		p-conv	-368964	0	-20221234	20592279
			g-conv	0	584	-6904	7365			g-conv	-584	0	-858670	858669
			rad	-30076	4238	6	-2			rad	-4238	0	-90	101
11	1084	3582	cond	-10843	8	0	0	1112	3128	cond	-8	0	0	0
	811		p-conv	0	601196	5814577	-6395519	839		p-conv	-601196	0	-20592356	21198072
			g-conv	0	630	-7365	8085			g-conv	-630	0	-858673	858218
			rad	-29951	4576	2	-5			rad	-4576	0	-101	115
10	1082	4061	cond	-11862	9	0	0	1113	3608	cond	-9	0	0	0
	809		p-conv	0	987467	6395599	-7364759	840		p-conv	-987467	0	-21198316	22187326
			g-conv	0	714	-8085	9311			g-conv	-714	0	-858227	856934
			rad	-29661	5169	5	-6			rad	-5169	0	-115	139
9	1079	4544	cond	-13548	10	0	0	1114	3532	cond	-10	0	0	0
	806		p-conv	0	1627829	7364877	-8976781	841		p-conv	-1627829	0	-22187645	23821202
			g-conv	0	801	-9311	11356			g-conv	-801	0	-856947	854246
			rad	-29380	5789	6	-6			rad	-5789	0	-140	173
8	1077	5425	cond	-16340	11	0	0	1116	4220	cond	-11	0	0	0
	804		p-conv	0	2690647	8976831	-11654562	843		p-conv	-2690647	0	-23821678	26520541
			g-conv	0	886	-11356	14756			g-conv	-886	0	-854263	849073
			rad	-29145	6399	8	-5			rad	-6399	0	-174	213
7	1076	7504	cond	-20970	12	0	0	1118	5224	cond	-12	0	0	0
	803		p-conv	0	4454832	11654718	-16102020	845		p-conv	-4454832	0	-26521055	30988105
			g-conv	0	963	-14756	20405			g-conv	-963	0	-849090	839541
			rad	-28985	8966	5	-3			rad	-8966	0	-214	256
6	1075	10997	cond	-28652	13	0	0	1120	8727	cond	-13	0	0	0
	802		p-conv	0	7384849	16102071	-23487064	847		p-conv	-7384849	0	-30988520	38390294
			g-conv	0	1033	-20406	29804			g-conv	-1033	0	-839552	822401
			rad	-28909	7488	3	2			rad	-7488	0	-256	288
5	1075	28892	cond	-33738	13	0	0	1123	20643	cond	-13	0	0	0
	802		p-conv	0	12255908	23486843	-35766850	850		p-conv	-12255908	0	-38388876	50664348
			g-conv	0	1084	-29807	45419			g-conv	-1084	0	-822392	792211
			rad	-28948	7907	-3	11			rad	-7907	0	-288	300
4	1076	32986	cond	-33778	14	0	1	1126	51526	cond	-14	0	0	0
	803		p-conv	0	20360894	35762991	-56158955	852		p-conv	-20360894	0	-50660223	71030970
			g-conv	0	1128	-45420	75476			g-conv	-1128	0	-792147	740036
			rad	-29064	8269	-11	860			rad	-8269	0	-298	288
3	1123	77573	cond	-34109	2	-1	0	1128	198611	cond	-2	0	0	0
	850		p-conv	0	33489481	56158052	-89727629	855		p-conv	-33489481	0	-71021079	104391065
			g-conv	0	131	-75476	114146			g-conv	-131	0	-739932	662403
			rad	-34479	1045	-860	73			rad	-1045	0	-283	-59
2	1125	497479	cond	-218174	12	0	-1	1128	1441361	cond	-12	0	0	-2
	852		p-conv	0	-89986671	89725047	0	855		p-conv	89986671	0	-104374348	14249526
			g-conv	0	385	-114139	0			g-conv	-385	0	-662297	0
			rad	-222616	3086	-73	-1777			rad	-3086	0	65	-5381

heat generated in streamer	698668	
heat generated in core	1767522	
total heat generated		2466190
heat transferred to cooling wall		-1349866
heat leaving top of riser		-15356635
heat entering bottom of riser		14249526
total		9215
% diff. of heat gen.		0

case: sh2

i	streamer temp (K and C)	q (W)		(W) west	east	north	south	core temp (K and C)	q (W)		(W) west	east	north	south
22	1183	511	cond	-1600	-4	0	0	1169	1061	cond	4	0	0	0
	910		p-conv	0	55734	551329	-561739	896		p-conv	-55734	0	-5513208	5565963
			g-conv	0	-318	-625	669			g-conv	318	0	-918367	917229
			rad	-42661	-2852	-2	-7			rad	2852	0	0	-127
21	1144	649	cond	-1675	7	0	0	1168	1131	cond	-7	0	0	0
	871		p-conv	0	64027	561799	-594560	895		p-conv	-64027	0	-5565892	5632503
			g-conv	0	548	-669	725			g-conv	-548	0	-917218	918393
			rad	-37278	4642	8	-4			rad	-4642	0	127	163
20	1127	807	cond	-1755	12	0	0	1170	1102	cond	-12	0	0	0
	853		p-conv	0	68242	594608	-637804	896		p-conv	-68242	0	-5632426	5706201
			g-conv	0	987	-725	787			g-conv	-987	0	-918380	920759
			rad	-34976	8182	4	-2			rad	-8182	0	-162	313
19	1119	699	cond	-1837	15	0	0	1172	1115	cond	-15	0	0	0
	846		p-conv	0	70534	637857	-686572	899		p-conv	-70534	0	-5706157	5783766
			g-conv	0	1223	-787	852			g-conv	-1223	0	-920751	923771
			rad	-33990	10071	2	-1			rad	-10071	0	-313	396
18	1116	920	cond	-1921	17	0	0	1175	1160	cond	-17	0	0	0
	843		p-conv	0	71782	686623	-738431	902		p-conv	-71782	0	-5783748	5863489
			g-conv	0	1357	-852	920			g-conv	-1357	0	-923769	927158
			rad	-33634	11189	1	0			rad	-11189	0	-396	447
17	1116	963	cond	-2006	18	0	0	1178	1198	cond	-18	0	0	0
	843		p-conv	0	72502	738449	-791766	905		p-conv	-72502	0	-5863476	5944489
			g-conv	0	1437	-920	989			g-conv	-1437	0	-927155	930770
			rad	-33617	11899	0	1			rad	-11899	0	-446	479
16	1118	1013	cond	-2089	18	0	0	1182	1161	cond	-18	0	0	0
	845		p-conv	0	72602	791757	-845188	909		p-conv	-72602	0	-5944464	6025667
			g-conv	0	1464	-989	1050			g-conv	-1464	0	-930766	934482
			rad	-33910	12218	-1	-1			rad	-12218	0	-479	496
15	1116	1035	cond	-2168	20	0	0	1186	1211	cond	-20	0	0	1
	843		p-conv	0	72302	845215	-900035	912		p-conv	-72302	0	-6025652	6107812
			g-conv	0	1599	-1050	1125			g-conv	-1599	0	-934480	938542
			rad	-33638	13368	1	1			rad	-13368	0	-496	548
14	1119	1099	cond	-2273	20	0	0	1190	1241	cond	-20	0	-1	1
	845		p-conv	0	109181	900048	-991875	916		p-conv	-109181	0	-6107807	6227027
			g-conv	0	1628	-1125	1240			g-conv	-1628	0	-938541	942617
			rad	-33973	13732	-1	1			rad	-13732	0	-548	567
13	1122	1239	cond	-2445	20	0	0	1194	1279	cond	-20	0	-1	1
	848		p-conv	0	170356	991887	-1145083	921		p-conv	-170356	0	-6227031	6407819
			g-conv	0	1653	-1240	1434			g-conv	-1653	0	-942618	946620
			rad	-34348	14068	-1	2			rad	-14068	0	-567	585
12	1126	1485	cond	-2725	20	0	0	1198	1369	cond	-20	0	-1	1
	853		p-conv	0	271785	1145117	-1399772	925		p-conv	-271785	0	-6407845	6690382
			g-conv	0	1649	-1434	1764			g-conv	-1649	0	-946624	950382
			rad	-34888	14198	-2	2			rad	-14198	0	-585	595
11	1131	1811	cond	-3184	20	0	0	1202	1480	cond	-20	0	-1	1
	858		p-conv	0	440464	1399757	-1822878	929		p-conv	-440464	0	-6690419	7141951
			g-conv	0	1632	-1764	2286			g-conv	-1632	0	-950390	953699
			rad	-35517	14215	-2	3			rad	-14215	0	-595	601
10	1136	2281	cond	-3944	20	0	0	1206	1582	cond	-20	0	-1	1
	863		p-conv	0	721361	1822862	-2526867	933		p-conv	-721361	0	-7142032	7874984
			g-conv	0	1602	-2286	3171			g-conv	-1602	0	-953710	956270
			rad	-36229	14125	-3	5			rad	-14125	0	-602	607
9	1143	3019	cond	-5199	19	0	0	1211	2166	cond	-19	0	-1	1
	869		p-conv	0	1189115	2526870	-3698991	937		p-conv	-1189115	0	-7875194	9076357
			g-conv	0	1561	-3171	4642			g-conv	-1561	0	-956296	957688
			rad	-37014	13944	-5	8			rad	-13944	0	-609	611
8	1149	5708	cond	-7282	19	0	0	1215	3901	cond	-19	0	-1	1
	876		p-conv	0	1968226	3698948	-5652727	942		p-conv	-1968226	0	-9076705	11057135
			g-conv	0	1516	-4642	7090			g-conv	-1516	0	-957625	956803
			rad	-37822	13739	-8	11			rad	-13739	0	-613	612
7	1154	7418	cond	-10744	18	0	0	1219	4436	cond	-18	0	-1	1
	881		p-conv	0	3266166	5652097	-8904789	946		p-conv	-3266166	0	-11057221	14338111
			g-conv	0	1481	-7090	11166			g-conv	-1481	0	-956810	952720
			rad	-38598	13584	-11	17			rad	-13584	0	-613	639
6	1160	5983	cond	-16499	18	0	0	1223	9023	cond	-18	0	-1	1
	887		p-conv	0	5429628	8904595	-14322079	950		p-conv	-5429628	0	-14338240	19783456
			g-conv	0	1455	-11166	17951			g-conv	-1455	0	-952728	942982
			rad	-39355	13508	-17	26			rad	-13508	0	-639	655
5	1165	3440	cond	-26067	18	0	0	1228	16605	cond	-18	0	-1	1
	892		p-conv	0	9029303	14321812	-23340099	955		p-conv	-9029303	0	-19783471	28830479
			g-conv	0	1442	-17948	29257			g-conv	-1442	0	-942983	923627
			rad	-40071	13530	-26	43			rad	-13530	0	-655	649
4	1170	13259	cond	-38725	17	0	1	1233	53614	cond	-17	0	-1	0
	897		p-conv	0	15017203	23343402	-38378208	959		p-conv	-15017203	0	-28832454	43847089
			g-conv	0	1425	-29257	50936			g-conv	-1425	0	-923690	887683
			rad	-40805	13548	-43	835			rad	-13548	0	-651	548
3	1227	38986	cond	-39044	3	-1	0	1237	218584	cond	-3	0	0	0
	954		p-conv	0	24725604	38377731	-63120989	963		p-conv	-24725604	0	-43852021	68419367
			g-conv	0	211	-50936	78657			g-conv	-211	0	-887783	830503
			rad	-49443	2152	-835	5			rad	-2152	0	-553	-193
2	1228	344006	cond	-249371	38	0	-1	1235	1803696	cond	-38	0	0	-8
	954		p-conv	0	-63135147	63119952	0	962		p-conv	63135147	0	-68422921	4809790
			g-conv	0	1101	-78657	0			g-conv	-1101	0	-830546	0
			rad	-316664	11210	-5	-3968			rad	-11210	0	188	-21765

heat generated in streamer	436133	
heat generated in core	2128113	
total heat generated		2564246
heat transferred to cooling wall		-1506717
heat leaving top of riser		-5880891
heat entering bottom of riser		4809782
	total	-13579
	% diff. of heat gen.	-1

case: sh3

i	streamer temp (K and C)	q (W)		(W) west	east	north	south	core temp (K and C)	q (W)		(W) west	east	north	south
22	1103	996	cond	-3336	-5	0	0	1086	1939	cond	5	0	0	0
	830		p-conv	0	316613	961446	-1243726	812		p-conv	-316613	0	-9614675	9927332
			g-conv	0	-425	-989	1315			g-conv	425	0	-720559	719175
			rad	-32123	-3051	-5	-6			rad	3051	0	0	-76
21	1083	1147	cond	-3781	0	0	0	1084	1887	cond	0	0	0	0
	810		p-conv	0	315695	1243672	-1530960	811		p-conv	-315695	0	-9927516	10242101
			g-conv	0	11	-1315	1638			g-conv	-11	0	-719188	718433
			rad	-29850	79	8	-5			rad	-79	0	76	-6
20	1073	1367	cond	-4180	3	0	0	1084	2034	cond	-3	0	0	0
	800		p-conv	0	312615	1530921	-1818308	811		p-conv	-312615	0	-10242282	10555129
			g-conv	0	242	-1638	1957			g-conv	-242	0	-718446	718047
			rad	-28733	1666	5	-3			rad	-1666	0	6	32
19	1068	1640	cond	-4593	5	0	0	1084	2147	cond	-5	0	0	0
	795		p-conv	0	308380	1818308	-2103488	811		p-conv	-308380	0	-10555290	10864631
			g-conv	0	378	-1967	2271			g-conv	-378	0	-718058	717893
			rad	-28126	2584	3	-2			rad	-2584	0	-33	57
18	1065	1777	cond	-4998	6	0	0	1085	2150	cond	-6	0	0	0
	791		p-conv	0	303422	2103445	-2384884	812		p-conv	-303422	0	-10864738	11169608
			g-conv	0	464	-2271	2580			g-conv	-464	0	-717900	717905
			rad	-27789	3154	2	-1			rad	-3154	0	-58	75
17	1063	2041	cond	-5395	6	0	0	1086	2240	cond	-6	0	0	0
	790		p-conv	0	297975	2384897	-2661486	812		p-conv	-297975	0	-11169724	11469366
			g-conv	0	518	-2580	2882			g-conv	-518	0	-717912	718039
			rad	-27611	3523	1	-1			rad	-3523	0	-75	87
16	1062	2231	cond	-5784	7	0	0	1086	2347	cond	-7	0	0	0
	789		p-conv	0	292226	2661454	-2932944	813		p-conv	-292226	0	-11469473	11763456
			g-conv	0	555	-2883	3179			g-conv	-555	0	-718046	718269
			rad	-27531	3772	1	0			rad	-3772	0	-87	96
15	1062	2342	cond	-6163	7	0	0	1087	2353	cond	-7	0	0	0
	789		p-conv	0	286241	2932681	-3198635	814		p-conv	-286241	0	-11763493	12051606
			g-conv	0	580	-3179	3468			g-conv	-580	0	-718271	718577
			rad	-27612	3948	0	0			rad	-3948	0	-96	104
14	1062	2610	cond	-6534	7	0	0	1088	2446	cond	-7	0	0	0
	789		p-conv	0	280189	3198565	-3458725	815		p-conv	-280189	0	-12051613	12333679
			g-conv	0	600	-3468	3743			g-conv	-600	0	-718577	718952
			rad	-27524	4091	0	-1			rad	-4091	0	-104	110
13	1061	2676	cond	-6897	8	0	0	1089	2543	cond	-8	0	0	0
	788		p-conv	0	275092	3458626	-3714150	816		p-conv	-275092	0	-12333622	12610794
			g-conv	0	654	-3743	3998			g-conv	-654	0	-718949	719434
			rad	-27387	4458	1	-6			rad	-4458	0	-110	124
12	1055	2901	cond	-7278	10	0	0	1090	2645	cond	-10	0	0	0
	782		p-conv	0	307008	3714166	-4003934	817		p-conv	-307008	0	-12610694	12920654
			g-conv	0	807	-3998	4336			g-conv	-807	0	-719428	720088
			rad	-26813	5469	6	-1			rad	-5469	0	-123	159
11	1054	3106	cond	-7807	11	0	0	1092	2746	cond	-11	0	0	0
	781		p-conv	0	498525	4003873	-4485878	819		p-conv	-498525	0	-12920542	13422599
			g-conv	0	861	-4336	4860			g-conv	-861	0	-720082	720502
			rad	-26726	5840	1	-1			rad	-5840	0	-159	177
10	1054	3462	cond	-8675	11	0	0	1094	2902	cond	-11	0	0	0
	781		p-conv	0	815763	4485828	-5286252	821		p-conv	-815763	0	-13422517	14242603
			g-conv	0	912	-4860	5729			g-conv	-912	0	-720497	720368
			rad	-26672	6194	1	0			rad	-6194	0	-177	199
9	1054	4416	cond	-10108	12	0	0	1096	3204	cond	-12	0	0	0
	780		p-conv	0	1342479	5286239	-6615439	822		p-conv	-1342479	0	-14242664	15590556
			g-conv	0	962	-5729	7172			g-conv	-962	0	-720371	719250
			rad	-26640	6550	0	0			rad	-6550	0	-199	226
8	1054	5883	cond	-12481	12	0	0	1098	3780	cond	-12	0	0	0
	780		p-conv	0	2217718	6615323	-8822339	825		p-conv	-2217718	0	-15590624	17815317
			g-conv	0	1010	-7173	9673			g-conv	-1010	0	-719253	716388
			rad	-26645	6896	0	2			rad	-6896	0	-227	260
7	1054	8914	cond	-16417	13	0	0	1100	4754	cond	-13	0	0	0
	781		p-conv	0	3673366	8822024	-12489134	827		p-conv	-3673366	0	-17815309	21498065
			g-conv	0	1050	-9573	13560			g-conv	-1050	0	-716387	710487
			rad	-26715	7206	-2	4			rad	-7206	0	-260	298
6	1056	13385	cond	-22961	13	0	0	1103	7003	cond	-13	0	0	0
	782		p-conv	0	6092591	12488383	-18581038	830		p-conv	-6092591	0	-21497587	27603025
			g-conv	0	1087	-13562	20186			g-conv	-1087	0	-710471	699225
			rad	-26839	7505	-5	9			rad	-7505	0	-298	326
5	1057	21254	cond	-33005	14	0	0	1106	13952	cond	-14	0	0	0
	784		p-conv	0	10114584	18579489	-28704706	833		p-conv	-10114584	0	-27601214	37731293
			g-conv	0	1120	-20188	31205			g-conv	-1120	0	-699180	678699
			rad	-27010	7790	-9	19			rad	-7790	0	-325	331
4	1059	32136	cond	-33076	14	0	1	1109	40110	cond	-14	0	0	0
	786		p-conv	0	16808017	28702018	-45539741	836		p-conv	-16808017	0	-37726183	54539470
			g-conv	0	1145	-31207	52391			g-conv	-1145	0	-678607	642497
			rad	-27234	8022	-19	683			rad	-8022	0	-327	305
3	1106	88847	cond	-33378	2	-1	0	1112	151312	cond	-2	0	0	0
	833		p-conv	0	27646934	45537749	-73244317	839		p-conv	-27646934	0	-54529236	82080344
			g-conv	0	147	-52392	79670			g-conv	-147	0	-642365	587597
			rad	-32437	1127	-684	40			rad	-1127	0	-298	-57
2	1108	368889	cond	-213438	19	0	-1	1112	1355749	cond	-19	0	0	-3
	834		p-conv	0	-73392700	73242438	0	839		p-conv	73392700	0	-82087212	8443092
			g-conv	0	809	-79567	0			g-conv	-809	0	-587503	0
			rad	-208873	4644	-40	-1859			rad	-4644	0	63	-7207

heat generated in streamer	551821	
heat generated in core	1610242	
total heat generated		2162062
heat transferred to cooling wall		-1226111
heat leaving top of riser		-9374778
heat entering bottom of riser		8443089
	total	4262
	% diff. of heat gen.	0

case: sh4

j	streamer temp (K and C)	q (W)		west (W)	east	north	south	core temp (K and C)	q (W)		west (W)	east	north	south
22	1055	1092	cond	-5182	-5	0	0	1037	2289	cond	5	0	0	0
	782		p-conv	0	560968	1478505	-2011281	764		p-conv	-560968	0	-14765558	15343007
			g-conv	0	-409	-1565	2163			g-conv	409	0	-682778	681065
			rad	-26770	-2569	-7	-8			rad	2569	0	-1	-44
21	1042	1408	cond	-5922	-1	0	0	1037	2440	cond	1	0	0	0
	768		p-conv	0	547673	2011218	-2534494	763		p-conv	-547673	0	-15343602	15889371
			g-conv	0	-115	-2163	2748			g-conv	115	0	-681092	679696
			rad	-25422	-710	8	-5			rad	710	0	43	-16
20	1034	1832	cond	-6841	1	0	0	1036	2559	cond	-1	0	0	0
	761		p-conv	0	533138	2534426	-3045407	763		p-conv	-533138	0	-15890044	16422095
			g-conv	0	45	-2748	3314			g-conv	-45	0	-679725	678548
			rad	-24719	271	5	-4			rad	-271	0	15	2
19	1030	2050	cond	-7337	2	0	0	1036	2606	cond	-2	0	0	0
	757		p-conv	0	518024	3045280	-3542316	763		p-conv	-518024	0	-16422840	16940262
			g-conv	0	143	-3314	3864			g-conv	-143	0	-678579	677570
			rad	-24305	866	4	-3			rad	-866	0	-3	15
18	1028	2523	cond	-8013	3	0	0	1037	2754	cond	-3	0	0	0
	754		p-conv	0	502670	3542183	-4025006	763		p-conv	-502670	0	-16941096	17443336
			g-conv	0	207	-3864	4396			g-conv	-207	0	-677603	676723
			rad	-24055	1247	3	-2			rad	-1247	0	-16	24
17	1026	2820	cond	-8686	3	0	0	1037	2879	cond	-3	0	0	0
	753		p-conv	0	487195	4024822	-4492776	764		p-conv	-487195	0	-17444259	17931088
			g-conv	0	249	-4397	4912			g-conv	-249	0	-676759	675988
			rad	-23905	1500	2	-1			rad	-1500	0	-26	31
16	1025	3435	cond	-9297	3	0	0	1037	2968	cond	-3	0	0	0
	752		p-conv	0	471824	4492546	-4945916	764		p-conv	-471824	0	-17932076	18403569
			g-conv	0	278	-4912	5410			g-conv	-278	0	-676025	675348
			rad	-23817	1675	1	-1			rad	-1675	0	-33	37
15	1024	3340	cond	-9908	4	0	0	1038	3081	cond	-4	0	0	0
	751		p-conv	0	456586	4945571	-5383523	764		p-conv	-456586	0	-18404550	18860751
			g-conv	0	301	-5410	5891			g-conv	-301	0	-675364	674790
			rad	-23766	1807	1	0			rad	-1807	0	-38	41
14	1024	3662	cond	-10497	4	0	0	1038	3375	cond	-4	0	0	0
	751		p-conv	0	441567	5383266	-5806924	765		p-conv	-441567	0	-18861737	19302675
			g-conv	0	316	-5892	6366			g-conv	-316	0	-674825	674299
			rad	-23745	1902	0	2			rad	-1902	0	-43	44
13	1025	3869	cond	-11066	4	0	0	1039	3236	cond	-4	0	0	0
	752		p-conv	0	425756	5806574	-6214013	765		p-conv	-425756	0	-19303671	19726792
			g-conv	0	304	-6366	6716			g-conv	-304	0	-674334	673966
			rad	-23844	1831	-2	-16			rad	-1831	0	-46	44
12	1016	4210	cond	-11582	6	0	0	1039	3522	cond	-6	0	0	0
	743		p-conv	0	342472	6213738	-6540842	766		p-conv	-342472	0	-19729713	20072370
			g-conv	0	521	-6719	7142			g-conv	-521	0	-673898	673780
			rad	-23005	3101	16	-3			rad	-3101	0	-46	81
11	1015	4360	cond	-12185	7	0	0	1040	3574	cond	-7	0	0	0
	741		p-conv	0	557183	6540504	-7083084	767		p-conv	-557183	0	-20073101	20631088
			g-conv	0	583	-7142	7740			g-conv	-583	0	-673604	673471
			rad	-22838	3466	3	-2			rad	-3466	0	-82	95
10	1013	4988	cond	-13142	8	0	0	1041	3842	cond	-8	0	0	0
	740		p-conv	0	911392	7082730	-7980964	768		p-conv	-911392	0	-20631599	21544549
			g-conv	0	635	-7741	8716			g-conv	-635	0	-673488	672497
			rad	-22726	3775	2	-3			rad	-3775	0	-96	109
9	1012	5637	cond	-14722	9	0	0	1042	4288	cond	-9	0	0	0
	739		p-conv	0	1499147	7980515	-9468149	769		p-conv	-1499147	0	-21545129	23046976
			g-conv	0	697	-8716	10341			g-conv	-697	0	-672515	670361
			rad	-22588	4145	3	-4			rad	-4145	0	-110	129
8	1010	6876	cond	-17336	9	0	0	1044	5006	cond	-9	0	0	0
	737		p-conv	0	2475027	9467678	-11933743	770		p-conv	-2475027	0	-23047229	25526718
			g-conv	0	767	-10342	13037			g-conv	-767	0	-670369	666213
			rad	-22444	4555	4	-5			rad	-4555	0	-130	156
7	1009	9162	cond	-21668	10	0	0	1045	6052	cond	-10	0	0	0
	736		p-conv	0	4094073	11933184	-16023128	772		p-conv	-4094073	0	-25526199	29627692
			g-conv	0	838	-13038	17516			g-conv	-838	0	-666199	658551
			rad	-22317	4985	5	-4			rad	-4985	0	-156	183
6	1008	13049	cond	-28852	11	0	0	1047	8553	cond	-11	0	0	0
	735		p-conv	0	6782400	16022337	-22807497	774		p-conv	-6782400	0	-29626252	36420108
			g-conv	0	906	-17517	24959			g-conv	-906	0	-658520	644832
			rad	-22232	5402	4	-1			rad	-5402	0	-182	206
5	1008	20120	cond	-30416	12	0	0	1050	14704	cond	-12	0	0	0
	734		p-conv	0	11253335	22806304	-34073919	777		p-conv	-11253335	0	-36416910	47686242
			g-conv	0	964	-24960	37338			g-conv	-964	0	-644776	620635
			rad	-22213	5767	1	7			rad	-5767	0	-203	221
4	1008	36163	cond	-30452	12	0	1	1052	40016	cond	-12	0	0	0
	735		p-conv	0	18692238	34072563	-52807089	779		p-conv	-18692238	0	-47680171	66380836
			g-conv	0	1007	-37338	61167			g-conv	-1007	0	-620756	579430
			rad	-22278	6052	-7	646			rad	-6052	0	-217	214
3	1050	58434	cond	-30758	1	-1	0	1055	140359	cond	-1	0	0	0
	776		p-conv	0	30735465	52806101	-83602457	782		p-conv	-30735465	0	-66371520	97029108
			g-conv	0	122	-61166	91816			g-conv	-122	0	-579348	518051
			rad	-26236	792	-646	60			rad	-792	0	-210	-24
2	1052	439559	cond	-196846	11	0	-1	1055	1236114	cond	-11	0	0	-2
	779		p-conv	0	-83873650	83604226	0	782		p-conv	83873650	0	-97027308	13017003
			g-conv	0	386	-91816	0			g-conv	-386	0	-518042	0
			rad	-169497	2484	-60	-1214			rad	-2484	0	26	-3602

heat generated in streamer	628590	
heat generated in core	1494217	
total heat generated		2122807
heat transferred to cooling wall		-1138036
heat leaving top of riser		-13991395
heat entering bottom of riser		13017001
total		10377
% diff. of heat gen.		0

case: sh5

j	streamer temp (K and C)	g (W)		west (W)	east (W)	north (W)	south (W)	core temp (K and C)	g (W)		west (W)	east (W)	north (W)	south (W)
22	1141	514	cond	-1728	-5	0	0	1124	1122	cond	5	0	0	0
	868		p-conv	0	97632	524191	-582107	851		p-conv	-97632	0	-5241813	5336187
			g-conv	0	-390	-513	800			g-conv	390	0	-750614	749384
			rad	-36831	-3106	-3	-7			rad	3106	0	0	-130
21	1107	546	cond	-1863	5	0	0	1123	1116	cond	-5	0	0	0
	833		p-conv	0	105330	582110	-658759	850		p-conv	-105330	0	-5336050	5442748
			g-conv	0	374	-600	694			g-conv	-374	0	-749364	749870
			rad	-32530	2837	7	-3			rad	-2837	0	131	91
20	1091	604	cond	-2003	9	0	0	1124	1132	cond	-9	0	0	0
	818		p-conv	0	109278	658793	-744397	851		p-conv	-109278	0	-5442585	5555549
			g-conv	0	743	-694	793			g-conv	-743	0	-749848	751210
			rad	-30737	5537	3	-2			rad	-5537	0	-89	200
19	1084	601	cond	-2144	12	0	0	1125	1130	cond	-12	0	0	0
	811		p-conv	0	111546	744429	-834706	852		p-conv	-111546	0	-5555365	5671811
			g-conv	0	943	-793	894			g-conv	-943	0	-751165	753011
			rad	-29947	6972	2	-1			rad	-6972	0	-199	261
18	1082	815	cond	-2288	13	0	0	1128	1234	cond	-13	0	0	0
	808		p-conv	0	112855	834786	-927984	855		p-conv	-112855	0	-5671633	5790016
			g-conv	0	1056	-894	996			g-conv	-1056	0	-752987	755073
			rad	-29640	7811	1	0			rad	-7811	0	-259	296
17	1081	900	cond	-2432	14	0	0	1130	1215	cond	-14	0	0	0
	808		p-conv	0	113676	926015	-1022671	857		p-conv	-113676	0	-5789806	5909475
			g-conv	0	1126	-996	1100			g-conv	-1126	0	-755045	757307
			rad	-29582	8348	0	0			rad	-8348	0	-295	321
16	1082	914	cond	-2578	14	0	0	1133	1237	cond	-14	0	0	0
	809		p-conv	0	114148	1022716	-1118226	860		p-conv	-114148	0	-5909252	6029678
			g-conv	0	1172	-1100	1206			g-conv	-1172	0	-757278	759658
			rad	-29662	8725	0	1			rad	-8725	0	-319	338
15	1084	1014	cond	-2722	14	0	0	1136	1253	cond	-14	0	0	0
	811		p-conv	0	113992	1118269	-1213543	863		p-conv	-113992	0	-6029468	6149787
			g-conv	0	1174	-1205	1293			g-conv	-1174	0	-759631	762039
			rad	-29968	8808	-1	-2			rad	-8808	0	-336	344
14	1078	1118	cond	-2860	17	0	0	1139	1327	cond	-17	0	0	0
	805		p-conv	0	104273	1213615	-1301839	865		p-conv	-104273	0	-6149589	6261368
			g-conv	0	1390	-1293	1402			g-conv	-1390	0	-762015	764905
			rad	-29235	10382	2	1			rad	-10382	0	-342	414
13	1080	1196	cond	-3031	17	0	0	1142	1256	cond	-17	0	0	0
	807		p-conv	0	162592	1301880	-1448620	869		p-conv	-162592	0	-6261184	6431756
			g-conv	0	1424	-1402	1562			g-conv	-1424	0	-764882	767780
			rad	-29451	10711	-1	1			rad	-10711	0	-412	433
12	1083	1391	cond	-3305	18	0	0	1146	1426	cond	-18	0	0	0
	810		p-conv	0	259092	1448680	-1692094	872		p-conv	-259092	0	-6431625	6698889
			g-conv	0	1434	-1562	1826			g-conv	-1434	0	-767765	770486
			rad	-29797	10881	-1	2			rad	-10881	0	-432	443
11	1087	1770	cond	-3764	18	0	0	1149	1526	cond	-18	0	0	0
	813		p-conv	0	419436	1692163	-2096177	876		p-conv	-419436	0	-6698795	7126723
			g-conv	0	1432	-1826	2264			g-conv	-1432	0	-770474	772869
			rad	-30209	10977	-2	3			rad	-10977	0	-442	453
10	1091	2176	cond	-4494	17	0	0	1153	1678	cond	-17	0	0	0
	818		p-conv	0	686238	2096247	-2767305	880		p-conv	-686238	0	-7126684	7821844
			g-conv	0	1421	-2264	2990			g-conv	-1421	0	-772864	774669
			rad	-30680	11004	-3	4			rad	-11004	0	-453	464
9	1095	2736	cond	-5718	17	0	0	1156	2014	cond	-17	0	0	1
	822		p-conv	0	1130363	2767382	-3883052	883		p-conv	-1130363	0	-7821854	8961718
			g-conv	0	1402	-2990	4197			g-conv	-1402	0	-774690	775550
			rad	-31203	10974	-4	6			rad	-10974	0	-464	476
8	1100	3590	cond	-7745	17	0	0	1160	2489	cond	-17	0	-1	1
	827		p-conv	0	1869911	3883128	-5739345	887		p-conv	-1869911	0	-8961754	10842198
			g-conv	0	1376	-4197	6203			g-conv	-1376	0	-775553	774811
			rad	-31764	10911	-6	9			rad	-10911	0	-476	493
7	1105	4274	cond	-11112	17	0	0	1164	3417	cond	-17	0	-1	1
	832		p-conv	0	3101988	5739482	-8829306	891		p-conv	-3101988	0	-10842209	13956413
			g-conv	0	1357	-6203	9542			g-conv	-1357	0	-774812	771391
			rad	-32332	10869	-9	14			rad	-10869	0	-493	516
6	1110	4323	cond	-16710	16	0	0	1168	6005	cond	-16	0	-1	1
	837		p-conv	0	5155308	8829606	-13974796	895		p-conv	-5155308	0	-13956390	19125842
			g-conv	0	1341	-9541	15100			g-conv	-1341	0	-771389	763423
			rad	-32905	10864	-14	21			rad	-10864	0	-516	541
5	1114	4615	cond	-26018	16	0	0	1173	13996	cond	-16	0	-1	1
	841		p-conv	0	8572321	13975703	-22542788	899		p-conv	-8572321	0	-19126316	27712764
			g-conv	0	1333	-15099	24352			g-conv	-1333	0	-763442	747565
			rad	-33470	10922	-21	34			rad	-10922	0	-542	532
4	1119	10935	cond	-36194	16	0	1	1177	47846	cond	-16	0	-1	0
	846		p-conv	0	14256138	22544246	-36811427	904		p-conv	-14256138	0	-27714926	41965079
			g-conv	0	1327	-24352	42097			g-conv	-1327	0	-747624	718153
			rad	-34026	11006	-34	690			rad	-11006	0	-535	451
3	1172	27313	cond	-36498	2	-1	0	1181	197622	cond	-2	0	0	0
	899		p-conv	0	23465396	36811380	-60286900	908		p-conv	-23465396	0	-41970176	65287271
			g-conv	0	201	-42097	64794			g-conv	-201	0	-718240	671439
			rad	-41033	1773	-690	9			rad	-1773	0	-456	-150
2	1172	300376	cond	-233156	35	0	-1	1179	1546120	cond	-35	0	0	-7
	899		p-conv	0	-60318187	60286929	0	906		p-conv	60318187	0	-65297791	4577136
			g-conv	0	1031	-64798	0			g-conv	-1031	0	-671547	0
			rad	-262995	9096	-9	-3031			rad	-9096	0	143	-16376

heat generated in streamer	371720	
heat generated in core	1836161	
total heat generated		2207881
heat transferred to cooling wall		-1325760
heat leaving top of riser		-5468748
heat entering bottom of riser		4577129
total		-9498
% diff. of heat gen.		0

case: sh2b

I	streamer temp (K and C)	g (W)		(W) west	east	north	south	core temp (K and C)	g (W)		(W) west	east	north	south
22	1183	511	cond	-1600	-4	0	0	1169	1061	cond	4	0	0	0
	910		p-conv	0	55734	551329	-581739	896		p-conv	-55734	0	-5513208	5585963
			g-conv	0	-318	-626	669			g-conv	318	0	-918387	917229
			rad	-42661	-2852	-2	-7			rad	2852	0	0	-127
21	1144	849	cond	-1675	7	0	0	1168	1131	cond	-7	0	0	0
	871		p-conv	0	64027	561799	-594560	895		p-conv	-64027	0	-5585892	5632503
			g-conv	0	548	-669	725			g-conv	-548	0	-917218	918393
			rad	-37278	4642	8	-4			rad	-4642	0	127	163
20	1127	607	cond	-1756	12	0	0	1170	1102	cond	-12	0	0	0
	853		p-conv	0	68242	594608	-637804	896		p-conv	-68242	0	-5632426	5706201
			g-conv	0	987	-725	787			g-conv	-987	0	-918360	920759
			rad	-34976	8182	4	-2			rad	-8182	0	-162	313
19	1119	699	cond	-1837	15	0	0	1172	1115	cond	-15	0	0	0
	846		p-conv	0	70534	637857	-686572	899		p-conv	-70534	0	-5706157	5783766
			g-conv	0	1223	-787	852			g-conv	-1223	0	-920751	923771
			rad	-33990	10071	2	-1			rad	-10071	0	-313	398
18	1116	920	cond	-1921	17	0	0	1175	1160	cond	-17	0	0	0
	843		p-conv	0	71782	686823	-738431	902		p-conv	-71782	0	-5783748	5863489
			g-conv	0	1357	-852	920			g-conv	-1357	0	-923769	927158
			rad	-33634	11189	1	0			rad	-11189	0	-398	447
17	1116	963	cond	-2005	18	0	0	1178	1198	cond	-18	0	0	0
	843		p-conv	0	72502	738449	-791766	905		p-conv	-72502	0	-5863475	5944489
			g-conv	0	1437	-920	989			g-conv	-1437	0	-927155	930770
			rad	-33617	11899	0	1			rad	-11899	0	-448	479
16	1118	1013	cond	-2089	18	0	0	1182	1161	cond	-18	0	0	0
	845		p-conv	0	72602	791767	-845188	909		p-conv	-72602	0	-5944464	6025867
			g-conv	0	1464	-989	1050			g-conv	-1464	0	-930766	934482
			rad	-33910	12218	-1	-1			rad	-12218	0	-479	498
15	1116	1035	cond	-2168	20	0	0	1186	1211	cond	-20	0	0	1
	843		p-conv	0	72302	845215	-900035	912		p-conv	-72302	0	-6025852	6107812
			g-conv	0	1599	-1050	1126			g-conv	-1599	0	-934480	938542
			rad	-33638	13368	1	1			rad	-13368	0	-498	548
14	1119	1099	cond	-2273	20	0	0	1190	1241	cond	-20	0	-1	1
	845		p-conv	0	109181	900048	-991875	916		p-conv	-109181	0	-6107807	6227027
			g-conv	0	1628	-1125	1240			g-conv	-1628	0	-938541	942617
			rad	-33973	13732	-1	1			rad	-13732	0	-548	567
13	1122	1239	cond	-2445	20	0	0	1194	1279	cond	-20	0	-1	1
	848		p-conv	0	170356	991887	-1145083	921		p-conv	-170356	0	-6227031	6407819
			g-conv	0	1653	-1240	1434			g-conv	-1653	0	-942618	946620
			rad	-34348	14068	-1	2			rad	-14068	0	-567	585
12	1126	1485	cond	-2725	20	0	0	1198	1369	cond	-20	0	-1	1
	853		p-conv	0	271785	1145117	-1399772	926		p-conv	-271785	0	-6407845	6690362
			g-conv	0	1649	-1434	1754			g-conv	-1649	0	-946824	950382
			rad	-34888	14198	-2	2			rad	-14198	0	-585	595
11	1131	1811	cond	-3184	20	0	0	1202	1480	cond	-20	0	-1	1
	858		p-conv	0	440464	1399757	-1822878	929		p-conv	-440464	0	-6690419	7141951
			g-conv	0	1632	-1754	2286			g-conv	-1632	0	-950390	953699
			rad	-35517	14215	-2	3			rad	-14215	0	-595	601
10	1136	2281	cond	-3944	20	0	0	1206	1582	cond	-20	0	-1	1
	863		p-conv	0	721361	1822862	-2526887	933		p-conv	-721361	0	-7142032	7874984
			g-conv	0	1602	-2286	3171			g-conv	-1602	0	-953710	956270
			rad	-36229	14125	-3	5			rad	-14125	0	-602	607
9	1143	3019	cond	-5199	19	0	0	1211	2166	cond	-19	0	-1	1
	869		p-conv	0	1189115	2526870	-3698991	937		p-conv	-1189115	0	-7875194	9078357
			g-conv	0	1561	-3171	4642			g-conv	-1561	0	-956296	957588
			rad	-37014	13944	-5	8			rad	-13944	0	-609	611
8	1149	5708	cond	-7282	19	0	0	1215	3901	cond	-19	0	-1	1
	876		p-conv	0	1968226	3698948	-5652727	942		p-conv	-1968226	0	-9076705	11057135
			g-conv	0	1516	-4642	7090			g-conv	-1516	0	-957625	956803
			rad	-37822	13739	-8	11			rad	-13739	0	-613	612
7	1154	7418	cond	-10744	18	0	0	1219	4436	cond	-18	0	-1	1
	881		p-conv	0	3266166	5652097	-8904789	946		p-conv	-3266166	0	-11057221	14338111
			g-conv	0	1481	-7090	11166			g-conv	-1481	0	-956810	952720
			rad	-38598	13584	-11	17			rad	-13584	0	-613	639
6	1160	5983	cond	-16499	18	0	0	1223	9023	cond	-18	0	-1	1
	887		p-conv	0	5429528	8904595	-14322079	950		p-conv	-5429528	0	-14338240	19783458
			g-conv	0	1455	-11166	17951			g-conv	-1455	0	-952728	942982
			rad	-39355	13508	-17	26			rad	-13508	0	-639	655
5	1165	3440	cond	-26067	18	0	0	1228	16605	cond	-18	0	-1	1
	892		p-conv	0	9029303	14321812	-23340089	955		p-conv	-9029303	0	-19783471	26830479
			g-conv	0	1442	-17948	29257			g-conv	-1442	0	-942983	923627
			rad	-40071	13530	-26	43			rad	-13530	0	-655	649
4	1170	13259	cond	-38725	17	0	1	1233	53614	cond	-17	0	-1	0
	897		p-conv	0	15017203	23343402	-38378208	959		p-conv	-15017203	0	-26832454	43847089
			g-conv	0	1425	-29257	50935			g-conv	-1425	0	-923690	887683
			rad	-40805	13548	-43	835			rad	-13548	0	-651	548
3	1227	38986	cond	-39044	3	-1	0	1237	218584	cond	-3	0	0	0
	954		p-conv	0	24725604	38377731	-63120989	963		p-conv	-24725604	0	-43852021	68419367
			g-conv	0	211	-50936	78657			g-conv	-211	0	-887783	830503
			rad	-49443	2152	-835	5			rad	-2152	0	-553	-193
2	1228	344006	cond	-249371	38	0	-1	1235	1803696	cond	-38	0	0	-8
	954		p-conv	0	-63135147	63119952	0	962		p-conv	63135147	0	-68422921	4809790
			g-conv	0	1101	-78657	0			g-conv	-1101	0	-830546	0
			rad	-316664	11210	-5	-3968			rad	-11210	0	188	-21765

heat generated in streamer	436133	
heat generated in core	2128113	
total heat generated		2564246
heat transferred to cooling wall		-1506717
heat leaving top of riser		-5880891
heat entering bottom of riser		4809782
	total	-13579
	% diff. of heat gen.	-1

case: sh700

I	streamer temp (K and C)	q (W)		west (W)	east (W)	north (W)	south (W)	core temp (K and C)	q (W)		west (W)	east (W)	north (W)	south (W)
22	1151	1092	cond	-3120	-5	0	0	1132	1923	cond	5	0	0	0
	878		p-conv	0	245824	1019170	-1224189	859		p-conv	-245824	0	-10191989	10433465
			g-conv	0	-434	-1215	1497			g-conv	434	0	-885071	883613
			rad	-38131	-3535	-8	-9			rad	3535	0	-1	-90
21	1128	1210	cond	-3443	1	0	0	1131	2006	cond	-1	0	0	0
	855		p-conv	0	245742	1224146	-1436869	858		p-conv	-245742	0	-10433807	10678744
			g-conv	0	80	-1497	1779			g-conv	-80	0	-883642	883044
			rad	-35122	626	9	-8			rad	-626	0	89	5
20	1116	1627	cond	-3760	4	0	0	1131	2111	cond	-4	0	0	0
	842		p-conv	0	243328	1436846	-1651586	858		p-conv	-243328	0	-10679149	10923560
			g-conv	0	359	-1779	2058			g-conv	-359	0	-883078	882983
			rad	-33611	2794	8	-4			rad	-2794	0	-7	59
19	1109	1605	cond	-4071	7	0	0	1132	2148	cond	-7	0	0	0
	836		p-conv	0	239742	1651509	-1864808	859		p-conv	-239742	0	-10924011	11165950
			g-conv	0	531	-2058	2333			g-conv	-531	0	-883019	883256
			rad	-32770	4089	4	-2			rad	-4089	0	-81	95
18	1105	1901	cond	-4376	8	0	0	1133	2227	cond	-8	0	0	0
	832		p-conv	0	235430	1864769	-2075492	860		p-conv	-235430	0	-11166471	11404711
			g-conv	0	636	-2333	2602			g-conv	-636	0	-883297	883756
			rad	-32318	4883	2	-1			rad	-4883	0	-97	119
17	1103	2040	cond	-4673	9	0	0	1134	2293	cond	-9	0	0	0
	830		p-conv	0	230725	2075412	-2282299	861		p-conv	-230725	0	-11405265	11639172
			g-conv	0	706	-2602	2864			g-conv	-706	0	-883799	884422
			rad	-32079	5409	1	-1			rad	-5409	0	-121	136
16	1102	2151	cond	-4983	9	0	0	1135	2363	cond	-9	0	0	0
	829		p-conv	0	225830	2282221	-2484896	862		p-conv	-225830	0	-11639790	11869048
			g-conv	0	757	-2864	3122			g-conv	-757	0	-884469	885223
			rad	-31950	5805	1	0			rad	-5805	0	-138	150
15	1101	2463	cond	-5247	10	0	0	1136	2656	cond	-10	0	0	0
	828		p-conv	0	220777	2484827	-2683138	863		p-conv	-220777	0	-11869781	12093927
			g-conv	0	794	-3122	3372			g-conv	-794	0	-885278	886124
			rad	-31912	6092	0	0			rad	-6092	0	-152	159
14	1101	2557	cond	-5522	10	0	0	1137	2446	cond	-10	0	0	0
	828		p-conv	0	215729	2683025	-2876518	864		p-conv	-215729	0	-12094660	12314140
			g-conv	0	826	-3372	3577			g-conv	-826	0	-886177	887140
			rad	-31906	6349	0	-8			rad	-6349	0	-162	171
13	1093	2922	cond	-5794	13	0	0	1139	2588	cond	-13	0	0	0
	820		p-conv	0	203345	2876443	-3060943	866		p-conv	-203345	0	-12315000	12523397
			g-conv	0	1050	-3578	3844			g-conv	-1050	0	-887202	888561
			rad	-30937	8001	8	-1			rad	-8001	0	-175	225
12	1093	3408	cond	-6137	14	0	0	1141	2714	cond	-14	0	0	0
	819		p-conv	0	325597	3060732	-3368346	868		p-conv	-325597	0	-12524260	12855428
			g-conv	0	1106	-3844	4237			g-conv	-1106	0	-888623	889882
			rad	-30872	8448	1	1			rad	-8448	0	-229	244
11	1093	3577	cond	-6681	14	0	0	1143	3087	cond	-14	0	0	0
	820		p-conv	0	527308	3368056	-3877805	870		p-conv	-527308	0	-12856286	13389482
			g-conv	0	1135	-4237	4880			g-conv	-1135	0	-889941	890795
			rad	-30960	8701	-1	1			rad	-8701	0	-247	259
10	1094	3941	cond	-7576	14	0	0	1145	3083	cond	-14	0	0	0
	821		p-conv	0	862097	3877536	-4723050	872		p-conv	-862097	0	-13390207	14259160
			g-conv	0	1160	-4880	5946			g-conv	-1160	0	-890843	890989
			rad	-31079	8934	-1	2			rad	-8934	0	-262	281
9	1096	5130	cond	-9056	14	0	0	1147	3633	cond	-14	0	0	0
	823		p-conv	0	1418291	4722776	-6126435	874		p-conv	-1418291	0	-14259806	15686903
			g-conv	0	1181	-5946	7716			g-conv	-1181	0	-891029	889903
			rad	-31243	9139	-2	3			rad	-9139	0	-284	307
8	1098	6236	cond	-11507	15	0	0	1150	5039	cond	-15	0	0	0
	824		p-conv	0	2343019	6125990	-8456254	877		p-conv	-2343019	0	-15686588	18038419
			g-conv	0	1198	-7717	10656			g-conv	-1198	0	-889942	888600
			rad	-31449	9326	-4	6			rad	-9326	0	-309	338
7	1100	7754	cond	-15571	15	0	0	1153	8926	cond	-15	0	0	0
	827		p-conv	0	3881479	8455634	-12327344	879		p-conv	-3881479	0	-18038784	21929235
			g-conv	0	1212	-10656	15539			g-conv	-1212	0	-886818	879422
			rad	-31703	9496	-6	10			rad	-9496	0	-340	368
6	1102	10328	cond	-22317	15	0	0	1156	10090	cond	-15	0	0	0
	829		p-conv	0	6438281	12326699	-18760880	882		p-conv	-6438281	0	-21928606	28381401
			g-conv	0	1224	-15540	23655			g-conv	-1224	0	-879396	865702
			rad	-31991	9669	-10	16			rad	-9669	0	-366	406
5	1105	12127	cond	-33519	15	0	0	1159	17316	cond	-15	0	0	0
	832		p-conv	0	10690107	18760388	-29453883	886		p-conv	-10690107	0	-28379349	39088293
			g-conv	0	1241	-23654	37159			g-conv	-1241	0	-865639	840647
			rad	-32302	9881	-16	29			rad	-9881	0	-403	413
4	1108	20600	cond	-35489	15	0	1	1162	46650	cond	-15	0	0	0
	835		p-conv	0	17765604	29454874	-47248778	889		p-conv	-17765604	0	-39084452	56858964
			g-conv	0	1252	-37156	63103			g-conv	-1252	0	-840564	796376
			rad	-32668	10048	-29	832			rad	-10048	0	-409	379
3	1158	52026	cond	-35813	2	-1	0	1166	161457	cond	-2	0	0	0
	885		p-conv	0	29236819	47252968	-76548400	893		p-conv	-29236819	0	-56854891	85999148
			g-conv	0	167	-63102	96427			g-conv	-167	0	-796319	729280
			rad	-39160	1444	-832	54			rad	-1444	0	-376	-52
2	1161	436468	cond	-229095	23	0	-1	1165	1644118	cond	-23	0	0	-4
	887		p-conv	0	-76729603	76548509	0	892		p-conv	76729603	0	-86009734	8929999
			g-conv	0	715	-96432	0			g-conv	-715	0	-729370	0
			rad	-252392	6103	-54	-2515			rad	-6103	0	51	-8966

heat generated in streamer	581164	
heat generated in core	1928867	
total heat generated		2510031
heat transferred to cooling wall		-1376776
heat leaving top of riser		-10059106
heat entering bottom of riser		8929995
	total	4144
	% diff. of heat gen.	0

case: sh900

i	streamer temp (K and C)	q (W)		(W) west	east	north	south	core temp (K and C)	q (W)		(W) west	east	north	south
22	1152	1004	cond	-3123	-5	0	0	1133	1745	cond	5	0	0	0
	878		p-conv	0	246006	1019934	-1225032	859		p-conv	-246006	0	-10199275	10441093
			g-conv	0	-433	-1216	1498			g-conv	433	0	-885704	884259
			rad	-38214	-3540	-6	-9			rad	3540	0	0	-91
21	1128	1177	cond	-3445	1	0	0	1132	1746	cond	-1	0	0	0
	855		p-conv	0	245899	1225042	-1437927	859		p-conv	-245899	0	-10441008	10686348
			g-conv	0	79	-1498	1780			g-conv	-79	0	-884251	883673
			rad	-35201	823	9	-6			rad	-823	0	92	4
20	1116	1291	cond	-3763	4	0	0	1132	1860	cond	-4	0	0	0
	843		p-conv	0	243515	1437936	-1652532	859		p-conv	-243515	0	-10686252	10931095
			g-conv	0	361	-1780	2059			g-conv	-361	0	-883665	883592
			rad	-33674	2810	6	-4			rad	-2810	0	-4	59
19	1109	1432	cond	-4074	6	0	0	1132	1841	cond	-6	0	0	0
	836		p-conv	0	239877	1652595	-1866113	859		p-conv	-239877	0	-10930978	11173349
			g-conv	0	530	-2059	2334			g-conv	-530	0	-883583	883841
			rad	-32840	4091	4	-2			rad	-4091	0	-58	94
18	1105	1644	cond	-4379	8	0	0	1133	1875	cond	-8	0	0	0
	832		p-conv	0	235564	1866130	-2076803	860		p-conv	-235564	0	-11173220	11411939
			g-conv	0	636	-2334	2604			g-conv	-636	0	-883831	884316
			rad	-32381	4891	2	-1			rad	-4891	0	-93	117
17	1103	1809	cond	-4676	9	0	0	1134	1957	cond	-9	0	0	0
	830		p-conv	0	230843	2076811	-2283721	861		p-conv	-230843	0	-11411828	11646174
			g-conv	0	705	-2604	2866			g-conv	-705	0	-884308	884954
			rad	-32142	5413	1	-1			rad	-5413	0	-117	134
16	1102	1869	cond	-4966	9	0	0	1135	2024	cond	-9	0	0	0
	829		p-conv	0	225917	2283780	-2486603	862		p-conv	-225917	0	-11646088	11876753
			g-conv	0	756	-2866	3124			g-conv	-756	0	-884948	885723
			rad	-32015	5802	1	0			rad	-5802	0	-134	148
15	1102	2076	cond	-5250	10	0	0	1137	2112	cond	-10	0	0	0
	829		p-conv	0	220840	2486577	-2684824	863		p-conv	-220840	0	-11875692	12100415
			g-conv	0	792	-3124	3374			g-conv	-792	0	-885719	886599
			rad	-31976	6086	0	0			rad	-6086	0	-147	158
14	1102	2284	cond	-5525	10	0	0	1138	2155	cond	-10	0	0	0
	829		p-conv	0	215764	2684860	-2878395	865		p-conv	-215764	0	-12100379	12320174
			g-conv	0	823	-3374	3580			g-conv	-823	0	-886596	887576
			rad	-31970	6340	0	-8			rad	-6340	0	-158	169
13	1094	2376	cond	-5796	13	0	0	1139	2144	cond	-13	0	0	0
	820		p-conv	0	203396	2878389	-3062491	866		p-conv	-203396	0	-12320146	12529016
			g-conv	0	1049	-3580	3846			g-conv	-1049	0	-887572	888960
			rad	-30989	8001	8	-1			rad	-8001	0	-168	223
12	1093	2790	cond	-6140	14	0	0	1141	2328	cond	-14	0	0	0
	820		p-conv	0	325664	3062529	-3370100	868		p-conv	-325664	0	-12529014	12860608
			g-conv	0	1104	-3846	4239			g-conv	-1104	0	-888960	890240
			rad	-30925	8438	1	1			rad	-8438	0	-223	241
11	1094	2798	cond	-6684	14	0	0	1143	2346	cond	-14	0	0	0
	821		p-conv	0	527417	3370079	-3879708	870		p-conv	-527417	0	-12860598	13394589
			g-conv	0	1133	-4239	4883			g-conv	-1133	0	-890239	891134
			rad	-31011	8690	-1	1			rad	-8690	0	-241	259
10	1095	3489	cond	-7579	14	0	0	1145	2497	cond	-14	0	0	0
	822		p-conv	0	862268	3879779	-4725720	872		p-conv	-862268	0	-13394646	14264307
			g-conv	0	1157	-4883	5949			g-conv	-1157	0	-891136	891311
			rad	-31135	8914	-1	2			rad	-8914	0	-259	281
9	1096	4232	cond	-9059	14	0	0	1148	2808	cond	-14	0	0	0
	823		p-conv	0	1418668	4725676	-6129281	874		p-conv	-1418668	0	-14264425	15691665
			g-conv	0	1179	-5949	7720			g-conv	-1179	0	-891318	890230
			rad	-31290	9128	-2	3			rad	-9128	0	-281	309
8	1098	5325	cond	-11511	15	0	0	1150	3404	cond	-15	0	0	0
	825		p-conv	0	2343731	6129183	-8459998	877		p-conv	-2343731	0	-15691886	18045977
			g-conv	0	1196	-7720	10661			g-conv	-1196	0	-890243	886972
			rad	-31494	9320	-3	6			rad	-9320	0	-309	345
7	1100	7304	cond	-15578	15	0	0	1153	4405	cond	-15	0	0	0
	827		p-conv	0	3883011	8459810	-12333552	880		p-conv	-3883011	0	-18046320	21942629
			g-conv	0	1211	-10662	15548			g-conv	-1211	0	-886988	879959
			rad	-31762	9495	-8	10			rad	-9495	0	-346	389
6	1103	8958	cond	-22333	15	0	0	1156	7558	cond	-15	0	0	0
	829		p-conv	0	6442735	12333261	-18771298	883		p-conv	-6442735	0	-21943227	28402929
			g-conv	0	1227	-15548	23669			g-conv	-1227	0	-879983	866359
			rad	-32044	9698	-10	16			rad	-9698	0	-390	421
5	1105	9598	cond	-33550	15	0	0	1160	16635	cond	-15	0	0	0
	832		p-conv	0	10699864	18770868	-29471673	886		p-conv	-10699864	0	-28403797	39123188
			g-conv	0	1247	-23669	37181			g-conv	-1247	0	-866365	841397
			rad	-32359	9932	-16	29			rad	-9932	0	-422	425
4	1108	13957	cond	-35528	15	0	1	1163	53687	cond	-15	0	0	0
	835		p-conv	0	17785258	29472192	-47278029	890		p-conv	-17785258	0	-39124759	56912056
			g-conv	0	1261	-37179	63144			g-conv	-1261	0	-841431	797119
			rad	-32725	10124	-29	835			rad	-10124	0	-427	381
3	1159	45018	cond	-35853	2	-1	0	1167	207219	cond	-2	0	0	0
	886		p-conv	0	29269667	47280628	-76596351	894		p-conv	-29269667	0	-56914882	86046926
			g-conv	0	175	-63143	96484			g-conv	-175	0	-797159	729685
			rad	-39237	1502	-834	52			rad	-1502	0	-383	-89
2	1161	433979	cond	-229230	23	0	-1	1166	1634745	cond	-23	0	0	-4
	888		p-conv	0	-76776729	76598169	0	893		p-conv	76776729	0	-86054177	8936124
			g-conv	0	705	-96490	0			g-conv	-705	0	-729746	0
			rad	-252841	6065	-53	-2520			rad	-6065	0	86	-9982

heat generated in streamer	554410	
heat generated in core	1957090	
total heat generated		2511499
heat transferred to cooling wall		-1378766
heat leaving top of riser		-10066260
heat entering bottom of riser		8936120
	total	2593
	% diff. of heat gen.	0

case: uh0

I	streamer temp (K and C)	g (W)		(W) west	east	north	south	core temp (K and C)	g (W)		(W) west	east	north	south
22	1055	1596	cond	-4660	3	0	0	1064	703	cond	-3	0	0	0
	782		p-conv	0	-530624	2615625	-2082684	791		p-conv	530624	0	-3041406	2509056
			g-conv	0	64	-3389	2745			g-conv	-64	0	-39205	40794
			rad	-4005	420	8	3			rad	-420	0	0	21
21	1060	1467	cond	-4693	3	0	0	1069	600	cond	-3	0	0	0
	787		p-conv	0	-396807	2082598	-1683134	796		p-conv	396807	0	-2509037	2110777
			g-conv	0	60	-2745	2216			g-conv	-60	0	-40794	42106
			rad	-4084	394	-3	2			rad	-394	0	-21	19
20	1064	1406	cond	-4720	3	0	0	1072	535	cond	-3	0	0	0
	791		p-conv	0	-297123	1683150	-1383343	799		p-conv	297123	0	-2110761	1812523
			g-conv	0	55	-2216	1820			g-conv	-55	0	-42106	43113
			rad	-4154	366	-2	2			rad	-366	0	-19	18
19	1068	1293	cond	-4672	3	0	0	1076	480	cond	-3	0	0	0
	795		p-conv	0	-223397	1383360	-1157191	803		p-conv	223397	0	-1812513	1588260
			g-conv	0	52	-1820	1521			g-conv	-52	0	-43112	43895
			rad	-4212	351	-2	1			rad	-351	0	-16	15
18	1071	1224	cond	-3982	3	0	0	1079	439	cond	-3	0	0	0
	798		p-conv	0	-168984	1157200	-986370	805		p-conv	168984	0	-1588254	1418610
			g-conv	0	51	-1521	1294			g-conv	-51	0	-43895	44516
			rad	-4261	345	-1	1			rad	-345	0	-15	14
17	1074	1144	cond	-3456	3	0	0	1081	406	cond	-3	0	0	0
	800		p-conv	0	-128487	985371	-853972	808		p-conv	128487	0	-1418606	1289618
			g-conv	0	52	-1294	1121			g-conv	-52	0	-44516	45024
			rad	-4299	359	-1	1			rad	-359	0	-14	14
16	1075	1072	cond	-3056	3	0	0	1084	379	cond	-3	0	0	0
	802		p-conv	0	-98112	853975	-752931	811		p-conv	98112	0	-1289615	1191140
			g-conv	0	57	-1121	988			g-conv	-57	0	-45024	45459
			rad	-4331	393	-1	0			rad	-393	0	-14	15
15	1077	986	cond	-2748	3	0	0	1086	369	cond	-3	0	0	0
	804		p-conv	0	-75254	752937	-674714	813		p-conv	75254	0	-1191145	1115633
			g-conv	0	62	-988	885			g-conv	-62	0	-45459	45844
			rad	-4363	432	0	0			rad	-432	0	-15	16
14	1079	983	cond	-2509	4	0	0	1089	354	cond	-4	0	0	0
	806		p-conv	0	-57782	674718	-614002	816		p-conv	57782	0	-1115645	1057710
			g-conv	0	69	-885	798			g-conv	-69	0	-45844	46199
			rad	-4394	484	0	-1			rad	-484	0	-16	18
13	1074	880	cond	-2325	7	0	0	1093	344	cond	-7	0	0	0
	801		p-conv	0	-41345	613996	-570214	820		p-conv	41345	0	-1057730	1016591
			g-conv	0	129	-798	765			g-conv	-129	0	-46199	46662
			rad	-4305	896	1	4			rad	-896	0	-18	35
12	1093	970	cond	-2256	2	0	0	1099	447	cond	-2	0	0	0
	820		p-conv	0	5681	570219	-672533	826		p-conv	-5681	0	-1016630	1022077
			g-conv	0	37	-765	750			g-conv	-37	0	-46664	46779
			rad	-4633	263	-4	0			rad	-263	0	-35	8
11	1094	976	cond	-2266	2	0	0	1100	404	cond	-2	0	0	0
	821		p-conv	0	8989	572519	-578188	827		p-conv	-8989	0	-1022100	1030957
			g-conv	0	44	-750	756			g-conv	-44	0	-46780	46874
			rad	-4637	322	0	0			rad	-322	0	-8	11
10	1093	1000	cond	-2305	3	0	0	1102	386	cond	-3	0	0	0
	820		p-conv	0	15989	578178	-591075	829		p-conv	-15989	0	-1030972	1046974
			g-conv	0	64	-756	774			g-conv	-64	0	-46874	47003
			rad	-4620	465	0	0			rad	-465	0	-11	17
9	1093	1021	cond	-2377	4	0	0	1105	409	cond	-4	0	0	0
	819		p-conv	0	28446	591062	-616619	832		p-conv	-28446	0	-1046982	1075561
			g-conv	0	85	-774	808			g-conv	-85	0	-47004	47160
			rad	-4617	617	0	0			rad	-617	0	-17	23
8	1093	1101	cond	-2510	6	0	0	1109	533	cond	-6	0	0	0
	820		p-conv	0	51306	616629	-665390	836		p-conv	-51306	0	-1075571	1127075
			g-conv	0	107	-808	872			g-conv	-107	0	-47160	47317
			rad	-4628	783	0	0			rad	-783	0	-23	29
7	1094	1208	cond	-2755	7	0	0	1114	672	cond	-7	0	0	0
	821		p-conv	0	94553	665401	-757822	841		p-conv	-94553	0	-1127058	1221958
			g-conv	0	137	-872	993			g-conv	-137	0	-47316	47442
			rad	-4638	1010	0	0			rad	-1010	0	-29	39
6	1095	1464	cond	-3217	9	0	0	1120	820	cond	-9	0	0	0
	821		p-conv	0	176897	757646	-933352	847		p-conv	-176897	0	-1221869	1399430
			g-conv	0	176	-993	1225			g-conv	-176	0	-47439	47456
			rad	-4653	1308	0	1			rad	-1308	0	-39	52
5	1097	2005	cond	-4094	12	0	0	1129	1242	cond	-12	0	0	0
	824		p-conv	0	334725	933396	-1267884	856		p-conv	-334725	0	-1399423	1735070
			g-conv	0	220	-1225	1669			g-conv	-220	0	-47456	47175
			rad	-4889	1666	-1	2			rad	-1666	0	-52	69
4	1101	2667	cond	-5169	14	0	0	1140	3196	cond	-14	0	0	0
	828		p-conv	0	639413	1267651	-1906465	867		p-conv	-639413	0	-1735106	2374649
			g-conv	0	268	-1669	2671			g-conv	-268	0	-47176	46176
			rad	-4767	2065	-2	37			rad	-2065	0	-69	86
3	1157	5165	cond	-5286	-1	0	0	1154	11950	cond	1	0	0	0
	883		p-conv	0	1154486	1908534	-3063706	881		p-conv	-1154486	0	-2374816	3520167
			g-conv	0	-15	-2671	4013			g-conv	15	0	-46179	43318
			rad	-5816	-128	-37	0			rad	128	0	-86	-17
2	1157	14260	cond	-10043	0	0	0	1151	76529	cond	0	0	0	-1
	884		p-conv	0	-3065182	3063693	0	878		p-conv	3065182	0	-3620165	504418
			g-conv	0	-73	-4013	0			g-conv	73	0	-43318	0
			rad	-11101	-621	0	-148			rad	621	0	17	-759

heat generated in streamer	43925	
heat generated in core	101196	
total heat generated		145122
heat transferred to cooling wall		-181208
heat leaving top of riser		-468374
heat entering bottom of riser		504417
total		-43
% diff. of heat gen.		0

case: sh6

I	streamer temp (K and C)	g (W)		(W) west	east	north	south	core temp (K and C)	g (W)		(W) west	east	north	south
22	889	314	cond	-4541	-3	0	0	877	896	cond	3	0	0	0
	616		p-conv	0	802263	715840	-1504386	604		p-conv	-802263	0	-7158269	7959498
			g-conv	0	-266	-411	910			g-conv	266	0	-301178	300054
			rad	-13279	-1006	-2	-3			rad	1006	0	0	-13
21	880	519	cond	-5812	-1	0	0	877	997	cond	1	0	0	0
	607		p-conv	0	838356	1504426	-2330806	604		p-conv	-838356	0	-7959357	8797442
			g-conv	0	-73	-910	1422			g-conv	73	0	-300049	298969
			rad	-12750	-271	3	-2			rad	271	0	13	-5
20	877	741	cond	-7136	0	0	0	877	1159	cond	0	0	0	0
	603		p-conv	0	869559	2330844	-3189288	604		p-conv	-869559	0	-8797313	9666830
			g-conv	0	11	-1422	1952			g-conv	-11	0	-298965	297895
			rad	-12526	42	2	-1			rad	-42	0	5	0
19	875	952	cond	-8503	1	0	0	877	1268	cond	-1	0	0	0
	601		p-conv	0	894292	3189368	-4073191	604		p-conv	-894292	0	-9666690	10561033
			g-conv	0	56	-1952	2497			g-conv	-56	0	-297891	296830
			rad	-12412	205	1	-1			rad	-205	0	0	4
18	874	1323	cond	-9903	1	0	0	877	1468	cond	-1	0	0	0
	600		p-conv	0	911838	4073262	-4975173	604		p-conv	-911838	0	-10560911	11472713
			g-conv	0	81	-2497	3052			g-conv	-81	0	-296827	295774
			rad	-12350	299	1	-1			rad	-299	0	-4	7
17	873	1537	cond	-11323	1	0	0	877	1602	cond	-1	0	0	0
	600		p-conv	0	922010	4976209	-5887535	604		p-conv	-922010	0	-11472595	12394492
			g-conv	0	97	-3052	3614			g-conv	-97	0	-295771	294733
			rad	-12319	356	1	0			rad	-356	0	-7	10
16	873	1872	cond	-12763	1	0	0	877	1825	cond	-1	0	0	0
	600		p-conv	0	924743	5887571	-6803027	604		p-conv	-924743	0	-12394389	13318824
			g-conv	0	106	-3614	4178			g-conv	-106	0	-294730	293710
			rad	-12305	391	0	0			rad	-391	0	-10	12
15	873	2004	cond	-14181	1	0	0	878	2008	cond	-1	0	0	0
	600		p-conv	0	920407	6803049	-7714296	605		p-conv	-920407	0	-13318708	14238628
			g-conv	0	112	-4178	4736			g-conv	-112	0	-293708	292712
			rad	-12303	413	0	0			rad	-413	0	-12	14
14	873	2336	cond	-15597	1	0	0	878	2064	cond	-1	0	0	0
	600		p-conv	0	909405	7714355	-8615024	605		p-conv	-909405	0	-14238506	15147353
			g-conv	0	116	-4738	5291			g-conv	-116	0	-292710	291748
			rad	-12308	428	0	0			rad	-428	0	-14	16
13	873	2517	cond	-16991	2	0	0	878	2292	cond	-2	0	0	0
	600		p-conv	0	894237	8615069	-9500736	605		p-conv	-894237	0	-15147263	16040707
			g-conv	0	122	-5291	5836			g-conv	-122	0	-291748	290820
			rad	-12311	450	0	0			rad	-450	0	-16	18
12	873	2667	cond	-18367	2	0	0	879	2507	cond	-2	0	0	0
	600		p-conv	0	886448	9500749	-10378755	605		p-conv	-886448	0	-16040624	16926061
			g-conv	0	127	-5836	6410			g-conv	-127	0	-290818	289918
			rad	-12318	469	0	8			rad	-469	0	-18	20
11	876	2928	cond	-19744	1	0	0	879	2646	cond	-1	0	0	0
	603		p-conv	0	879519	10378833	-11249652	606		p-conv	-879519	0	-16925974	17804072
			g-conv	0	61	-6410	6840			g-conv	-61	0	-289916	288993
			rad	-12509	227	-8	-14			rad	-227	0	-20	8
10	871	3104	cond	-20893	2	0	0	879	2853	cond	-2	0	0	0
	597		p-conv	0	692071	11249702	-11934226	606		p-conv	-692071	0	-17803984	18494770
			g-conv	0	197	-6840	7313			g-conv	-197	0	-288991	288318
			rad	-12173	721	14	-3			rad	-721	0	-8	34
9	869	3581	cond	-22251	3	0	0	880	3046	cond	-3	0	0	0
	596		p-conv	0	1134990	11934334	-13062851	607		p-conv	-1134990	0	-18494676	19628766
			g-conv	0	240	-7313	7989			g-conv	-240	0	-288316	287282
			rad	-12100	880	3	-7			rad	-880	0	-34	44
8	867	3808	cond	-22810	4	0	0	881	3439	cond	-4	0	0	0
	594		p-conv	0	1878585	13062888	-14936013	607		p-conv	-1878585	0	-19628676	21507124
			g-conv	0	314	-7988	9131			g-conv	-314	0	-287281	285427
			rad	-11962	1148	7	-9			rad	-1148	0	-44	62
7	864	4794	cond	-22848	5	0	0	882	4064	cond	-5	0	0	0
	591		p-conv	0	3114518	14936126	-18047654	609		p-conv	-3114518	0	-21507093	24622633
			g-conv	0	400	-9131	11038			g-conv	-400	0	-285427	282182
			rad	-11814	1460	9	-9			rad	-1460	0	-62	85
6	862	6397	cond	-22898	6	0	0	883	5747	cond	-6	0	0	0
	589		p-conv	0	5172703	18047733	-23220807	610		p-conv	-5172703	0	-24622724	29797594
			g-conv	0	491	-11038	14224			g-conv	-491	0	-282183	276526
			rad	-11682	1789	9	-7			rad	-1789	0	-85	113
5	861	9296	cond	-22962	7	0	0	886	10833	cond	-7	0	0	0
	587		p-conv	0	8607830	23220898	-31834641	612		p-conv	-8607830	0	-29798002	38407470
			g-conv	0	574	-14224	19550			g-conv	-574	0	-276530	266702
			rad	-11602	2096	7	0			rad	-2096	0	-113	144
4	861	14150	cond	-23035	8	0	1	889	30045	cond	-8	0	0	0
	587		p-conv	0	14354094	31834581	-46204633	615		p-conv	-14354094	0	-38408403	52752447
			g-conv	0	641	-19550	29799			g-conv	-641	0	-266708	249685
			rad	-11602	2351	0	300			rad	-2351	0	-144	169
3	889	25224	cond	-23341	1	-1	0	892	112849	cond	-1	0	0	0
	616		p-conv	0	23446076	46204478	-69675338	619		p-conv	-23446076	0	-52753955	76113936
			g-conv	0	77	-29800	42887			g-conv	-77	0	-249692	223488
			rad	-13264	299	-300	22			rad	-299	0	-170	-6
2	890	249801	cond	-149382	8	0	0	892	647735	cond	-8	0	0	-1
	617		p-conv	0	-69835457	69674774	0	619		p-conv	69835457	0	-76114357	6372664
			g-conv	0	276	-42887	0			g-conv	-276	0	-223490	0
			rad	-85428	1068	-22	-602			rad	-1068	0	5	-1641

heat generated in streamer	339665	
heat generated in core	841345	
total heat generated		1181010
heat transferred to cooling wall		-808831
heat leaving top of riser		-6744019
heat entering bottom of riser		6372663
	total	822
% diff. of heat gen.		0