C.1

FLUIDIZED BED CLAUS REACTOR STUDIES

by

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A B S T R A C T

Fluidized bed reactor studies were performed on the Claus reaction, ie. $2\text{H}_2\text{S} + \text{SO}_2 \rightleftharpoons 3/n \text{S}_n + 2\text{H}_2\text{O}$. The basic objective was to determine whether the performance of the Claus process could be improved by replacing conventional fixed bed reactors with fluidized bed reactors.

A computational procedure was developed which, unlike previous methods, does not require the user to specify the initial values for the iterative solution of the equilibrium equations. It is therefore possible to achieve, consistently, significant reductions in computer time and cost. The computer programme was used to simulate various idealized Claus plants. The results of the equilibrium calculations indicated that, for feed gases consisting of pure H_2S , sulphur conversions in excess of 99% are attainable by using a Claus furnace and two fluidized bed reactors in series.

To substantiate the theoretical predictions, experimental studies were performed using a single fluidized bed reactor (0.1 m ID). The effects of temperature (150 - 300°C), flow rates (15 - 30 l/min), feed composition ($0.06 < \text{H}_2\text{S} < 18\%$, $0.03 < \text{SO}_2 < 9\%$, $73 < \text{N}_2 < 99.91\%$) and bed height (0.12, 0.25 m) on the sulphur conversion were examined. The experimental results showed the same general trends as the theoretical predictions. However, the measured

sulphur conversions exceed the theoretical values by up to 8%. Reasons for these discrepancies are discussed.

Based on the theoretical and experimental studies, fluidized bed reactors appear to be technically superior to the conventional fixed bed devices. However, a proper commercial evaluation has to await longer term studies with larger fluidized beds.

To my high school mathematics teacher,
Mr. J.W.K. Wellington, a man who laid
the foundation of my scientific career
and to my mother, Madame Afua Nyame,
a woman whose toils, guidance and prayers
have made me what I am.

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Chapter 1

1 INTRODUCTION

The frequent dramatic price increases of light crude oil, caused by excessive world demand for energy, has affected the economic growth rate of both rich and poor nations. Canada, attempting to solve her energy problems, has accelerated the development of her huge reserves of heavy oil and natural gas. However, these resources do not produce "clean" energy. They contain significant amounts of sulphur compounds which are usually removed in the form of hydrogen sulphide, an extremely poisonous gas.

Hydrogen sulphide may be oxidized with air to elemental sulphur by the Claus process. Using this process, Canada produced approximately 6 million tons of sulphur in 1978 making her the second largest producer in the world [1].

The Claus process was originally developed commercially by C.F. Claus in 1883 when he oxidized H_2S with stoichiometric amounts of air over red hot iron oxide [2] :

(n varies from 2 to 8 depending on the reaction temperature).

The reaction is exothermic ($\Delta H_{1.1} = -145$ to -173 kcal) and, at high temperatures, the conversion efficiency of sulphur is low.

To improve the efficiency of the original Claus process, I.G. Forbenindustrie developed the two-stage "split-stream"

process [3]. In the first stage of the process, one-third of the H_2S is oxidized with air to SO_2 in a free flame combustion furnace:

($\Delta H_{1.2} = -124 \text{ kcal}$, $T = 250^\circ\text{C}$, $P = 1 \text{ atm}$)

In the second stage, the SO_2 is reduced with the remaining two-thirds H_2S at 250°C over bauxite:

($\Delta H_{1.3} = 21 \text{ Kcal}$, $T = 250^\circ\text{C}$, $P = 1 \text{ atm}$)

The improvement of this process over the original Claus process is the heat distribution. Over 80% of the total heat of reaction is liberated before catalytic conversion.

I.G. Farbenindustrie [3] further improved the Claus process by developing the "straight - through" process. This is the famous modified Claus process used in most, modern industrial plants. In this process, all the H_2S is first oxidized with stoichiometric amounts of air in a free flame combustion furnace at about 1100°C to produce a mixture of sulphur dioxide, elemental sulphur, water vapour, hydrogen sulphide and nitrogen:

Subsequently the furnace off-gases are passed through a sulphur condenser and one or more catalytic converters where Reaction 1.3 occurs. After each converter sulphur is removed by condensation to shift the equilibrium to the product side.

There are two major advantages of this process over the split stream process. In the furnace, between 90 to 95% of the total heat of reaction is liberated and over 70% of the total sulphur conversion may be achieved.

A furnace plus three catalytic reactors can achieve a total sulphur conversion efficiency of about 95%. The remaining sulphur compounds are incinerated to SO_2 and discharged into the atmosphere. It has, however, been observed that both animals and plants are affected by even low levels of SO_2 . For example, one hour exposure to 0.5 ppmv SO_2 can lead to lung damage. Forest, fiber and cereal crops have also been damaged by one hour exposure to 0.8 ppmv SO_2 . Furthermore, excessive SO_2 emissions have contributed to the formation of haze and smog which reduces visibility over long distances [4].

Consequently most industrialized nations [5] have passed stringent antipollution laws requiring less than 500 ppmv SO_2 in the stack gases of Claus units. To meet such severe emission standards, sulphur conversion efficiencies greater than 99% must be achieved. This has led to the introduction of tail gas processes. However, these processes are expensive and often difficult to operate.

As an alternate to tail gas treatment, the performance of the Claus process itself could be improved. Traditionally, fixed beds are employed as the catalytic reactors. Since the Claus reactions are exothermic and fixed bed catalytic reactors do not

permit efficient heat removal, the process conversion is inevitably limited. Furthermore, fixed bed reactors cannot be operated at low temperatures where thermodynamic yields are high since sulphur may condense thereby fouling the catalyst. To overcome these problems, the use of fluidized bed reactors is proposed. Such reactors not only allow efficient heat removal but also permit continuous catalyst regeneration should fouling occur [22].

A fluidized bed consists of fine particles supported by an upward moving gas mixture. Normally the bulk of the gas mixture flows through the bed in the form of bubbles. These bubbles carry few particles in their surrounding clouds and trailing wakes. This part of the bed is referred to as bubble or lean phase. The remaining gas percolates through the catalyst in a manner similar to the flow through a fixed bed. The porosity of this section of the bed, referred to as continuous or dense phase, is close to that of a fixed bed.

The main advantages of fluidized beds over the fixed beds for the Claus reaction are:

- (i) The bed temperature is uniform due to the intense agitation of the catalyst particles by the rapidly rising bubbles.
- (ii) Operation at temperatures below the sulphur dew point (where thermodynamic yields are high) is possible. Operation even below the melting point of sulphur is feasible. Catalyst deactivation caused by condensed sulphur can be prevented by continuously circulating

the catalyst between the reactor and a regenerator. The congealing of the bed by the condensed sulphur should be prevented by the intense agitation of the bed.

(iii) Catalyst deactivation from sulphation and carbon deposition can also be controlled by circulating the catalyst between the reactor and a regenerator.

(iv) The catalyst activity is enhanced by the large specific surface area of the fine catalyst particles.

(v) The pressure drop is moderate in fluidized beds.

(vi) Pelletising, which is an important cost item in the production of catalysts, is not required for fluidized bed catalysts.

On the other hand, the major disadvantages of fluidized bed catalytic reactors are [22]:

(i) Lowering of conversion efficiency due to the fact that the gas by-passes the catalyst in the form of bubbles.

(ii) Reduction of conversion efficiency by backmixing.

(iii) Attrition of the catalyst particles and erosion of the reactor walls by the intense bed agitation. However, the Claus catalysts, which are usually activated alumina, have high resistance to abrasion and crushing [73].

(iv) Elutriation of very fine particles from the bed.

To determine the suitability of the fluidized bed, a mathematical model simulating a Claus furnace plus two fluidized

bed reactors in series was first developed (chapter 3). The results of these studies were very promising, indicating total conversions in excess of 99% as compared with 90% conversions for fixed bed processes.

To substantiate the theoretical predictions, experimental studies using a single fluidized bed reactor were undertaken. A two reactor system would, undoubtedly, have provided more information but very high construction costs and possible operating problems with solid circulation were anticipated. Consequently, a single reactor was chosen.

The design and operation of the laboratory-scale fluidized bed Claus reactor were performed to examine the feasibility of replacing the first and /or second fixed bed reactor in a standard Claus process. The feed to the fluidized bed reactor was therefore prepared to represent the product streams from the furnace or first fixed bed reactor. However, partly for experimental convenience, the feed streams were free of sulphur and water vapour thus presupposing the existence of total sulphur and water condensers. The implication of water removal is considered in Section 6.1.

Chapter 2

2 LITERATURE REVIEW

The literature review is divided into two major sections, viz. Claus reaction and fluidized beds.

2.1. CLAUS REACTION

2.1.1. Theoretical Studies

A knowledge of the thermodynamic yield is essential in determining the feasibility of a chemical reaction under various conditions of temperature and pressure. Although a high thermodynamic yield does not always imply a high yield in practice, a very low thermodynamic yield usually indicates the impracticability of the process.

The first detailed thermodynamic study of the Claus reaction was published by Gamson and Elkins [3]. Using the equilibrium constant method, they estimated the equilibrium composition and the thermodynamic yield of sulphur for a mixture of H_2S and stoichiometric amounts of air. They considered temperatures ranging from 400 to 1600⁰K and pressures of 1/2, 1 and 2 atm.

The equilibrium yield of sulphur exhibited a minimum at about 850⁰K (Fig. 2.1). Gamson and Elkins attributed this phenomenon to the shift in the predominant sulphur species with temperature. At low temperatures (below 850⁰K) the predominant polymers are S_6 , and S_8 , and the overall reaction is highly exothermic. Hence, according to Le Châtelier's principle, the sulphur yield must decrease with increasing temperature. At temperatures above 850⁰K, the large sulphur polymers dissociate endothermically (mostly to S_2) and the

overall reaction becomes progressively less exothermic leading to increasing sulphur yields [6].

Despite the shortcomings of the work of Gamson and Elkins such as using thermodynamic data published in 1937 [7], their results agree quite well with findings published recently. (see Fig. 2.1).

Using the free energy minimization technique developed by White *et al.* [8], McGregor [9] also determined the equilibrium composition and sulphur yield for a stoichiometric mixture of H_2S and air. He considered the temperature range of 400 to 1750⁰K and a pressure of 1 atm; free energy data compiled by McBride *et al.* were utilized [10]. In addition to the substances considered by Gamson and Elkins [3], McGregor also included S and H_2 in his calculations.

Figure 2.1 shows good agreement between the results of McGregor, and Gamson and Elkins. The slightly higher values of the sulphur yields of McGregor, can be attributed to the different free energy data.

Maadah and Maddox [11] also employed the free energy minimization technique to estimate the equilibrium composition and sulphur yield of the Claus Reaction. They used the free energy data compiled by Kellogg [12] and accounted for a large number of reactions and impurities (eg. hydrocarbons, carbon dioxide, water and ammonia). Maadah and Maddox concluded from their results that

Figure 2.1: Claus reaction equilibrium conversion versus temperature

small amounts of impurities do not seem to have a major effect on sulfur conversions. They attributed the small decreases in sulphur yields in the presence of impurities to the decreased concentration of H_2S in the acid gas feed. They also observed that the equilibrium sulphur yield and composition were not significantly affected by considering all 7 sulphur species or just S_2 , S_6 and S_8 . However, the tail gas composition showed notable differences. When all sulphur species are considered, the combined concentration of H_2S and SO_2 is lower by about 12% for typical acid gases containing impurities ($H_2S = 89.72$, $CO_2 = 4.98$, $CH_4 = 0.8$, $H_2O = 4.5\%$) and by about 15% for pure H_2S .

Bragg [13] has developed a computer program to predict the performance of a Claus plant under both equilibrium and non-equilibrium conditions. A free energy minimization technique was used to determine the chemical reaction equilibria. The predicted and measured plant performance agreed quite well.

Kellogg [12] has shown that, at temperatures above $600^{\circ}K$, sulphur vapour contains significant amounts of all polymers ranging from S_2 to S_8 . Based on these findings, Bennett and Meisen [14] studied the Claus reaction extensively utilizing the key component method developed by Kellogg [12]. They used mainly the free energy data compiled by McBride *et al.* [10]. They accounted for all sulphur polymers as well as a large number of nitrogen and sulphur compounds, and free radicals. Their results agreed with the findings of Kellogg,

but not all the compounds and free radicals were present in significant quantities. The equilibrium sulphur yields (see Fig. 2.1) correspond closely to those of Gamson and Elkins, and McGregor. Again, minor differences at temperatures below 1500°K are attributable to different free energy data. The notable deviation above 1500°K results mainly from dissociation reactions including the formation of monatomic sulphur.

2.1.2. Experimental Studies

Although fluidized bed Claus reactors have not been reported in the literature, extensive studies on fixed beds are available.

Ability of solid substances to catalyse the reaction between H_2S and SO_2 was established when, in 1927, Taylor and Wesley [56] observed that the reaction rate was proportional to the surface area of their Pyrex glass reactor operated between 370 and 730°C . They also estimated the reaction orders for H_2S and SO_2 to be 1.5 and 1.0 , respectively.

Studying the ability of metallic sulphides to catalyse the reaction between H_2S and SO_2 , Murthy and Rao [57] found cobalt thiomolybdate to be the best catalyst. They observed that no reaction would occur at 25°C without water. They used hydrated and anhydrous salt to control the moisture content of the reactor. In the presence of water, they obtained an overall reaction order of 2.0 .

Using commercial bauxite in a recycle reactor, McGregor [9] studied the kinetics of the Claus reaction. He developed the following expression for the reaction rate:

$$r = k_0 \exp(-E/RT) P_{H_2S}^a P_{SO_2}^b \quad \text{gmole/hr-g-catalyst} \quad 2.1$$

where $k_0 = 2.198 \pm 0.564 \text{ hr}^{-1}$

$$E = 7589 \pm 451 \text{ cal.}$$

$$R = 1.98 \text{ cal/g mole } ^\circ K$$

$$a = 0.963 \pm 0.0448$$

$$b = 0.359 \pm 0.135$$

and T denotes the temperature in $^\circ K$. P_{H_2S} and P_{SO_2} denote the partial pressures (in mm Hg) of H_2S and SO_2 , respectively. This expression also agreed with previous rate measurements [59].

McGregor recommended a process consisting of three converters in series, to improve sulphur recovery. The significant aspect of this scheme is the condensation of water between the last two converters to shift the reaction equilibrium to the product side. This recommendation was based on his findings that, while low partial pressures of water vapour had an autocatalytic effect on the reaction, high partial pressures caused marked retardation. He also observed that the Claus reaction occurs predominantly on the external surface of the catalyst.

Dalla Lana *et al.* [58] have proposed the following rate expression for the Claus reaction:

$$r = \left(\frac{K P_{\text{H}_2\text{S}}^{1.0} P_{\text{SO}_2}^{0.5}}{1 + 0.00423 P_{\text{H}_2\text{O}}} \right) \exp \left(-7400/RT \right) \quad 2.2$$

Although this expression indicates that water vapour acts as an inhibitor, they observed that condensed water and molten sulfur catalyze the reaction.

Using the data obtained under widely varying conditions Grancher [60] obtained similar rate expressions for the Claus reaction. Based on his findings, the reaction is limited by the internal diffusion through the macropores. Consequently, he recommended the use of small catalyst particles with large pores.

The control of the Claus reaction by pore diffusion has also been reported by Landau *et al.* [62] and George [61]. Landau *et al.* based their conclusion on the fact that the activity of their bauxite catalyst increased with decreasing particle size. George, however, reached the same conclusion based on the low activation energy of 5.5 kcal/mole. He also obtained 1.0 and 0 as the kinetic orders for H_2S and SO_2 , respectively. In addition, he found water vapour to be inhibiting.

Using a fixed-bed, integral flow reactor, George [63] studied the catalytic activities of acids and bases for the Claus reaction. The acids and bases were supported on Chromosorb - A. He found that, while acidity did not have any effect, basicity considerably

improved the catalytic activity for the Claus reaction.

Pearson [64] also examined the activity of various Claus catalysts such as:

- (1) Kaiser S-201 activated alumina,
- (2) Kaiser S-501 activated alumina,
- (3) activated bauxite and (4) cobalt-molybdenum.

He observed that all of these catalysts have good initial activity, but that the Kaiser S-501 and cobalt-molybdenum catalysts have the highest resistance to catalyst poisoning.

2.1.3. Industrial Claus Process

Since 1883 when C.F. Claus first developed the commercial-scale process for converting H_2S to elemental sulphur, this process has undergone considerable modifications. The three modifications used in modern industrial Claus plants are straight through, split stream and direct oxidation [9]. The corresponding flowsheets are shown in Fig. 2.2. The choice of process depends primarily on the concentrations of H_2S and hydrocarbons in the feed gas. The amounts of heavy and unsaturated hydrocarbons can, however, be substantially reduced by first passing the acid gas through charcoal adsorption beds [70]. The reason is that they poison the catalyst in the reactors by depositing layers of carbon [68].

	STRAIGHT THROUGH	SPLIT FLOW	DIRECT OXIDATION
H_2S	50 - 100%	15 - 50%	2 - 15%
HYDROCARBON	< 2%	< 5%	> 5%

Fig. 2.2 Industrial Claus Processes [9]

In the straight - through process, the entire acid gas plus the stoichiometric amount of air are introduced into the furnace which operates at about 1100°C. The following primary reactions occur:

The subscript n denotes the number of sulphur atoms per molecule; at 1100°C, $n \approx 2$. The oxidation of H_2S is incomplete and the furnace off-gas contains mainly sulphur vapour, SO_2 , H_2S , H_2O and N_2 . This gas mixture is passed through a series of two or more reactors, containing activated alumina catalyst, to convert H_2S and SO_2 to sulphur according to the reaction,

The sulphur is condensed and the gas mixture is preheated to the optimal temperature before each reactor. The optimal temperatures for two reactors in series are usually about 280 and 230°C, respectively [71].

In the split-stream process, one-third of the acid gas is oxidized in the furnace according to reaction 2.4. The remaining two-thirds of the acid gas is mixed with the furnace products and passed through a series of two or more reactors where Reaction 2.5 occurs. In this process, primarily SO_2 and H_2O are produced in the furnace. The sulphur recovery is achieved in the catalytic reactors.

In the direct oxidation process, acid gases containing low contrations of H_2S are mixed with stoichiometric amounts of air and fed directly to the reactors.

The most efficient of the three processes is the straight through process where sulphur conversion efficiencies of 93 to 97% can be obtained by a furnace plus two reactors in series [71]. In the direct oxidation process, conversion efficiencies of 80 to 85% are common [70]. The conversion efficiency of the split stream process is about 87 to 93%.

In all three processes, the effluent from the last reactor may be further treated in tail gas units to satisfy air-pollution standards. The main tail gas processes involve liquid oxidation and dry bed adsorption [65, 66, 67, 93]. In the liquid oxidation processes, the tail gases containing about 1.5% H_2S , 0.75 SO_2 , 8.25% CO_2 and 89.5% N_2 are treated with solutions containing an alkaline compound and an oxidizing agent. In the dry bed adsorption processes, the tail gas is contacted with hydrated ferric oxide which reacts to form ferric sulphide. The latter is subsequently oxidized to sulphur and ferric oxide when exposed to oxygen.

Sulfreen units have also been used to treat tail gases. In the sulfreen process, the tail gas is contacted with activated alumina maintained below the sulphur dew point. The sulphur formed deposits on the catalyst which is regenerated periodically when the conversion efficiency drops substantially below a specified value [71].

2.2. FLUIDIZED BED

2.2.1. Fluidization

When a fluid flows upward through a bed of small particles supported in a vertical container by a grid, the pressure drop across the bed increases with the fluid velocity until the bed begins to expand. After this point, the pressure drop remains constant and the particles lose permanent contact with each other (Fig. 6.2). The particles move freely and the bed is said to be fluidized. The appearance of the bed is similar to that of a boiling liquid. The velocity at which the bed begins to expand is called the minimum or the incipient fluidization velocity.

Usually the pressure drop decreases slightly from a maximum value to a constant value. This behaviour is due to the resettling of the particles in the loosest arrangement [19]. The difference between the two pressure drops has been attributed to the friction between the individual particles just before they move freely [49].

When the fluid velocity is gradually decreased and fluidization ceases the pressure drop of the fixed bed may be less than for the initial fixed bed. This phenomenon is due to the fact that the particles are more loosely packed than they were before fluidization. The bed height is always greater after defluidization. When the fluid velocity is increased beyond the minimum fluidization velocity, the bed becomes less dense and, at a velocity called a terminal or free falling velocity, the particles are blown out of the bed.

Depending on the nature of the fluid, velocity of the fluid, particle size and density, and bed diameter and height, a fluidized bed can assume any of these regimes:

Particulate Fluidization - This regime is sometimes called *smooth fluidization* because the bed expands smoothly. There is no bubble formation and no bed surface fluctuation. This is typical of liquid fluidization. For gas fluidization, this regime occurs just above the minimum fluidization velocity. According to Kunii and Levenspiel [22], particulate fluidization occurs when

$$Q_F < 100 \quad 2.6$$

where

$$Q_F = (Fr_{mf}) (Re_{mf}) \frac{(\rho_p - \rho)}{\rho} \frac{L_{mf}}{d_b}, \quad 2.7$$

$$Fr_{mf} = \frac{U_{mf}^2}{d_p g} \quad 2.8$$

and

$$Re_{mf} = \frac{\rho U_{mf} d_p}{\mu} \quad 2.9$$

Bubbling fluidization - This regime is also called, *aggregative fluidization* because voids, bubbles or fluid pockets rise through the bed and break at the surface. The bubbles are small near the distributor and they grow mostly by coalescence as they rise through the bed. The rising bubbles agitate the bed and this generates

near-perfect mixing. This regime usually occurs when the fluid is a gas and the velocity is high. Normally, when

$$Q_F > 100 \qquad 2.10$$

bubbling fluidization will occur [22].

Slugging Fluidization - Slugging occurs when the gas bubbles occupy the entire column cross-section. This usually arises when the gas velocity and the ratio between the bed height and diameter are high. Although slugging provides fairly good gas-solid contacting, it is undesirable because of severe mechanical stress on the apparatus and erratic pressure drop across the bed [54]. Also, the bed surface moves up and down at a regular frequency.

For other modes of fluidization see Grace *et al.* [50].

2.2.2. Basic Design Factors

The most important factors which must be considered when designing a fluidized bed catalytic reactor are:

- i) Catalyst particles size (d_p) and density (ρ_p)
- ii) Minimum fluidization velocity, U_{mf}
- iii) Terminal velocity, U_t
- iv) L/D Ratio (bed height/bed diameter)
- v) Distributor
- vi) Bubbles diameter, velocity and frequency

These factors are further discussed below

i) *Catalyst particles size and density* - The catalyst used in fluidized bed reactors is usually subjected to size reduction operation such as crushing with a gyratory breaker. This operation creates size distribution and the average particle size, d_p , is determined by sieve analysis:

$$d_p = 1 / \sum_i (x_i / d_{p_i}) \quad 2.11$$

where x_i denotes the fraction of material in size interval i and d_{p_i} denotes the arithmetic mean of the mesh dimensions of the two sieves that define the fraction i .

For a mixture of particles of different size and shape the sphericity, ϕ_s , must also be considered [22].

If the particles are fine and non-porous, the particle density can be determined by the volume displacement method.

ii) *Minimum fluidization velocity* - At this velocity the bed of fine catalyst particles begins to expand when gas is passed upward through it. This velocity can be estimated experimentally by plotting the bed pressure drop as a function of gas velocity. (See Fig. 6.2)

The minimum fluidization velocity can also be predicted from a number of correlations [22, 49, 51, 52, 53]. A good set of correlations for estimating U_{mf} are:

For $Ar < 10^3$,

$$U_{mf} = 0.00075 \ g \ d_p^2 (\rho_p - \rho) / \mu \quad 2.12$$

For $Ar > 10^7$

$$U_{mf} = 0.202 \ [g \ d_p (\rho_p - \rho) / \rho]^{1/2} \quad 2.13$$

For $10^3 < Ar < 10^7$,

$$U_{mf} = \frac{\mu}{d_p \rho} [(739.84 + 0.0408 \ Ar)^{1/2} - 27.2] \quad 2.14$$

$$\text{Where } Ar = \frac{g d_p^3 \rho (\rho_p - \rho)}{\mu^2} \quad 2.15$$

It has been observed that there is channelling if the difference between the experimental and predicted value is greater than 20%.

iii) *Terminal Velocity* - The upper limit of the gas flow rate through the fluidized bed is given by the terminal velocity if cyclones are not provided. At this velocity, the gravitational force is equal to the fluid drag acting on the particles and hence [22]

$$U_t = \left[\frac{4g \cdot d_p (\rho_p - \rho)}{3 \rho C_D} \right]^{1/2} \quad 2.16$$

where

$$C_d = \frac{24}{Re_p} \text{ for } Re_p < 0.4 \quad 2.17$$

$$C_d = \frac{10}{Re_p^{1/2}} \quad \text{for } 0.4 < Re_p < 500 \quad 2.18$$

$$C_d = 0.4 \quad \text{for } 500 < Re_p < 200,000 \quad 2.19$$

$$\text{and } Re_p = \frac{\rho U_t d_p}{\mu} \quad 2.20$$

From Eqs. 2.12, 2.13 and 2.16,

$$\frac{U_t}{U_{mf}} = 74 \quad \text{for small particles} \quad 2.21$$

$$\text{and } \frac{U_t}{U_{mf}} = 8.6 \quad \text{for large particles} \quad 2.22$$

While average particle size based on sieve analysis is used to determine U_{mf} , the smallest size of solids, which are present in appreciable amounts, is recommended for estimating U_t [22].

iv) *L/D Ratio* - The diameter of the bed, D , is usually fixed by the gas flow rate and fluidization velocity which must lie between the minimum fluidization and the terminal velocity. The bed height, L , is determined by the gas-solid contacting time and the heat transfer area between the wall and the bed. Raising the bed height enhances both parameters. However, for a slender bed, high L may lead to slugging. Surprisingly, Jordan [54] recommends that for small beds (less than 150 mm in diameter),

$$1 < L/D < 10 \quad 2.23$$

and for large beds,

$$1 < L/D < 5, \quad 2.24$$

even though temperature gradient may occur if, $L/D > 5$

v) *Distributor* - The choice of distributor depends both on the desired quality of fluidization and the pressure drop. Although high pressure drops may lead to good fluidization the power consumption of the blower may become excessive [16]. High pressure drops can also hinder the circulation of solids between stages [22].

According to Kunii and Levenspiel [22], the distributor pressure drop, ΔP_D , must satisfy the following conditions to achieve good fluidization:

$$\begin{aligned} \Delta P_D &> 0.10 \Delta P_B \\ \Delta P_D &> 100 \Delta P_E \\ \Delta P_D &\geq 35 \text{ cm of H}_2\text{O} \end{aligned}$$

where ΔP_B and ΔP_E denote the bed pressure drop and the expansion loss at the inlet connection to the vessel, respectively. When these conditions are not met, baffles should be used to improve the quality of fluidization.

For a list of successful industrial distributors and the design of orifice plate distributors see reference 16 or 22.

vi) *Bubbles* - Bubbles are important characteristics of gas fluidized beds. They are responsible for most of the features which differentiate a packed bed from a fluidized bed. They modify the gas flow through the system and cause particle movement which generally results in rapid and extensive particle mixing and, consequently, very high heat transfer coefficients between the bed and immersed surfaces (including the containing wall) [55].

Bubbles begin to form, near the distributor, when the fluidization velocity exceeds the minimum fluidization velocity. The bubble size does not only increase with height above the distributor, but it also increases with the gas velocity. The former is due to coalescence, expansion and mass transfer from the dense phase. The bubbles also split or attain a stable size. As a result, there may be a broad distribution of bubble sizes at any horizontal level [20].

The bubble's shape varies from a shallow spherical cap to an almost complete sphere. The shape can be grossly distorted by walls, submerged surfaces or obstructions and splitting or coalescence [55].

Associated with the bubble are a cloud and wake (Fig. 2.3). The cloud is the region surrounding the top part of the bubble. It is formed when gas flowing upwards through the bubble roof is dragged down by the particles sliding down the bubble surface. Most of the mass transfer between the bubble and the dense phase occurs in

Fig. 2.3: Gas bubble in a fluidized bed

the cloud. (For correlations predicting mass transfer coefficient see reference 41 or 19).

Tailing the bubble is the wake which appears to complete the spherical shape of the bubble. It occupies $1/4$ to $1/3$ of the bubble volume. The solid mixing caused by the bubbles takes place through the wakes. The particles are carried upwards in the wakes and downwards everywhere else [37].

Chapter 3

3 SIMULATION OF VARIOUS TYPES OF CLAUS PLANTS

3.1. INTRODUCTION

A thermodynamic equilibrium model was developed to simulate the performance of a Claus furnace and two fluidized bed Claus reactors in series. The four cases shown in Fig. 3.1 were considered. In Cases 1 and 2, a total water condenser is present upstream of the first reactor. In addition, the sulphur formed in the second reactor, which is maintained below the sulphur melting point, is removed from the catalyst in a regenerator in Case 1. For Case 2, the sulphur-laden catalyst is recycled to the first reactor. Cases 3 and 4 are similar to Cases 1 and 2, except that the water condensers are absent.

Table 3.1: Components of the streams shown in Figure 3.1

Stream No.	Components
1	Air (N_2 , O_2)
1A	H_2S
2, 5	S_2 , S_4 , S_6 , S_8 , H_2S , SO_2 , H_2O , N_2
3, 6, 7	H_2S , SO_2 , H_2O , N_2
4	H_2S , SO_2 , N_2
8	Sulphur laden catalyst
9	Catalyst
10, 11	SO_2 , H_2O , N_2
12	Elemental Sulphur
13	H_2O
14	Regenerator off gas containing elemental sulphur

CASE 1: NO CATALYST RECYCLE, WATER CONDENSED

CASE 2: CATALYST RECYCLED, WATER CONDENSED

CASE 3: NO CATALYST RECYCLE, NO WATER CONDENSED

CASE 4: CATALYST RECYCLED, NO WATER CONDENSED

Fig. 3.1 : Flow diagrams of modified Claus processes (for components of streams see Table 3.1)

In order to establish the validity of the computational procedure, a fifth case involving only the furnace was considered. The results from this case were compared with those of Gamson and Elkins [3], McGregor [9], and Bennett and Meisen [14].

The computational procedure for Case 1 is described below. The procedure for the other cases are logical extensions and are not presented in detail here.

3.2 ASSUMPTIONS

The principal assumptions made in the development of the equilibrium model are as follows:

- * The furnace feed consists of pure H_2S and stoichiometric amounts of air.
- * 70% sulphur conversion is achieved in the furnace. One-third of the H_2S unconverted to sulphur is oxidized to SO_2 .
- * The total pressure inside the reactors is maintained at 0.5, 1.0 or 2.0 atm.
- * The temperature of the first reactor ranges from 400 to 850°K while that of the second reactor is kept at 383.2°K , i.e. just below the sulphur melting point.

For sake of simplicity, impurities such as ammonia and hydrocarbons were not considered in this work. Also, in practice, attempts are made to remove them as much as possible because they

reduce the performance of the furnace and deactivate the catalyst in the reactors. [74, 75]

The sulphur conversion of 70% in the furnace was chosen because this value is typical for industrial Claus plants [71]. In Case 5, the second assumption is not made since the furnace itself is being modelled. The temperature and pressure ranges stated above cover the operating conditions of Claus plants [1].

3.3 EQUILIBRIUM EQUATIONS

First Reactor

The equilibrium reactions assumed to occur in the first reactor are:

It is easy to show that,

$$K_1 = [\text{H}_2\text{O}]^2 \gamma^{3/8} / ([\text{H}_2\text{S}]^2 [\text{SO}_2]) \quad 3.5$$

$$[\text{S}_2] = K_2 \gamma^{1/4} \quad 3.6$$

$$[\text{S}_4] = K_3 \gamma^{1/2} \quad 3.7$$

$$[\text{S}_6] = K_4 \gamma^{3/4} \quad 3.8$$

where $[i]$ denotes the partial pressure of component i and

$$Y = [S_8].$$

The equilibrium constants K_1 , K_2 , K_3 and K_4 were evaluated using the free energy data compiled by McBride *et al.* [10]. By making elemental balances for H, O, S and N, it can be shown that

$$[SO_2] = B_1 P - B_2 Y^{1/4} - B_3 Y^{1/2} - B_4 Y^{3/4} - B_5 Y \quad 3.9$$

$$[H_2O] = C_1 P + C_2 Y^{1/4} + C_3 Y^{1/2} + C_4 Y^{3/4} + C_5 Y \quad 3.10$$

where, $B_1 = \beta\alpha/\eta$

$$B_2 = K_2\beta(\alpha + 2\beta + \gamma)/\eta$$

$$B_3 = K_3\beta(\alpha + 4\beta + 2\gamma)/\eta$$

$$B_4 = K_4\beta(\alpha + 6\beta + 3\gamma)/\eta$$

$$B_5 = \beta(\alpha + 8\beta + 4\gamma)/\eta \quad 3.11$$

$$C_1 = (3\beta - 2\alpha)/\eta$$

$$C_2 = K_2\beta(2\alpha + 3\beta + 2\gamma)/\eta$$

$$C_3 = K_3\beta(2\alpha + 9\beta + 4\gamma)/\eta$$

$$C_4 = K_4\beta(2\alpha + 15\beta + 6\gamma)/\eta$$

$$C_5 = \beta(2\alpha + 21\beta + 8\gamma)/\eta \quad 3.12$$

and

$$\alpha = 1 - \phi \quad 3.13$$

$$\beta = 2\alpha / 3 \quad 3.14$$

$$\eta = \alpha(\gamma + 3\beta) + (3\beta - 2\alpha)(\beta + \gamma/2) \quad 3.15$$

ϕ denotes the fractional yield of sulphur achieved by the furnace (taken as 0.7) for Cases 1 to 4, γ is the ratio between N_2 and O_2 in air and P is the total pressure in the reactor. Substituting Eqs. 3.9 and 3.10 into Eq. 3.5 gives,

$$K_1 = \frac{(C_1 P + C_2 \gamma^{1/4} + C_3 \gamma^{1/2} + C_4 \gamma^{3/4} + C_5 \gamma)^2 \gamma^{3/8}}{4(B_1 P - B_2 \gamma^{1/4} - B_3 \gamma^{1/2} - B_4 \gamma^{3/4} - B_5 \gamma)^3} \quad 3.16$$

Equation 3.16 has only one unknown (γ) and is regarded as the equilibrium equation for the first reactor.

If the total number of moles of gas leaving the first reactor per unit time is denoted by δ , then it follows from an oxygen balance that,

$$\delta = \beta P / (2 [SO_2] + [H_2O]) \quad 3.17$$

Hence, the molar flow rates of SO_2 and H_2O leaving the first reactor are respectively given by,

$$\theta_1 = \delta [SO_2] \quad 3.18$$

$$\theta_2 = \delta [H_2O] \quad 3.19$$

These equations are based on the fact that 1 mole of H_2S , 0.5 mole of O_2 and 1.881 moles of N_2 are fed to the furnace per unit time.

Second Reactor

The second reactor is assumed to operate below the sulphur melting point. The primary reaction is therefore,

where S_M denotes monoclinic sulphur. Hence,

$$K_5 = [\text{H}_2\text{O}]^2 / ([\text{H}_2\text{S}]^2 [\text{SO}_2])$$

$$\text{or} \quad K_5 = \frac{\{((2\theta_1 + \theta_2)(P-3x) - \gamma x)/\theta\}^2}{4x^3} \quad 3.21$$

$$\text{where} \quad x = [\text{SO}_2] \quad 3.22$$

$$\text{and} \quad \theta = 2\theta_1 + \theta_2 + \gamma/2 \quad 3.23$$

Equation 3.21 is the basic equilibrium equation for the second reactor.

3.4 SOLUTION OF THE EQUILIBRIUM EQUATIONS

The equilibrium equation for the first reactor (Eq. 3-16) is a function with a discontinuity at

$$B_1P - B_2Y^{1/4} - B_3Y^{1/2} - B_4Y^{3/4} - B_5Y = 0 \quad 3.24$$

This is illustrated in Fig. 3.2 where $\psi\{Y\}$, given by

$$\psi\{Y\} = K_1 - \frac{(C_1P + C_2Y^{1/4} + C_3Y^{1/2} + C_4Y^{3/4} + C_5Y)^2 Y^{3/8}}{(B_1P - B_2Y^{1/4} - B_3Y^{1/2} - B_4Y^{3/4} - B_5Y)^3} \quad 3.25$$

is plotted as a function of Y .

Fig. 3.2 : Schematic plot of the equilibrium equation

The point of discontinuity is denoted by Y_s .

As seen from Fig. 3.2, the solution of Eq. 3.16, Y_0 , lies in the region

$$0 < Y_0 < Y_s \quad 3.26$$

Hence, to obtain Y_0 , Y_s is first determined by solving Eq. 3.24.

The latter is a continuous, well behaved function and can be easily solved iteratively. Two values of Y (i.e. Y_1 and Y_2) are then selected such that,

$$\psi\{Y_1\} < 0 < \psi\{Y_2\} \quad 3.27$$

Initially the value of Y_1 is chosen as,

$$Y_1 = Y_s - \epsilon_1 \quad 3.28$$

where ϵ_1 can be any arbitrary positive value such as 0.1. The value of ϵ_1 is then reduced or increased a number of times by a factor of 2 until Condition 3.27 is satisfied. The value of Y_2 is determined similarly.

After the estimation of Y_1 and Y_2 , these values are fed by the main computer programme (see Appendix A) to a subprogramme called ZEROIN. This subprogramme uses the secant and bisection methods to converge iteratively to the exact solution, Y_0 [76].

Knowing Y_0 , the equilibrium partial pressure of S_8 , the partial pressures of the other components and the equilibrium composition and conversion can be calculated from Eqs. 3.6 to 3.10

and the material balances.

The equilibrium equation for the second reactor, Eq. 3.21, is a cubic function in terms of x and it can be solved analytically. The correct solution is the root which is real, positive and also leads to a molar flow rate of SO_2 less or equal to the initial value. For more details see Appendix A and Reference 86.

Chapter 4

4 EXPERIMENTAL APPARATUS

4.1. REACTION EQUIPMENT

The experimental apparatus which was used to carry out the Claus reaction in a fluidized is shown schematically in Fig. 4.1 and pictorially in Fig. 4.2. It consisted of four major components, i.e. the fluidized bed reactor, nitrogen regeneration system, gas analysis system and safety devices.

4.1.1. Fluidized Bed Reactor

The fluidized bed reactor (0.1 m ID x 0.86 m high with a freeboard section 0.2 m ID x 0.3 m high) is shown in Figs. 4.3 and 4.4. It was constructed from 316 ss tubing 6 mm thick. Two layers of a wire mesh (Dynapore, type 401420, made from 316 ss by Michigan Dynamics, Inc., Garden City, N.J.) were used as the distributor. A similar mesh was installed at the top of the reactor to prevent catalyst elutriation.

Along the reactor, two 1/2" NPT (National pipe taper thread) ports were provided for continuous catalyst circulation. In addition the reactor was constructed in six sections to permit bed heights of 0.25, 0.37, and 0.50 m.

The reactor was heated electrically with stainless-steel-shielded nichrome wires (type D/R19S2, made by Pyrotenax, Inc., Toronto, Ontario) wound on the outside of the reactor. The total

Fig. 4.1: Flow diagram of the equipment (All dimensions in mm)

Fig. 4.2: General view of the apparatus

Fig. 4.3: Reactor,scrubber and driers

Fig. 4.4: Fluidized bed reactor

power supplied by the heater was 2 Kw. To cool the reactor in case of overheating, water cooling coils were also wound on the outside of the reactor. Thermal insulation was provided by a 25 mm thick Cerablanket (made by Carborundum, Inc., Niagara Falls, N.Y.). To monitor the temperature inside the reactor, four Iron-Constantan thermocouples were located at 30 mm below and 75, 650 and 1000 mm above the distributor. The second and fourth thermocouples provided the input to two proportional temperature controllers (model 49, made by Omega Engineering, Inc., Stamford, Conn.) to maintain the desired reactor temperature.

The pressure inside the reactor was monitored by 2 nitrogen-purged, mercury-in-glass manometers. To prevent sulphur from clogging the tubes connecting the reactor and the manometers, about 100 ml/min of nitrogen was admitted through each pressure port.

A spring loaded relief valve prevented excessive pressure build-up inside the reactor. The relief valve cracked opened at 7.5 psig and opened fully at 10 psig.

The flow rate of the gases fed to the reactor (i.e. H_2S , SO_2 and N_2) were measured with rotameters. Pictorial views of the front and back of the control panel, showing the rotameters and the connecting tubing are presented in Figs. 4.5 and 4.6, respectively. The specifications and the functions of the various rotameters are listed in Table 4.1.

Fig. 4.5: Front of control panel

Fig. 4.6: Back of control panel

Table 4.1 : Specifications of the rotameters

PROGRAM CODE	MANU- FACTURER	TUBE NO	FLOAT	AIR FLOW RANGE (ml/min)	GAS MEASURED	REGRESSION COEFFICIENTS* (a; b; c)	STANDARD DEVIATION ABOUT THE LINE
L963	Roger Gilmont	F1100	Glass	5 - 260	N ₂	-5.9051; 1.2439; 0.02129	7.48
E1402	Roger Gilmont	F1500	Glass	5,000-75,000	N ₂	181.04; 269.86; 0.087756	315.0
R7M251	Brooks	R-7M-25-1	SS	4000-46,000	N ₂	-132.57; 219.87; -0.15072	423.0
RSS604	Matheson	604	SS	1000-16,900	H ₂ S	-288.09; 126.52; -0.041227	37.67
RG604	Matheson	604	Glass	400-9,000	H ₂ S	-405.18; 68.15; -0.0064719	35.71
LSS604	Matheson	604	SS	1000-16,900	SO ₂	-441.68; 134.21; -0.070844	267.77
LG604	Matheson	604	Glass	400-9,000	SO ₂	-364.0; 65.289; 0.022695	112.65
RSS602	Matheson	602	SS	40-859	H ₂ S	-27.481; 3.0538; 0.029168	17.62
RG602	Matheson	602	Glass	20-386	H ₂ S	-6.6041; 0.80274; 0.01361	11.37
LSS602	Matheson	602	SS	40-859	SO ₂	-15.776; 4.6763; 0.019225	13.04

* Flow rate, $V = a + bx + cx^2$ ml/min, where x is the scale reading on the rotameter in mm, except R-8m-25-2 for which x is the index on the tube (maximum = 1)

Contd.

Table 4.1 : Specifications of the rotameters

PROGRAM CODE	MANU- FACTURER	TUBE NO	FLOAT	AIR FLOW RANGE (ml/min)	GAS MEASURED	REGRESSION COEFFICIENTS* (a; b; c)	STANDARD DEVIATION ABOUT THE LINE
LG602	Matheson	602	Glass	20-386	SO ₂	-5.808; 1.3618; 0.010939	13.33
LISS603	Matheson	603	SS	200-4820	SO ₂ /N ₂	-12.197; 43.642; -0.069732	34.26
LI G603	Matheson	603	Glass	100-2440	SO ₂ /N ₂	-61.4; 22.480; -0.0357	19.97
L2SS603	Matheson	603	SS	200-4820	N ₂	-27.493; 44.859; -0.087808	20.40
L2G603	Matheson	603	Glass	100-2440	N ₂	-47.952; 22.026; -0.038328	19.27
L3SS603	Matheson	603	SS	200-4820	N ₂	45.013; 45.482; -0.090123	33.23
L3G603	Matheson	603	Glass	100-2440	N ₂	27.767; 20.717; -0.027647	31.18
L4SS603	Matheson	603	SS	200-4820	Sample	45.013; 45.482; -0.090123	33.23
L4G603	Matheson	603	Glass	100-2440	Sample	27.767; 20.717; -0.027647	31.18
R-8M-252	Brooks	R-8M-25-2	SS 8-RS-8	100,000-90,000	Air	6685.5; 142040; -56597	1562.6

* Flow rate, $V = a + bx + cx^2$ ml/min. where x is the scale reading on the rotameter in mm, except R-8M-25-2 for which x is the index on the tube (maximum = 1)

The nitrogen and sulphur dioxide streams were preheated electrically upstream of the reactor with nichrome wires which were heavily insulated with fiberglass. To avoid sulphur condensation, the line between the reactor and scrubber was similarly heated. The power supplied by the preheater and the exhaust heater were 1.2 and 0.4 Kw, respectively. Two Iron-Constantan thermocouples and two proportional temperature controllers were also provided to maintain the desired temperatures in the heated lines.

To observe the quality of fluidization, two identical sight glasses were installed 340 mm above the distributor. The sight glasses were located diametrically opposite each other with one behind and the other in front of the reactor. The one-inch NPT ports for accepting the sight glasses were inclined at 60° to the reactor.

One of the sight glasses is shown in Figs. 4.7 to 4.9. A machinable glass spacer was sandwiched between two Pyrex glasses. To prevent fogging of the inner Pyrex glass by condensed sulphur, the space between the Pyrex glasses was heated with a nichrome wire. The resistance of the nichrome wire was 40 ohms and the maximum voltage which it could tolerate without glowing was about 25 volts. The nichrome wire was held in place by eight pins mounted in the recess of the machinable glass spacer. To provide illumination, light from a 60 w light bulb was shone through the sight glass located behind the reactor. With this arrangement, the surface of the fluidized bed was always observable.

Fig. 4.7: Disassembled sight glass

Fig. 4.8: Mounted sight glass

A system for continuously feeding fresh catalyst to the reactor and collecting the spent catalyst was also provided (see Fig. 4.10). The feed tank consisted of a 9" I.D. QVF glass column and a 9" to 2" reducer. The flow rate of the catalyst was controlled by a shutter valve similar to the one shown in figs. 4.19 to 4.21. The shutter opening was adjustable from about 1/2 to 1/16 in.

To prevent the passage of the hot gas mixture from the reactor to the feed tank, a small flow of nitrogen (20 to 200 ml/min) was provided to purge the feed line. The purge line was also connected to the top of the feed tank to equalize the pressure of the latter with that of the feed line. A relief valve was installed at the top of the feed tank to prevent excessive pressure build up in case the feed line became plugged by condensed sulphur. Again this relief valve cracked open at 7.5 psig and it opened fully at 10 psig.

The catalyst discharge tank is also a 9" I.D. QVF glass column. To isolate the discharge tank, a ball valve was installed in the discharge line. The isolation of the discharge tank was necessary since the latter should be replaced when fully loaded without stopping the experiment. Four roller castors were placed at the bottom of the tank to ease transportation.

Fig. 4.10 : Continuous catalyst feed system

4.1.2. Nitrogen Regeneration System

Over 90% of the nitrogen fed to the reactor was recycled to minimize nitrogen usage. In addition to N_2 , the effluent from the reactor usually contained H_2S , SO_2 , H_2O and elemental sulphur. The purpose of the regeneration system was therefore to remove these components from the recycle nitrogen stream.

The undesirable components were separated from the nitrogen by passing the reactor effluent through an aqueous NaOH scrubber as well as glass columns packed with KOH and $CaSO_4$ pellets.

The NaOH scrubber consisted of a QVF column packed with $\frac{1}{4}$ " Ceramic Berl Saddles (see Figs. 4.1, 4.3 and 4.11). A solution containing approximately 50 wt % NaOH was pumped continuously and concurrently with the reactor gas through the scrubber. The flow rate of the solution was about 2 l/min. Co-current operation was chosen to avoid possible flooding of the scrubber. (A 50 wt % NaOH solution is very viscous and hence a counter-current flow is most likely to cause flooding.) In addition to passing through the scrubber, the gas was bubbled through the solution in the reservoir with a sparger to ensure almost complete removal of H_2S and SO_2 . A cooling coil located in the reservoir removed the heat of absorption. The temperature in the reservoir was maintained at about $15^{\circ}C$. To prevent entrainment of spray and mist, the gas was passed through glass wool filter located at the bottom of the scrubber, before it was sent to the driers.

Fig. 4.11 : Scrubber and reservoir

The driers consisted of two glass columns filled with KOH and CaSO_4 pellets (see Fig. 4.1, 4.3 and 4.12). The scrubbed gas was passed through the KOH column before the CaSO_4 unit, because KOH has a high capacity while CaSO_4 has a high efficiency for moisture removal [77]. A liquid disengagement port situated between the two columns ensured that any dissolved KOH did not flow into the CaSO_4 column.

Potassium hydroxide is deliquescent; therefore, a saturated solution was formed after absorbing the moisture. This solution flowed through the wire mesh at the bottom and it was collected in the stainless steel section which had a solid base. A port at the centre of the base, while allowing the gas to flow to the bottom glass column, prevented the solution from passing to the column. A valve at the side of the stainless steel section permitted the drainage of the solution.

To recycle the regenerated nitrogen, a bellow pump (model MB-302, manufactured by Metal Bellows Corp., Sharon, Mass.) was provided. The pump had a maximum capacity of 85 l/min at 1 atm. A regulating valve and a rotameter were used to control and measure the flow rate of the nitrogen, respectively.

When a sample of the regenerated nitrogen was tested, the H_2S and SO_2 concentrations were below detectable limits of 2 and 1 ppm, respectively. Therefore the regeneration system was more than 99.99% efficient.

Fig. 4.12 : Driers

4.1.3 Gas Analysis System

Most H_2S and SO_2 analysers cannot handle gas mixtures containing moisture and sulphur (especially in the form of particulates). Hence, samples from the reactor had to be conditioned first by removing these components. In conditioning the sample, it was essential to prevent the formation of liquid sulphur and water since they could cause further reaction between H_2S and SO_2 .

To maintain dry surfaces in the conditioning system it was necessary to use the multistage system shown in Fig. 4.13. The conditioning system consisted essentially of a sulphur condenser, driers and a filter. The sulphur condenser contained CaCl_2 and glass wool. The separation of sulphur particulates was accomplished by maintaining the temperature of the sulphur condenser at about 105°C . The temperature was controlled by varying the flow rate of the gas sample.

The first drier for removing moisture also contained CaCl_2 and glass wool. The temperature was kept at about 10°C by using a water cooling coil. Further conditioning was provided by a second drier and a fine filter which removed particulates larger than $0.3\ \mu\text{m}$ in diameter. A diaphragm pump (Air Cadet, model 7530-40, supplied by Cole-Parmer Instrument Co., Chicago, Ill.) which has a maximum capacity of 14.748 l/min at 1 atm was used as the sampling pump.

After conditioning the sample, it was diluted approximately 10 times with a known amount of air. The air dilution was performed

Fig. 4.13: Sample conditioning system (All dimensions in mm)

to reduce the quenching action of H_2S on the SO_2 analyser (for details see Section 5.2.2). The sample flow rate was maintained at 4.8 ml/min to keep the temperature of the sulphur condenser at the desired temperature of 105°C . After dilution, a portion of the sample was introduced into the gas analysers. The latter instruments were a Pulsed Fluorescence SO_2 Analyser (model 40, made by Thermo Electron Corp., Hopkinton, Mass.) and a Photoionization H_2S Monitor (model PI 201, made by HNU Systems, Inc., Newton, Mass.). These instruments were calibrated as described in section 5.2.2. The signals from these instruments and the thermocouples were recorded with a datalogger (model 2240A, made by John Fluke, Mfg. Co., Inc., Mountlake Terrace, Washington). The datalogger was capable of accepting 20 inputs of dc voltages from thermocouples and other sensors. The datalogger could be programmed to give full scale readings of 100 mv, 1000 mv, 10 v and 100 v.

For temperature measurement, the instrument was capable of accepting signals from J, K, T, and R type thermocouples. The reference junction temperature of the thermocouples was established internally by means of block connector, forward biased diode and a microprocessor.

Furthermore, the instrument has a built-in clock giving the date and time. Other features are listed in Table 4.2.

Table 4.2 : Features of the datalogger

S C A N C O N T R O L	F U N C T I O N
Reset	Stops all scan and output functions.
Single	Scans sequentially between first and last channel. Stops automatically on the last channel selected.
Interval	Sequential scanning between the first and the last channel is repeated at time interval set. The interval can be any time from 1 sec. to 24 hr.
Continuous	Sequential scanning is repeated continuously. The time interval depends on the number of channels. For 15 channels it is less than 1 second.
Monitor	Used for continuously monitoring a single channel which is selected from the keyboard. Readings can be recorded on the printer attached to the instrument.

The entire conditioning system functioned well. There was no detectable change in concentration when a known sample of H_2S , SO_2 and N_2 was passed through the conditioning system.

Since a moisture generator was unavailable, the conditioning system could not be tested with samples containing moisture. To circumvent this problem, dry samples of known concentrations of H_2S and SO_2 in N_2 were passed over CaCl_2 which had been used previously in the conditioning system. The CaCl_2 would thus contain the appropriate moisture to simulate the condition of a sample containing moisture.

The test indicated that as long as the surface of the CaCl_2 remained dry the sample concentrations with respect to H_2S and SO_2 remained unchanged. However, when wet CaCl_2 was tested, it reduced the concentrations of H_2S and SO_2 by about 5 and 10% respectively. In terms of sulphur conversion efficiency, this is equivalent to about 0.5 percentage points and lies within the overall experimental error (see Section 6.4). Throughout the experimental runs, great care was exercised to ensure that the surface of the CaCl_2 remained dry.

4.1.4. Safety Devices

Since H_2S and SO_2 are extremely toxic, strict precautions were taken to ensure the safe operation of the equipment. All joints were leak-proofed and the entire equipment (including the gas cylinders) was enclosed (see Fig. 4.2 and 4.14). A small vacuum (approximately 30 mm H_2O) was created in the enclosure by a fan located on the roof of the laboratory and connected to the enclosure. In case of a loss in vacuum due to a fan failure or other reason, a pressure switch (see Fig. 4.15) mounted on the control panel would shut down the entire equipment including the solenoid valves on the H_2S and SO_2 cylinders (see Fig. 4.15). The complete equipment shut-down was accomplished by switching off the main power supply to the equipment (see Fig. 4.16).

To ensure the safe operation of the equipment further, the H_2S concentration in the suction line between the fan and the enclosure was frequently checked with the H_2S analyser. When the concentration exceeded approximately 10 ppm, an alarm, which was a built-in feature of the H_2S analyser, would sound. Because all joints were always leak-proofed, there was no detectable amount of H_2S in the suction line (i.e. less than 2 ppm).

Personnel working in the vicinity of the equipment were also provided with H_2S sensitive tags (made by Metronics, Inc., Santa Clare, California). A colour code on the tag indicated the

Fig. 4.14: Enclosed gass cylinders and solenoid valves

Fig. 4.15: Pressure switch

Fig. 4.16: Electrical circuit of the equipment

amount of H_2S to which the operator had been exposed. A gas mask with H_2S absorbing canister (model 457069, made by Mine Safety Appliances Co. of Canada Ltd., Downsview, Ontario) was also provided in case the operator had to work in an atmosphere containing high levels of H_2S . The allowable limit of 8-hour exposure is 10 ppm [78].

4.2 MATERIALS USED

The catalyst used in the fluidized bed was activated alumina manufactured by Kaiser Aluminium and Chemical Corporation in Baton Rouge, Louisiana. It has the commercial designation Kaiser S - 501. The catalyst contains mostly aluminium oxide promoted with some lithium oxide. It is available as small spheres with a size range of $-3 + 6$ mesh. To use it in the fluidized bed it was ground and sieved to $-35 + 150$ mesh. The solid density of the catalyst particles was estimated using a volume displacement method. To avoid the solubility of some of the components in water, manometer fluid was used as the displacing liquid. For detailed properties of the catalyst see Table 4.3

The gases used were supplied by Canadian Liquid Air Ltd., Vancouver, B.C. The purity of SO_2 and H_2S were 99.98 and 99.9%, respectively. For nitrogen the purity was 99.99%.

Table 4.3

Properties of catalyst (activated alumina,
Kaiser S - 501)

Chemical Analysis in % Dry Basis [79].

Al_2O_3 and Inorganic Promoters	93.5
Loss on Ignition	6.0
Na_2O	0.45
Fe_2O_3	0.02
SiO_2	0.02

Physical Properties

Solid Density	3160 kg/m ³
U_{mf}	0.0245 m/s at STP
ϵ_{mf}	0.692
Average Diameter (as determined by Eq. 2.11)	145 μm

Size Distribution

Diameter range (μm)	d_{P_i} (μm)	Weight fraction X_i
295 - 250	272.5	0.126
250 - 212	231.0	0.0273
212 - 208	210.0	0.0118
208 - 275	191.5	0.126
175 - 147	161.0	0.388
147 - 53	100.0	0.320

4.3 SOLID CIRCULATION

Before it was decided to use the single reactor, the catalyst circulation between two fluidized beds at ambient temperature was studied. The schematic diagram of the apparatus is shown in Fig. 4.17. The two fluidized beds, which were constructed from plexiglass, are similar in all respects.

Since the two fluidized beds operated in series with respect to the gas flow, the pressure inside the first fluidized bed was always maintained above that of the second reactor. This prevented the possibility of catalyst passing directly from the second to the first fluidized bed. To return the catalyst from the second to the first bed, a system of hoppers, rotary valves and ball valves was developed. When filling Hopper A and emptying Hopper B, Ball valves 1 and 3 were opened and 2 and 4 were closed, and vice versa. With such a system, the catalyst circulation was smooth and could be maintained for prolonged periods. The only additional problem encountered was the severe wearing of the blades of the rotary valves (details are shown in Fig. 4.18). This problem, however, could be eliminated by replacing the rotary valves with shutter valves shown in Figs. 4.19 to 4.21. The flow rate of the catalyst is mainly a function of the diameter of the shutter opening which could be varied from about 2 to 38 mm. The maximum catalyst flow rate achieved was about 4 g/s.

(All dimensions in mm)

Fig. 4.18: Rotary valve

Fig. 4.19: Shutter device

Fig. 4.20 P Rotor of the shutter device

SECTION D-D

Fig. 4.21: Leaf of the shutter device

In addition to studying solid circulation, one of the fluidized beds was used to determine the minimum fluidization velocity of the catalyst particles.

Chapter 5

5 EXPERIMENTAL PROCEDURE

5.1. REACTION PROCEDURE

The Claus reaction was performed in a fluidized bed by using the equipment described in Section 4.1. For safety reasons, it was absolutely essential to ensure that all joints were leak-proofed. In addition, since the reactor feed was to be free of oxygen, all oxygen had to be removed from the reactor and recycle system. Furthermore, the catalyst could be deactivated by oxygen and sulphur compounds so that provisions had to be made for catalyst regeneration. The procedures described below meet these various provisions.

5.1.1. Equipment Start-up

To achieve the conditions mentioned above and to ensure the smooth operation of the equipment, the following start-up procedure was adopted:

1. Remove the fluorocarbon panel in front of the reactor
2. Disconnect the front sight glass from the reactor.
3. Through the port of the sight glass, introduce about 1.2 or 2.4 kg of the catalyst to give a bed height of approximately 0.12 or 0.25 m, respectively.
4. Remount the sight glass and test for leaks by pressurizing the reactor and nitrogen recycle loop with nitrogen from the

gas cylinders. The pressure in the reactor was maintained at about 10 psig. To test for leaks, soap solution was applied to all joints. Most leaks did occur at the flanges which were then further tightened. The Swagelok fittings rarely leaked provided the appropriate procedure was adopted for tightening the nuts [89].

5. Replace the fluorocarbon panel and seal all the edges of the enclosure with 100 mm wide, duct sealing tape.
6. Start purging oxygen from the reactor system by switching on the sample pump. Maintain the pressure in the reactor at about 560 mm Hg absolute for 30 mins.
7. Introduce nitrogen into the reactor system until the pressure returns to atmospheric levels.
8. Switch on the bellow booster pump to fluidize the bed.
9. Purge about 10% of the total gas flow rate through the reactor for about 24 hrs with the sampling pump to ensure that virtually all oxygen is removed from the system (see Appendix D).
10. Switch on the caustic solution circulation pump, gas analysers, datalogger and heaters for the sight glass, preheaters, reactor and reactor-scrubber line.
11. Circulate cold water through the cooling coils in the caustic tank.
12. Monitor all thermocouples every 15 mins until the desired, steady temperatures are reached. (This procedure usually

requires about 1 hour).

13. Eliminate the last traces of oxygen and regenerate the catalyst, by admitting a small flow of H_2S (20 ml/min) into the reactor for about 30 min.

The reactor system is now ready for a run.

5.1.2. Reaction Process

All experiments were performed with the reactors maintained at atmospheric pressure. This condition was achieved by decreasing or increasing the flow rate of nitrogen into the nitrogen recycle system to compensate for the purge. In addition to purging nitrogen with the sampling pump, a valve located downstream of the booster pump could also be used to vent additional nitrogen.

To ensure proper performance of the gas analyses, their electronic zeroes were always checked according to the instruction manuals [90, 91]. At the beginning of a run, the calibration curve for the analysers was also validated by using a sample of known composition from the feed to the reactor. If significant differences were detected, a new calibration curve was generated as described in Section 5.2.2.

In order to obtain the maximum yield of sulphur, the H_2S and SO_2 concentrations in the reactor feed were maintained at a ratio of 2/1. This ratio was achieved by adopting the following procedure:

1. Choose the flow rate of hydrogen sulphide, F_{H_2S} from the appropriate rotameter Calibration Table (see Appendix B).
2. Calculate the scale reading which gives the flow rate of SO_2 precisely half that of H_2S from:

$$H = J + \frac{(F_{SO_2})_{J+10} - (F_{SO_2})_H}{(F_{SO_2})_{J+10} - (F_{SO_2})_J} \quad 5.1$$

where,

$J = 10, 20, 30 \dots \text{etc.}$

$(F_{SO_2})_H = 0.5 F_{H_2S}$,

$(F_{SO_2})_J$ and $(F_{SO_2})_{J+10}$ denote the flow rate at the scale reading of J and $J+10$ mm respectively, of the SO_2 rotameter.

The calibration table for the latter is also given in Appendix B. A summary of select results is presented in Table 5.1.

3. Open the solenoid valves mounted on the H_2S and SO_2 cylinders.
4. Open the H_2S and SO_2 cylinders and set the line pressures to about 15 psig using the valves on the regulators.
5. Set the hydrogen sulphide flow rate to the desired value by adjusting the regulating valve on the rotameter. At the same time set the float in the SO_2 rotameter to the scale reading of H , which was estimated from Eq. 5.1. When the regulating valves situated downstream of the rotameters are opened, the pressure inside these rotameters falls. Hence by trial and error adjust the pressures and the float positions to the

Table 5.1 : Select flow rates of reactants ($\text{H}_2\text{S}/\text{SO}_2$ ratio are 2/1)

H_2S				SO_2				
ROTAMETER CODE	PRESSURE IN ROTAMETER (psi)	SCALE READING (mm)	FLOW RATE AT S T P ml/mm	ROTAMETER CODE	PRESSURE IN ROTAMETER (psi)	SCALE READING (mm)	FLOW RATE AT STP by (ml/mm)	
							INTERPOLATION	REGRESSION
RG602	30	20	19.5	LG602	30	11.0	9.8	10.0
RG602	30	30	38.9	LG602	30	17.0	19.5	19.5
RG602	30	40	61.9	LG602	30	24.0	31.0	31.5
RG602	30	50	88.5	LG602	30	30.5	44.3	43.6
RG602	30	60	118.6	LG602	30	38.0	59.3	58.6
RG602	30	70	152.3	LG602	30	46.0	76.2	75.9
RG602	30	80	189.6	LG602	30	54.0	94.8	94.6
RG602	30	90	230.4	LG602	30	62.0	115.2	114.6
RG602	30	100	274.8	LG602	30	71.0	137.4	138.6

Contd. Table 5.1 : Select flow rates of reactants (H_2S/SO_2 ratio are 2/1)

H_2S				SO_2				
ROTAMETER CODE	PRESSURE IN ROTAMETER (psi)	SCALE READING (mm)	FLOW RATE AT S T P ml/mm	ROTAMETER CODE	PRESSURE IN ROTAMETER (psi)	SCALE READING (mm)	FLOW RATE AT STP by (ml/mm)	
							INTERPOLATION	REGRESSION
RG602	30	110	322.7	LG602	30	79.0	161.4	161.5
RG602	30	120	374.2	LG602	30	87.5	187.1	187.1
RG602	30	140	487.9	LG602	30	104.5	244.0	243.0
RSS602	30	90	633.4	LG602	30	124.5	316.7	316.5
RG604	30	20	1251.2	LSS602	32.3	99.0	625.6	626.2
RG604	30	30	2139.5	LG604	30	22.5	1070.0	1060.1
RG604	30	40	3026.2	LG604	30	30.0	1533.8	1533.5
RG604	30	50	3911.2	LG604	30	36.5	1955.6	1945.7
RG604	30	60	4794.2	LG604	30	43.5	2400.0	2391.7

predetermined values.

6. Withdraw a sample of the feed gas to the reactor thereby checking the calibration curve of the gas analysers.
7. Monitor the concentration of H_2S and SO_2 in the sample taken from the reactor outlet. At steady state, which is usually attained after about 30 min, record the readings from the analysers.
8. To determine the proper operation of the nitrogen regeneration system, analyse a sample of the regenerated nitrogen.
9. Record the flow rates of all the gases by noting the pressures inside the rotameters and the positions of the floats. The following flow rates were recorded:
 - (i) Nitrogen in the feed
 - (ii) Nitrogen for purging the manometers
 - (iii) H_2S in the feed
 - (iv) SO_2 in the feed
 - (v) Product Sample
 - (vi) Air for diluting the product sample
10. At the completion of Step 9, the entire procedure is repeated using new flow rates for H_2S and SO_2 . The range of operating variables investigated are listed in Table 5.2

Table 5.2 : Operating variables and their ranges

Operating Variable	Range
Bed Heights	0.12 and 0.25 m
Bed Temperatures	150, 200, 250, 280, 300°C
Reactant Concentrations	0.06 to 18% H ₂ S 0.03 to 9% SO ₂ (H ₂ S/SO ₂ ratio of 2/1)
Superficial gas Velocity, U	2 to 4 m/min at STP
U/U _{mf}	4 to 12.5

Although the continuous catalyst circulation system was tested, no attempt was made to obtain data using that system. The fluidized bed reactor was run only in batch mode.

5.1.3. Catalyst Regeneration

After a series of runs, the catalyst was regenerated *in situ* before complete equipment shut-down. The regeneration was particularly important after runs at low temperatures where sulphur condensation on the catalyst did occur. For runs at high temperatures it was still essential to regenerate the catalyst to avoid possible sulphation.

Although the manufacturers of the catalyst recommended 340 to 370°C [80] for regeneration, 300°C proved to be a suitable temperature. The elevated temperatures apply to coarse catalyst particles (- 3 + 6 mesh). Such particles have a high percentage of pore space and hence elevated regeneration temperatures are required to evaporate condensed sulphur from the pores. However, in the present work, fine particles (- 35 + 150 mesh) were used and the condensation of sulphur occurred primarily on the outside surface of the particles. Hence the comparatively low regeneration temperature of 300°C was adequate.

To overcome possible sulphation, a small flow of H_2S was introduced into the reactor to reduce any sulphate compounds.

No loss of catalyst activity was ever observed provided the catalyst was regenerated by using the following procedure:

1. Close the SO_2 gas cylinder
2. Switch off the solenoid valve on the SO_2 cylinder.
3. Close the regulating valves located downstream of the rotameters used to measure H_2S and SO_2 flow rates.
4. Set the temperature controllers to 300°C .
5. Circulate only nitrogen through the reactor system for about 24 hrs to remove any condensed sulphur from the catalyst.
6. Admit a small flow of H_2S (20 ml/min) into the nitrogen stream entering the reactor.
7. Allow the equipment to run under this condition for about 3 hrs. to reduce all possible sulphation.

5.1.4. Equipment Shut-down

The main problem likely to occur during equipment shut-down is the sudden loss of pressure in the reactor when the booster pump is switched off. The loss of pressure might cause air to leak into the reactor and, if there are any sulphur compounds present, sulphation of the catalyst could occur. To avoid this problem, the following procedure was adopted:

1. Close the H_2S gas cylinder.
2. Switch off the solenoid valve on the H_2S cylinder.
3. Close the regulating valve located down-stream of the

rotameter which measures the H_2S flow rate.

4. Switch off the heaters, gas analysers, data logger and caustic solution circulation pump.
5. Turn off the cold water for the cooling coils.
6. Admit nitrogen from a cylinder into the reactor to raise its pressure to about 7 psig.
7. Switch off the booster pump and allow all heated components to cool overnight.
8. In preparation for the next series of runs, clean the sampling system and refill the condenser and the driers with CaCl_2 and glass wool. Also inspect the filter cartridge and replace it if severely contaminated.

5.1.5. Scrubber Clean-up

The condensation of sulphur in the reactor off-gas occurred mostly at the top of the scrubber. The formation of salts such as Na_2S , NaHS , Na_2SO_3 and NaHSO_3 also took place at the scrubber top. Hence, even though the NaOH solution might not be totally spent, it was necessary to clean the scrubber before any blockage arose.

Sulphur, which is partially soluble in aqueous sodium hydroxide, imparted a dark red colour to the solution. When the solution became diluted, during the washing of the scrubber with water, it changed colour to dark green and then to a light green.

The dark green was probably caused by ferrous sulphide which hydrolysed to ferrous ions in more dilute solution. In addition to the compounds listed above, there were also iron, aluminium and silicon compounds in the scrubber due to the elutriation of very small quantities of the catalyst from the reactor.

To ensure adequate clean-up of the scrubber the following procedure was adopted:

1. Check to make sure the discharge valve at the bottom of the caustic reservoir is connected, through a pump, to the waste disposal tank.
2. Open the discharge valve and switch on the discharge pump.
3. After emptying the tank, close the discharge valve and fill the reservoir with water.
4. Circulate the water through the scrubber for about 30 min.
5. Repeat steps 2 to 4 about four times.
6. Open the top of the scrubber and remove the packing, at the top of the column and clean it with a brush to get rid of the condensed sulphur.
7. Clean the inside wall of the top of the column as well as the covering plate to remove condensed sulphur.
8. Replace the top plate of the scrubber and wash the tower again three times using steps 2 to 4. At this stage, the solution is very dilute and can be discharged directly into the drain.

5.2. CALIBRATION OF INSTRUMENTS

5.2.1. Calibration of Rotameters

The rotameters had to be calibrated very accurately since they were used to prepare gas mixtures for calibrating the analytical instruments. In addition, the dilution factor of the reactor product sample was also estimated from flow measurements.

The rotameters were calibrated with standard flowmeters such as a soap bubble meter, electronic mass meter and wet-test meter. The soap bubble meter was used for the measurement of flow rates ranging from 10 to 1000 ml/min since it is very accurate within this range [77]. The time required for a soap bubble to move between two marks enclosing a known volume was determined with an electronic timer activated by two photocells.

For flow rates between 500 and 2000 ml/min an electronic mass flowmeter was used. It consisted essentially of an electrically heated tube and an arrangement of thermocouples to measure the differential cooling caused by a gas passing through the tube.

The wet-test meter was used for the measurement of flow rates between 1.0 l/min and 100 l/min. The principle of the wet-test meter involves the measurement of gas flow by counting the revolutions of a shaft upon which water-sealed, gas-carrying cups of fixed capacity are mounted.

The equation for calculating the flow rate at standard conditions for a given position of the float in the rotameter

is given by [88],

$$V_1 = \frac{V_2 \cdot P_2}{T_2} \left(\frac{T_3 \cdot T_1}{P_3 \cdot P_1} \right)^{0.5} \quad 5.2$$

where V_1 is the volumetric flow rate at standard conditions of T_1 and P_1 and V_2 is the flow rate at the conditions of T_2 and P_2 inside the reference flowmeter. T_3 and P_3 denote the temperature and pressure inside the rotameter.

Air was used to calibrate the rotameters. For other gases such as N_2 , H_2S and SO_2 , the equivalent flow rates were estimated from the following equation [89],

$$V_i = V_1 (\rho_i)^{-0.5} \quad 5.3$$

where V_i denotes the volumetric flow rate of gas i at standard conditions and ρ_i denotes its specific gravity with respect to air. The computer programme for calculating the flow rates together with a typical output are presented in Appendix B.

5.2.2. Calibration of Analytical Instruments

The H_2S and SO_2 concentrations were measured with a Photoionization Monitor and a Pulsed Fluorescent Analyser, respectively. These instruments were calibrated with the apparatus shown schematically in Fig 5.1. Samples of H_2S and SO_2 were generated by double dilution with N_2 and air. In the sample

Fig. 5.1 : Flowsheet for calibration of analytical instruments

mixtures, the concentration of SO_2 was always kept at half of H_2S , since this ratio was also maintained in the feed to the fluidized bed Claus reactor.

The final dilution of the samples with air was necessitated by the fact that the product samples from Claus reactor had to be diluted with air. The purpose of the air dilution was to minimize the quenching effect of H_2S on the SO_2 analyser. The quenching effect was further studied by measuring the signal from the SO_2 analyser for sample mixtures with and without H_2S . The effect of SO_2 on the H_2S analyser was similarly investigated.

The analysis of the calibration data indicated that the signal from the SO_2 analyser was affected by the presence of H_2S in the sample. The wavelength of the ultraviolet light source for the instrument ranged from 1900 to 2300 $\text{\AA}$. Unfortunately this falls into the absorption band of H_2S , i.e. 1900-2700 $\text{\AA}$ [82].

The quenching action of H_2S obeys the Lambert-Beer law,

$$E = E_0 \exp (-K[\text{H}_2\text{S}]) \quad 5.4$$

where E and E_0 denote the instrument signals for samples with and without H_2S , respectively. To correct for the presence of H_2S , the extinction coefficient, K was evaluated and found to be 2.06×10^{-4} / ppm H_2S (see Fig. 5.2). Hence by knowing $[\text{H}_2\text{S}]$

Fig. 5.2: Estimation of extinction coefficient due to H₂S

from the photoionization monitor and E from the SO₂ analyser, E₀ could be determined. The true SO₂ concentration was then estimated from a calibration plot of [SO₂] versus E₀ shown in Figs. 5.3 and 5.4.

At low concentrations of SO₂, the calibration plot is almost linear (Fig. 5.3). However, at high concentrations some curvature as well as scatter are noted. The curvature at high concentrations can be attributed to the fact that the fluorescence of SO₂, F, is an exponential function of SO₂ concentration [83].

$$F = C_1 \{1 - \exp(-C_2 [\text{SO}_2])\} \quad 5.5$$

The parameters C₁ and C₂ are constants. At low concentrations of SO₂, Eq. 5.5 can be approximated by the linear relationship,

$$\begin{aligned} F &= C_1 C_2 [\text{SO}_2] \\ \text{or} \quad &= K [\text{SO}_2] \end{aligned} \quad 5.6$$

The H₂S analyser uses photoionization as the principle of detection. For a compound to be detectable, its ionization potential must be less than or equal to the energy of the photons emitted by the ultraviolet light source in the instrument. The energy of the light source of this instrument, i.e. 10.2 eV, is lower than the ionization potential of all other compounds in the sample stream: SO₂ = 12.063 eV, N₂ = 15.76 eV and O₂ = 12.063 eV. Hence there was no interference from any of these compounds.

Fig. 5.3: Calibration curve for SO₂ analyser

Fig. 5.4: Calibration curve for SO₂ analyser

The calibration curve for low and high concentrations of the H_2S analyser are presented in Figs. 5.5 and 5.6, respectively. It is noteworthy that, like the SO_2 calibration curves, there was less scatter at low than at high concentrations. This can be explained by the fact that at high concentrations, the flow rate of the dilution gases were low; hence the floats of the rotameters were at the bottom of the scale where the accuracy is low. Because of the slight curvature, second degree polynomials were fitted to the experimental points using the method of least squares.

Fig. 5.5: Calibration curve for H₂S analyser

Fig. 5.6: Calibration curve for H_2S analyser

Chapter 6

6 RESULTS AND DISCUSSION

6.1. SIMULATION OF VARIOUS TYPES OF CLAUS PLANTS

The validity of the computational procedure was deduced from the good agreement between the present results and those of other workers for Case 5. As seen from Fig. 2.1, the discrepancies are very small and they can be attributed to using somewhat different free energy data.

Table 6.1 summarizes the equilibrium conversions of the Claus processes containing two fluidized bed catalytic reactors in series. It is noteworthy that the total conversion is constant with respect to the first reactor temperature. The reason for this is that the second reactor compensates (at least theoretically) for the deficiencies of the first reactor. Since the composition of the stream leaving the second reactor depends primarily on the reactor temperature (and this was kept at 383.2°K), the overall conversion is also constant.

The recycle of sulphur-laden catalyst does not noticeably affect the total conversion. The total conversion is the same for Cases 1 and 2 as well as Cases 3 and 4. A separate catalyst regenerator does therefore not appear to be necessary.

Table 6.1: Estimates of sulphur conversions in modified Claus process incorporating two fluidized bed reaction. (Temperature in second reactor is set at 383.2°K the furnace yield is assumed to be 70%)

TEMP in First Reactor °K	S U L P H U R C O N V E R S I O N S %											
	Case 1			Case 2			Case 3			Case 4		
	First Reactor	Second Reactor	Total	First Reactor	Second Reactor	Total	First Reactor	Second Reactor	Total	First Reactor	Second Reactor	Total
400	99.63	73.37	99.97	99.63	73.37	99.97	98.86	72.21	99.90	98.86	72.24	99.90
450	98.83	91.67	99.97	98.84	91.68	99.97	96.35	91.30	99.90	96.45	91.34	99.90
500	97.08	96.66	99.97	97.15	96.68	99.97	90.87	96.51	99.90	91.54	96.55	99.90
550	93.96	98.39	99.97	94.26	98.40	99.97	81.26	98.30	99.90	83.80	98.35	99.90
600	89.27	99.09	99.97	90.17	99.10	99.97	67.02	99.04	99.90	74.09	99.09	99.90
650	83.17	99.42	99.97	85.27	99.43	99.97	49.35	99.37	99.90	63.98	99.43	99.90
700	76.26	99.59	99.97	80.20	99.60	99.97	32.11	99.53	99.90	54.95	99.61	99.90
750	69.74	99.68	99.97	75.71	99.70	99.97	22.77	99.59	99.90	48.07	99.70	99.90
800	65.79	99.72	99.97	72.69	99.74	99.97	23.21	99.59	99.90	44.32	99.75	99.90
850	65.96	99.71	99.97	72.07	99.75	99.97	26.56	99.57	99.90	44.32	99.75	99.90

Comparison of the total conversions in Cases 1 and 2 with those of Cases 3 and 4 indicates that the removal of water from the furnace effluent slightly enhances the total conversion. Hence, the conversion efficiency of Claus processes could be improved further if moisture is removed from the furnace off-gas. However, this might result in unacceptable corrosion rates unless drying agents, rather than water condensers, are used.

The sulphur partial pressure was predicted, by means of the mathematical model, as a function of the reactor temperature and the H_2S concentration in the feed. Table 6.2 indicates that, within the range of 150 to 300°C, the partial pressure of sulphur is virtually independent of the reactor temperature. It is only a function of the H_2S concentration in the feed. Furthermore, the dew point of a compound is only a function of its partial pressure. Hence, a relationship could be developed between the sulphur dew point and the concentration of H_2S in the feed. For this purpose, the following equation is proposed:

$$\ln (C_F) = a + bT + c/T + d/T^2 \quad 6.1$$

where C_F % and $T^{\circ}K$ denote the concentration of H_2S in the feed and the sulphur dew point, respectively. The coefficients are,

$$a = 4.597288$$

$$b = 0.00542412$$

$$c = 1,439.83$$

$$d = -2,208,580$$

Table 6.2 : Partial pressures (atm) and dew points ($^{\circ}\text{C}$) of sulphur

Reactor Temp. $^{\circ}\text{C}$	H_2S Concentration in the Feed*					
	20%	10%	3%	1%	0.5%	0.1%
150	0.0403	0.0195	0.0058	0.0019	0.0010	0.0019
180	0.0405	0.0196	0.0058	0.0019	0.0010	0.0020
200	0.0406	0.0197	0.0058	0.0020	0.0010	0.0020
220	0.0408	0.0198	0.0059	0.0020	0.0010	0.0020
250	0.0410	0.0200	0.0059	0.0020	0.0010	0.0020
280	0.0412	0.0201	0.0060	0.0020	0.0010	0.0021
300	0.0412	0.0201	0.0060	0.0020	0.0010	0.0022
Dew Point	281.3	256.0	219.2	191.8	176.3	145.3

* SO_2 is half the concentration of H_2S and the balance is nitrogen

Equation 6.1 is similar to that developed for the prediction of sulphur vapour pressure by Meisen and Bennett [81].

The distribution of the sulphur polymers in the first reactor at 1 atm is shown in Fig. 6.1. At temperatures below 300°C, the principal sulphur polymers are S_6 and S_8 . Above 300°C, the dominant sulphur polymer is S_2 . S_4 is present in significant amounts between 400 and 600°C.

6.2 EXPERIMENTAL RESULTS

6.2.1. Minimum Fluidization Velocity

The minimum fluidization velocity for the catalyst particles was determined by fluidizing a bed of the particles with air in a Plexiglas column (100 mm ID). The distributor was similar to that used in the reactor.

By plotting the pressure drop across the bed as a function of the gas velocity, 0.0245 m/s was obtained as the minimum fluidization velocity (See Fig. 6.2). This value agrees well with the theoretical estimate of 0.0268 m/s (see Section 2.2.2). The difference between the experimental and theoretical values is 7.8%, indicating that there was no channelling.

Fig. 6.1: Equilibrium partial pressures of sulphur polymers

Fig. 6.2: Pressure drop versus air velocity for a bed of activated alumina (Kaiser S-501)

6.2.2. Sulphur Conversions

The sulphur conversion was calculated from the following equation:

$$C = \left[1 - \frac{F_{N_2} X_{out}}{F_{in}(1-X_{out})} \right] \times 100 \quad 6.2$$

where F_{N_2} is the nitrogen flow rate (assumed to be constant), F_{in} is the total flow rate of H_2S and SO_2 in the reactor feed and X_{out} is the total mole fraction of H_2S and SO_2 in the reactor effluent *after* moisture and sulphur removal. The computer programme for analysing the experimental data is presented in Appendix C.

6.2.2-1 Experimental and Theoretical Sulphur Conversions

In agreement with most previous studies on the Claus process [1, 14], it was observed that the experimental conversions are somewhat higher than the equilibrium values predicted from thermodynamic calculations. This finding is evident from Fig. 6.3 which shows the sulphur conversions as a function of temperature for a fixed H_2S feed concentration of 0.5%. Figure 6.4 which shows the sulphur conversions at 250 and 280°C as a function of H_2S feed concentration ranging from 0.06 to 1.0% also supports this finding.

Bennett and Meisen [84] had attributed the discrepancies

Fig. 6.3: Sulphur conversion as a function of reactor temperature (Operating conditions: H_2S - 0.5%, SO_2 - 0.25%, N_2 - 99.25%, pressure - 1 atm)

Fig. 6.4: Sulphur conversion as a function of H_2S concentration in feed (Operating conditions: bed height - 0.25 m, H_2S/SO_2 ratio - 2/1, pressure - 1 atm)

to possible inaccurate thermodynamic data. By slightly changing the free energy of the chemical species, they were able to match the experimental and theoretical conversions.

6.2.2-2 Effect of Temperature on Sulphur Conversion

As shown by Figs. 6.3 and 6.4, the experimentally determined sulphur conversions decrease with increasing temperature above 200°C. This suggests that the Claus reaction (which is strongly exothermic) is thermodynamically controlled.

However, below about 200°C the opposite behaviour is observed. This phenomenon is also confirmed by Fig. 6.5 which shows the experimental sulphur conversions at 150 and 200°C as a function of H₂S feed concentration ranging from about 0.05 to 1.0%. The conversions at 150°C are generally lower than those at 200°C. However, there is an exception for H₂S feed concentrations less than about 0.25%. Below 0.25%, the conversions at 150°C approach the values at 200°C; and, at an H₂S feed concentration of about 0.05%, the conversion at 150°C is higher than that at 200°C.

Thus the sulphur conversions are reduced at low temperatures coupled with high H₂S feed concentrations. The reason for this phenomenon is catalyst fouling caused by sulphur condensation. The latter could be observed experimentally by noting a yellow film on the catalyst. Sulphur condensation could also be predicted by calculating the thermodynamic equilibrium

Fig. 6.5: Sulphur conversion as a function of H_2S concentration in the feed (Operating conditions : H_2S/SO_2 ratio - 2/1)

partial pressure of sulphur (for details see Section 6.1) and comparing it with the sulphur vapour pressure.

6.2.2-3 Effect of U/U_{mf} on Sulphur Conversion

A weak, linear relationship was found to exist between the sulphur conversion and the ratio of the superficial gas velocity, U , to the minimum fluidization velocity, U_{mf} . This is presented in Fig. 6.6 which shows the sulphur conversion as a function of U/U_{mf} at a reactor temperature of 150°C and an H_2S feed concentration of 0.85%. The experimental conversion decreased from 99.8 to 98.7% when U/U_{mf} was increased from 4 to 8. This indicates that the Claus reaction is very fast and the performance of the fluidized bed is only slightly affected by gas by-passing the catalyst in the form of bubbles.

6.2.2-4 Effect of Bed Height on Sulphur Conversion

The sulphur conversions at 150 and 200°C and for bed heights of 0.12 and 0.25 m are presented in Fig. 6.5. The results indicate that the experimental conversions are virtually the same for the two bed heights. Once again, this implies that the Claus reaction is fast and goes essentially to completion within a bed height of about 0.12 m.

Fig. 6.6 : Sulphur conversion as a function of U/U_{mf} (Operating conditions: bed height -0.25 m, H_2S - 0.85%, SO_2 -0.425%, N_2 - 98.725%, pressure - 1 atm, temperature - 150°C)

6.2.2-5 Effect of H₂S Feed Concentration on Sulphur Conversion

Figures 6.4, 6.5 and 6.7 indicate that the sulphur conversion increases as the feed concentration of the reactants increases. Such behaviour is generally true when the number of moles decreases during the reaction. For the Claus reaction,

3 moles react to form $2 + \frac{3}{n}$ moles of product. According to Fig. 6.1, at temperatures less than 300°C, the average value of n is greater than 3 and therefore the reduction in moles occurred.

6.2.2-6 Comparison of Fluidized and Fixed Beds Sulphur Conversions

Figure 6.8 indicates that, at 280°C and for the feed concentrations of about 0.05 to 1.0%, sulphur conversions comparable to those obtainable with a fixed bed can be achieved in the fluidized bed. To operate the reactor as a fixed bed while maintaining the gas flow rate constant and in the same direction as the fluidized bed, about 2.4 kg of large spheres of the catalyst (-5+8 mesh) was used.

It was also observed that at 300°C and at 3% H₂S feed concentration, the fluidized bed conversion of 95.7% is comparable with 94.3% which was obtained by Gamson and Elkins [3] and 96.2%

Fig. 6.7: Sulphur conversion as a function of H₂S concentration in feed (operating conditions: bed height - 0.25 m, H₂S/SO₂ ratio - 2/1, pressure - 1 atm, temperature - 300°C, U/U_{mf} - 8.4)

Fig. 6.8: Sulphur conversion as a function of H_2S concentration in the feed (Operating conditions: bed height - 0.25 m, H_2S/SO_2 ratio - 2/1, pressure - 1 atm, temperature - 280°C)

obtained by Dalla Lana [85] using fixed beds.

6.3 PRACTICAL IMPLICATIONS

Based on the equilibrium predictions and the experimental findings, the modified Claus process shown in Fig. 6.9 is proposed. In this process, the traditional fixed bed reactors have been replaced by two fluidized bed reactors in series. The first and second reactors operate at temperatures above the dew point and below the melting point of sulphur, respectively. The first reactor functions as a reactor as well as a regenerator. Most of the H_2S and SO_2 in the furnace off-gas are converted to sulphur in the first reactor. The sulphur which condenses on the catalyst in the second reactor is recycled to and evaporated in the first reactor. A condenser located between the two reactors removes the sulphur from the first reactor effluent.

In another Claus process (See Fig. 6.10), a separate regenerator is provided to remove the sulphur formed on the catalyst in the second reactor. Although this process contains more units than the first process, it may be easier to design and operate. The circulation of catalyst between two reactors which are in series with respect to the gas flow requires proper pressure balance.

Equilibrium calculations based on these processes indicate that total sulphur conversion efficiencies in excess of

Fig. 6.9: Modified Claus process based on fluidized bed technology (Reactor 1 acts also as a regenerator)

Fig. 6.10: Modified Claus process based on fluidized bed technology (A separate catalyst regenerator is provided)

99% can be achieved. The experimental results based on the fluidized bed Claus reactor suggest that experimental sulphur conversions may be even higher.

6.4 ERROR ANALYSIS

The experimental sulphur conversion, C , was evaluated from the calibration curves of the rotameters and the analytical instruments. Hence the variance of C can be evaluated from the following equation,

$$\sigma_C^2 = \sum_{k=1}^7 \left\{ \left(\frac{\partial C}{\partial x_k} \right)_{x_j} \sigma_{x_k} \right\}^2$$

where x_k denotes the nominal flow rates of (1) the fluidizing N_2 , (2) H_2S (3) SO_2 , (4) product sample, (5) dilution air. x_6 and x_7 represent the concentrations of H_2S and SO_2 estimated from the readings of the gas analysers, respectively. The subscript x_j denotes that all variables except the k th one are held constant. The partial derivatives were calculated approximately by estimating the change in C for a small change in one of the variables while keeping the rest constant.

Table 6.3 summarizes the results of the calculations for the runs performed at $280^\circ C$. The first part of the table gives the numerical approximations of the partial derivatives. The second part of the table lists the variances and the standard deviations.

Table 6.3: Error analysis

Temperature = 280°C

Bed height = 0.25 m

Variable	Partial Derivatives for Various Variables				
	H ₂ S Feed Concentration				
	0.1830%	0.3522%	0.5611%	0.8102%	0.9795%
x_1	-1.3588×10^{-4}	-9.0587×10^{-5}	-7.4464×10^{-5}	-5.2845×10^{-5}	-3.8679×10^{-5}
x_2	4.9289×10^{-2}	1.6327×10^{-2}	8.2157×10^{-3}	3.9091×10^{-3}	2.4196×10^{-3}
x_3	4.9189×10^{-2}	1.6357×10^{-2}	8.3008×10^{-3}	3.6219×10^{-3}	2.0503×10^{-3}
x_4	9.3286×10^{-4}	5.1342×10^{-4}	4.1074×10^{-4}	3.0805×10^{-4}	2.0531×10^{-4}
x_5	-1.2030×10^{-4}	-7.6915×10^{-5}	-6.3110×10^{-5}	-2.9161×10^{-5}	2.1385×10^{-5}
x_6	-3.300×10^{-2}	-1.8889×10^{-2}	-1.1111×10^{-2}	-8.5714×10^{-3}	-7.1429×10^{-3}
x_7	-3.6667×10^{-2}	-2.000×10^{-2}	-1.222×10^{-2}	-8.5714×10^{-3}	-7.1429×10^{-3}
σ_c^2	0.78645	0.098879	0.031904	0.00712	0.00299
σ_c^2	0.88682	0.31445	0.17862	0.083738	0.05684

According to Table 6.3, the variances and hence the standard deviations decrease as the feed concentrations of H_2S increase. This trend can be explained by the sensitivity test which is summarized in Table 6.4. According to this test, the largest contribution to the variances arises from X_2 and X_3 which are the flow rates of H_2S and SO_2 , respectively. At low feed concentrations of H_2S the flow rates of the reactants are low and the floats in the rotameters are close to the bottom. Hence even very small errors in reading the position of the floats leads to large errors in the estimation of the sulphur conversion efficiency.

The average value of the standard deviation based on the mean of the variances for the runs at 280°C was 0.4306%. Hence the average error in the estimation of the sulphur conversion efficiency can be taken as ranging from about ± 0.5 to $\pm 1.0\%$.

Table 6.4 : Sensitivity test

Temperature = 280°C
 Bed Height = 0.25 m
 H₂S Feed Concentration = 0.5611%

Variable	$\Delta C/\Delta x_k$	σ_{x_k}	$(\Delta C/\Delta x_k)^2 \sigma_{x_k}^2$
x_1	-7.4464×10^{-5}	315.00	5.5019×10^{-4}
x_2	8.2157×10^{-3}	11.37	8.7259×10^{-3}
x_3	8.3008×10^{-3}	13.33	1.2243×10^{-2}
x_4	4.1074×10^{-4}	31.18	1.6402×10^{-4}
x_5	-6.3110×10^{-5}	1562.60	9.7251×10^{-3}
x_6	-1.1111×10^{-2}	1.1172	1.5412×10^{-4}
x_7	-1.222×10^{-2}	1.5127	3.417×10^{-4}

Chapter 7

7 CONCLUSIONS

7.1. SIMULATION OF VARIOUS TYPES OF CLAUS PLANTS

A mathematical model based on thermodynamic equilibrium calculations has been developed to estimate the product composition and sulphur conversion of various Claus processes. The computational procedure has considerable advantages over a similar method developed by Gamson and Elkins [3]. For instance, the present procedure selects its own initial values for the iterative solution of the equilibrium equations. This leads to a substantial saving of computer time and money.

The results of the calculations indicated that sulphur conversion efficiencies in excess of 99% can be achieved using a furnace and two fluidized bed reactors in series. The recycle of sulphur-laden catalyst from the second to the first reactor does not affect the overall sulphur conversion efficiency significantly. Hence the overall sulphur conversion efficiency is very similar to the two proposed processes (see Section 6.4). Finally, according to the thermodynamic calculations, removal of moisture from the furnace off-gas can improve the overall sulphur conversion efficiency.

7.2 EQUIPMENT PERFORMANCE

The equipment used to perform the experiments functioned very satisfactorily and safely. There was no detectable amount of H_2S and SO_2 in the neighbourhood of the equipment.

The temperature control of the reactor worked exceptionally well. The temperature of the fluidized bed could be controlled within $\pm 0.5\%$.

The purification of the recycled nitrogen was satisfactory. With a purge of about 10%, the purity of the recycled nitrogen could be maintained above 99.99%.

The sampling system functioned well. Dry surfaces were maintained in the conditioning units to eliminate further reaction between H_2S and SO_2 .

7.3 EXPERIMENTAL RESULTS

Second degree polynomials were fitted to the raw data of the variables involved in the estimation of the experimental conversion using the method of least squares. An error analysis indicated that the experimental sulphur conversions were determined with uncertainties less than about $\pm 1.0\%$. This is quite good considering the large number of variables involved. The high accuracy was achieved by rigorously calibrating each instrument.

From the experimental results presented in Section 6.2, the following conclusions can be drawn:

1. Sulphur conversions comparable to those attained in fixed bed Claus reactors can be achieved in fluidized bed reactors. This is due to the fact that the Claus reactions are fast. In addition, the catalyst activity has been enhanced by the large specific surface area of the fine particles used in the fluidized bed reactor as opposed to the coarse particles used in the fixed bed reactors.
2. The reactions are complete within a shallow bed height of about 0.12 m. This is again due to the high reaction rates and the large specific area of the fine catalyst particles.
3. Defluidization did not occur when experiments were performed in the presence of condensing sulphur. Although the sulphur build-up was low, the prevention of defluidization could be largely attributed to the rapid agitation of the bed by the gas bubbles.
4. Sulphur condensation reduces the activity of the catalyst. Contrary to thermodynamic predictions, sulphur conversions at 150°C were lower than those of 200°C. For H₂S feed concentrations between 0.2 and 1.0%, the sulphur dew point lies between 150°C and 200°C.

5. Fluidized bed Claus reactors operating at temperatures near 300°C can be used as catalyst regenerators. There was no condensed sulphur on the catalyst at 300°C even when the H_2S and SO_2 feed concentrations ranged up to 18 and 9%, respectively.

Chapter 8

8 RECOMMENDATIONS

1. In industrial Claus plants, the moisture in the furnace off-gas is allowed to enter the catalytic reactors even though its removal could substantially increase the sulphur conversion. It is therefore recommended that a moisture generator be provided to introduce water vapour into the feed of the experimental reactor. Such a system could also be used for additional testing of the sample conditioning procedure.
2. Runs should be conducted with impurities such as CO_2 , COS and CS_2 in the reactor feed.
3. Additional runs should be performed under condensing conditions to determine the rate of catalyst fouling.
4. Tests should be performed to study the long term stability of the catalyst.
5. Runs should be undertaken to obtain data using continuous catalyst circulation through the reactor. The results will be useful in the design of an industrial unit.
6. Exploratory studies should be conducted to investigate the direct oxidation of H_2S with air in the fluidized bed Claus reactor. If successful, such an arrangement could be of importance where H_2S concentrations are very low and SO_2 is absent.

7. Consideration should be given to building a larger pilot plant with a fluidized bed diameter of approximately 300 - 600 mm in diameter in order to elucidate scale-up problems. Such a large system could contain two reactors in series.

NOMENCLATURE

$B_1 \dots B_5$	Coefficients in the equilibrium equation
C	Sulphur conversion, %
C_i	Initial concentration of oxygen, %
C_f	Final concentration of oxygen
$C_1 \dots C_5$	Coefficients in the equilibrium equation
d_p	Particle diameter, μm
d_{p_i}	Arithmetic mean of the mesh dimensions of the two sieves that define the fraction i , μm (eq. 2.11)
d_b	Bed diameter, m
E, E_0	The signal from the SO_2 analyser for samples with and without H_2S .
F_{in}	Total flow rate of H_2S and SO_2 in the reactor feed
F_{N_2}	Flow rate of nitrogen through the reactor.
g	Gravitational acceleration, m/s^2
k_o	Reaction rate constant hr^{-1}
$K_i, i=1, 5$	Equilibrium Constants (chapter 3)
L	Bed height, m
L_{mf}	Bed height at U_{mf} , m
P	Total pressure in a reactor (atm)
r	Reaction rate, $gmole/hr - g-catalyst$

U	Superficial velocity, based on empty cross-section, m/s
U_{mf}	Minimum fluidization velocity, m/s
V	Volume of purged system, l
V_1	Volumetric flow rate of air at standard conditions, ml/min.
V_i	Volumetric flow rate of gas i at standard conditions, ml/min.
X_{out}	Total mole fraction of H_2S and SO_2 in the reactor effluent
x	Partial pressure of SO_2 (atm)
x_i	Fraction of material in size interval (eq. 2.11)
X_j, X_k	Variables of the error analysis
Y	Partial pressure of S_8 (atm)

Greek Symbols

ϵ	Voidage fraction of the bed
ϵ_{mf}	Voidage fraction at U_{mf}
μ	Fluid viscosity, Kg/ms
ρ	Fluid density, Kg/m ³
ρ_g	Gas density, Kg/m ³
ρ_i	Specific gravity of gas i with respect to air
ρ_p	Solid particles density, kg/m ³
ϕ	Fractional yield of sulphur achieved by the furnace
ϕ_s	Sphericity of particles
γ	Ratio between N ₂ and O ₂ in air
ΔP	Pressure drop across the bed, cm H ₂ O

REFERENCES

1. Anon, *Hydro. Proc.* 57, (1) 181 (1978).
2. George Z.M., *Phosphorous and Sulphur*, 1, 315-322 (1976).
3. Gamson B.W., Elkins R.H., *Chem. Eng. Prog.*, 49, 203 (1953).
4. Crynes B., Chemical Reactions as a Means of Separation - Sulfur Removal, Marcel Dekker, Inc., New York, (1977).
5. Durr J.H., Woertz B.B., Black C.L., *Proc. of American Petroleum Institute Refining Department, 41st Midyear Meeting*, 577-587 (1976).
6. Bennett H.A., Ph.D. thesis, University of British Columbia, Vancouver, B.C. (1979).
7. Kelley K.K., *U.S. Bur Mines Bull.* 406, (1937).
8. White W.B., Johnson S.M., Dantzig G.B., *J. Chem. Phys.* 28, 751 (1958).
9. Mc-Gregor D.E., Ph.D. Thesis, University of Alberta, Edmonton, Alberta (1971).
10. McBride B.J., Hermel S., Elders J.G., Gordon S., Thermodynamic Properties to 6000°K for 210 Substances Involving the First 18 Elements, NASA SP-3001, Washington, D.C. (1963).
11. Maadah A.G., Maddox R.N., *Hydro. Proc.*, 57, (8) 143 (1978).
12. Kellogg H.H., *Met. Trans.*, 2, 2161 (1971).
13. Bragg J.R., *AIChE Symposium Series*, 72, (156), 48-62 (1976).
14. Bennett H.A., Meisen A., *Can. J. Chem. Eng.*, 51, 720 (Dec. 1973).
15. Detry D., Drowart J., Goldfinger P., Keller H., and Rickert H., *Z. Phys. Chem.*, 55, 314 (1967).
16. Gomezplata A., Kugelman A.M., "Process Systems" in Gas-Solids Handling in the Process Industries, Marchello, J.M. Gomezplata, A., Marcel Dekker, Inc., New York (1976).

17. Carberry J.J., Chemical and Catalytic Reaction Engineering, McGraw-Hill, New York (1976).
18. Wen C.Y., Fan L.T., Models for Flow Systems and Chemical Reactors, Marcel Dekker, Inc., New York (1976).
19. Froment G.F., Bischoff K.B., Chemical Reactor Analysis and Design, John Wiley and Sons, New York, (1979).
20. Bukur D., Caram H.S., Amundson, N.R., "Some Models of Fluidized Bed Reactors" in Chemical Reactor Theory A Review, Lapidus L., Amundson N.R., Prentice-Hall, Inc. Englewood Cliffs, New Jersey (1977).
21. Wen C.Y., Yu Y.H., *A.I. Ch. E. J.*, 12, 610 (1966).
22. Kunii D., Levenspiel O., Fluidization Engineering, John Wiley and Sons, Inc., New York, (1969).
23. Orr Jr. C., Particulate Technology, McMillan, New York, (1966).
24. Toomey R.D., Johnstone H.F., *Chem. Eng. Prog. Symp. Series*, 49 (5), 51 (1953).
25. Levenspiel O., Walton J.S., *Chem. Eng. Prog. Symp. Series*, 50, (9), 1, (1954).
26. Dow W.M., Jakob M., *Chem. Eng. Prog.*, 47, 637 (1951).
27. Van Heerden G., Nobel P., Van Krevelen D.W., *Chem. Eng. Sci.*, 1, 51 (1951).
28. Wen C.Y., Leva M., *A.I. Ch. E.* 2, 482 (1956).
29. Kato K., Wen C.Y., *Chem. Eng. Sci.*, 24, 1351-1369 (1969).
30. Davidson J.F., Harrison D., Darton R.C., La Nauze R.D., "The Two-Phase Theory of Fluidization and Its Application to Chemical Reactor" in Chemical Reactor Theory A Review, Lapidus, L., Amundson, N.R., Prentice-Hall, Inc., Englewood Cliffs, New Jersey (1977).
31. Davidson J.F., Harrison D., Fluidized Particles, Cambridge University Press, New York (1963).
32. Geldart D., "The Behaviour of Freely Bubbling Fluidized Beds", Ph.D. dissertation, University of Bradford, U.K., (1971).

33. Toor F.D., Calderbank, P.H., "Performance of an 18 in Diameter Fluidized - Bed Catalytic Reactor with a Pseudo First-Order Reaction and Discussion of Scale-up Problems," in *Proc. of the Symp. on Fluidization, Montreal, I Chem. E. Sump. Ser.* (30), 12 (1968).
34. Hovmand S., Davidson, J.F., "Chemical Conversion in a Slugging Fluidized Bed," *Trans. Inst. Chem. Engrs.* 46, T190 (1968).
35. Behie L.A., Kehoe P., "The Grid Region in a Fluidized Bed Reactor," *A.I.Ch. E.* 19, 1070 (1973).
36. Chavarie C., Grace J.R., "Chemical Reaction in a Two-Dimensional Fluidized Bed," *Proc. of the 5th European Symp. on Chemical Reaction Engineering*, Elsevier, Amsterdam, B 9-37 (1972).
37. Rowe P.N., "The effect of Bubbles on Gas-Solid Contacting in Fluidized Beds," *Chem. Eng, Prog. Symp. Ser.*, 58 (38), 42 (1962).
38. Fryer C., Porter D.E., "Countercurrent Backmixing Model for Fluidized Bed Catalytic Reactors. Applicability of Simplified Solutions," *Ind. Eng. Chem. Fund.*, 11, 383 (1972).
39. Latham R., Potter O.E., "Back-mixing of Gas in a 6-in diameter Fluidized Bed," *Chem. Eng. J.*, 1, 152 (1970).
40. Davidson J.R., Harrison D., *Fluidized Particles*, Cambridge University Press, New York (1963).
41. Pyle D.L., "Fluidized Bed Reactors: A Review," *Advances in Chemistry Series No. 109 Chemical Reaction Engineering*, American Chemical Society, Washington, D.C. p.106 (1972).
42. Rowe P.N., Partridge B.A., *Trans. Inst. Chem. Engrs.* 43, T157 (1965).
43. Chiba T., Kobayashi, H., *Chem. Eng. Sci.* 25, p. 1375 (1970).
44. Toei R., Matsuno R., Miyakawa H., Nishiya K., Komagawa Y., *Chem. Eng. (Tokyo)* 32, p. 565 (1968).
45. Partridge B.A., Rowe P.N., *Trans. Inst. Chem. Engrs.* 44 T335 (1966).

46. Latham R., Hamilton C., Potter O.E., *Brit. Chem. Eng.* 13, 5, 333 (1968).
47. Orcutt J.C., Davidson J.F., Pigford R.L., *Chem. Eng. Progr. Symp. Ser.* 58, 38 (1962).
48. Toor F.D., Calderbank P.H., *Proc. Symp. Fluidization*, Netherlands University Press, Amsterdam, P 652 (1967).
49. Michell S.J., *Fluid and Particle Mechanics*, Pergamon Press, New York, P 318 (1970).
50. Grace J.R., Wen C.Y., Yerushalmi J., "Fluidization" in *Handbook of Multiphase Systems* by Hetsroni, G., Hemisphere Pub. Co., Washington D.C. (1980).
51. Leva M., *Fluidization*, McGraw-Hill, New York (1960).
52. Brotz W., *Fundamentals of Chemical Reaction Engineering*, Addison - Wesley Pub. Co. (1965).
53. Miller C.O., Logwinuk A.K., *Ind. Eng. Chem.*, 43, 1220 (1951).
54. Jordan D.G., *Chemical Process Development, Part 1*, Interscience Publishers, New York (1968).
55. Rowe P.N., Experimental Properties of Bubbles, in *Fluidization* edited by Davidson, J.F., Harrison D., Academic Press, New York (1971).
56. Taylor H.A., Wesley W.A., *J. Chem. Phys.* 31, 216 (1927).
57. Murthy A.R., Rao S.B., *Proc. Ind. Acad. Sci.* 24A, 283 (1951).
58. Dalla Lana I.G., McGregor D.E., Liu C.L., and Cormode A.E., *Paper 2-2 V. Eur and 2nd Int. Symp. Chem. Reaction Eng.*, Amsterdam, May 1972.
59. Cormode D.A., *M.Sc. Thesis*, University of Alberta, Edmonton (1965).
60. Grancher P., *Hydro Proc.* 57 (7), 1978.
61. George Z.M., *J. Catal.* 32, 261 (1974).
62. Landau M., Molyneux A., Houghton R., *I. Chem. E. Symp. Series*, No. 27, (1968).

63. George Z.M., in Sulfur Removal and Recovery from Industrial Processes, Adv. Chem. Series, No. 139, John B. Pfeiffer, Ed., Amer. Chem. Soc. Washington D.C. (1975).
64. Pearson M.J, "Recent Developments in Claus Catalysts", pub. by Kaiser Aluminium and Chemical Corporation and presented at the Canadian Natural Gas Processors' Association in Calgary, Nov. 24, 1972.
65. Maddox R.N., in Chemical Reactions As a means of Separation - Sulfur Removal. by Crynes B.L., Published by Marcel Dekker, Inc., New York.
66. Naber J.E., Wesselingh J.A., Groenendaal W., Dodd D.E., "The Shell Claus Off-Gas Treating Process", Proc. of 53rd Annual Convention of Gas Processors Association, 53 (1974).
67. Barthel Yves *et.al.* in Sulfur Removal and Recovery from Industrial Processes, Adv. Chem. Series, No. 139, John B. Pfeiffer, Ed., Amer. Chem. Soc. Washington, D.C. (1975).
68. Estep J.W., McBride G.T., West J.R. in Advances in Petroleum Chemistry and Refining, 6, 315, McKetta, J.J. ed., Interscience, N.Y. (1962).
69. Gray J.H., Handwerk G.E., Petroleum Refining Technology and Economics, 190, Marcel Dekker, Ind., New York (1975).
70. Goar B.G., Hydro. Proc., 47 (9), 249 (1968).
71. Kopp S.P., Morin M.M., "Sulphur Recovery at the Ram River Gas Plant," Prof. Gas Cond. Conf. University of Oklahoma, Norman, OK. (1977).
72. Meisen A., "A Novel Fluidized Bed Claus Proc." presented at the 27th Can. Chem. Eng. Conf., Calgary, Alberta, October 23 - 27 (1977).
73. Audas F.G., Gas and Coke, 13, 229 (1951).
74. Goar B.G., Hydro. Proc., 53 (7), 129 (1974).
75. Kunkel L.V., "A Review of Improvements of the Claus Sulfur Recovery Process," Proc. Annual Conv. Gas Proc. Ass. 57, 147 (1978).

76. Schampine L., Allen R., Numerical Computing: An Introduction, W.B. Saunder, 242 (1973).
77. Nelson G.O., Controlled Test Atmospheres - Principles and Techniques, Ann Arbor Science Pub., Inc. (1971).
78. Archibold R.G., *Hydro. Proc.*, 56 (3), 219 (1977).
79. Kaiser Chemicals Private Communication, Baton Rouge, LA. (1977).
80. Norman W.S. "There are Ways to Smoother Operation of Sulphur Plants," *Proc. Gas Cond. Conf.*, Univ. of Oklahoma, Norman, OK. (1976).
81. Meisen A., Bennet H.A., *Hydro. Proc.*, 58 (12), 131 (1979).
82. Watanable K., Jursa A.S., *J. Chem. Phys.*, 41, 1650 (1964).
83. Thermo Electron Corporation, Instruction Manual for Model 40 Pulsed Fluorescent SO₂ Analyser (1976).
84. Bennett H.A., Meisen A., *Can. J. Chem. Eng.* (in press).
85. Dalla Lana I.G., "Catalysis Research on the Modified Claus Process," *Energy Proc./Canada*, 70 (4), 34, 1978.
86. Perry R.H., Chilton C.H., Chemical Engineers Handbook, 5th ed. McGraw-Hill, New York (1973).
87. Hammond W.A., Drierite, the Versatile Desiccant and Its Applications in the Drying of Solids, Liquids and Gases, The Stoneman Press, Columbus, Ohio (1958).
88. Cosidine D.M., Process Instruments and Controls Handbook, McGraw-Hill Book Company, New York (1974).
89. Callahan F.J., Jr., Swagelok Tube Fitting and Installation Manual, Markad Service Co., Cleveland, Ohio (1974).
90. Instruction Manual for Model HO Pulsed Fluorescent SO₂ Analyser, TE5405-30-76, Thermo Electron Corporation, Hopkinton, Mass.
91. Instruction Manual for PI 201 Photoionization Monitor, HNU Systems, Inc., Newton, Mass.

92. Instruction Manual for Datalogger Model 2240A, P/N 427948,
John Fluke Mfg. Co., Inc., Mountlake Terrace, Washington.
93. Kohl A.L., Riesenfeld F.C., Gas Purification, McGraw-Hill
Book Co., New York (1980).

APPENDIX A

COMPUTER PROGRAMME FOR THE SIMULATION OF
VARIOUS TYPES OF CLAUS PLANTS

The Fortran IV computer programme was used for predicting the performance of two fluidized bed Claus reactors in series. The equilibrium composition and conversion in each reactor were estimated. In addition, total process conversions (including the furnace) were calculated.

The programme for Case 1 (see section 3.1), listed subsequently, consists of a main programme and five subprogrammes. A caption at the beginning of each set of listings describes its function. The main symbols used in the programme are defined by the comment statements at the beginning of the main programme.

To check the validity of the algorithms, material balances for all the elements present in the reactors were performed. In the computer output, the temperatures are in degrees Kelvin and the equilibrium composition consists of the partial pressures of the components in atmospheres. For more details on the Equilibrium model see Section 3.1.

```

C *****
C *
C * THIS PROGRAMME DETERMINES THE MATERIAL BALANCE OF THE CLAUS *
C * REACTION AT EQUILIBRIUM IN TWO FLUIDIZED BED REACTORS IN *
C * SERIES USING THE EQUILIBRIUM CONSTANT METHOD *
C *
C * DELFT = CHANGE IN GIBBS FREE ENERGY FOR THE STANDARD STATE *
C * PER FORMULA IN GRAM CALORIES *
C * RK = EQUILIBRIUM CONSTANT *
C * A = COEFFICIENTS FOR THE FREE ENERGY EXPRESSIONS *
C * TEMP = TEMPERATURE *
C * H2S = PARTIAL PRESSURE OF HYDROGEN SULPHIDE *
C * S = PARTIAL PRESSURE OF SULPHUR *
C * S2 = PARTIAL PRESSURE OF SULPHUR POLYMER OF 2 ATOMS *
C * S4 = PARTIAL PRESSURE OF SULPHUR POLYMER OF 4 ATOMS *
C * S6 = PARTIAL PRESSURE OF SULPHUR POLYMER OF 6 ATOMS *
C * S8 = PARTIAL PRESSURE OF SULPHUR POLYMER OF 8 ATOMS *
C * SO2 = PARTIAL PRESSURE OF SULPHUR DIOXIDE *
C * H2O = PARTIAL PRESSURE OF WATER *
C * N2 = PARTIAL PRESSURE OF NITROGEN *
C * O2 = PARTIAL PRESSURE OF OXYGEN *
C * B,C = COEFFICIENTS OF POLYNOMIALS *
C * RR = PERCENTAGE CONVERSION IN THE FLAME COMBUSTION *
C * N = NUMBER OF TEMPERATURES USED *
C * BH = PARTIAL PRESSURES OF COMPONENTS IN THE SECOND REACTOR *
C * CHM = PARTIAL PRESSURES OF COMPONENTS IN THE FIRST REACTOR *
C * M = NUMBER OF CHEMICAL SPECIES *
C * SENAM = NAME OF SPECIES *
C * DEL = TOTAL MOLES PER UNIT TOTAL PRESSURE IN FIRST REACTOR *
C * A1 = MOLES OF SO2 IN FIRST REACTOR *
C * A2 = MOLES OF H2S IN FIRST REACTOR *
C * %CCNV1 = CONVERSION IN FIRST REACTOR *
C * %CCNV2 = CONVERSION IN SECOND REACTOR *
C * TCCNV12 = TOTAL CONVERSION IN FIRST AND SECOND REACTOR *
C * TCCNV = TOTAL CONVERSION IN FURNACE + REACTORS *
C * TEP = TOTAL PRESSURE AT EQUILIBRIUM *
C *****
C
C
C
C

```

```

IMPLICIT REAL*8 (A-H,O-Z), INTEGER (I-N)
DIMENSION A(20,20), B(10), C(10), D(500), EH(20,20), CHM(20,20), SPNAM(2
10), RK(10), TT(20), FCCN1(20), PCONV2(20), TCONV(20), V(20)
DIMENSION FF(20), IFAG1(20), FRTT(20)
DIMENSION VB(20,20), VC(20,20)
DIMENSION ATCM(5), AMEI(5), AMBO(5), TCOV12(20)
COMMON /AMMA/RK,B,C,F
COMMON /AFUA/T1,T2,T3,T4,T5,A
EXTERNAL F
EXTERNAL G
READ(5,860) (ATCM(I), I=1,5)
REAL(5,200) M
READ(5,200) N
WRITE(6,320)

```

```

WRITE (6,330)
WRITE (6,340)
WRITE (6,350)
WRITE (6,340)
WRITE (6,330)
WRITE (6,340)
DO 10 II=1,M
  READ (5,300) SPNAM (II), (A (II,J),J=1,7)
  WRITE (6,310) SPNAM (II), (A (II,J),J=1,7)
10  WRITE (6,340)
  WRITE (6,330)
  T=383.2D0
  T1=1.0D0-DLCG (T)
  T2=T
  T3=T*T
  T4=T3*T
  T5=T4*T
  DELFT5=2.0D0*FRT (3)+3.0D0*FRT (10)-2.0D0*FRT (2)-FRT (1)
  RK (5) =DEXP (-DEFLT5)
  DO 7C IN=1,3
    READ (5,100) P
    READ (5,100) TI
    READ (5,100) RR
  DO 20 I=1,N
    ZI=I-1
    T=TI+ZI*50.0D0
    TT (I)=I
C
C ***** CALCULATION OF EQUILIBRIUM CCNSTANTS
C
  T1=1.0D0-DLOG (T)
  T2=T
  T3=T*T
  T4=T3*T
  T5=T4*T
  DO 30 K=1,7
    FRIT (K)=A (K,1)*T1-A (K,2)*T2*0.5D0-A (K,3)*T3/6.0D0-A (K,4)*T4/12.0D
30  10-A (K,5)*T5*0.05D0+A (K,6)/T2-A (K,7)
    DELFT1=2.0D0*FRIT (3)+0.375D0*FRIT (7)-2.0D0*FRIT (2)-FRIT (1)
    RK (1) =DEXP (-DEFLT1)
    DELFT2=FRIT (4)-0.25D0*FRIT (7)
    RK (2) =DEXP (-DEFLT2)
    DELFT3=FRIT (5)-0.5D0*FRIT (7)
    RK (3) =DEXP (-DEFLT3)
    DELFT4=FRIT (6)-0.75D0*FRIT (7)
    RK (4) =DEXP (-DEFLT4)
    WRITE (6,360)
    WRITE (6,370)
    WRITE (6,380)
    WRITE (6,660) TT (I)
    WRITE (6,380)
    WRITE (6,370)
    WRITE (6,380)
    WRITE (6,390)

```

```

WRITE (6,380)
WRITE (6,370)
WRITE (6,380)
DO 40 K=1,5
WRITE (6,400) K, RK(K)
40 WRITE (6,380)
WRITE (6,370)

C
C ***** CALCULATION OF THE EQUILIBRIUM DATA FOR THE FIRST REACTOR
C
KK=1
D(1)=0.0DC
41 IF (KK.EQ.2) GO TO 65
R = RR-D(KK)
KK=KK+1

C
C ***** CALCULATION OF COEFFICIENTS OF POLYNOMIALS
C
BTA=2.0D0*(1.0D0-RR)/3.0D0
APH=1.0D0-R
BR = (3.762D0+3.0D0*BTA)*APH-(2.0D0*APH-3.0D0*BTA)*(1.881D0-BTA)
B(1)=ETA*APH/ER
B(2)=RK(2)*ETA*(APH+2.0D0*ETA+3.762D0)/BR
B(3)=RK(3)*BTA*(APH+4.0D0*ETA+7.524D0)/ER
B(4)=RK(4)*ETA*(APH+6.0D0*ETA+11.286D0)/BR
B(5)=ETA*(APH+8.0D0*ETA+15.048D0)/BR
CR=ER
C(1)=- (2.0D0*APH-3.0D0*BTA)*BTA/CR
C(2)=RK(2)*ETA*(2.0D0*APH+3.0D0*ETA+7.524D0)/CR
C(3)=RK(3)*BTA*(2.0D0*APH+9.0D0*ETA+15.048D0)/CR
C(4)=RK(4)*ETA*(2.0D0*APH+15.0D0*ETA+22.572D0)/CR
C(5)=ETA*(2.0D0*APH+21.0D0*ETA+30.096D0)/CR

C
C ***** PRINTING THE COEFFICIENTS OF FUNCTIONS
C
WRITE (6,370)
WRITE (6,370)
WRITE (6,380)
WRITE (6,410)
WRITE (6,380)
WRITE (6,370)
WRITE (6,380)
DO 43 JI=1,5
WRITE (6,420) JI,B(JI)
43 WRITE (6,380)
WRITE (6,370)
WRITE (6,380)
DO 44 JI=1,5
WRITE (6,430) JI,C(JI)
44 WRITE (6,380)
WRITE (6,370)
BS=0.1D0
CS=0.0D0
CALL ZERCIN(G,BS,CS,0.0D0,1.0D-05,IFLAG)

```

```

56      EPSL1=0.01D0
      EPSL1=EPSL1*C.1D0
      IF (BS.LE.EPSL1) GC TO 56
45      EB=BS-EPSL1
      FB=F(EB)
      IF (FB.IT.0.0D0) GC TO 46
      EPSL1=EPSL1*0.5D0
      GO TO 45
46      EPSL2=0.0001D0
47      EPSL2=EPSL2*C.1D0
      IF (BS.LE.EPSL2) GC TO 47
49      CC=BS-EPSL2
      FC=F(CC)
      IF (FC.GT.0.0D0) GC TO 48
      EPSL2=EPSL2*2.0D0
      IF (BS.LE.EPSL2) GC TO 47
      GO TO 49
48      RELEP=1.0E-10
      CALL ZERCIN(F,EB,CC,0.0D0,RELEP,IFLAG)
      X=EB
      FF(I)=F(X)
      LFLAG1(I)=IFLAG
      X2=X**0.25D0
      X3=X2*X2
      X4=X3*X2
      Q =B(1)*P-E(2)*X2-B(3)*X3-B(4)*X4-B(5)*X
      S =C(1)*P+C(2)*X2+C(3)*X3+C(4)*X4+C(5)*X
      S1=RK(2)*X2
      S2=RK(3)*X3
      S3=RK(4)*X4
      S4=3.760D0*(Q+0.5D0*S)
      CHM(I,1)=Q
      CHM(I,2)=2.0D0*Q
      CHM(I,3)=S
      CHM(I,4)=S1
      CHM(I,5)=S2
      CHM(I,6)=S3
      CHM(I,7)=X
      CHM(I,8)=S4
      CHM(I,9)=0.0D0
      TOTS=3.0D0*Q+2.0D0*S1+4.0D0*S2+6.0D0*S3+8.0D0*X
      PCCN1(I)=(1.0D0-3.0D0*Q/TOTS)*100.D0

C
C      ***** CALCULATION OF THE EQUILIBRIUM DATA FOR THE SECCND REACTOR
C
      DEL = ETA/(2.0D0*Q+S)
      A1=DEL*Q
      A2=DEL*S
      ALF=A2+2.0D0*A1+1.880D0
      AL=1.880D0/ALF
      U1=(AL-3.0D0)
      U2=(AL-1.0D0)
      U3=P*RK(5)
      B1=-U1*U1/U3/4.0D0

```



```

C1=+U1*U2/U3/2.0D0
D1=-U2*U2/U3/4.0D0
CALL CUERCT(B1,C1,D1,Y,A1,ALP)
BH(I,1)=Y*P
BH(I,2)=2.0D0*Y*P
BH(I,3)=(1.0D0-3.0D0*Y-AL*(1.0D0-Y))*P
BH(I,4)=A1*(1.0D0-Y)*P
BH(I,5)=3.0D0*(A1-Y*ALF/(1.0D0-Y))
V(I)=BH(I,1)+BH(I,2)+BH(I,3)+BH(I,4)
D(KK)=3.0D0*(A1-Y*ALF/(1.0D0-Y))
EPS2=LABS(D(KK)-D(KK-1))
IF(EPS2.GT.1.0D-C6) GO TO 41
65  KR=KK-1
PCCNV2(I)=(1.0D0-Y*ALP/A1/(1.0D0-Y))*100.0D0
TCCV12(I)=(DEL*(TCTS-3.0D0*Q)+D(KK))*100.0D0/0.3D0
TCCNV(I)=70.0D0+(DEL*(TOTS-3.0D0*Q)+D(KK))*100.0D0
AMBI(1)=1.0D0-RR
AMBO(1)=3.0D0*Y*ALP/(1.0D0-Y)+DEL*(TCTS-3.0D0*Q)+D(KK)
AMBI(2)=2.0D0*(1.0D0-RR)/3.0D0
AMBO(2)=A2+2.0D0*A1
AMBI(3)=4.0D0*(1.0D0-RR)/3.0D0
AMBO(3)=2.0D0*(A2+2.0D0*A1)
AMBI(4)=1.88D0
AMBO(4)=1.88D0
AMBI(5)=1.0D0-RR
AMBO(5)=DEL*TCTS
WRITE(6,810)
WRITE(6,830)
WRITE(6,840)
WRITE(6,820)
WRITE(6,840)
WRITE(6,830)
WRITE(6,840)
DO 90 IA=1,5
90  WRITE(6,850) ATCM(IA),AMBI(IA),AMEC(IA)
WRITE(6,840)
WRITE(6,830)
20  CCNTINUE
WRITE(6,500)
WRITE(6,510)
WRITE(6,520)
WRITE(6,580) P
WRITE(6,520)
WRITE(6,510)
WRITE(6,520)
WRITE(6,560)
WRITE(6,520)
WRITE(6,510)
WRITE(6,520)
WRITE(6,540)
WRITE(6,520)
WRITE(6,510)
WRITE(6,520)
DO 61 I=1,N

```

```

61  WRITE(6,530) TT(I), (CHM(I,J), J=1,9), FCCN1(I)
    WRITE(6,520)
    WRITE(6,510)
    WRITE(6,510)
    WRITE(6,510)
    WRITE(6,500)
    WRITE(6,600)
    WRITE(6,590)
    WRITE(6,570)
    WRITE(6,590)
    WRITE(6,600)
    WRITE(6,590)
    WRITE(6,620)
    WRITE(6,590)
    WRITE(6,600)
    WRITE(6,590)
    DC 52 I=1,N
    WRITE(6,610) TT(I), (BH(I,J), J=1,5), V(I), PCCNV2(I), TCOV12(I), TCGNV(
2I)
52  WRITE(6,590)
    WRITE(6,600)
    WRITE(6,600)
    WRITE(6,600)
    WRITE(6,360)
    WRITE(6,690)
    WRITE(6,680)
    WRITE(6,670)
    WRITE(6,680)
    WRITE(6,690)
    DC 55 IC=1,N
    WRITE(6,700) IC, FF(IC), IC, IFAG1(IC)
55  WRITE(6,680)
    WRITE(6,690)
70  CONTINUE
100  FORMAT(5D10.3)
200  FORMAT(I2)
300  FORMAT(A4,4D15.7,/,3D15.7)
310  FORMAT(10X,'*',A4,2X,7D15.7,2X,'*')
320  FORMAT('1',/////////)
330  FORMAT(10X,115(1H*))
340  FORMAT(10X,'*',113X,'*')
350  FORMAT(10X,'*',43X,'COEFFICIENTS OF FREE ENERGY',43X,'*')
360  FORMAT('1',/////////)
370  FORMAT(50X,32(1H*))
380  FORMAT(50X,'*',30X,'*')
390  FORMAT(50X,'*',5X,'EQUILIBRIUM CCNSTANTS',4X,'*')
400  FORMAT(50X,'*',4X,'RK('',I2,'')=',D15.7,4X,'*')
410  FORMAT(50X,'*',2X,'CCEFFICIENTS OF POLYNOMIALS',1X,'*')
420  FORMAT(50X,'*',5X,'B('',I1,'')=',D15.7,5X,'*')
430  FORMAT(50X,'*',5X,'C('',I1,'')=',D15.7,5X,'*')
500  FORMAT('1',/////////)
510  FORMAT(8X,116(1H*))
520  FORMAT(8X,'*',114X,'*')
530  FORMAT(8X,'*',F8.2,4X,10F10.5,2X,'*')

```

```

540  FORMAT(8X,'*',3X,'TEMP',8X,'SO2',7X,'H2S',7X,'H2O',8X,'S2',8X,'S4'
1,8X,'S6',8X,'S8',8X,'N2',8X,'O2',6X,'%CCNV1',4X,'*')
560  FORMAT(8X,'*',35X,'EQUILIBRIUM COMPOSITION FOR THE FIRST REACTOR',
134X,'*')
580  FORMAT(8X,'*',49X,'PRESSURE=',F6.2,50X,'*')
570  FORMAT(13X,'*',29X,'EQUILIBRIUM COMPOSITION FOR THE SECOND REACTOR
1',29X,'*')
590  FORMAT(13X,'*',104X,'*')
600  FORMAT(13X,106(1H*))
610  FORMAT(13X,'*',F8.2,4X,9F10.5,2X,'*')
620  FORMAT(13X,'*',3X,'TEMP',8X,'SO2',7X,'H2S',7X,'H2O',8X,'N2',8X,'SH
1',7X,'TEP',6X,'%CCNV2',4X,'TCCNV12',4X,'TCONV',2X,'*')
660  FORMAT(50X,'*',4X,'TEMPERATURE=',F10.2,4X,'*')
670  FORMAT(35X,'*',18X,'OUTPUT FROM ZERCIN',18X,'*')
680  FORMAT(35X,'*',54X,'*')
690  FORMAT(35X,56(1H*))
700  FORMAT(35X,'*',7X,'FF(',I2,')=',D15.7,6X,'FLAG(',I2,')=',1X,I2,7X,
1'')
810  FORMAT('1',/////////)
820  FORMAT(35X,'*',1X,'GRAM ATOM OF',14X,'INPUT',15X,'OUTPUT',7X,'*')
830  FORMAT(35X,62(1H*))
840  FORMAT(35X,'*',60X,'*')
850  FORMAT(35X,'*',7X,A1,7X,2F20.8,5X,'*')
860  FORMAT(5A1)
870  FORMAT(8F10.5)
      STCP
      END

```

```

C *****
C *
C * SUBPROGRAMME FOR CALCULATING F/RT WHERE F
C * IS GIBBS FREE ENERGY
C *
C *****
C
FUNCTION FRT(K)
IMPLICIT REAL*8 (A-H,O-$), INTEGER (I-N)
DIMENSION A(20,10)
COMMON /AFUA/T1,T2,T3,T4,T5,A
FRT=A(K,1)*T1-A(K,2)*T2*0.5D0-A(K,3)*T3/6.0D0-A(K,4)*T4/12.0D0-A(K
1,5)*T5*0.05D0+A(K,6)/T2-A(K,7)
RETURN
END
C
C
C *****
C *
C * SUBPROGRAMME FOR CALCULATING THE MAIN FUNCTION
C *
C *****
C
FUNCTION F(X)
IMPLICIT REAL*8 (A-H,C-$), INTEGER (I-N)
DIMENSION RK(10),E(10),C(10),CHM(20,20)
COMMON /AMMA/RK,E,C,P
X2=X**0.25D0
X3=X2*X2
X4=X3*X2
ZC=B(1)*P-E(2)*X2-E(3)*X3-E(4)*X4-E(5)*X
ZA=C(1)*F+C(2)*X2+C(3)*X3+C(4)*X4+C(5)*X
F=RK(1)-ZA*ZA*X**0.375D0*0.25D0/ZC/ZC/ZC
RETURN
END
C
C
C *****
C * SUBPROGRAMME FOR CALCULATING THE FUNCTION
C * WHICH DETERMINES THE PCINI WHERE THE MAIN
C * FUNCTION IS NOT CONTINUOUS
C *
C *****
C
FUNCTION G(X)
IMPLICIT REAL*8 (A-H,O-$), INTEGER (I-N)
DIMENSION RK(10),E(10),C(10),CHM(20,20)
COMMON /AMMA/RK,E,C,F
X2=X**0.25D0
X3=X2*X2
X4=X3*X2
G=B(1)*P-B(2)*X2-B(3)*X3-B(4)*X4-E(5)*X
RETURN
END

```

```

*****
*
*               SUBROUTINE ZERCIN
*
*   ZERCIN COMPUTES A ROOT OF THE NON LINEAR EQUATION
*   F(X)=0 WHERE F(X) IS A CONTINUOUS REAL FUNCTION OF
*   A SINGLE VARIABLE X. THE METHOD USED IS A COMBINATION
*       OF BISECTION AND THE SECANT
*
*   NORMAL INPUT CONSISTS OF A CONTINUOUS FUNCTION F AND
*   AN INTERVAL (E,C) SUCH THAT F(E)*F(C).LE.0.0D0. EACH
*   ITERATION FINDS NEW VALUES OF B AND C SUCH THAT THE
*   INTERVAL(B,C) IS SHRUNK AND F(E)*F(C).LE.0.0D0. THE
*       STOPPING CRITERION IS
*
*       DABS(E-C).LE.2.0*(RELER*DAES(B)+ABSER)
*
*   WHERE RELER=RELATIVE ERROR AND ABSER=ABSOLUTE ERROR
*   ARE INPUT QUANTITIES. AS B AND C ARE USED FOR BOTH
*   INPUT AND OUTPUT, THEY MUST BE VARIABLES IN THE
*       CALLING PROGRAMME
*
*   IF 0 IS A POSSIBLE ZERO, ONE SHOULD NOT CHOOSE ABSER=0.
*
*   THE OUTPUT VALUE OF B IS THE BETTER APPROXIMATION TO
*   A ROOT AS B AND C ARE ALWAYS REDEFINED SO THAT
*       DABS(F(B)).LE.DABS(F(C)).
*
*   A FLAG, IFLAG IS PROVIDED AS AN OUTPUT QUANTITY. IT MAY
*       ASSUME THE VALUES 1-5 WHERE
*
*   IFLAG=1 IF F(E)*F(C).LT.0 AND THE CRITERION IS MET
*
*       =2 IF A VALUE B IS FOUND SUCH THAT THE COMPUTED
*           VALUE F(B) IS EXACTLY ZERO. THE INTERVAL (B,C)
*           MAY NOT SATISFY THE STOPPING CRITERION.
*
*       =3 IF DAES(F(B)) EXCEEDS THE INPUT VALUES
*           DABS(F(B)), DABS(F(C)). IN THIS CASE IT IS
*           LIKELY THAT B IS CLOSE TO A POLE OF F
*
*       =4 IF NO CDD ORDER ZERO WAS FOUND IN THE INTERVAL.
*           A LOCAL MINIMUM MAY HAVE BEEN OBTAINED.
*
*       =5 IF TOO MANY FUNCTION EVALUATIONS WERE MADE.
*           (AS PROGRAMMED, 500 ARE ALLOWED)
*
*****
SUBROUTINE ZERCIN(F,B,C,ABSER,RELER,IFLAG)
IMPLICIT REAL*8 (A-H,O-Z), INTEGER (I-N)

```

(HERE AN IBM 360/67)

U=1.0D-10

```

RE=DMAX1(RELER,U)
IC=0
ACBS=DAES(B-C)
A=C
FA=F(A)
FB=F(E)
FC=FA
KCCUNT=2
FX=DMAX1(DAES(FE),DAES(FC))
1 IF(DAES(FC).GE.DAES(FB)) GC TO 2
C
C *****INTERCHANGE E AND C SO THAT DABS(F(B)).LE.DABS(F(C))
C
A=E
FA=FB
B=C
FB=FC
C=A
FC=FA
2 CMB=0.5D0*(C-B)
ACMB=DAES(CME)
TOI=RE*DAES(E)+AESER
C
C *****TEST STOPPING CRITERION AND FUNCTION COUNT.
C IF(ACMB.LE.TCL) GC TC 8
IF(KCCUNT.GT.500) GO TC 12
C
C *****CALCULATE NEW ITERATE IMPLICITLY AS B+P/Q
C *****WHERE WE ARRANGE P.GE.0.D0. THE IMPLICIT
C *****FCRM IS USED TO PREVENT CVERFLOW
C
P=(E-A)*FE
Q=FA-FE
IF(P.GE.0.D0) GC TO 3
P=-P
Q=-Q
C
C *****UPDATE A, CHECK IF REDUCTION IN THE SIZE OF BRACKETING
C *****INTERVAL IS SATISFACTORY. IF NOT, BISECT UNTIL IT IS.
C
3 A=E
FA=FB
IC=IC+1
IF(IC.LT.4) GO TO 4
IF(8.0D0*ACME.GE.ACBS) GO TO 6
IC=0
ACES=ACME
C
C *****TEST FOR TOO SMALL A CHANGE
C
4 IF(P.GT.DABS(Q)*TCL) GO TO 5
C
C *****INCREMENT BY TOLERANCE

```

```

C      B=B+DSIGN(TCL,CME)
      GO TO 7
C
C      *****RCOT OUGHT TO BE BETWEEN E AND (C+B)/2.
C
C      IF (P-GE.CME*Q) GO TO 6
C
C      *****USE SECANT RULE
C
      B=B+E/Q
      GO TO 7
C
C      *****USE BISECTION
C
      B=0.5D0*(C+E)
C
C      *****HAVE COMPLETED COMPUTATION FOR NEW ITERATE B.
C
      7      FB=F(B)
      IF (FE.EQ.0.0D0) GO TO 9
      KCCUNT=KCCUNT+1
      IF (DSIGN(1.0D0,FE).NE.DSIGN(1.0D0,FC)) GO TO 1
      C=A
      FC=FA
      GO TO 1
C
C      *****FINISHED SET IFLAG.
C
      8      IF (DSIGN(1.0D0,FE).EQ.DSIGN(1.0D0,FC)) GO TO 11
      IF (CAES(FB).GT.FX) GO TO 10
      IFLAG=1
      RETURN
      9      IFLAG=2
      RETURN
      10     IFLAG=3
      RETURN
      11     IFLAG=4
      RETURN
      12     IFLAG=5
      RETURN
      END

```

```

C *****
C *
C *
C *
C *
C *
C *
C *
C *****
SUBROUTINE CUBRCT (E1,C1,D1,Y,P1,ALF)
IMPLICIT REAL*8 (A-H,O-$), INTEGER (I-N)
DIMENSION H (10)
P= (3.0D0*C1-E1*E1)/3.0D0
Q= (27.0D0*D1-9.0D0*E1*C1+2.0D0*E1*E1*B1)/27.0D0
R= (P/3.0D0)**3+ (Q/2.0D0)**2
IF (R.LT.0D0) GO TC 2
AS=-Q*0.5D0+DSQRT (R)
AR=DAES (AS)
A=AR**0.33333333DC
IF (AS.LT.0.0D0) A=-A
BS=-Q*0.5D0-DSQRT (R)
BR=DAES (BS)
B=BR**0.33333333DC
IF (BS.LT.0.0D0) B=-B
IF (R.EQ.0D0) GO TC 1
Y=A+B -B1/3.0D0
RETURN
1 Y1=A+E-E1/3.0D0
Y2=- (A+E)/2.0D0-E1/3.0D0
Y3=Y2
F1=Y1*ALF/ (1.0D0-Y1)
F2=Y2*ALF/ (1.0D0-Y2)
F3=Y3*ALF/ (1.0D0-Y3)
GO TC 4
2 V=3.0D0*Q/2.0D0/F*DSQRT (3.0D0/ (-P))
V=ABS (V)
W=V*DSQRT (1.0D0-V*V)
U=DATAN (W)
DUMMY=1.0D0
IF (Q.LT.0D0) DUMMY=-1.0D0
DO 3 K=1,3
Z=K
3 H (K)=DUMMY*2.0D0* (-P/3.0D0)**0.5D0*DCOS (U/3.0D0+120.0D0*Z)
Y1=H (1)
Y2=H (2)
Y3=H (3)
F3=Y3*ALF/ (1.0D0-Y3)
F2=Y2*ALF/ (1.0D0-Y2)
F1=Y1*ALF/ (1.0D0-Y1)
4 IF (F1.LT.0.0D0.OR.F1.GT.P1) GO TC 5
Y=Y1
RETURN
5 IF (F2.LT.0.0D0.OR.F2.GT.P1) GO TO 6
Y=Y2
RETURN
6 Y=Y3

```


RETURN
END

SOHNS

11

10

SO2 +3.2257132D+00 +5.6551207D-03 -2.4970208D-07 -4.2206766D-09
 +2.1392733D-12 -3.6904476D+04 +9.8177036D+00
 H2S +3.9163074D+00 -3.5138671D-04 +4.2191312D-06 -2.7453665D-09
 +4.8584365D-13 -3.6095585D+03 +2.3660042D+00
 H2O +4.1565016D+00 -1.7244334D-03 +5.6982316D-06 -4.5930044D-09
 +1.4233654D-12 -3.0288770D+04 -6.8616246D-01
 S2 +2.6999349D+00 +6.2749549D-03 -9.2870775D-06 +6.5393276D-09
 -1.7802282D-12 +1.4504935D+04 +1.0534222D+01
 S4 +6.3056669D+00 +1.2549910D-02 -1.8574155D-05 +1.3078655D-08
 -3.5604564D-12 +1.4389870D+04 -2.2860887D+00
 S6 +6.0892429D+00 +1.8824865D-02 -2.7861233D-05 +1.9617983D-08
 -5.3406846D-12 +1.1264370D+04 +7.3202322D+00
 S8 +7.7838968D+00 +2.5099820D-02 -3.7148310D-05 +2.6157310D-08
 -7.1209128D-12 +1.0114584D+04 +4.7621792D+00
 N2 +3.6916148D+00 -1.3332552D-03 +2.6503100D-06 -9.7688341D-10
 -9.9772234D-14 -1.0628336D+03 +2.287498D+00
 O2 +3.7189946D+00 -2.5167288D-03 +8.5837353D-06 -8.2998716D-09
 +2.7082180D-12 -1.0576706D+03 +3.9080704D+00
 SM -3.7836657D+00 -1.2642081D-01 +1.0408762D-03 -2.1584163D-06
 +1.1150175D-09 +1.2900773D+03 +3.373418D+01
 S +2.9137258D+00 +3.1294061D-04 -2.6092508D-06 +3.1382439D-09
 -1.1708988D-12 +3.2568272D+04 +3.5681154D+00
 +0.050D+01
 +4.000D+02
 +0.070D+01
 +0.100D+01
 +4.000D+02
 +0.070D+01
 +0.200D+01
 +4.000D+02
 +0.070D+01

```

*****
*
*                                COEFFICIENTS OF FREE ENERGY                                *
*
*****
*
*SD2      0.3225713E+01  0.5655121E-02 -0.2497021E-06 -0.4220677E-08  0.2139273E-11 -0.3690448E+05  0.9817704E+01
*
*H2S      0.3916307E+01 -0.3513867E-03  0.4219131E-05 -0.2745366E-08  0.4858436E-12 -0.3609558E+04  0.2366004E+01
*
*H2O      0.4156502E+01 -0.1724433E-02  0.5698232E-05 -0.4593004E-08  0.1423365E-11 -0.3028877E+05 -0.6861625E+00
*
*S2       0.2699935E+01  0.6274955E-02 -0.9287077E-05  0.6539328E-08 -0.1780228E-11  0.1450494E+05  0.1053422E+02
*
*S4       0.6305667E+01  0.1254991E-01 -0.1857415E-04  0.1307866E-07 -0.3560456E-11  0.1438987E+05 -0.2286089E+01
*
*S6       0.6089243E+01  0.1882486E-01 -0.2786123E-04  0.1961798E-07 -0.5340685E-11  0.1126437E+05  0.7320232E+01
*
*S8       0.7783897E+01  0.2509982E-01 -0.3714831E-04  0.2615731E-07 -0.7120913E-11  0.1011458E+05  0.4762179E+01
*
*N2       0.3691615E+01 -0.1333255E-02  0.2650310E-05 -0.9768834E-09 -0.9977223E-13 -0.1062834E+04  0.2287498E+01
*
*O2       0.3718995E+01 -0.2516729E-02  0.8583735E-05 -0.8299872E-08  0.2708218E-11 -0.1057671E+04  0.3908070E+01
*
*SM       -0.3783666E+01 -0.1264208E+00  0.1040876E-02 -0.2158416E-05  0.1115017E-08  0.1290077E+04  0.3373418E+02
*
*S        0.2913726E+01  0.3129406E-03 -0.2609251E-05  0.3138244E-08 -0.1170899E-11  0.3256827E+05  0.3568115E+01
*
*****

```

```

*****
*
* C(5) = 0.5333333E+01
*
* C(4) = 0.6040210E-01
*
* C(3) = 0.3152803E-06
*
* C(2) = 0.6518769E-07
*
* C(1) = -0.2121013E-17
*
*****
*
* B(5) = 0.2590249E+01
*
* B(4) = 0.2950868E-01
*
* B(3) = 0.1558332E-06
*
* B(2) = 0.3334107E-07
*
* B(1) = 0.4585053E-01
*
*****
*
* COEFFICIENTS OF POLYNOMIALS
*
*****
*
* RK( 5) = 0.2239496E+11
*
* RK( 4) = 0.1510052E-01
*
* RK( 3) = 0.1182301E-06
*
* RK( 2) = 0.4889077E-07
*
* RK( 1) = 0.9323100E+08
*
*****
*
* EQUILIBRIUM CONSTANTS
*
*****
*
* TEMPERATURE = 400.00
*
*****

```

```

*****
*
*   TEMPERATURE=   550.00   *
*
*****
*
*   EQUILIBRIUM CONSTANTS   *
*
*****
*
*   RK( 1)=  0.1588409E+05   *
*
*   RK( 2)=  0.2186750E-03   *
*
*   RK( 3)=  0.1479178E-03   *
*
*   RK( 4)=  0.2008956E+00   *
*
*   RK( 5)=  0.2239496E+11   *
*
*****
*****
*****
*
*   COEFFICIENTS OF POLYNOMIALS *
*
*****
*
*   B(1)=  0.4585053E-01   *
*
*   B(2)=  0.1491254E-03   *
*
*   B(3)=  0.1949630E-03   *
*
*   B(4)=  0.3925799E+00   *
*
*   B(5)=  0.2590249E+01   *
*
*****
*
*   C(1)= -0.2121013E-17   *
*
*   C(2)=  0.2915666E-03   *
*
*   C(3)=  0.3944474E-03   *
*
*   C(4)=  0.8035822E+00   *
*
*   C(5)=  0.5333333E+01   *
*
*****

```

```

*****
*
*   TEMPERATURE=    600.00   *
*
*****
*
*   EQUILIBRIUM CONSTANTS   *
*
*****
*
*   RK( 1)=  0.2274510E+04   *
*
*   RK( 2)=  0.1433363E-02   *
*
*   RK( 3)=  0.7504737E-03   *
*
*   RK( 4)=  0.3585224E+00   *
*
*   RK( 5)=  0.2239496E+11   *
*
*****
*****
*****
*
*   COEFFICIENTS OF POLYNOMIALS *
*
*****
*
*   B(1)=  0.4585053E-01   *
*
*   B(2)=  0.9774824E-03   *
*
*   B(3)=  0.9891617E-03   *
*
*   B(4)=  0.7006063E+00   *
*
*   B(5)=  0.2590249E+01   *
*
*****
*
*   C(1)= -0.2121013E-17   *
*
*   C(2)=  0.1911151E-02   *
*
*   C(3)=  0.2001263E-02   *
*
*   C(4)=  0.1434089E+01   *
*
*   C(5)=  0.5333333E+01   *
*
*****

```

```

*****
*
*   GRAM ATOM OF           INPUT           OUTPUT           *
*
*****
*
*       S           0.30000000           0.30000000           *
*
*       O           0.20000000           0.20000000           *
*
*       H           0.40000000           0.40000000           *
*
*       N           1.88000000           1.88000000           *
*
*       S           0.30000000           0.30000000           *
*
*****

```

```

*****
*
*                                     PRESSURE=  0.50
*
*****
*
*                               EQUILIBRIUM COMPOSITION FOR THE FIRST REACTOR
*
*****
*
*  TEMP      SO2      H2S      H2O      S2      S4      S6      S8      N2      O2      %CONV1
*
*****
*  400.00      0.00010  0.00020  0.04699  0.00000  0.00000  0.00042  0.00849  0.08871  0.0      99.57754
*
*  450.00      0.00032  0.00064  0.04652  0.00000  0.00000  0.00114  0.00787  0.08866  0.0      98.65269
*
*  500.00      0.00079  0.00158  0.04552  0.00001  0.00000  0.00237  0.00676  0.08855  0.0      96.65058
*
*  550.00      0.00162  0.00323  0.04378  0.00006  0.00001  0.00392  0.00525  0.08838  0.0      93.12879
*
*  600.00      0.00283  0.00566  0.04122  0.00035  0.00005  0.00531  0.00364  0.08814  0.0      87.91712
*
*  650.00      0.00437  0.00873  0.03796  0.00153  0.00014  0.00595  0.00220  0.08778  0.0      81.29340
*
*  700.00      0.00600  0.01200  0.03435  0.00503  0.00033  0.00527  0.00106  0.08714  0.0      74.11591
*
*  750.00      0.00729  0.01458  0.03123  0.01217  0.00051  0.00300  0.00031  0.08614  0.0      68.16809
*
*  800.00      0.00765  0.01531  0.03003  0.01941  0.00040  0.00073  0.00003  0.08524  0.0      66.23892
*
*  850.00      0.00725  0.01449  0.03069  0.02235  0.00019  0.00009  0.00000  0.08494  0.0      67.92038
*
*****
*****
*****

```


PRESSURE = 1.00

EQUILIBRIUM COMPOSITION FOR THE FIRST REACTOR

TEMP	SO2	H2S	H2O	S2	S4	S6	S8	N2	O2	%CONV1
------	-----	-----	-----	----	----	----	----	----	----	--------

400.00	0.00017	0.00035	0.09403	0.00000	0.00000	0.00071	0.01710	0.17743	0.0	99.63392
--------	---------	---------	---------	---------	---------	---------	---------	---------	-----	----------

450.00	0.00055	0.00110	0.09322	0.00000	0.00000	0.00195	0.01602	0.17734	0.0	98.82987
--------	---------	---------	---------	---------	---------	---------	---------	---------	-----	----------

500.00	0.00138	0.00275	0.09147	0.00001	0.00000	0.00411	0.01407	0.17715	0.0	97.07801
--------	---------	---------	---------	---------	---------	---------	---------	---------	-----	----------

550.00	0.00284	0.00568	0.08839	0.00007	0.00002	0.00697	0.01132	0.17685	0.0	93.96190
--------	---------	---------	---------	---------	---------	---------	---------	---------	-----	----------

600.00	0.00503	0.01007	0.08378	0.00043	0.00007	0.00979	0.00822	0.17643	0.0	89.27387
--------	---------	---------	---------	---------	---------	---------	---------	---------	-----	----------

650.00	0.00787	0.01574	0.07778	0.00191	0.00022	0.01156	0.00533	0.17582	0.0	83.17030
--------	---------	---------	---------	---------	---------	---------	---------	---------	-----	----------

700.00	0.01104	0.02208	0.07092	0.00649	0.00054	0.01129	0.00294	0.17485	0.0	76.25548
--------	---------	---------	---------	---------	---------	---------	---------	---------	-----	----------

750.00	0.01394	0.02788	0.06426	0.01699	0.00099	0.00818	0.00117	0.17322	0.0	69.74140
--------	---------	---------	---------	---------	---------	---------	---------	---------	-----	----------

800.00	0.01558	0.03116	0.05993	0.03203	0.00110	0.00327	0.00022	0.17125	0.0	65.78716
--------	---------	---------	---------	---------	---------	---------	---------	---------	-----	----------

850.00	0.01541	0.03081	0.05969	0.04159	0.00067	0.00059	0.00002	0.17015	0.0	65.95573
--------	---------	---------	---------	---------	---------	---------	---------	---------	-----	----------


```

*****
*
*                               EQUILIBRIUM COMPOSITION FOR THE SECOND REACTOR
*
*****
*
*  TEMP      SO2      H2S      H2O      N2      SM      TEP      %CONV2      TCONV12      TCONV
*
*****
*  400.00      0.00007    0.00015    0.19215    1.80763    0.00072    2.00000    75.59681    99.92260    99.97678
*
*  450.00      0.00007    0.00015    0.19215    1.80763    0.00282    2.00000    92.37998    99.92260    99.97678
*
*  500.00      0.00007    0.00015    0.19215    1.80763    0.00741    2.00000    96.96035    99.92260    99.97678
*
*  550.00      0.00007    0.00015    0.19215    1.80763    0.01566    2.00000    98.53844    99.92260    99.97678
*
*  600.00      0.00007    0.00015    0.19215    1.80763    0.02825    2.00000    99.18468    99.92260    99.97678
*
*  650.00      0.00007    0.00015    0.19215    1.80763    0.04498    2.00000    99.48648    99.92260    99.97678
*
*  700.00      0.00007    0.00015    0.19215    1.80763    0.06459    2.00000    99.64178    99.92260    99.97678
*
*  750.00      0.00007    0.00015    0.19215    1.80763    0.08450    2.00000    99.72597    99.92260    99.97678
*
*  800.00      0.00007    0.00015    0.19215    1.80763    0.10027    2.00000    99.76896    99.92260    99.97678
*
*  850.00      0.00007    0.00015    0.19215    1.80763    0.10591    2.00000    99.78124    99.92260    99.97678
*
*****
*****
*****

```

APPENDIX B
COMPUTER PROGRAMME FOR THE ROTAMETERS
CALIBRATION TABLE

Below is the Fortran IV computer language listings of the programme used to compute the rotameters calibration table. From the linear regression coefficients of the air calibration curve, the calibration table for other gases at different pressures inside the rotameter were computed. The temperature was kept at 21°C.

A sample of the output for each rotameter is included in the listings. For more details see Section 5.2.1.

```

C *****
C *
C * PROGRAMME FOR COMPUTING THE FLCW RATE THROUGH THE *
C * ROTAMETERS AT DIFFERENT PRESSURES FOR N2 , H2S , SC2 *
C *
C *****
C *
C * A,E,C = CCEFFICIENTS OF POLYNOMIALS FOR AIR FLOW RATE *
C * AGF = VOLUMETRIC FLOW RATE (ML/MIN) *
C * GFM = MOLAR FLCW RATE (CMO/E/MIN) *
C * FA = AIR FLCW RATE L/MIN *
C * SG = SPECIFIC GRAVITY *
C * GAS = SYMBOL OF GAS *
C * RCT = CODE FOR ROTAMETER *
C * P = PRESSURE INSIDE ROTAMETER *
C * PA = CNE ATMOSPHERE *
C * DCF = FLOW FACTOR *
C *****
C
C IMPLICIT REAL*8 (A-H,C-Z)
C DIMENSION A(20),E(20),C(20),SR(30),F(20),T(10),AGF(30,30)
C DIMENSION GFM(30,30),FA(30,30),RCT(20),GAS(5),SG(5)
C READ (5,100) SGA,FA,LA,TA
C DO 1 I=1,3
C READ(5,100) SG(I)
1 READ(5,920) GAS(I)
C DO 2 I=1,19
C READ(5,930) RCT(I)
C READ(5,100) A(I),E(I),C(I)
2 WRITE(6,960) RCT(I),A(I),E(I),C(I)
C
C ***** ESTIMATE AIR FLOW RATE AGAINST SCALE READING
C
C DO 3 I=1,19
C DO 3 K=1,25
C XX=K
C X=XX/10.0D0
C SR(K)=X*100.0D0
3 FA(I,K)=A(I)+E(I)*X+C(I)*X**2
C
C ***** CHOOSE TEMPERATURE
C
C KK = 1
C DO 30 I=1,KK
C YY=I
C Y =YY*21.0D0+273.2D0
C T(I)=Y
C
C ***** CHOOSE ROTAMETER
C
C DO 30 J=1,19
C READ(5,970) MA
C

```

```

C      ***** CHCCSE GAS
C
C      DO 30 K=1,3
C
C      ***** WRITE RESULTS
C
C      WRITE(6,910)
C      WRITE(6,200)
C      WRITE(6,300)
C      WRITE(6,800)
C      WRITE(6,300)
C      WRITE(6,200)
C      WRITE(6,300)
C      WRITE(6,900) T(I),RCT(J),GAS(K)
C      WRITE(6,300)
C      WRITE(6,200)
C
C      ***** CHCCSE PRESSURE
C
C      DO 10 L=1,9
C      ZL=L
C      Z =ZL*5.0DC
C      IF (L.EQ.3) Z=14.7LD
C      P(L)=Z
C
C      ***** CALCULATE FLOW FACTOR
C
C      DSF =SGA*TA*2/SG(K)/Y/PA
C      DDF =DSQRT(LSF)
C
C      ***** CALCULATING ACTUAL GAS FLCW RATE
C      ***** CHCCSE SCALE READING
C
C      DO 10 M=1,MA
C      AGF(M,L)=FA(J,M)*DDF*1000. DO
C      GFM(M,L)=AGF(M,L)*PA/TA/1.20746E+03
10    CCNTINUE
C
C      ***** PRINTING FLOW RATE AGAINST PRESSURE AND SCALE READING
C
C      WRITE(6,500)
C      WRITE(6,120)
C      WRITE(6,600) (P(II),II=1,9)
C      WRITE(6,400)
C      WRITE(6,200)
C      WRITE(6,540)
C      WRITE(6,200)
C      DO 20 KA=1,MA
C      WRITE(6,700) SR(KA), (AGF(KA,KB),KB=1,9)
20    CCNTINUE
C      WRITE(6,200)
C      WRITE(6,950)
C      WRITE(6,200)
C      DO 21 KA=1,MA

```



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21  WRITE(6,750) SR(KA), (GFM(KA,KB), KB=1,9)
    CCNTINUE
    WRITE(6,200)
30  CCNTINUE
100  FORMAT(8F10.5)
120  FORMAT(10X,'*',10X,100(1H*))
200  FCFORMAT(10X,111(1H*))
300  FORMAT(10X,'*',109X,'*')
400  FORMAT(10X,'*',10(10X,'*'))
500  FORMAT(10X,'*SCALE REAL*',38X,'PRESSURE (PSI)',47X,'*')
600  FORMAT(10X,'*      (MM)      ',9(2X,F5.1,3X,'*'))
700  FORMAT(10X,'*',2X,F5.1,3X,'*',9(1X,F8.1,1X,'*'))
750  FCFORMAT(10X,'*',2X,F5.1,3X,'*',9(2X,F7.4,1X,'*'))
800  FORMAT(10X,'*',41X,'CALBRATION CF ROTAMETERS',42X,'*')
900  FORMAT(10X,'*',29X,'TEMPERATURE=',F5.1,4X,'ROTAMETER=',A8,4X,'GAS=
1',A3,3CX,'*')
910  FORMAT('1',//)
920  FORMAT(A3)
930  FORMAT(A8)
940  FORMAT(10X,'*',10X,'*',33X,'VOLUMETRIC  FLCW  RATE  (ML/MIN)',33X,
2'*)
950  FORMAT(10X,'*',10X,'*',34X,'MOLAR  FLCW  RATE  (GMOLE/MIN)',34X,'*
3')
960  FORMAT(10X,A8,3F10.5)
970  FCFORMAT(I2)
    STCP
    ENL

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15
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15

CALBRATION OF ROTAMETERS

TEMPERATURE=294.2 ROTAMETER= L963 GAS= N2

SCALE READ

PRESSURE (PSI)

(MM)

VOLUMETRIC FLOW RATE (ML/MIN)

MOLAR FLOW RATE (GMOLE/MIN)

10.0	5.1	7.3	8.8	10.3	11.5	12.6	13.6	14.5	15.4
20.0	16.3	23.1	28.0	32.6	36.5	39.9	43.1	46.1	48.9
30.0	30.0	42.4	51.4	60.0	67.1	73.5	79.4	84.8	90.0
40.0	46.2	65.3	79.2	92.4	103.3	113.2	122.3	130.7	138.6
50.0	65.0	91.9	111.4	129.9	145.2	159.1	171.8	183.7	194.9
60.0	86.2	121.9	147.8	172.4	192.8	211.2	228.1	243.9	258.7
70.0	110.0	155.6	188.6	220.0	246.0	269.5	291.1	311.2	330.0
80.0	136.3	192.8	233.8	272.7	304.8	333.9	360.7	385.6	409.0
90.0	165.2	233.6	283.2	330.3	369.3	404.6	437.0	467.2	495.5
100.0	196.5	278.0	337.0	393.1	439.5	481.4	520.0	555.9	589.6
10.0	0.0002	0.0003	0.0004	0.0004	0.0005	0.0005	0.0006	0.0006	0.0006
20.0	0.0007	0.0010	0.0012	0.0013	0.0015	0.0017	0.0018	0.0019	0.0020
30.0	0.0012	0.0018	0.0021	0.0025	0.0028	0.0030	0.0033	0.0035	0.0037
40.0	0.0019	0.0027	0.0033	0.0038	0.0043	0.0047	0.0051	0.0054	0.0057
50.0	0.0027	0.0038	0.0046	0.0054	0.0060	0.0066	0.0071	0.0076	0.0081
60.0	0.0036	0.0050	0.0061	0.0071	0.0080	0.0087	0.0094	0.0101	0.0107
70.0	0.0046	0.0064	0.0078	0.0091	0.0102	0.0111	0.0120	0.0129	0.0137
80.0	0.0056	0.0080	0.0097	0.0113	0.0126	0.0138	0.0149	0.0160	0.0169
90.0	0.0068	0.0097	0.0117	0.0137	0.0153	0.0167	0.0181	0.0193	0.0205
100.0	0.0081	0.0115	0.0139	0.0163	0.0182	0.0199	0.0215	0.0230	0.0244

*
* CALIBRATION OF ROTAMETERS *
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*****  
*****  
*****  
*****      TEMPERATURE=294.2    ROTAMETER=    E1402    GAS= N2      *****  
*****  
*****
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*
*****
+SCALE READ+          PRESSURE (PSI) *****

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[illegible]

	5.0	10.0	14.7	20.0	25.0	30.0	35.0	40.0	45.0
(MM)									

VOLUMETRIC FLOW RATE (ML/MIN)

VOLUMETRIC FLOW RATE (L/MIN)											
10.0	4678.7	6616.6	8022.3	9357.3	10461.8	11460.4	12378.6	13233.3	14036.0		
20.0	9260.4	13096.2	15878.2	18520.8	20706.8	22683.2	24500.7	26192.3	27781.1		
30.0	13852.5	19590.4	23752.1	27705.0	30975.1	33931.6	36650.3	39180.8	41557.5		
40.0	18455.0	26099.3	31643.8	36910.1	41266.7	45205.4	48827.4	52198.7	55365.1		
50.0	23068.0	32623.0	39553.3	46135.9	51581.5	56504.7	61032.1	65246.1	69203.9		
60.0	27691.3	39161.4	47480.7	55382.6	61919.7	67829.6	73264.3	78322.9	83073.9		
70.0	32325.1	45714.5	55425.9	64650.1	72281.0	79179.9	85524.1	91429.1	96975.2		
80.0	36969.2	52282.4	63389.0	73938.5	82665.7	90555.8	97811.4	104564.8	110907.7		
90.0	41623.8	58865.0	71370.0	83247.6	93073.7	101957.1	110126.2	117729.9	124871.4		
100.0	46288.8	65462.2	79368.7	92577.6	103504.9	113383.9	122468.6	130924.5	138866.4		

 * 100.0 * 46288.8 * 65462.2 * 79368.7 * 92577.6 * 103504.9 * 113383.9 * 122788.9 * 131888.9 * 140888.9 * 149888.9 * 158888.9 * 167888.9 * 176888.9 * 185888.9 * 194888.9 * 203888.9 * 212888.9 * 221888.9 * 230888.9 * 239888.9 * 248888.9 * 257888.9 * 266888.9 * 275888.9 * 284888.9 * 293888.9 * 302888.9 * 311888.9 * 320888.9 * 329888.9 * 338888.9 * 347888.9 * 356888.9 * 365888.9 * 374888.9 * 383888.9 * 392888.9 * 401888.9 * 410888.9 * 419888.9 * 428888.9 * 437888.9 * 446888.9 * 455888.9 * 464888.9 * 473888.9 * 482888.9 * 491888.9 * 500888.9 * 509888.9 * 518888.9 * 527888.9 * 536888.9 * 545888.9 * 554888.9 * 563888.9 * 572888.9 * 581888.9 * 590888.9 * 599888.9 * 608888.9 * 617888.9 * 626888.9 * 635888.9 * 644888.9 * 653888.9 * 662888.9 * 671888.9 * 680888.9 * 689888.9 * 698888.9 * 707888.9 * 716888.9 * 725888.9 * 734888.9 * 743888.9 * 752888.9 * 761888.9 * 770888.9 * 779888.9 * 788888.9 * 797888.9 * 806888.9 * 815888.9 * 824888.9 * 833888.9 * 842888.9 * 851888.9 * 860888.9 * 869888.9 * 878888.9 * 887888.9 * 896888.9 * 905888.9 * 914888.9 * 923888.9 * 932888.9 * 941888.9 * 950888.9 * 959888.9 * 968888.9 * 977888.9 * 986888.9 * 995888.9 * 1004888.9 * 1013888.9 * 1022888.9 * 1031888.9 * 1040888.9 * 1049888.9 * 1058888.9 * 1067888.9 * 1076888.9 * 1085888.9 * 1094888.9 * 1103888.9 * 1112888.9 * 1121888.9 * 1130888.9 * 1139888.9 * 1148888.9 * 1157888.9 * 1166888.9 * 1175888.9 * 1184888.9 * 1193888.9 * 1202888.9 * 1211888.9 * 1220888.9 * 1229888.9 * 1238888.9 * 1247888.9 * 1256888.9 * 1265888.9 * 1274888.9 * 1283888.9 * 1292888.9 * 1301888.9 * 1310888.9 * 1319888.9 * 1328888.9 * 1337888.9 * 1346888.9 * 1355888.9 * 1364888.9 * 1373888.9 * 1382888.9 * 1391888.9 * 1400888.9 * 1409888.9 * 1418888.9 * 1427888.9 * 1436888.9 * 1445888.9 * 1454888.9 * 1463888.9 * 1472888.9 * 1481888.9 * 1490888.9 * 1500888.9 * 1509888.9 * 1518888.9 * 1527888.9 * 1536888.9 * 1545888.9 * 1554888.9 * 1563888.9 * 1572888.9 * 1581888.9 * 1590888.9 * 1600888.9 * 1609888.9 * 1618888.9 * 1627888.9 * 1636888.9 * 1645888.9 * 1654888.9 * 1663888.9 * 1672888.9 * 1681888.9 * 1690888.9 * 1700888.9 * 1709888.9 * 1718888.9 * 1727888.9 * 1736888.9 * 1745888.9 * 1754888.9 * 1763888.9 * 1772888.9 * 1781888.9 * 1790888.9 * 1800888.9 * 1809888.9 * 1818888.9 * 1827888.9 * 1836888.9 * 1845888.9 * 1854888.9 * 1863888.9 * 1872888.9 * 1881888.9 * 1890888.9 * 1900888.9 * 1909888.9 * 1918888.9 * 1927888.9 * 1936888.9 * 1945888.9 * 1954888.9 * 1963888.9 * 1972888.9 * 1981888.9 * 1990888.9 * 2000888.9 * 2009888.9 * 2018888.9 * 2027888.9 * 2036888.9 * 2045888.9 * 2054888.9 * 2063888.9 * 2072888.9 * 2081888.9 * 2090888.9 * 2100888.9 * 2109888.9 * 2118888.9 * 2127888.9 * 2136888.9 * 2145888.9 * 2154888.9 * 2163888.9 * 2172888.9 * 2181888.9 * 2190888.9 * 2200888.9 * 2209888.9 * 2218888.9 * 2227888.9 * 2236888.9 * 2245888.9 * 2254888.9 * 2263888.9 * 2272888.9 * 2281888.9 * 2290888.9 * 2300888.9 * 2309888.9 * 2318888.9 * 2327888.9 * 2336888.9 * 2345888.9 * 2354888.9 * 2363888.9 * 2372888.9 * 2381888.9 * 2390888.9 * 2400888.9 * 2409888.9 * 2418888.9 * 2427888.9 * 2436888.9 * 2445888.9 * 2454888.9 * 2463888.9 * 2472888.9 * 2481888.9 * 2490888.9 * 2500888.9 * 2509888.9 * 2518888.9 * 2527888.9 * 2536888.9 * 2545888.9 * 2554888.9 * 2563888.9 * 2572888.9 * 2581888.9 * 2590888.9 * 2600888.9 * 2609888.9 * 2618888.9 * 2627888.9 * 2636888.9 * 2645888.9 * 2654888.9 * 2663888.9 * 2672888.9 * 2681888.9 * 2690888.9 * 2700888.9 * 2709888.9 * 2718888.9 * 2727888.9 * 2736888.9 * 2745888.9 * 2754888.9 * 2763888.9 * 2772888.9 * 2781888.9 * 2790888.9 * 2800888.9 * 2809888.9 * 2818888.9 * 2827888.9 * 2836888.9 * 2845888.9 * 2854888.9 * 2863888.9 * 2872888.9 * 2881888.9 * 2890888.9 * 2900888.9 * 2909888.9 * 2918888.9 * 2927888.9 * 2936888.9 * 2945888.9 * 2954888.9 * 2963888.9 * 2972888.9 * 2981888.9 * 2990888.9 * 3000888.9 * 3009888.9 * 3018888.9 * 3027888.9 * 3036888.9 * 3045888.9 * 3054888.9 * 3063888.9 * 3072888.9 * 3081888.9 * 3090888.9 * 3100888.9 * 3109888.9 * 3118888.9 * 3127888.9 * 3136888.9 * 3145888.9 * 3154888.9 * 3163888.9 * 3172888.9 * 3181888.9 * 3190888.9 * 3200888.9 * 3209888.9 * 3218888.9 * 3227888.9 * 3236888.9 * 3245888.9 * 3254888.9 * 3263888.9 * 3272888.9 * 3281888.9 * 3290888.9 * 3300888.9 * 3309888.9 * 3318888.9 * 3327888.9 * 3336888.9 * 3345888.9 * 3354888.9 * 3363888.9 * 3372888.9 * 3381888.9 * 3390888.9 * 3400888.9 * 3409888.9 * 3418888.9 * 3427888.9 * 3436888.9 * 3445888.9 * 3454888.9 * 3463888.9 * 3472888.9 * 3481888.9 * 3490888.9 * 3500888.9 * 3509888

		MOLAR FLOW RATE (GMOLE/MIN)									
*	*	*****									
*	*	0.2737	0.3319	0.3871	0.4328	0.4741	0.5121	0.5474	0.5806		
*	10.0	0.1935	0.5417	0.6568	0.7661	0.8566	0.9383	1.0135	1.0835	1.1492	
*	20.0	0.3831	0.8104	0.9826	1.1461	1.2813	1.4036	1.5161	1.6208	1.7191	
*	30.0	0.5730	1.0797	1.3090	1.5269	1.7071	1.8700	2.0198	2.1593	2.2903	
*	40.0	0.7634	1.3495	1.6362	1.9085	2.1338	2.3374	2.5247	2.6990	2.8628	
*	50.0	0.9543	1.6200	1.9641	2.2910	2.5614	2.8059	3.0307	3.2400	3.4365	
*	60.0	1.1455	1.8911	2.2928	2.6744	2.9901	3.2754	3.5379	3.7821	4.0116	
*	70.0	1.3372	2.1628	2.6222	3.0586	3.4196	3.7460	4.0462	4.3255	4.5879	
*	80.0	1.5293	2.4351	2.9524	3.4437	3.8502	4.2177	4.5556	4.8701	5.1656	
*	90.0	1.7219	2.7080	3.2832	3.8297	4.2817	4.6904	5.0662	5.4160	5.7445	
*	100.0	1.9148									
*	*	*****									

CALIBRATION OF ROTAMETERS												
TEMPERATURE=294.2 ROT METER= R/M251 GAS= N2												
PRESSURE(P/PSI)												
SCALE READ												
(MM) * 5.0 * 10.0 * 14.7 * 20.0 * 25.0 * 30.0 * 35.0 * 40.0 * 45.0												
VOLUMETRIC FLOW RATE (ML/MIN)												
MOLAR FLOW RATE (CMLE/MIN)												
10.0	1216.5	1720.4	2095.9	2633.0	2720.2	2979.8	3218.5	3440.8	3649.5	3847.2	4034.9	4212.6
20.0	2493.7	3526.7	4275.9	4981.5	5576.2	6108.4	6597.8	7053.4	7481.2	7881.9	8255.6	8612.3
30.0	3753.1	5301.7	6354.0	7506.2	8392.2	9193.2	9929.8	10615.4	11259.8	11863.8	12437.3	12980.3
40.0	4994.6	6983.4	8544.0	9989.2	11168.3	12234.2	13214.5	14126.9	14983.8	15796.3	16564.3	17297.8
50.0	6218.2	8634.9	10662.0	12336.4	13904.3	15231.4	16451.8	17451.8	18337.8	19119.8	19897.8	20671.3
60.0	7423.9	10478.9	12729.4	14647.9	16000.4	17256.6	18418.9	19496.1	20498.1	21435.9	22309.4	23119.4
70.0	8611.8	12178.9	14766.2	17223.6	19256.6	21094.5	22784.7	24357.8	25835.9	27249.4	28608.4	29912.9
80.0	9781.8	13843.8	16772.2	19563.5	21872.7	23660.3	25360.6	26982.4	28537.8	29999.8	31467.8	32841.3
90.0	10934.9	15484.8	18747.7	21867.7	24448.9	26782.4	28928.3	30928.3	32828.3	34628.3	36328.3	37928.3
100.0	12084.9	17066.8	20692.5	24136.2	26985.1	29560.6	31929.1	34133.7	36233.7	38233.7	40133.7	41933.7
110.0	13234.9	18645.6	22606.6	26368.8	29481.3	32495.1	34882.7	37291.2	39591.2	41791.2	43891.2	45891.2
120.0	14384.9	20199.0	24490.0	28565.8	31937.5	34985.8	37789.0	40398.1	42898.1	45298.1	47598.1	49798.1
130.0	15534.9	21727.2	26342.9	30726.9	34353.7	37532.6	40479.0	43279.0	45979.0	48579.0	51079.0	53479.0
140.0	16684.9	23230.1	28155.0	32942.0	36730.0	40235.7	42935.7	45435.7	47835.7	50135.7	52335.7	54435.7
150.0	17834.9	24707.7	29956.5	35147.1	38995.9	42162.6	44762.6	47262.6	49662.6	51962.6	54162.6	56262.6
160.0	18984.9	26160.0	31717.4	36995.9	41362.6	45102.5	48202.5	50702.5	53102.5	55402.5	57602.5	59702.5
170.0	19507.0	27587.1	33447.5	39014.0	43619.0	47782.2	51610.7	54810.7	57810.7	60710.7	63510.7	66210.7
180.0	20498.2	28988.8	35147.1	40986.4	45833.9	50210.1	54353.9	57853.9	60753.9	63553.9	66253.9	68853.9
190.0	21471.5	30365.3	36816.0	42933.9	48011.7	52594.2	56803.1	60730.6	64330.6	67730.6	71030.6	74230.6
200.0	22426.9	31716.5	38454.2	44873.0	50148.1	54934.5	59334.5	63434.5	67034.5	70434.5	73734.5	76934.5
210.0	23364.5	33042.4	40061.7	46729.0	52244.6	57231.1	61731.1	65831.1	69431.1	72831.1	76131.1	79331.1
220.0	24284.2	34343.0	41638.7	48568.3	54301.0	59483.0	64083.0	68283.0	72083.0	75583.0	78983.0	82283.0
230.0	25186.0	35618.3	43184.9	50311.9	56317.5	61632.1	66332.1	70532.1	74332.1	77832.1	81132.1	84332.1
240.0	26069.9	36868.4	44700.5	52019.7	58294.0	63871.9	68871.9	73171.9	76871.9	80371.9	83771.9	87071.9
250.0	26935.9	38093.1	46185.5	53871.8	60230.5	65979.2	71265.7	76186.3	80807.7	85329.1	89750.5	94071.9

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*****
*                                     *
*                                CALBRATION  OF  ROTAMETERS                                *
*                                     *
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*****
*
*          TEMPERATURE=294.2    ROTAMETER=  RSS604    GAS=H2S
*
*****
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*****
#SCALE READ*                                PRESSURE(PSI)*****

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	(MM)	5.0	10.0	14.7	20.0	25.0	30.0	35.0	40.0	45.0
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* VOLUMETRIC FLOW RATE (ML/MIN) *

*	10.0	*	522.3	*	738.6	*	895.5	*	1044.5	*	1167.8	*	1279.3	*	1381.8	*	1477.2	*	1566.8	*
*	20.0	*	1198.1	*	1694.4	*	2054.4	*	2396.3	*	2679.1	*	2934.8	*	3169.9	*	3388.8	*	3594.4	*
*	30.0	*	1873.6	*	2649.6	*	3212.5	*	3747.1	*	4189.4	*	4589.2	*	4957.0	*	5299.2	*	5620.7	*
*	40.0	*	2548.5	*	3604.2	*	4369.8	*	5097.1	*	5698.7	*	6242.6	*	6742.8	*	7208.4	*	7645.6	*
*	50.0	*	3223.1	*	4558.1	*	5526.4	*	6446.2	*	7207.0	*	7894.9	*	8527.5	*	9116.3	*	9669.2	*
*	60.0	*	3897.2	*	5511.5	*	6682.3	*	7794.4	*	8714.4	*	9546.1	*	10311.0	*	11022.9	*	11691.6	*
*	70.0	*	4570.8	*	6464.2	*	7837.4	*	9141.7	*	10220.7	*	11196.2	*	12093.3	*	12928.3	*	13712.5	*
*	80.0	*	5244.1	*	7416.2	*	8991.7	*	10488.1	*	11726.1	*	12845.3	*	13874.5	*	14832.5	*	15732.2	*
*	90.0	*	5916.8	*	8367.7	*	10145.3	*	11833.7	*	13230.5	*	14493.3	*	15654.5	*	16735.4	*	17750.5	*
*	100.0	*	6589.2	*	9318.5	*	11298.1	*	13178.4	*	14733.9	*	16140.1	*	17433.3	*	18637.0	*	19767.6	*
*	110.0	*	7261.1	*	10268.7	*	12450.2	*	14522.2	*	16236.3	*	17786.0	*	19211.0	*	20537.5	*	21783.3	*
*	120.0	*	7932.5	*	11218.3	*	13601.5	*	15865.1	*	17737.7	*	19430.7	*	20987.5	*	22436.6	*	23797.6	*
*	130.0	*	8603.6	*	12167.3	*	14752.0	*	17207.1	*	19238.1	*	21074.3	*	22762.9	*	24334.5	*	25810.7	*
*	140.0	*	9274.1	*	13115.6	*	15901.8	*	18548.3	*	20737.6	*	22716.9	*	24537.1	*	26231.2	*	27822.4	*
*	150.0	*	9944.3	*	14063.3	*	17050.9	*	19888.5	*	22236.1	*	24358.4	*	26310.1	*	28126.6	*	29832.8	*

```
*****
*          *          MOLAR FLOW RATE (GMOLE/MIN)          *
*****
```

*	10.0	*	0.0216	*	0.0306	*	0.0370	*	0.0432	*	0.0483	*	0.0529	*	0.0572	*	0.0611	*	0.0648	*
*	20.0	*	0.0496	*	0.0701	*	0.0850	*	0.0991	*	0.1108	*	0.1214	*	0.1311	*	0.1402	*	0.1487	*
*	30.0	*	0.0775	*	0.1096	*	0.1329	*	0.1550	*	0.1733	*	0.1898	*	0.2051	*	0.2192	*	0.2325	*
*	40.0	*	0.1054	*	0.1491	*	0.1808	*	0.2109	*	0.2357	*	0.2582	*	0.2789	*	0.2982	*	0.3163	*
*	50.0	*	0.1333	*	0.1886	*	0.2286	*	0.2667	*	0.2981	*	0.3266	*	0.3528	*	0.3771	*	0.4000	*
*	60.0	*	0.1612	*	0.2280	*	0.2764	*	0.3224	*	0.3605	*	0.3949	*	0.4265	*	0.4560	*	0.4836	*
*	70.0	*	0.1891	*	0.2674	*	0.3242	*	0.3782	*	0.4228	*	0.4632	*	0.5003	*	0.5348	*	0.5672	*
*	80.0	*	0.2169	*	0.3068	*	0.3720	*	0.4339	*	0.4851	*	0.5314	*	0.5739	*	0.6136	*	0.6508	*
*	90.0	*	0.2448	*	0.3461	*	0.4197	*	0.4895	*	0.5473	*	0.5995	*	0.6476	*	0.6923	*	0.7343	*
*	100.0	*	0.2726	*	0.3855	*	0.4674	*	0.5452	*	0.6095	*	0.6677	*	0.7212	*	0.7710	*	0.8177	*
*	110.0	*	0.3004	*	0.4248	*	0.5150	*	0.6007	*	0.6716	*	0.7358	*	0.7947	*	0.8496	*	0.9011	*
*	120.0	*	0.3281	*	0.4641	*	0.5627	*	0.6563	*	0.7338	*	0.8038	*	0.8682	*	0.9281	*	0.9844	*
*	130.0	*	0.3559	*	0.5033	*	0.6102	*	0.7118	*	0.7958	*	0.8718	*	0.9416	*	1.0066	*	1.0677	*
*	140.0	*	0.3836	*	0.5426	*	0.6578	*	0.7673	*	0.8579	*	0.9397	*	1.0150	*	1.0851	*	1.1509	*
*	150.0	*	0.4114	*	0.5818	*	0.7053	*	0.8227	*	0.9198	*	1.0076	*	1.0884	*	1.1635	*	1.2341	*

[illegible]

CALBRATION OF ROTAMETERS											
TEMPERATURE=294.2 ROTAMETER= LG604 GAS=S02											
SCALE READ											
PRESSURE (PSI)											
VOLUMETRIC FLOW RATE (ML/MIN)											
(MM)											
5.0	10.0	14.7	20.0	25.0	30.0	35.0	40.0	45.0			
10.0	112.9	159.6	193.5	225.8	252.4	276.5	298.6	319.3	338.6	1105.9	388.6
20.0	368.6	521.3	632.1	737.3	824.3	903.0	975.3	1042.7	1105.9	1878.5	1105.9
30.0	626.2	885.5	1073.6	1252.3	1400.1	1533.8	1656.6	1771.0	1878.5	2656.3	1878.5
40.0	885.4	1252.2	1518.2	1770.9	1979.9	2168.8	2342.6	2504.4	2656.3	3439.4	2656.3
50.0	1146.5	1621.3	1965.8	2292.9	2563.6	2808.2	3033.3	3242.7	3439.4	4227.8	3439.4
60.0	1409.3	1993.0	2416.4	2818.5	3151.2	3452.0	3728.5	3986.0	4227.8	5021.4	3986.0
70.0	1673.8	2367.1	2870.0	3347.6	3742.8	4100.0	4428.5	4734.3	5021.4	5820.4	4734.3
80.0	1940.1	2743.8	3326.6	3880.3	4338.3	4752.3	5133.1	5487.5	5820.4	6624.6	5487.5
90.0	2208.2	3122.9	3786.3	4416.4	4937.7	5409.0	5842.4	6245.7	6624.6	7434.1	6245.7
100.0	2478.0	3504.5	4248.9	4951.1	5541.1	6069.9	6556.3	7008.9	7434.1	8248.9	7008.9
110.0	2749.6	3888.6	4714.6	5499.3	6148.4	6735.2	7274.8	7777.1	8248.9	9069.0	7777.1
120.0	3023.0	4275.1	5183.3	6046.0	6759.6	7404.8	7998.1	8550.3	9069.0	9894.3	8550.3
130.0	3298.1	4664.2	5655.1	6596.2	7374.8	8078.7	8725.9	9328.4	9894.3	10724.9	9328.4
140.0	3575.0	5055.8	6129.8	7149.9	7993.9	8756.9	9458.5	10111.5	10724.9	11560.8	9458.5
150.0	3853.6	5449.8	6607.6	7707.2	8616.9	9439.4	10195.7	10899.6	11560.8		
MOLAR FLOW RATE (GMOLE/MIN)											
10.0	0.0047	0.0066	0.0080	0.0093	0.0104	0.0114	0.0124	0.0132	0.0140	0.0457	0.0140
20.0	0.0152	0.0216	0.0261	0.0305	0.0341	0.0374	0.0403	0.0431	0.0457	0.0777	0.0457
30.0	0.0259	0.0366	0.0444	0.0518	0.0579	0.0634	0.0685	0.0733	0.0777	0.1099	0.0777
40.0	0.0366	0.0518	0.0628	0.0733	0.0819	0.0897	0.0969	0.1036	0.1099	0.1423	0.1099
50.0	0.0474	0.0671	0.0813	0.0949	0.1060	0.1162	0.1255	0.1341	0.1423	0.1749	0.1423
60.0	0.0583	0.0824	0.1000	0.1166	0.1304	0.1428	0.1542	0.1649	0.1749	0.2077	0.1749
70.0	0.0692	0.0979	0.1187	0.1385	0.1548	0.1696	0.1832	0.1958	0.2077	0.2408	0.2077
80.0	0.0803	0.1135	0.1376	0.1605	0.1795	0.1966	0.2123	0.2270	0.2408	0.2740	0.2408
90.0	0.0913	0.1292	0.1566	0.1827	0.2043	0.2238	0.2417	0.2584	0.2740	0.3075	0.2740
100.0	0.1025	0.1450	0.1758	0.2050	0.2292	0.2511	0.2712	0.2899	0.3075	0.3412	0.3075
110.0	0.1137	0.1609	0.1950	0.2275	0.2543	0.2786	0.3009	0.3217	0.3412	0.3752	0.3412
120.0	0.1251	0.1769	0.2144	0.2501	0.2796	0.3063	0.3309	0.3537	0.3752	0.4093	0.3752
130.0	0.1364	0.1929	0.2339	0.2729	0.3051	0.3342	0.3610	0.3859	0.4093	0.4437	0.4093
140.0	0.1479	0.2091	0.2536	0.2958	0.3307	0.3622	0.3913	0.4183	0.4437	0.4782	0.4437
150.0	0.1594	0.2254	0.2733	0.3188	0.3565	0.3905	0.4218	0.4509	0.4782		

* CALIBRATION OF ROTAMETERS *

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*****
*
* TEMPERATURE=294.2 ROTAMETER= RSS602 GAS=H2S
*
*****

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 SCALE READ
 PRESSURE (PSI)

5.0	10.0	14.7	20.0	25.0	30.0	35.0	40.0	45.0
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VOLUMETRIC FLOW RATE (ML/MIN)

* 9.6 * 0.6 * 5.8 * 8.1 * 1.2 * 7.9 * 9.9 * 9.7 * 4.2

[illegible]

***** MOLAR FLOW RATE (GMOLE/MIN) *****

150.0	*	*	0.0240	*	0.0340	*	0.0412	*	0.0481	*	0.0538	*	0.0589	*	0.0636	*	0.0680	*	0.0721	*
140.0	*	*	0.0215	*	0.0304	*	0.0399	*	0.0430	*	0.0481	*	0.0527	*	0.0569	*	0.0608	*	0.0645	*
130.0	*	*	0.0191	*	0.0270	*	0.0327	*	0.0382	*	0.0427	*	0.0467	*	0.0505	*	0.0540	*	0.0572	*
120.0	*	*	0.0168	*	0.0237	*	0.0288	*	0.0336	*	0.0375	*	0.0411	*	0.0444	*	0.0475	*	0.0504	*
110.0	*	*	0.0146	*	0.0207	*	0.0251	*	0.0293	*	0.0327	*	0.0358	*	0.0387	*	0.0414	*	0.0439	*
100.0	*	*	0.0126	*	0.0178	*	0.0216	*	0.0252	*	0.0282	*	0.0309	*	0.0333	*	0.0356	*	0.0378	*
90.0	*	*	0.0107	*	0.0151	*	0.0183	*	0.0214	*	0.0239	*	0.0262	*	0.0283	*	0.0303	*	0.0321	*
80.0	*	*	0.0089	*	0.0126	*	0.0153	*	0.0179	*	0.0200	*	0.0219	*	0.0236	*	0.0252	*	0.0268	*
70.0	*	*	0.0073	*	0.0103	*	0.0125	*	0.0146	*	0.0163	*	0.0178	*	0.0193	*	0.0206	*	0.0218	*
60.0	*	*	0.0058	*	0.0082	*	0.0099	*	0.0115	*	0.0129	*	0.0141	*	0.0153	*	0.0163	*	0.0173	*
50.0	*	*	0.0044	*	0.0062	*	0.0075	*	0.0088	*	0.0098	*	0.0107	*	0.0116	*	0.0124	*	0.0131	*
40.0	*	*	0.0031	*	0.0044	*	0.0054	*	0.0063	*	0.0070	*	0.0077	*	0.0083	*	0.0088	*	0.0094	*
30.0	*	*	0.0020	*	0.0028	*	0.0034	*	0.0040	*	0.0045	*	0.0049	*	0.0053	*	0.0057	*	0.0060	*
20.0	*	*	0.0010	*	0.0014	*	0.0017	*	0.0020	*	0.0022	*	0.0025	*	0.0026	*	0.0028	*	0.0030	*
10.0	*	*	0.0001	*	0.0002	*	0.0003	*	0.0004	*	0.0005	*	0.0005	*	0.0006	*	0.0007	*	0.0008	*


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*****  
*                                     *  
*                                CALBRATION OF ROTAMETERS                               *  
*                                     *  
*****
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*
* TEMPERATURE=294.2 ROTAMETER= LSS602 GAS=S02
*
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*****
*SCALE READ*                                PRESSURE(PSI)*****

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[illegible]

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*****
*                                     VOLUMETRIC FLOW RATE (ML/MIN)                                     *
```

10.0	12.8	18.0	21.9	25.5	28.5	31.2	33.8	36.1	38.3
20.0	33.1	46.8	56.8	66.2	74.1	81.1	87.6	93.7	99.4
30.0	55.0	77.8	94.3	110.0	122.9	134.7	145.5	155.5	164.9
40.0	78.3	110.8	134.3	156.7	175.1	191.9	207.2	221.5	235.0
50.0	103.2	145.9	176.9	206.3	230.7	252.7	272.9	291.8	309.5
60.0	129.5	183.1	222.0	259.0	289.5	317.2	342.6	366.3	388.5
70.0	157.3	222.5	269.7	314.6	351.8	385.3	416.2	444.9	471.9
80.0	186.6	263.9	320.0	373.2	417.3	457.1	493.7	527.8	559.9
90.0	217.4	307.5	372.8	434.8	486.2	532.6	575.2	615.0	652.3
100.0	249.7	353.1	428.2	499.4	558.4	611.7	660.7	706.3	749.1
110.0	283.5	400.9	486.1	567.0	633.9	694.4	750.0	801.8	850.5
120.0	318.8	450.8	546.6	637.5	712.8	780.8	843.4	901.6	956.3
130.0	355.5	502.8	609.6	711.0	795.0	870.9	940.6	1005.6	1066.6
140.0	393.8	556.9	675.2	787.6	880.5	964.6	1041.8	1113.8	1181.3
150.0	433.5	613.1	743.3	867.0	969.4	1061.9	1147.0	1226.2	1300.6

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*****
*                               MOLAR FLOW RATE (GMOLE/MIN)                               *
*****
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*	10.0	*	0.0005	*	0.0007	*	0.0009	*	0.0011	*	0.0012	*	0.0013	*	0.0014	*	0.0015	*	0.0016	*
*	20.0	*	0.0014	*	0.0019	*	0.0023	*	0.0027	*	0.0031	*	0.0034	*	0.0036	*	0.0039	*	0.0041	*
*	30.0	*	0.0023	*	0.0032	*	0.0039	*	0.0045	*	0.0051	*	0.0056	*	0.0060	*	0.0064	*	0.0068	*
*	40.0	*	0.0032	*	0.0046	*	0.0056	*	0.0065	*	0.0072	*	0.0079	*	0.0086	*	0.0092	*	0.0097	*
*	50.0	*	0.0043	*	0.0060	*	0.0073	*	0.0085	*	0.0095	*	0.0105	*	0.0113	*	0.0121	*	0.0128	*
*	60.0	*	0.0054	*	0.0076	*	0.0092	*	0.0107	*	0.0120	*	0.0131	*	0.0142	*	0.0152	*	0.0161	*
*	70.0	*	0.0065	*	0.0092	*	0.0112	*	0.0130	*	0.0146	*	0.0159	*	0.0172	*	0.0184	*	0.0195	*
*	80.0	*	0.0077	*	0.0109	*	0.0132	*	0.0154	*	0.0173	*	0.0189	*	0.0204	*	0.0218	*	0.0232	*
*	90.0	*	0.0090	*	0.0127	*	0.0154	*	0.0180	*	0.0201	*	0.0220	*	0.0238	*	0.0254	*	0.0270	*
*	100.0	*	0.0103	*	0.0146	*	0.0177	*	0.0207	*	0.0231	*	0.0253	*	0.0273	*	0.0292	*	0.0310	*
*	110.0	*	0.0117	*	0.0166	*	0.0201	*	0.0235	*	0.0262	*	0.0287	*	0.0310	*	0.0332	*	0.0352	*
*	120.0	*	0.0132	*	0.0186	*	0.0226	*	0.0264	*	0.0295	*	0.0323	*	0.0349	*	0.0373	*	0.0396	*
*	130.0	*	0.0147	*	0.0208	*	0.0252	*	0.0294	*	0.0329	*	0.0360	*	0.0389	*	0.0416	*	0.0441	*
*	140.0	*	0.0163	*	0.0230	*	0.0279	*	0.0326	*	0.0364	*	0.0399	*	0.0431	*	0.0461	*	0.0489	*
*	150.0	*	0.0179	*	0.0254	*	0.0307	*	0.0359	*	0.0401	*	0.0439	*	0.0474	*	0.0507	*	0.0538	*

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*****
*
*                                     CALBRATION OF ROTAMETERS
*
*****
*
*          TEMPERATURE=294.2    ROTAMETER=  LG602    GAS=S02
*
*****
*          SCALE READ*          PRESSURE(PSI)
*
*  (MM)    *    5.0    *    10.0    *    14.7    *    20.0    *    25.0    *    30.0    *    35.0    *    40.0    *    45.0
*
*****
*          *          VOLUMETRIC FLOW RATE (ML/MIN)
*
*  10.0    *    3.5    *    4.9    *    5.9    *    6.9    *    7.7    *    8.5    *    9.1    *    9.8    *    10.4
*  20.0    *    10.0   *    14.1   *    17.2   *    20.0   *    22.4   *    24.5   *    26.5   *    28.3   *    30.0
*  30.0    *    17.4   *    24.6   *    29.8   *    34.8   *    38.9   *    42.6   *    46.0   *    49.2   *    52.2
*  40.0    *    25.7   *    36.3   *    44.0   *    51.3   *    57.4   *    62.8   *    67.9   *    72.6   *    77.0
*  50.0    *    34.7   *    49.1   *    59.6   *    69.5   *    77.7   *    85.1   *    91.9   *    98.3   *    104.2
*  60.0    *    44.7   *    63.2   *    76.6   *    89.4   *    99.9   *    109.5  *    118.2  *    126.4  *    134.1
*  70.0    *    55.5   *    78.5   *    95.1   *    111.0  *    124.1  *    135.9  *    146.8  *    156.9  *    166.5
*  80.0    *    67.1   *    94.9   *    115.1  *    134.3  *    150.1  *    164.4  *    177.6  *    189.9  *    201.4
*  90.0    *    79.6   *    112.6  *    136.5  *    159.2  *    178.0  *    195.0  *    210.6  *    225.2  *    238.8
*  100.0   *    93.0   *    131.5  *    159.4  *    185.9  *    207.8  *    227.7  *    245.9  *    262.9  *    278.9
*  110.0   *    107.1  *    151.5  *    183.7  *    214.3  *    239.6  *    262.4  *    283.5  *    303.0  *    321.4
*  120.0   *    122.2  *    172.8  *    209.5  *    244.3  *    273.2  *    299.3  *    323.2  *    345.6  *    366.5
*  130.0   *    138.1  *    195.2  *    236.7  *    276.1  *    308.7  *    338.2  *    365.3  *    390.5  *    414.2
*  140.0   *    154.8  *    218.9  *    265.4  *    309.6  *    346.1  *    379.1  *    409.5  *    437.8  *    464.3
*  150.0   *    172.4  *    243.8  *    295.5  *    344.7  *    385.4  *    422.2  *    456.0  *    487.5  *    517.1
*
*****
*          *          MOLAR FLOW RATE (GMOLE/MIN)
*
*  10.0    *    0.0001 *    0.0002 *    0.0002 *    0.0003 *    0.0003 *    0.0003 *    0.0004 *    0.0004 *    0.0004
*  20.0    *    0.0004 *    0.0006 *    0.0007 *    0.0008 *    0.0009 *    0.0010 *    0.0011 *    0.0012 *    0.0012
*  30.0    *    0.0007 *    0.0010 *    0.0012 *    0.0014 *    0.0016 *    0.0018 *    0.0019 *    0.0020 *    0.0022
*  40.0    *    0.0011 *    0.0015 *    0.0018 *    0.0021 *    0.0024 *    0.0026 *    0.0028 *    0.0030 *    0.0032
*  50.0    *    0.0014 *    0.0020 *    0.0025 *    0.0029 *    0.0032 *    0.0035 *    0.0038 *    0.0041 *    0.0043
*  60.0    *    0.0018 *    0.0026 *    0.0032 *    0.0037 *    0.0041 *    0.0045 *    0.0049 *    0.0052 *    0.0055
*  70.0    *    0.0023 *    0.0032 *    0.0039 *    0.0046 *    0.0051 *    0.0056 *    0.0061 *    0.0065 *    0.0069
*  80.0    *    0.0028 *    0.0039 *    0.0048 *    0.0056 *    0.0062 *    0.0068 *    0.0073 *    0.0079 *    0.0083
*  90.0    *    0.0033 *    0.0047 *    0.0056 *    0.0066 *    0.0074 *    0.0081 *    0.0087 *    0.0093 *    0.0099
*  100.0   *    0.0038 *    0.0054 *    0.0066 *    0.0077 *    0.0086 *    0.0094 *    0.0102 *    0.0109 *    0.0115
*  110.0   *    0.0044 *    0.0063 *    0.0076 *    0.0089 *    0.0099 *    0.0109 *    0.0117 *    0.0125 *    0.0133
*  120.0   *    0.0051 *    0.0071 *    0.0087 *    0.0101 *    0.0113 *    0.0124 *    0.0134 *    0.0143 *    0.0152
*  130.0   *    0.0057 *    0.0081 *    0.0098 *    0.0114 *    0.0128 *    0.0140 *    0.0151 *    0.0162 *    0.0171
*  140.0   *    0.0064 *    0.0091 *    0.0110 *    0.0128 *    0.0143 *    0.0157 *    0.0169 *    0.0181 *    0.0192
*  150.0   *    0.0071 *    0.0101 *    0.0122 *    0.0143 *    0.0159 *    0.0175 *    0.0189 *    0.0202 *    0.0214
*
*****

```


CALIBRATION OF ROTAMETERS

TEMPERATURE=294.2 ROTAMETER= LG603 GAS= N2

PRESSURE(PSI)

SCALE READ

(MM)

VOLUMETRIC FLOW RATE (ML/MIN)

MOLAR FLOW RATE (GMOLE/MIN)

10.0	20.0	30.0	40.0	50.0	60.0	70.0	80.0	90.0	100.0	110.0	120.0	130.0	140.0	150.0	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*</
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CALBRATION OF ROTAMETERS

TEMPERATURE=294.2 ROTAMETER= L2SS603 GAS= N2

PRESSURE (PSI)

SCALE READ

(MM)

VOLUMETRIC FLOW RATE (ML/MIN)

10.0	244.5	345.8	419.3	489.1	546.8	599.0	647.0	691.7	733.6
20.0	495.0	700.0	848.7	990.0	1106.8	1212.4	1309.6	1400.0	1484.9
30.0	735.0	1039.4	1260.2	1470.0	1643.5	1800.4	1944.6	2078.9	2205.0
40.0	964.6	1364.1	1653.9	1929.2	2156.9	2362.8	2552.1	2728.3	2893.8
50.0	1183.8	1674.1	2029.8	2367.6	2647.0	2899.6	3132.0	3348.2	3551.3
60.0	1392.5	1969.4	2387.7	2785.1	3113.8	3411.0	3684.3	3938.7	4177.6
70.0	1590.9	2249.9	2727.8	3181.8	3557.7	3977.6	4357.2	4706.4	5031.3
80.0	1778.8	2515.7	3050.1	3357.7	3977.6	4357.2	4706.4	5031.3	5336.5
90.0	1956.4	2766.7	3354.4	3912.7	4374.5	4792.1	5176.0	5533.4	5869.1
100.0	2123.5	3003.0	3641.0	4246.9	4748.2	5201.4	5618.1	6006.0	6370.4
110.0	2280.1	3224.6	3909.6	4560.3	5098.6	5585.2	6032.7	6449.2	6840.4
120.0	2426.4	3431.5	4160.4	4852.8	5425.6	5943.5	6419.7	6863.0	7279.3
130.0	2562.3	3623.6	4393.4	5124.6	5729.4	6276.3	6779.2	7202.0	7603.2
140.0	2687.7	3801.0	4608.5	5375.4	6009.9	6583.5	7111.0	7602.0	8063.2
150.0	2802.7	3963.7	4805.7	5605.5	6267.1	6865.3	7415.4	7927.4	8408.2

MOLAR FLOW RATE (GMOLE/MIN)

10.0	0.0101	0.0205	0.0290	0.0351	0.0410	0.0458	0.0502	0.0542	0.0579
20.0	0.0304	0.0430	0.0564	0.0684	0.0798	0.0892	0.0977	0.1056	0.1129
30.0	0.0490	0.0693	0.0815	0.0988	0.1152	0.1288	0.1411	0.1524	0.1629
40.0	0.0693	0.0939	0.1056	0.1262	0.1472	0.1619	0.1810	0.1982	0.2141
50.0	0.0892	0.1188	0.1388	0.1569	0.1757	0.1964	0.2152	0.2324	0.2485
60.0	0.1094	0.1399	0.1604	0.1817	0.2027	0.2244	0.2459	0.2656	0.2839
70.0	0.1296	0.1601	0.1817	0.2027	0.2244	0.2459	0.2656	0.2839	0.2998
80.0	0.1497	0.1802	0.2027	0.2244	0.2459	0.2656	0.2839	0.2998	0.3145
90.0	0.1698	0.2003	0.2224	0.2439	0.2656	0.2839	0.2998	0.3145	0.3279
100.0	0.1899	0.2204	0.2424	0.2639	0.2856	0.3039	0.3204	0.3335	0.3478
110.0	0.2099	0.2404	0.2624	0.2839	0.3056	0.3239	0.3404	0.3535	0.3678
120.0	0.2299	0.2604	0.2824	0.3039	0.3256	0.3439	0.3604	0.3735	0.3878
130.0	0.2499	0.2804	0.3024	0.3239	0.3456	0.3639	0.3804	0.3935	0.4078
140.0	0.2699	0.3004	0.3224	0.3439	0.3656	0.3839	0.4004	0.4135	0.4278
150.0	0.2899	0.3204	0.3424	0.3639	0.3856	0.4039	0.4204	0.4335	0.4478

185

CALBRATION OF ROTAMETERS

TEMPERATURE=294.2 ROTAMETER= L3SS603 GAS= N2

PRESSURE(PsI)

SCALE READ

(MM)

5.0 10.0 14.7 20.0 25.0 30.0 35.0 40.0 45.0

VOLUMETRIC FLOW RATE (ML/MIN)

10.0	291.1	411.7	499.1	582.2	650.9	713.1	770.2	823.4	873.3
20.0	544.8	770.5	934.2	1089.7	1218.3	1334.6	1441.5	1541.0	1634.5
30.0	787.9	1114.2	1350.9	1575.7	1761.7	1929.9	2084.5	2228.4	2363.6
40.0	1020.2	1442.8	1749.3	2040.4	2281.2	2499.0	2699.2	2885.6	3060.6
50.0	1241.8	1756.2	2129.3	2483.7	2776.9	3041.9	3285.6	3512.5	3725.5
60.0	1452.8	2054.6	2491.0	2905.6	3248.6	3558.6	3843.8	4109.2	4358.4
70.0	1653.1	2337.8	2834.4	3306.2	3696.4	4049.2	4373.6	4675.6	4959.2
80.0	1842.7	2605.9	3159.5	3685.3	4120.3	4513.6	4875.2	5211.8	5528.0
90.0	2021.5	2858.9	3466.2	4043.1	4520.3	4951.7	5348.5	5717.8	6064.6
100.0	2189.7	3096.8	3754.6	4379.5	4896.4	5363.7	5793.5	6193.5	6569.2
110.0	2347.2	3319.5	4024.7	4694.5	5248.6	5749.6	6210.2	6639.0	7041.7
120.0	2494.1	3527.1	4276.4	4988.1	5576.9	6109.2	6598.7	7054.3	7482.2
130.0	2630.2	3719.6	4509.8	5260.4	5881.3	6442.6	6958.8	7439.3	7890.6
140.0	2755.6	3897.0	4724.9	5511.2	6161.8	6749.9	7290.7	7794.1	8266.9
150.0	2870.4	4059.3	4921.7	5740.7	6418.3	7030.9	7594.3	8118.6	8611.1

MOLAR FLOW RATE (GMOLE/MIN)

10.0	0.0120	0.0319	0.0206	0.0241	0.0269	0.0295	0.0319	0.0341	0.0361
20.0	0.0225	0.0461	0.0386	0.0451	0.0504	0.0552	0.0596	0.0637	0.0676
30.0	0.0326	0.0641	0.0559	0.0652	0.0729	0.0798	0.0862	0.0922	0.0978
40.0	0.0422	0.0844	0.0724	0.0844	0.0944	0.1034	0.1117	0.1194	0.1266
50.0	0.0514	0.1027	0.1030	0.1202	0.1344	0.1472	0.1590	0.1700	0.1803
60.0	0.0601	0.1173	0.1173	0.1368	0.1529	0.1675	0.1809	0.1934	0.2051
70.0	0.0684	0.1307	0.1307	0.1525	0.1704	0.1867	0.2017	0.2156	0.2287
80.0	0.0762	0.1434	0.1434	0.1673	0.1870	0.2048	0.2213	0.2365	0.2509
90.0	0.0836	0.1553	0.1553	0.1812	0.2025	0.2219	0.2397	0.2562	0.2717
100.0	0.0906	0.1665	0.1665	0.1942	0.2171	0.2378	0.2569	0.2746	0.2913
110.0	0.0971	0.1769	0.1769	0.2063	0.2307	0.2527	0.2730	0.2918	0.3095
120.0	0.1032	0.1866	0.1866	0.2176	0.2433	0.2665	0.2879	0.3077	0.3264
130.0	0.1088	0.1955	0.1955	0.2280	0.2549	0.2792	0.3016	0.3224	0.3420
140.0	0.1140	0.2036	0.2036	0.2375	0.2655	0.2908	0.3142	0.3358	0.3562
150.0	0.1187	0.2162	0.2162	0.2519	0.2809	0.3072	0.3319	0.3538	0.3742

CALBRATION OF ROTAMETERS

TEMPERATURE=294.2 ROTAMETER= L36603 GAS= N2

PRESSURE(PST)

SCALE READ

(MM)

VOLUMETRIC FLOW RATE (ML/MIN)

10.0	104.8	148.2	179.6	209.5	234.3	254.5	277.2	296.3	314.3
20.0	222.7	315.0	381.9	445.4	498.0	545.5	589.3	629.9	668.2
30.0	337.4	477.1	578.5	674.8	754.4	826.4	892.7	954.3	1012.2
40.0	448.8	634.7	769.5	897.6	1003.5	1099.3	1187.4	1269.4	1346.4
50.0	556.9	787.6	954.9	1113.8	1245.3	1364.1	1473.4	1575.2	1670.7
60.0	661.7	935.8	1134.7	1323.5	1479.7	1620.9	1750.8	1871.7	1985.2
70.0	763.3	1079.5	1308.8	1526.6	1723.2	1926.5	2110.4	2279.5	2436.9
80.0	861.6	1218.5	1477.3	1723.2	1926.5	2110.4	2279.5	2436.9	2584.7
90.0	956.6	1352.8	1640.2	1913.1	2139.0	2343.1	2530.9	2705.6	2869.7
100.0	1048.3	1482.5	1797.4	2096.6	2344.1	2567.8	2773.5	2965.0	3144.9
110.0	1136.7	1607.6	1949.1	2273.5	2541.8	2784.4	3007.5	3215.2	3410.2
120.0	1221.9	1728.0	2095.1	2443.8	2732.2	2993.0	3232.8	3456.0	3665.7
130.0	1303.8	1843.8	2235.5	2607.5	2915.3	3193.6	3449.5	3687.6	3911.3
140.0	1382.4	1955.0	2370.3	2764.7	3091.1	3386.1	3657.4	3909.9	4147.1
150.0	1457.7	2061.5	2499.4	2915.4	3259.5	3570.6	3856.7	4123.0	4373.1

MOLAR FLOW RATE (GMOLE/MIN)

10.0	0.0061	0.0130	0.0158	0.0184	0.0206	0.0226	0.0244	0.0261	0.0276
20.0	0.0092	0.0140	0.0197	0.0239	0.0279	0.0312	0.0342	0.0369	0.0395
30.0	0.0140	0.0186	0.0230	0.0263	0.0318	0.0371	0.0415	0.0451	0.0491
40.0	0.0186	0.0263	0.0326	0.0395	0.0469	0.0547	0.0612	0.0671	0.0724
50.0	0.0230	0.0387	0.0447	0.0541	0.0632	0.0706	0.0773	0.0835	0.0893
60.0	0.0356	0.0504	0.0560	0.0611	0.0713	0.0797	0.0873	0.0943	0.1008
70.0	0.0356	0.0504	0.0560	0.0611	0.0713	0.0797	0.0873	0.0943	0.1008
80.0	0.0396	0.0560	0.0613	0.0744	0.0867	0.0970	0.1062	0.1147	0.1227
90.0	0.0434	0.0647	0.0715	0.0867	0.1011	0.1130	0.1238	0.1337	0.1430
100.0	0.0470	0.0665	0.0806	0.0940	0.1051	0.1152	0.1244	0.1330	0.1411
110.0	0.0505	0.0715	0.0867	0.1011	0.1130	0.1238	0.1337	0.1427	0.1525
120.0	0.0539	0.0763	0.0925	0.1079	0.1206	0.1321	0.1427	0.1513	0.1617
130.0	0.0572	0.0809	0.0981	0.1144	0.1279	0.1401	0.1513	0.1617	0.1716
140.0	0.0603	0.0853	0.1034	0.1206	0.1348	0.1477	0.1595	0.1706	0.1809
150.0	0.0633	0.0883	0.1063	0.1235	0.1377	0.1506	0.1617	0.1716	0.1809

***** CALIBRATION OF ROTAMETERS *****

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* TEMPERATURE=294.2 ROTAMETER=L4SS603 GAS=N2
*

PRESSURE(PST)

SCALE READ

VOLUMETRIC FLOW RATE (ML/MIN) *****

10.0	*	291.1	*	411.7	*	499.1	*	582.2	*	650.9	*	713.1	*	775.4	*	837.7	*	900.0	*	962.3	*	1024.6	*	1086.9	*	1149.2	*	1211.5	*	1273.8	*	1336.1	*	1398.4	*	1460.7	*	1523.0	*	1585.3	*	1647.6	*	1709.9	*	1772.2	*	1834.5	*	1896.8	*	1959.1	*	2021.4	*	2083.7	*	2146.0	*	2208.3	*	2270.6	*	2332.9	*	2395.2	*	2457.5	*	2519.8	*	2582.1	*	2644.4	*	2706.7	*	2769.0	*	2831.3	*	2893.6	*	2955.9	*	3018.2	*	3080.5	*	3142.8	*	3205.1	*	3267.4	*	3329.7	*	3392.0	*	3454.3	*	3516.6	*	3578.9	*	3641.2	*	3703.5	*	3765.8	*	3828.1	*	3890.4	*	3952.7	*	4015.0	*	4077.3	*	4139.6	*	4201.9	*	4264.2	*	4326.5	*	4388.8	*	4451.1	*	4513.4	*	4575.7	*	4638.0	*	4700.3	*	4762.6	*	4824.9	*	4887.2	*	4949.5	*	5011.8	*	5074.1	*	5136.4	*	5198.7	*	5261.0	*	5323.3	*	5385.6	*	5447.9	*	5510.2	*	5572.5	*	5634.8	*	5697.1	*	5759.4	*	5821.7	*	5884.0	*	5946.3	*	6008.6	*	6070.9	*	6133.2	*	6195.5	*	6257.8	*	6320.1	*	6382.4	*	6444.7	*	6507.0	*	6569.3	*	6631.6	*	6693.9	*	6756.2	*	6818.5	*	6880.8	*	6943.1	*	7005.4	*	7067.7	*	7130.0	*	7192.3	*	7254.6	*	7316.9	*	7379.2	*	7441.5	*	7503.8	*	7566.1	*	7628.4	*	7690.7	*	7753.0	*	7815.3	*	7877.6	*	7939.9	*	8002.2	*	8064.5	*	8126.8	*	8189.1	*	8251.4	*	8313.7	*	8376.0	*	8438.3	*	8500.6	*	8562.9	*	8625.2	*	8687.5	*	8749.8	*	8812.1	*	8874.4	*	8936.7	*	8999.0	*	9061.3	*	9123.6	*	9185.9	*	9248.2	*	9310.5	*	9372.8	*	9435.1	*	9497.4	*	9559.7	*	9622.0	*	9684.3	*	9746.6	*	9808.9	*	9871.2	*	9933.5	*	9995.8	*	10058.1	*	10120.4	*	10182.7	*	10245.0	*	10307.3	*	10369.6	*	10431.9	*	10494.2	*	10556.5	*	10618.8	*	10681.1	*	10743.4	*	10805.7	*	10868.0	*	10930.3	*	10992.6	*	11054.9	*	11117.2	*	11179.5	*	11241.8	*	11304.1	*	11366.4	*	11428.7	*	11491.0	*	11553.3	*	11615.6	*	11677.9	*	11740.2	*	11802.5	*	11864.8	*	11927.1	*	11989.4	*	12051.7	*	12114.0	*	12176.3	*	12238.6	*	12300.9	*	12363.2	*	12425.5	*	12487.8	*	12550.1	*	12612.4	*	12674.7	*	12737.0	*	12799.3	*	12861.6	*	12923.9	*	12986.2	*	13048.5	*	13110.8	*	13173.1	*	13235.4	*	13297.7	*	13360.0	*	13422.3	*	13484.6	*	13546.9	*	13609.2	*	13671.5	*	13733.8	*	13796.1	*	13858.4	*	13920.7	*	13983.0	*	14045.3	*	14107.6	*	14169.9	*	14232.2	*	14294.5	*	14356.8	*	14419.1	*	14481.4	*	14543.7	*	14606.0	*	14668.3	*	14730.6	*	14792.9	*	14855.2	*	14917.5	*	14979.8	*	15042
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30.0	*	787.9	*	1114.2	*	1350.9	*	1575.7	*	1761.7	*	1929.9	*	2084.5	*	2228.4	*	2363.6	*	3060.6	*
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40.0	*	1020.2	*	1442.8	*	1749.3	*	2040.4	*	2281.2	*	2499.0	*	3041.9	*	3285.6	*	3512.5	*	3725.5	*
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60.0	*	1452.8	*	2054.6	*	2491.0	*	2905.6	*	3248.6	*	3558.6	*	3843.8	*	4109.2	*	4358.4	*	4599.2	*
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70.0	*	1653.1	*	2337.8	*	2834.4	*	3306.2	*	3698.4	*	4049.2	*	4513.6	*	4875.2	*	5211.8	*	5528.0	*
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90.0	*	2021.5	*	2858.9	*	3466.2	*	4043.1	*	4520.3	*	4951.7	*	5348.5	*	5717.8	*	6084.8	*	6569.2	*
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100.0	*	2189.7	*	3096.8	*	3754.6	*	4319.5	*	4898.4	*	5248.6	*	5749.6	*	6210.2	*	6639.0	*	7041.7	*
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110.0	*	2347.2	*	3527.1	*	4276.4	*	4988.1	*	5576.9	*	6109.2	*	6598.7	*	7054.3	*	7482.2	*	7890.6	*
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130.0	*	2630.2	*	3719.6	*	4509.8	*	5260.4	*	5881.5	*	6472.0	*	6749.9	*	7290.7	*	7794.1	*	8266.9	*
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150.0	*	2870.4	*	4059.3	*	4921.7	*	5740.7	*	6418.3	*	7030.9	*	7594.3	*	8118.8	*	8611.1	*
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MOLAR FLOW RATE (GMOLE/MIN)

*****0.0361 0.0341 * 0.0295 * 0.0269 * 0.0237 * 0.0205 * 0.0173 * 0.0141 * 0.0109 * 0.0077 * 0.0045 * 0.0013 *****

10.0	*	0.0120	*	0.0170	*	0.0208	*	0.0241	*	0.0259	*	0.0269	*	0.0272	*	0.0273	*	0.0274	*	0.0275	*	0.0276	*	0.0277	*	0.0278	*	0.0279	*	0.0280	*	0.0281	*	0.0282	*	0.0283	*	0.0284	*	0.0285	*	0.0286	*	0.0287	*	0.0288	*	0.0289	*	0.0290	*	0.0291	*	0.0292	*	0.0293	*	0.0294	*	0.0295	*	0.0296	*	0.0297	*	0.0298	*	0.0299	*	0.0300	*	0.0301	*	0.0302	*	0.0303	*	0.0304	*	0.0305	*	0.0306	*	0.0307	*	0.0308	*	0.0309	*	0.0310	*	0.0311	*	0.0312	*	0.0313	*	0.0314	*	0.0315	*	0.0316	*	0.0317	*	0.0318	*	0.0319	*	0.0320	*	0.0321	*	0.0322	*	0.0323	*	0.0324	*	0.0325	*	0.0326	*	0.0327	*	0.0328	*	0.0329	*	0.0330	*	0.0331	*	0.0332	*	0.0333	*	0.0334	*	0.0335	*	0.0336	*	0.0337	*	0.0338	*	0.0339	*	0.0340	*	0.0341	*	0.0342	*	0.0343	*	0.0344	*	0.0345	*	0.0346	*	0.0347	*	0.0348	*	0.0349	*	0.0350	*	0.0351	*	0.0352	*	0.0353	*	0.0354	*	0.0355	*	0.0356	*	0.0357	*	0.0358	*	0.0359	*	0.0360	*	0.0361	*	0.0362	*	0.0363	*	0.0364	*	0.0365	*	0.0366	*	0.0367	*	0.0368	*	0.0369	*	0.0370	*	0.0371	*	0.0372	*	0.0373	*	0.0374	*	0.0375	*	0.0376	*	0.0377	*	0.0378	*	0.0379	*	0.0380	*	0.0381	*	0.0382	*	0.0383	*	0.0384	*	0.0385	*	0.0386	*	0.0387	*	0.0388	*	0.0389	*	0.0390	*	0.0391	*	0.0392	*	0.0393	*	0.0394	*	0.0395	*	0.0396	*	0.0397	*	0.0398	*	0.0399	*	0.0400	*	0.0401	*	0.0402	*	0.0403	*	0.0404	*	0.0405	*	0.0406	*	0.0407	*	0.0408	*	0.0409	*	0.0410	*	0.0411	*	0.0412	*	0.0413	*	0.0414	*	0.0415	*	0.0416	*	0.0417	*	0.0418	*	0.0419	*	0.0420	*	0.0421	*	0.0422	*	0.0423	*	0.0424	*	0.0425	*	0.0426	*	0.0427	*	0.0428	*	0.0429	*	0.0430	*	0.0431	*	0.0432	*	0.0433	*	0.0434	*	0.0435	*	0.0436	*	0.0437	*	0.0438	*	0.0439	*	0.0440	*	0.0441	*	0.0442	*	0.0443	*	0.0444	*	0.0445	*	0.0446	*	0.0447	*	0.0448	*	0.0449	*	0.0450	*	0.0451	*	0.0452	*	0.0453	*	0.0454	*	0.0455	*	0.0456	*	0.0457	*	0.0458	*	0.0459	*	0.0460	*	0.0461	*	0.0462	*	0.0463	*	0.0464	*	0.0465	*	0.0466	*	0.0467	*	0.0468	*	0.0469	*	0.0470	*	0.0471	*	0.0472	*	0.0473	*	0.0474	*	0.0475	*	0.0476	*	0.0477	*	0.0478	*	0.0479	*	0.0480	*	0.0481	*	0.0482	*	0.0483	*	0.0484	*	0.0485	*	0.0486	*	0.0487	*	0.0488	*	0.0489	*	0.0490	*	0.0491	*	0.0492	*	0.0493	*	0.0494	*	0.0495	*	0.0496	*	0.0497	*	0.0498	*	0.0499	*	0.0500	*	0.0501	*	0.0502	*	0.0503	*	0.0504	*	0.0505</
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30.0	*	0.0326	*	0.0461	*	0.0559	*	0.0652	*	0.0729	*	0.0798	*	0.0862	*	0.0922	*	0.0978	*	0.1034	*	0.1117	*	0.1194	*	0.1266	*
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40.0	*	*	0.0422	*	0.0597	*	0.0124	*	0.0844	*	0.0844	*	0.0149	*	0.1258	*	0.1359	*	0.1453	*	0.1541
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60.0	*	0.0601	*	0.0850	*	0.1030	*	0.1202	*	0.1344	*	0.1472	*	0.1590	*	0.1700	*	0.1809	*	0.1934	*	0.2051
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70.0	*	0.0684	*	0.0967	*	0.1113	*	0.1388	*	0.1525	*	0.1704	*	0.1867	*	0.2017	*	0.2156	*	0.2287
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90.0	*	0.0836	*	0.1183	*	0.1434	*	0.1673	*	0.1870	*	0.2048	*	0.2219	*	0.2397	*	0.2562	*	0.2717
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100.0	*	0.0906	*	0.1281	*	0.1555	*	0.1812	*	0.2079	*	0.2378	*	0.2569	*	0.2746	*	0.2913	*	0.3095	*
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120.0	*	0.1032	*	0.1459	*	0.1769	*	0.2063	*	0.2307	*	0.2527	*	0.2730	*	0.2879	*	0.3077	*	0.3264
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130.0	*	*	0.1088	*	0.1539	*	0.1888	*	0.2178	*	0.2549	*	0.2792	*	0.3016	*	0.3224	*	0.3420	*	0.3562	*
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CALBRATION OF ROTAMETERS

TEMPERATURE=294.2 ROTAMETER= L4G603 GAS= N2

PRESSURE (PSI)

SCALE READ

(MM)	5.0	10.0	14.7	20.0	25.0	30.0	35.0	40.0	45.0

VOLUMETRIC FLOW RATE (ML/MIN)

10.0	104.8	148.2	179.6	209.5	234.3	256.6	277.2	296.3	314.3
20.0	222.7	315.0	381.9	445.4	498.0	545.5	589.3	629.9	668.2
30.0	337.4	477.1	578.5	674.8	754.4	826.4	892.7	954.3	1012.2
40.0	448.8	634.7	769.5	897.6	1003.5	1099.3	1187.4	1269.4	1346.4
50.0	556.9	787.6	954.9	1113.8	1245.3	1364.1	1473.4	1575.2	1670.7
60.0	661.7	935.8	1134.7	1323.5	1479.7	1620.9	1750.8	1871.7	1985.2
70.0	763.3	1079.5	1308.8	1526.6	1706.8	1869.7	2019.5	2158.9	2289.9
80.0	861.6	1218.5	1477.3	1723.2	1926.5	2110.4	2279.5	2436.9	2584.7
90.0	956.6	1352.8	1640.2	1913.1	2139.0	2343.1	2530.9	2705.6	2869.7
100.0	1048.3	1482.5	1797.4	2096.6	2344.1	2567.8	2773.5	2965.0	3144.9
110.0	1136.7	1607.6	1949.1	2273.5	2541.8	2784.4	3007.5	3215.2	3410.2
120.0	1221.9	1728.0	2095.1	2443.8	2732.2	2993.0	3232.8	3456.0	3665.7
130.0	1303.8	1843.8	2235.5	2607.5	2915.3	3193.6	3449.5	3687.6	3911.3
140.0	1382.4	1955.0	2370.3	2764.7	3091.1	3386.1	3657.4	3909.9	4147.1
150.0	1457.7	2061.5	2499.4	2915.4	3259.5	3570.6	3856.7	4123.0	4373.1

MOLAR FLOW RATE (GMOL/MIN)

10.0	0.0043	0.0061	0.0074	0.0087	0.0097	0.0106	0.0115	0.0123	0.0130
20.0	0.0092	0.0130	0.0158	0.0184	0.0206	0.0226	0.0244	0.0261	0.0276
30.0	0.0140	0.0197	0.0239	0.0279	0.0312	0.0342	0.0369	0.0395	0.0419
40.0	0.0186	0.0263	0.0318	0.0371	0.0415	0.0455	0.0491	0.0525	0.0557
50.0	0.0230	0.0326	0.0395	0.0461	0.0515	0.0564	0.0610	0.0652	0.0691
60.0	0.0274	0.0387	0.0469	0.0547	0.0612	0.0671	0.0724	0.0774	0.0821
70.0	0.0316	0.0447	0.0541	0.0632	0.0706	0.0773	0.0835	0.0893	0.0947
80.0	0.0356	0.0504	0.0611	0.0713	0.0797	0.0873	0.0943	0.1008	0.1069
90.0	0.0396	0.0560	0.0678	0.0791	0.0885	0.0969	0.1047	0.1119	0.1187
100.0	0.0434	0.0613	0.0744	0.0867	0.0970	0.1062	0.1147	0.1227	0.1301
110.0	0.0470	0.0665	0.0806	0.0940	0.1051	0.1152	0.1244	0.1330	0.1411
120.0	0.0505	0.0715	0.0867	0.1011	0.1130	0.1238	0.1337	0.1430	0.1516
130.0	0.0539	0.0763	0.0925	0.1079	0.1206	0.1321	0.1427	0.1525	0.1618
140.0	0.0572	0.0809	0.0981	0.1144	0.1279	0.1401	0.1513	0.1617	0.1716
150.0	0.0603	0.0853	0.1034	0.1206	0.1348	0.1477	0.1595	0.1706	0.1809

APPENDIX C

COMPUTER PROGRAMME FOR THE DATA ANALYSIS

Listed below is the computer programme for the estimation of the sulphur conversions from the experimental data. The flow rates of the feed gases were estimated from the second order linear regression coefficients of the rotameter calibration curves. The compositions of the reactor effluent were also estimated from second order linear regression coefficients of the calibration curves for the H_2S and SO_2 analysers. Finally the sulphur conversion was determined using Eq. 6.2.

```

C      *  PROGRAMME FOR DATA ANALYSIS
C      *  DATA IS FROM FLUIDIZED BED CLAUD REACTOR
C
C      CFN = COEFF. FOR THE CALIB. CURVE OF THE ROTA. FOR FLUID. NITROGEN
C      CLN = CCEF. FOR THE CALIB. CURVE OF THE ROTA. FOR N2 PURGING
C              MANOMETER
C      CMN = CCEF. FOR THE CALIB. CURVE OF THE ROTA. FOR N2 PURGING
C              FEED LINE
C      CHSS= CCEF. FOR THE CALIB. CURVE OF THE ROTA. FOR H2S - SS FLOAT
C      CHSG= CCEF. FOR THE CALIB. CURVE OF THE ROTA. FOR H2S - GLASS
C              FLOAT
C      CSCS= CCEF. FOR THE CALIB. CURVE OF THE ROTA. FOR SO2 - SS FLOAT
C      CSCG= CCEF. FOR THE CALIB. CURVE OF THE ROTA. FOR SO2 - GLASS
C              FLOAT
C      CHSA= CCEF. FOR THE CALIB. CURVE OF THE ROTA. FOR AIR DILUTING
C              SAMPLE TO H2S ANALYSER
C      CSAM= CCEF. FOR THE CALIB. CURVE OF THE ROTA. FOR SAMPLE
C      CASA= CCEF. FOR THE CALIB. CURVE OF THE ROTA. FOR AIR DILUTING
C              SAMPLE
C
C      T   = ROOM TEMPERATURE
C      TR  = REACTION TEMPERATURE
C      P   = ATMOSPHERIC PRESSURE
C      PR  = PRESSURE INSIDE REACTOR
C      BH  = BED HEIGHT
C      R   = GAS CONSTANT
C      M   = NUMBER OF RUNS
C      AN  = NAME OF GASES
C      XFN = SCALE READING OF FLUIDIZING NITROGEN ROTAMETER
C      XPN = SCALE READING OF N2 PURGING FEEDLINE ROTAMETER
C      XHS = SCALE READING OF H2S ROTAMETER
C      HSO = SCALE READING OF SO2 ROTAMETER
C      FFN = FLOW RATE OF FLUIDIZING NITROGEN
C      FLN = FLOW RATE OF NITROGEN PURGING MANOMETER
C      FMN = FLOW RATE OF NITROGEN PURGING CATALYST FEED LINE
C      FHS = FLOW RATE OF H2S
C      FSO = FLOW RATE OF SO2
C      FHA = FLOW RATE OF AIR DILUTING SAMPLE TO H2S ANALYSER
C      FSM = FLOW RATE OF SAMPLE
C      FSA = FLOW RATE OF AIR DILUTING SAMPLE
C      PFN = PRESSURE INSIDE FLUIDIZING N2 ROTAMETER
C      PFN = PRESSURE INSIDE ROTAMETER PURGING FEEDLINE
C      PHS = PRESSURE INSIDE H2S ROTAMETER
C      HSC = PRESSURE INSIDE SO2 ROTAMETER
C      DSF = DENSITY FACTOR,  $20.69 = 294.2 \times 14.7 / 0.96724$ 
C      AFN = MOLAR FLOW RATE OF NITROGEN
C      AHS = MOLAR FLOW RATE OF H2S
C      ASO = MOLAR FLOW RATE OF SO2
C      EHS = MILLIVOLTS ,H2S , FEED
C      ESC = VOLTS ,SO2 , FEED
C      EPS = MILLIVOLTS ,H2S , PRODUCT
C      EPC = VOLTS ,SO2 , PRODUCT
C      PRM = PRESSURE INSIDE ROTAMETER FOR AIR - PRODUCT
C      FSA = AIR FLOW RATE - PRODUCT
C      G2  = FLOW RATE OF SAMPLE TO H2S ANALYSER FOR CALIBRATION
C      F2  = FLOW RATE OF SAMPLE TO H2S ANALYSER FOR ANALYSIS

```



```

IMPLICIT REAL*8 (A-H,C-$)
EXTERNAL LAUX
COMMON M
DIMENSION EHS(20),ESC(20),IRCOD(20),EHS(5),BSO(5),D1(20),D2(20)
DIMENSION EX(20),IY(20),DYF(20),DWT(20),DE1(5),DE2(5),DP(5)
DIMENSION DXX(20),DYY(20),DYYF(20),EPS(20),EPO(20),XP(20),PP(20)
DIMENSION F1(20),F2(20),CPS(20),CFC(20),CPN(20),CN2(20),CHS(20)
DIMENSION CSC(20),XS(20),PS(20),F2(20),G2(20)
DIMENSION CFN(5),CLN(5),CMN(5),CHSS(5),CHSG(5),CSOS(5),CSCG(5)
DIMENSION CHSA(5),CSAM(5),CASA(5),AN(5),FFN(20),FLN(20),FMN(20)
DIMENSION FHS(20),FSC(20),AFN(20),AHS(20),ASO(20),FSA(20),PRM(20)
DIMENSION UMFNO(20)

```

C
C
C

```

**** READING COEF. FROM ROTAMETER CALIBRATION CURVE

```

```

READ(5,100) SFN,(CFN(I),I=1,3)
READ(5,100) SLN,(CLN(I),I=1,3)
READ(5,100) SMN,(CMN(I),I=1,3)
READ(5,100) SHSS,(CHSS(I),I=1,3)
READ(5,100) SHSG,(CHSG(I),I=1,3)
READ(5,100) SSCS,(CSCS(I),I=1,3)
READ(5,100) SSCG,(CSCG(I),I=1,3)
READ(5,100) SHSA,(CHSA(I),I=1,3)
READ(5,100) SSAM,(CSAM(I),I=1,3)
READ(5,100) SASA,(CASA(I),I=1,3)

```

C
C
C

```

**** WRITING COEF. FROM ROTAMETER CALIBRATION CURVE

```

```

WRITE(6,1000)
WRITE(6,1100)
WRITE(6,1300)
WRITE(6,1400)
WRITE(6,1300)
WRITE(6,1100)
WRITE(6,1300)
WRITE(6,1200) SFN,(CFN(I),I=1,3)
WRITE(6,1300)
WRITE(6,1200) SMN,(CMN(I),I=1,3)
WRITE(6,1300)
WRITE(6,1200) SHSS,(CHSS(I),I=1,3)
WRITE(6,1300)
WRITE(6,1200) SHSG,(CHSG(I),I=1,3)
WRITE(6,1300)
WRITE(6,1200) SSCS,(CSCS(I),I=1,3)
WRITE(6,1300)
WRITE(6,1200) SSCG,(CSCG(I),I=1,3)
WRITE(6,1300)
WRITE(6,1200) SHSA,(CHSA(I),I=1,3)
WRITE(6,1300)
WRITE(6,1200) SSAM,(CSAM(I),I=1,3)
WRITE(6,1300)
WRITE(6,1200) SASA,(CASA(I),I=1,3)
WRITE(6,1300)

```

```

WRITE(6,1200) SLN,(CLN(I),I=1,3)
WRITE(6,1300)
WRITE(6,1100)
C
C ***** READING AND WRITING GENERAL OPERATING DATA
C
NCCUNT = 2
DO 97 KA=1,NCCUNT
READ(5,200) T,TR,P,PR,EH,UMF
WRITE(6,2000)
WRITE(6,2100) T
WRITE(6,2200) TR
WRITE(6,2300) P
WRITE(6,2400) PR
WRITE(6,2500) EH
WRITE(6,2600) UMF
C
C ***** ANALYSING THE DATA FOR EACH RUN
C
READ(5,300) NR
WRITE(6,3000) NR
DO 50 I=1,NR
READ(5,300) IRCCL(I)
C
C ***** READING OPERATING DATA FOR EACH RUN
C
READ(5,400) XFN,XLN,XMN,XHS,XSC,XP(I),FSA(I),XS(I)
READ(5,400) PFN,FLN,FMN,PHS,PSC,PF(I),FPM(I),PS(I)
READ(5,400) EPS(I),EPC(I),F2(I)
READ(5,300) IFHS,IFSC
XLN =XLN/100.D0
XMN =XMN/100.D0
XHS =XHS/100.D0
XSC =XSC/100.D0
XP(I)=XP(I)/100.D0
XFN =XFN/100.D0
XS(I)=XS(I)/100.D0
C
C ***** CALCULATING FEED FLCW RATES
C
CALL FLCW(XFN,PFN,T,20.69D0,CFN,FR)
FFN(I)=FR
CALL FLCW(XLN,FLN,T,20.69D0,CIN,FR)
FLN(I)=FR
CALL FLCW(XMN,FMN,T,20.69D0,CMN,FR)
FMN(I)=FR
FFN(I)=FFN(I)+FLN(I)+FMN(I)
AFN(I)=FFN(I)/24141.17E0
IF(IFES.GT.1) GO TO 10
CALL FLCW(XHS,PHS,T,16.818D0,CHSG,FR)
GO TO 20
CALL FLCW(XHS,PHS,T,16.818D0,CHSS,FR)
10 FHS(I)=FR
20

```

```

      AHS(I)=FHS(I)/24141.17D0
      IF (IFSC.GT.1) GC TO 30
      CALL FLCW(XSC,PSC,T,8.8407D0,CSCG,FR)
      GO TO 40
30    CALL FLCW(XSC,PSC,T,8.8407D0,CSCS,FR)
40    FSC(I)=FR
      ASC(I)=FSC(I)/24141.17D0
C
C      ***** CALCULATING FEED COMPOSITION
C
      TOTF = FFN(I) + (FHS(I)+FSO(I))*0.791667D0
      TCTF = TCTF*TR*14.7D0/294.2D0/60.D0/PR
      VEL = TCTF/81.0732D0
      UMFNC(I)=VEL/UMF
      TMCLA=(AFN(I)+AHS(I)+ASO(I))/10C.D0
      CN2(I)=AFN(I)/TMCLA
      CHS(I)=AHS(I)/TMCLA
      CSC(I)=ASC(I)/TMCLA
50    CCNTINUE
C
C      **** READING THE PARAMETERS FOR CALIBRATING H2S AND
C      SC2 ANALYSERS
C
      READ(5,300) NS
      DY(1)=0.0D0
      DYY(1)=C.0D0
      DX(1)=0.0D0
      LXX(1)=C.0D0
      DO 58 I=2,NS
      READ(5,300) IGHS,IGSC
      READ(5,400) XCN,XSM,XSA,XR,XHS,XSO
      READ(5,400) PCN,PSM,PSA,PR,PHS,ESC
      READ(5,400) FHS(I),ESO(I),G2(I)
      XCN =XCN/100.D0
      XSM =XSM/100.D0
      XR =XR/100.D0
      XHS =XHS/100.D0
      XSC =XSC/100.D0
C
C      **** CALCULATING THE VARIABLES FOR CURVE FITTING TO THE
C      **** CALIBRATING DATA FOR H2S AND SC2
C
      CALL FLCW(XCN,PCN,T,20.69D0,CFN,FR)
      FN=FR
      CALL FLCW(XSM,PSM,T,20.69D0,CSAM,FR)
      FS=FR
      DSF=20.01D0*PSA/T
      DDF=DSQRT(DSF)
      FA =XSA*DDF
      D1(I)=(FS+FA)/FS
      AF =FN/24141.17D0
      CALL FLCW(XR,PR,T,20.01D0,CHSA,FR)
      D2(I)=FR/G2(I)
      IF (IGHS.GT.1) GC TO 51

```

```

      CALL FLCW(XHS,PHS,T,16.818D0,CHSG,FR)
      GO TO 52
51  CALL FLCW(XHS,PHS,T,16.818D0,CHES,FR)
52  RHS=FR/24141.17D0
      IF (ICSC-GI.1) GC TO 53
      CALL FLCW(XSC,PSC,T,8.8407D0,CSCG,FR)
      GO TO 54
53  CALL FLCW(XSC,PSC,T,8.8407D0,CSCS,FR)
54  RSC=FR/24141.17D0
      TMCL = (AF+RHS+RSC)/1.0D06
      DY(I)=RHS/TMCL/D1(I)/D2(I)
      DYY(I)=RSC/TMCL/D1(I)
      DX(I) =EHS(I)
      VV    =C.000206D0*DY(I)*D2(I)
      DXX(I)=DEXF(VV)*ESC(I)*1000.0D0
58  CCNTINUE
      N=NS
      M=3
      NI=10
      DEFS=C.00001D0
      DO 60 J=1,3
60  DP(J)=0.0D0
      WRITE(6,4000)
      CALL DLQF(DX,DY,DYF,DWT,DE1,DE2,DP,0.0D0,N,M,NI,ND,DEPS,DAUX)
      IF (ND.NE.1) GC TO 71
      DO 65 J=1,3
65  BHS(J)=DF(J)
      WRITE(6,4100)
      DO 70 J=1,N
70  WRITE(6,4200) DX(J),DY(J),DYF(J)
71  M=3
      NI=10
      DEFS=C.00001D0
      DO 80 J=1,3
80  DP(J)=0.0D0
      WRITE(6,4000)
      CALL DLQF(DXX,DYY,DYYF,DWT,DE1,DE2,DP,0.0D0,N,M,NI,ND,DEPS,DAUX)
      IF (ND.NE.1) GO TO 91
      DO 85 J=1,3
85  BSC(J)=DF(J)
      WRITE(6,4300)
      DO 90 J=1,N
90  WRITE(6,4200) DXX(J),DYY(J),DYYF(J)
C
C  **** PRINTING FEED COMPOSITION
C
      WRITE(6,3100)
      WRITE(6,3200)
      WRITE(6,3300)
      WRITE(6,3400)
      WRITE(6,3500)
      DO 95 I=1,NR
95  WRITE(6,3600) IRCCD(I),FFN(I),FHS(I),FSC(I),AFN(I),AHS(I),ASO(I),C

```

```

1N2 (I) ,CHS (I) ,CSC (I) ,UMFNO (I)
WRITE (6,3800)
WRITE (6,3900) (D1 (I) ,I=2,N)
WRITE (6,3900) (D2 (I) ,I=2,N)
C
C
C      ****   CALCULATING   PRODUCT   COMPOSITION

WRITE (6,3100)
WRITE (6,5000)
WRITE (6,5100)
WRITE (6,5200)
DO 96 I=1,NR
XT  =XS (I)
PT  =FS (I)
CALL FLCW (XT,PT,T,20.01D0,CHSA,FR)
P2 (I)=FR/F2 (I)
XR  =XF (I)
PR  =FF (I)
CALL FLCW (XR,PR,T,20.69D0,CSAM,FR)
RR  =FR
DSF  =20.01D0*FRM (I)/T
DDF  =DSQRT (DSF)
RS  =FSA (I)*DDF
P1 (I)=(RR+RS)/RR
S    =EFS (I)
SS  =EHS (1)+S*EHS (2)+S*S*BHS (3)
CPS (I)=SS*P1 (I)*P2 (I)/10000.D0
V    =0.000206D0*S*P2 (I)
Q    =DEXF (V)*EFC (I)*1000.0D0
W    =ESC (1)+Q*ESC (2)+Q*Q*ESO (3)
CPC (I)=W*P1 (I)/10000.DC
CN2 (I)=100.D0-CPS (I)-CFO (I)
QV   =AFN (I)/CN2 (I)
QS   =QV*CPS (I)
PH2S  =(1.0D0-QS/AHS (I))*100.D0
QT    =QV*CPC (I)
PSO2  =(1.0D0-QT/ASO (I))*100.D0
TS=(1-(QS+QT)/(AHS (I)+ASO (I)))*100.D0
WRITE (6,5300) IRCCD (I) ,CN2 (I) ,CPS (I) ,CFC (I) ,PH2S ,PSO2 ,TS
96  CCNTINUE
WRITE (6,5400)
WRITE (6,5500) (F1 (I) ,I=1,NR)
WRITE (6,5500) (F2 (I) ,I=1,NR)
WRITE (6,4000)
97  CCNTINUE
GC TO 99
91  WRITE (6,5600)
100 FORMAT (6X,A4,3D10.5)
200 FORMAT (8E10.2)
300 FORMAT (5X,5I3)
400 FORMAT (8E10.4)
1000 FORMAT ('1',//////////)
1100 FORMAT (33X,64(1H*))

```

```

1200  FORMAT(33X,'*',2X,A4,10X,3D15.5,1X,'*')
1300  FORMAT(33X,'*',62X,'*')
1400  FORMAT(33X,'*',9X,'COEF CF CALIBRATION CURVE FOR RCTAMETER',9
1X,'*')
2000  FORMAT(/////)
2100  FORMAT(45X,'ROOM TEMPERATURE           =',F10.2,/)
2200  FORMAT(45X,'REACTION TEMPERATURE        =',F10.2,/)
2300  FORMAT(45X,'ATMOSPHERIC PRESSURE         =',F10.2,/)
2400  FORMAT(45X,'PRESSURE INSIDE REACTOR      =',F10.2,/)
2500  FORMAT(45X,'FEED HEIGHT                  =',F10.2,/)
2600  FORMAT(45X,'MINIMUM FLUIDIZING VELOCITY  =',F10.2,/)
3000  FORMAT(45X,'NUMBER CF RUNS               =',I3,/)
3100  FORMAT('1',/////////)
3200  FORMAT(58X,'FEED CONDITIONS',////////)
3300  FORMAT(9X,'RUN CODE',6X,'VOLUMETRIC FLOW RATE',11X,'MOLAR FLOW RAT
1E',18X,'COMPOSITION',/)
3400  FORMAT(24X,'(ML/MIN;760MM,21C)',15X,'(GMOL/MIN)',24X,'% ',/)
3500  FORMAT(23X,3(2HN2,7X,3EH2S,7X,3HSO2,6X),'.NUMF',////)
3600  FORMAT(10X,I3,4X,1CF10.4,/)
3800  FORMAT(////,16X,'DILUTION FACTORS FOR FEED',////)
3900  FORMAT(////,16X,1CF10.2,/,16X,10F10.2)
4000  FORMAT('1',//)
4100  FORMAT(14X,'X',20X,'Y',20X,'YF')
4200  FORMAT(8X,F10.4,11X,F10.4,11X,F10.4,/)
4300  FORMAT(14X,'XX',19X,'YY',19X,'YYF',/)
5000  FORMAT(43X,'PRODUCT COMPOSITION AND CONVERSION EFFICIENCY',////////)
5100  FORMAT(22X,'RUN CODE',25X,'COMPOSITION (%)',25X,'PERCENT CONVERSION
1',/)
5200  FORMAT(40X,'N2',19X,'H2S',17X,'SO2',12X,'%H2S',6X,'%SO2',7X,'%TS',
1////)
5300  FORMAT(24X,I3,9X,F10.5,10X,F10.5,10X,F10.5,5X,3F10.3,/)
5400  FORMAT(////,20X,'DILUTION FACTORS FOR PRODUCT',////)
5500  FORMAT(20X,1CF10.2,/)
5600  FORMAT(////////,10X,'UNABLE TO FIT A CURVE')
99    STOP
      END

```

```

FUNCTION DAUX(DP,ED,DX,L)
IMPLICIT REAL*8 (A-H,C-$)
DIMENSION DP(1),ED(1)
COMMON M
DD(1)=1.0D0
DAUX =DP(1)
DO 10 J=2,M
  DD(J)=DD(J-1)*DX
10 DAUX =DAUX+DP(J)*DD(J)
RETURN
END
C *****
C *
C *   SUBROUTINE TO CALCULATE FLOW RATE   *
C *
C *****
SUBROUTINE FLOW(X,PF,TF,R,CF,FR)
IMPLICIT REAL*8 (A-H,C-$)
DIMENSION CF(5)
DN  =CF(1)+X*CF(2)+X*X*CF(3)
LSF =R*PF/TF
DDF =DSQRT(DSF)
FR  =LN*DDF*1000.D0
RETURN
END

```

```

*****
*
*           COEF OF CALIBRATION CURVE FOR ROTAMETER
*
*****
*
*   CFN           0.18104E+00    0.76986E+02    0.87756E+00
*
*   CMN           -0.59100E-02    0.12439E+00    0.21290E+00
*
*   CHSS          -0.27480E-01    0.30538E+00    0.29168E+00
*
*   CHSG          -0.66000E-02    0.80270E-01    0.13610E+00
*
*   CSOS          -0.15780E-01    0.46763E+00    0.19225E+00
*
*   CSOG          -0.58100E-02    0.13618E+00    0.10939E+00
*
*   CHSA          0.27770E-01    0.20717E+01    -0.27647E+00
*
*   CSAM          0.45010E-01    0.45482E+01    -0.90123E+00
*
*   CASA          -0.66855E+01    0.14204E+03    -0.56597E+02
*
*   CLN           -0.59100E-02    0.12439E+00    0.21290E+00
*
*****

```

```

ROOM TEMPERATURE      =    294.00
REACTION TEMPERATURE  =    553.20
ATMOSPHERIC PRESSURE  =    14.72
PRESSURE INSIDE REACTOR =    14.72
BED HEIGHT            =    10.00
MINIMUM FLUIDIZING VELOCITY =    1.27
NUMBER OF RJNS        =    6

```


INTERMEDIATE ESTIMATES OF PARAMETERS, SUM OF SQUARES

0.0	0.0	0.0	63.099
0.71731E-02	0.26467	-0.31354E-02	3.3518
0.71731E-02	0.26467	-0.31354E-02	3.3518

FINAL ESTIMATES OF PARAMETERS

0.71731E-02	0.26467	-0.31354E-02
-------------	---------	--------------

NO OF ITERATIONS= 3

SUM OF SQUARES 3.3518

X	Y	YF
0.0	0.0	0.0072

6.4000	1.6010	1.5726
--------	--------	--------

8.1000	2.1260	1.9453
--------	--------	--------

15.2000	2.6839	3.3058
---------	--------	--------

25.6000	3.7456	4.7279
---------	--------	--------

23.5000	5.8978	4.4954
---------	--------	--------

INTERMEDIATE ESTIMATES OF PARAMETERS, SUM OF SQUARES

0.0	0.0	0.0	2208.6
0.97211	0.23506	-0.23828E-03	4.5382
0.97211	0.23506	-0.23828E-03	4.5382

FINAL ESTIMATES OF PARAMETERS

0.97211	0.23506	-0.23828E-03
---------	---------	--------------

NO OF ITERATIONS= 3

SUM OF SQUARES
XX

4.5382

YY

YYF

0.0	0.0	0.9721
30.0989	9.4159	7.8314
51.8306	12.7516	12.5155
70.3951	16.0983	16.3386
105.8199	22.2480	23.1783
172.0743	34.6872	34.3651

FEED CONDITIONS

RUN CODE	VOLUMETRIC FLOW RATE			MOLAR FLOW RATE			COMPOSITION			
	(ML/MIN; 760MM, 21C)			(GMOLE/MIN)			%			
	N2	H2S	SO2	N2	H2S	SO2	N2	H2S	SO2	NUMF
20	33600.7907	61.6527	31.3612	1.3918	0.0026	0.0013	99.7239	0.1830	0.0931	10.2357
21	33346.3513	118.0768	58.3607	1.3813	0.0049	0.0024	99.4737	0.3522	0.1741	10.1784
22	33346.3513	188.6976	94.1811	1.3813	0.0078	0.0039	99.1588	0.5611	0.2801	10.2040
23	33346.3513	273.5151	138.0417	1.3813	0.0113	0.0057	98.7809	0.8102	0.4089	10.2350
24	32314.0338	321.2476	160.7502	1.3385	0.0133	0.0067	98.5303	0.9795	0.4902	9.9382
25	32314.0338	151.6127	75.6091	1.3385	0.0063	0.0031	99.3017	0.4659	0.2323	9.8769

PRODUCT COMPOSITION AND CONVERSION EFFICIENCY

RUN CODE	COMPOSITION(%)			PERCENT CONVERSION		
	N2	H2S	SO2	%H2S	%SO2	%TS
20	99.98733	0.01003	0.00264	94.530	97.173	95.421
21	99.98415	0.01283	0.00302	96.377	98.275	97.005
22	99.97944	0.01717	0.00339	96.965	98.800	97.576
23	99.97897	0.01553	0.00550	98.106	98.671	98.296
24	99.98213	0.01260	0.00527	98.733	98.940	98.802
25	99.98039	0.01608	0.00353	96.571	98.492	97.210

ROOM TEMPERATURE	=	293.70
REACTION TEMPERATURE	=	573.20
ATMOSPHERIC PRESSURE	=	14.55
PRESSURE INSIDE REACTOR	=	14.55
BED HEIGHT	=	10.00
MINIMUM FLUIDIZING VELOCITY	=	1.25
NUMBER OF RJNS	=	6

INTERMEDIATE ESTIMATES OF PARAMETERS, SUM OF SQUARES

0.0	0.0	0.0	46.726
0.42801E-01	1.0880	-0.47432E-01	0.23487E-01
0.42801E-01	1.0880	-0.47432E-01	0.23487E-01

FINAL ESTIMATES OF PARAMETERS

0.42801E-01	1.0880	-0.47432E-01
-------------	--------	--------------

NO OF ITERATIONS= 3

SUM OF SQUARES	0.23487E-01		
X		Y	YF
0.0		0.0	0.0428
1.4000		1.4979	1.4730
1.6500		1.7399	1.7038
2.3000		2.3668	2.2942
3.8000		3.3747	3.4922
6.1000		4.9461	4.9145

INTERMEDIATE ESTIMATES OF PARAMETERS, SUM OF SQUARES

0.0	0.0	0.0	1459.2
0.31510	0.39543E-01	-0.60499E-05	0.64964
0.31510	0.39543E-01	-0.60499E-05	0.64964

FINAL ESTIMATES OF PARAMETERS

0.31510	0.39543E-01	-0.60499E-05
---------	-------------	--------------

NO OF ITERATIONS= 3

SUM OF SQUARES 0.64964
 XX

YY

YYF

0.0	0.0	0.3151
185.5068	7.8241	7.4424
220.7002	9.0883	8.7476
321.3862	12.3627	12.3988
493.0634	17.8255	18.3416
828.3754	29.0651	28.9202

FEED CONDITIONS

RUN CODE	VOLUMETRIC FLOW RATE			MOLAR FLOW RATE			COMPOSITION			
	(ML/MIN;760MM,21C)			(GMOLE/MIN)			%			
	N2	H2S	SO2	N2	H2S	SO2	N2	H2S	SO2	NUMF
53	31021.6362	19.3795	11.4183	1.2850	0.0008	0.0005	99.9008	0.0624	0.0368	10.0504
54	30608.8548	38.6731	19.3360	1.2679	0.0016	0.0008	99.8108	0.1261	0.0631	9.9238
55	30608.8548	61.5075	31.2873	1.2679	0.0025	0.0013	99.6978	0.2003	0.1019	9.9327
56	30513.3511	87.8827	43.2904	1.2640	0.0036	0.0018	99.5720	0.2868	0.1413	9.9116
57	30465.4870	117.7988	58.2233	1.2620	0.0049	0.0024	99.4255	0.3844	0.1900	9.9076
58	30561.1402	188.2533	93.9593	1.2659	0.0078	0.0039	99.0850	0.6104	0.3046	9.9658

PRODUCT COMPOSITION AND CONVERSION EFFICIENCY

RUN CODE	COMPOSITION(%)			PERCENT CONVERSION		
	N2	H2S	SO2	%H2S	%SO2	%TS
53	99.99423	0.00539	0.00038	91.374	98.954	94.184
54	99.99160	0.00780	0.00060	93.827	99.052	95.569
55	99.98093	0.01758	0.00149	91.249	98.544	93.709
56	99.98266	0.01605	0.00129	94.425	99.090	95.965
57	99.97762	0.01988	0.00250	94.857	98.691	96.125
58	99.97322	0.02245	0.00433	96.355	98.592	97.099

APPENDIX D

PURGING-TIME OF REACTOR SYSTEM

The presence of oxygen in the reactor system could adversely affect the activity of the catalyst at high temperatures. In addition, since it did not constitute part of the feed gas, it was absolutely necessary to purge it from the reactor as well as the nitrogen recycle loop.

The purging-time, τ , for a system of known volume, V , is given by [77]

$$\tau = 2.303 \frac{V}{Q} \log \frac{C_i}{C_f}$$

where C_i and C_f denote the initial and final concentration of oxygen. Q denotes the purge rate.

It is easy to show that the oxygen concentration is reduced from 21% to 1 ppb within a period of about 6 hrs at a purge rate of 5 l/min; the volume of the system was approximately 90 l.