Detailed Measurements on a Row of Jets in a Crossflow — With Applications

by

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ABSTRACT

The arrangement of multiple jets issuing perpendicularly to a crossflow is a fundamental fluid flow problem relevant to several engineering applications. One such application is the film cooling of gas turbine blades by discrete hole injection; another is the injection of combustion air in the lower levels of a Kraft recovery boiler. Both have been investigated experimentally and computationally. As the associated flow fields are three-dimensional and highly complex, and the effects of system parameters — such as fluid injection rate and hole spacing — on system performance are not fully appreciated, two experimental studies were conducted. The first was designed to amass detailed measurements about a single row of jets, and to analyze the data with regard to film cooling. The second was designed to determine the characteristics of the flow field in a Kraft recovery boiler.

In the first set of experiments, a row of six square jets spaced at 3.0 jet widths was arranged in a low-speed wind tunnel, and air was injected into the free stream at jet-to-crossflow velocity ratios (R) of 0.5, 1.0, and 1.5. The row was aligned at 90° to the direction of the crossflow, and the jet axes were perpendicular to the tunnel floor. Jet and crossflow air were maintained at approximately equal temperatures. Measurements of the mean velocities and six flow stresses were acquired by three-component, coincidence-mode, laser Doppler velocimetry (LDV). Seed particles necessary for this technique were generated in both the jet and crossflow air by means of commercially available smoke machines. To complement the detailed measurements, flow visualization was performed by transmitting the laser light through a cylindrical lens, thereby brightly illuminating a given portion of the test section with a 5 mm wide sheet of light. Only the jets were seeded with smoke; therefore it was possible to acquire video recordings showing the penetration of the jets in various cross-tunnel planes.

Results of the LDV measurements revealed distinctive trends of jets in a crossflow such as 3-D separation on the lee side of injection and counter-rotating vortex pairs; however, these were less evident in the case of the weakest (R=0.5) jets. For R ≥ 1.0, the jets penetrated
the turbulent free stream boundary layer and interacted with the crossflow, while in the case of $R=0.5$, they did not. Flow visualization clearly demonstrated the turbulent fluctuations in the flow, as well as possible unsteadiness. Mixing of the jets with the crossflow and with one another, as indicated by the penetration of smoke, increased dramatically with velocity ratio.

In the second set of experiments, water was injected through three levels of injection ports in a 1/28 scale model of a Kraft recovery boiler, thereby simulating the isothermal flow of combustion air. Flow velocities and normal stresses in selected cross-sections were measured with two-component random-mode LDV. A second optical measurement method, particle image velocimetry (PIV), was used to examine the large-scale unsteadiness thought to be present in the boiler.

For the conditions investigated, results showed that the flow was distributed neither evenly nor symmetrically across the boiler, and that day-to-day variations in the mean flow patterns were possible. The flow was generally characterized by a vertically rising core surrounded by regions of recirculation in the lower furnace, and a more even velocity distribution higher up. The core tended to drift toward one of the boiler walls, as opposed to rising vertically up the center. PIV results revealed the presence of large-scale low-frequency fluctuations in the flow, which motivates one to reconsider the meaning of mean and fluctuating velocities in such an arrangement. These unsteady flow conditions were largely considered to be a factor of the non-uniform distribution of fluid injection, and the instabilities this may have induced.
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<th>Symbol</th>
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<tbody>
<tr>
<td>D</td>
<td>jet diameter (= jet width)</td>
</tr>
<tr>
<td>J</td>
<td>jet-to-crossflow momentum ratio</td>
</tr>
<tr>
<td>N</td>
<td>number of data points in a record</td>
</tr>
<tr>
<td>$N_d$</td>
<td>data density</td>
</tr>
<tr>
<td>$N_p$</td>
<td>particle arrival rate</td>
</tr>
<tr>
<td>$R$</td>
<td>jet-to-crossflow velocity ratio</td>
</tr>
<tr>
<td>$T_\lambda$</td>
<td>integral time scale</td>
</tr>
<tr>
<td>$U, V, W$</td>
<td>mean velocity component w.r.t. axes $x, y, z$ respectively</td>
</tr>
<tr>
<td>$U(t), V(t), W(t)$</td>
<td>instantaneous velocity w.r.t. axes $x, y, z$ respectively</td>
</tr>
<tr>
<td>$\mathbf{V}$</td>
<td>3-D velocity vector</td>
</tr>
<tr>
<td>$V_{le}$</td>
<td>bulk jet velocity</td>
</tr>
<tr>
<td>$d$</td>
<td>particle diameter</td>
</tr>
<tr>
<td>$i$</td>
<td>denotes i-th data point in a record</td>
</tr>
<tr>
<td>$k$</td>
<td>turbulence kinetic energy</td>
</tr>
<tr>
<td>$u, v, w$</td>
<td>fluctuating velocity component w.r.t. axes $x, y, z$ respectively</td>
</tr>
<tr>
<td>$u', v', w'$</td>
<td>rms velocity w.r.t. axes $x, y, z$ respectively</td>
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<tr>
<td>$u, v$</td>
<td>fluid velocity, particle velocity</td>
</tr>
<tr>
<td>$\dot{v}$</td>
<td>particle acceleration</td>
</tr>
<tr>
<td>$\overline{uv}, \overline{uw}, \overline{uv}$</td>
<td>Reynolds stresses</td>
</tr>
<tr>
<td>$x, y, z$</td>
<td>axes of the tunnel coordinate system</td>
</tr>
<tr>
<td>$\alpha, \beta, \gamma$</td>
<td>angles of misalignment w.r.t axes $x, y, z$ respectively</td>
</tr>
<tr>
<td>$\beta_1, \beta_2$</td>
<td>percent error in mean/variance of velocity</td>
</tr>
<tr>
<td>$\rho$</td>
<td>density</td>
</tr>
<tr>
<td>$\nu$</td>
<td>kinematic viscosity</td>
</tr>
<tr>
<td>F.S.</td>
<td>denotes full-scale</td>
</tr>
<tr>
<td>cf</td>
<td>denotes crossflow</td>
</tr>
<tr>
<td>f</td>
<td>denotes fluid</td>
</tr>
<tr>
<td>fs</td>
<td>denotes free stream</td>
</tr>
<tr>
<td>i.d.</td>
<td>denotes inside diameter</td>
</tr>
<tr>
<td>p</td>
<td>denotes particle</td>
</tr>
<tr>
<td>sb</td>
<td>denotes set, bulk</td>
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1.1 Background

There exist several engineering applications for which the study of jets issuing into a crossflow is of primary relevance. These include dispersion of pollutants, gas injection in combustors, V/STOL transition flight aerodynamics, and film cooling of gas turbine blades. With respect to the last application, one of the current design priorities is to reduce the effect of the high temperature inlet gases in the first stages of a gas turbine, thus permitting even higher operating inlet temperatures for improvements in engine efficiency. Once advances in material technology have been implemented, the effects of high inlet temperature may be further reduced with film cooling. This is a process whereby cold gas is introduced to the boundary layer, typically near the leading edge of the blade, to generate a thin layer of insulation between the blade's exterior surface and the hot gases. An effective form of cold gas injection is through a wide slot, but structural considerations limit this design's practicality. An alternate method is to inject the cold gas through a row, or array, of discrete holes at the leading edge of the blade, as sketched in Figure 1. With the addition of cold gas comes the possible penalty of aerodynamic loss (e.g., reduced lift) and reduced engine cycle efficiency; therefore, a set of parameters including hole spacing and injection rate needs to be examined and recommended.

In research, discrete hole film cooling is often simplified by studying a row of jets issuing into a uniform crossflow from a flat plate, where the flow, temperature, pressure, and heat transfer at the wall are examined. Based on previous investigations of this application, an injection hole spacing of approximately three diameters provides good spanwise film coverage, and film cooling effectiveness is considered best for jet-to-crossflow velocity ratios of unity or less. Variations in the jet injection angle with respect to the direction of the crossflow
are possible, and include jets directed upstream or downstream, as well as the standard 90° jet.

With respect to combustion applications, specifically, Kraft recovery boilers, oxygen is typically supplied to the reactor in the form of heated air through ports located about the periphery of the lower furnace (Figure 2). The fuel is black liquour — a viscous fluid effluent from a wood pulping process, composed of organic compounds and reusable chemicals — and is injected in the lower furnace as a coarse spray. The purpose of a Kraft recovery boiler is twofold: 1) to generate power, and 2) to recover useful chemicals. Therefore, a configuration of heat exchangers is arranged in the upper furnace for the generation of steam; in the lower furnace, a smelt bed — a lava-like mound of recyclable non-organic compounds — slowly exits the boiler where it is further processed. In contrast to film cooling, injection rates in a recovery boiler are very high, as they are designed for deep penetration of combustion air and thorough mixing with combustion reagents. Because of the large number of injection ports and their non-uniform arrangement along the boiler's walls, the flow field and mixing levels are not known with a high level of certainty. The result may be a combination of inefficient and unfavourable processes, for example, carry-over of particulates into the heat exchangers, or high thermal loads on the boiler walls.

Investigations of recovery boiler flows have been performed on actual boilers in the absence of combustion, but smaller scaled models prove to be much more practical and convenient. A disadvantage in either case is that the experiments are typically isothermal, as a hostile combustion environment does not favour reliable velocity measurements. Nevertheless, isothermal flow experiments can still provide valuable information regarding the complex flow field in a recovery boiler.

1.2 Aerodynamics of Jets in a Crossflow

For a single strong jet (ie. $R \gg 1.0$, where $R = V_{jet}/V_{fr}$) in a crossflow, the flow field is characterized by a jet which penetrates the free stream boundary layer and is deflected by the
crossflow. The jet centerline curves most strongly in the near jet region and flattens out downstream (Figure 3). As fluid from the free stream is diverted to either side of the obstructing jet, shear stresses induce a rotating motion which develops into a pair of counter-rotating vortices. Fric and Roshko (1989) describe the other primary vortices in the flow. One is a ring vortex which circumscribes the jet as it exits the jet channel. Another is a horseshoe vortex in the near field upstream of the jet exit — a result of the deceleration of free stream fluid as it approaches the obstructing jet. The third is a wake vortex pair which has the appearance of a Karman vortex street, though it is thought to be generated not at the jet/crossflow interface, but at the wall in the near jet region. According to Andreopoulos (1985), the near field of strong jets is controlled largely by complex inviscid dynamics, as opposed to that of a weak jet, which is turbulence dominated. Therefore, a weak jet (e.g. $R \leq 1.0$) may not exhibit all the characteristics described above, particularly in the presence of a thick free stream boundary layer.

A configuration involving a row of jets introduces a new parameter — the spacing to diameter ratio $s/D$. For the extreme case of $s/D=1.0$ (i.e. a 2-D slot), jet penetration is strongest. As the spacing increases toward an intermediate value somewhere between three and five diameters, the jet penetration decreases, partly due to the increasing entrainment of free stream fluid (Sterland and Hollingsworth, 1975). As spacing further increases, free stream fluid begins to flow between the jets, thereby elevating the lee side pressure and causing the jets to penetrate deeper into the crossflow. The single jet marks the other extreme case of $s/D=\infty$ where penetration is high. In the application of turbine blade cooling by discrete hole injection, typical design spacing corresponds to that of weak jet penetration. In a Kraft recovery boiler, designs include rectangular jets with a large aspect ratio, a wide range of possible spacing, and large velocity ratios ($R \gg 1.0$).
1.3 Previous Work

The first part of this study is primarily concerned with multiple jets and low velocity ratios. Previous literature concerning single jets is still relevant and some examples of work involving such jets are cited below. A description of some of the literature involving multiple jets and relevant numerical work is also made.

A number of experimental studies have been performed for the single jet: Andreopoulos and Rodi (1984), and Perry et al. (1993) for example. The former was one of the most detailed works wherein mean velocities and six flow stresses were measured with a 3-component hot wire probe. The authors were able to thoroughly describe the flow field for R=0.5, 1.0, and 2.0, and to evaluate the usefulness of the eddy-viscosity model based on their findings.

Weak multiple jets issuing normally into a crossflow have been studied experimentally by Sugiyama and Usami (1979) who reported pressures and mean velocities for a row of nine jets spaced at 3D and exiting at R=2.0. Khan et al. (1982) reported jet concentration and mean velocities for s/D=2 and s/D=4 and R=2.3, and compared their results to a coarse-grid numerical simulation. Isaac and Jakubowski (1985) used hot-wire probes to measure mean velocities and five flow stresses in the region about tandem jets exiting at R=2. Studies involving even lower velocity ratios, which better represent the application of the turbine blade cooling, are less common. Peña and Arts (1992) reported 2-component LDV measurements for velocity ratios as low as 0.5. They also varied the spacing from 3D to 5D, and varied the jet density from 1.0p_r to 2.0p_r. Their primary interest was in the flow several diameters downstream of the injection hole.

The case of multiple jets issuing into a crossflow at an angle of less than 90° to the surface is also of great relevance to the application of turbine blade cooling, as this configuration induces less aerodynamic mixing between injected and free stream fluids. Kadotani and Goldstein (1979) examined the effects of boundary layer thickness, Reynolds number, and free stream turbulence intensity on film cooling effectiveness, and velocity and
temperature distribution. They used a row of jets inclined at 35° to the mainstream direction, and issuing into the crossflow at velocity ratios between R=0.2 and R=1.5. Two-component LDV velocity measurements were reported by Foucault et al (1992) on a row of 45° inclined jets exiting at R=0.6 and R=1.6. Distributions of temperature and temperature fluctuations were also reported in this paper.

Some studies have examined the flow field in the region about a jet exiting a scaled model of a turbine blade (Beeck et al., 1992), (Benz et al, 1993) The geometry was simplified to a slot jet exiting a 2-D blade in both papers. Both experimental measurements and numerical simulations were performed by these authors.

Normal jets in a crossflow have also been represented by numerical simulations. Demuren (1993) examined a single jet issuing into a crossflow at R=0.5 and R=2.0 with a finite-volume multi-grid method, and compared the results with those of Andreopoulos and Rodi. Kim and Benson (1993) used a multiple-time-scale model to calculate the flow field of a row of jets for R=2.3, and captured some interesting structures in the near jet region.

In summary, previous experimental work on weak jets has included simple geometry cases such as the single jet normal to a crossflow. At the other end of the spectrum, one encounters more complex cases, such as a row of inclined jets, or a 2-D representation of a turbine blade with slot cooling. For a range of conditions (eg. various geometries), numerical simulations have been performed, in which the results were compared to those of corresponding experimental measurements. Based on the extent of previous literature, it is apparent that there lies a gap in the understanding of flow issuing from a row of jets issuing perpendicularly to a crossflow at velocity ratios, R, less than 2.0. In particular, there is a need for detailed velocity measurements in the near- and mid-field of these jets (ie. between zero and five diameters downstream of injection), in part for the validation of numerical simulations.

The second part of this study deals with the highly complex flow field in a recovery boiler. The problem is not easily simplified as is the film cooling application; therefore,
fundamental studies of recovery boiler flows are uncommon. Furthermore, it is not so much the trajectory of individual jets that is deemed important in this case, but the large-scale trends in the overall flow patterns.

Recently, a series of experiments was performed on a water model of the Kraft recovery boiler located in Plymouth, North Carolina using non-intrusive optical measurement techniques (Ketler, 1993). The investigation showed that moderately small shifts in the distribution of injection fluid may lead to large changes in the overall flow field, thereby indicating the system's sensitivity to the boundary conditions. The study also revealed large-scale (ie. a characteristic length scale equal to 1/2 the boiler width), low-frequency fluctuations in the flow.

One of the existing fundamental studies was that of Quick (1994), in which the flow in the region around opposing rows of jets was investigated experimentally and computationally. It was found that the flow instabilities inherent to such a physical configuration of jets resulted in a low-frequency periodic oscillation between two modes. Experiments and computations led to the same general results.

1.4 Purpose of the Film Cooling Experiments

The focus of this set of experiments was on the flow field about a row of six 90° jets in a crossflow. Mean velocities and six flow stresses were measured using three-component coincidence-mode laser Doppler Velocimetry (LDV), a non-intrusive technique which — to the best of the authors' knowledge — had previously not been applied to jets in a crossflow. The importance of this measurement method is explained later in the thesis. The results are reported in the form of vector plots, contour plots, and xy-profiles, and trends with changing R are compared. Low velocity ratios were used (ie. R=0.5, 1.0, and 1.5) to best represent the conditions of a cooling jet in a turbine blade. Although the R=1.5 value may have been somewhat high for film cooling, the set of data for this case was considered to be useful for future comparison with a numerical simulation.
Flow visualization was also performed, and video recordings were made of the jet motion and the jet penetration and the fluctuations in time of these observed quantities. Square jets were used in this study because these increased the practicality of altering the jet spacing and jet aspect ratio in future experiments, and because these are more accurately represented in numerical simulations which use a simple orthogonal code. Throughout this thesis, references are made to the "diameter" of the jet. This terminology is rooted in the past study of jets, as well as in the practical machining of cooling holes, where round jets are customarily used. The term "diameter" is to be equated here to "jet width".

1.5 Purpose of the Recovery Boiler Experiments

This set of experiments was designed to obtain reliable measurements of the flow field inside a model of the Kamloops #2 recovery boiler. Three cases were studied, all using LDV (two-component random-mode) and PIV — particle image velocimetry — to provide images and velocity measurements. The first test case was a model representation of the flow patterns previously studied in a cold flow (isothermal, no combustion) run of the full-scale boiler, in which hot film velocity measurements were acquired at the liquour gun level (Abdullah et al., 1994). In addition, a numerical simulation of the same conditions was performed by the Computation Fluid Dynamics (CFD) group at the University of British Columbia. As the full-scale investigation was somewhat limited, the purpose of the first test case was to examine the flow field through several distinctive regions, and to provide a broader set of velocity data for comparison with both the CFD calculations and the full-scale measurements. The second and third test cases involved a fairly uniform distribution of injection through the various ports to study whether or not the flow field in the boiler would be steady and symmetric.

1.6 Organization

The first two sections of Chapters 2 and 3 (sections 2.1, 2.2, and 3.1, 3.2) describe the experimental arrangements and instrumentation used in the low-R wind tunnel study.
Remaining sections (2.3, 2.4, and 3.3, 3.4) describe the same topics for the higher-R recovery boiler model cases. Subsections of Chapters 2 through 6 are identified by their headings as referring to one of the two major applications of the present jet study: "wind tunnel" (film cooling) or "recovery boiler".

Figure 1: A gas turbine blade and film cooling system
Figure 2: A Kraft recovery boiler (Adams and Frederick, 1988)

Figure 3: Flow field of a single jet in a crossflow (Sherif and Pletcher, 1989)
CHAPTER 2
EXPERIMENTAL SETUP

2.1 Wind Tunnel

2.1.1 General

The wind tunnel experiments were performed in the Mechanical Engineering Aerodynamics Laboratory at the University of British Columbia. The wind tunnel used to generate the crossflow was a 267 mm × 406 mm open-loop forced-draft tunnel with a maximum air speed of 12 m/s (Figure 4). The tunnel was driven by a 3.8 kW D.C. motor coupled to a fan. Air speed was regulated by a dial control, and could be measured at any time by pitot tube or by LDV. When measured by LDV, the speed could be set to within 0.5% of a desired value. The test section, shown in Figure 5, was 1016 mm long, and was located just downstream of a 4:1 area contraction section. Flow uniformity was achieved with five screens and a 50 mm thick section of honeycomb between the inlet and the test section. To ensure that a fully turbulent boundary layer was present in the test section, a 2.4 mm trip wire was affixed to the tunnel floor at the test section entry. The coordinate system used in the experiments is shown in Figure 5. The origin corresponds to the center of one of the middle two jets designated EAST1. Additional details of the tunnel and test section are provided in the following sections.

2.1.2 Test Section Walls

The side walls of the test section were made of clear plexiglass for observation and flow visualization purposes. The ceiling was constructed of 3 mm plywood and the floor of 12.7 mm plexiglass painted flat black. The painted floor reduced bright reflections which were undesirable with respect to both Doppler signal signal-to-noise ratio (SNR) and eye safety. The ceiling and one side wall were designed with several removable sections to allow for unobstructed transmission of the laser beams. Therefore, two small areas of the test
section were left open, one in the ceiling and one in the side wall. The size of the openings was just large enough to allow the beam pairs from each LDV probe to enter the tunnel without being obstructed or refracted. The openings also allowed the Doppler signal to return to the probe with minimal attenuation. An effort was made to prevent air from exiting the tunnel through these holes, as these could disrupt the uniformity and bulk speed of the crossflow. Since the jet exits were located on the tunnel floor and measurements were made far from the tunnel walls, it was assumed that the openings had minimal influence on the flowfield under consideration. The wind tunnel test section was nominally at room pressure in any case; therefore, the air interchange was minimal.

2.1.3 Jets

The row of six square jets was arranged on the tunnel floor perpendicular to the direction of the crossflow. The jets were separated by three diameters, centerline to centerline, and issued into the crossflow at 90° to the floor surface. Each jet measured 12.7 mm × 12.7 mm in cross-section and had an entry length of 6 diameters (Figure 6). The entries to the jet ducts were sharp-edged, as opposed to nozzle-shaped; therefore, a top-hat jet exit profile was not expected. Air flow to the jets was supplied by a 400 kPa (static) compressed air line and was regulated by two flow regulators configured in series. A 0.918 m³/min (F.S.) rotometer was used to measure the volume flow. A 406 mm diameter by 500 mm tall plenum — or settling chamber — was positioned below the tunnel floor between the air line and the jet channels. The lower half of the plenum consisted of various screens and other mesh-like flow distributing devices.

2.1.4 Smoke Source

A Rosco 1500 smoke generator was used to seed the crossflow while a Genie device seeded the jet air. Both machines used Roscoe smoke fluid — a proprietary CSA-approved water-based solution. Seeding the crossflow was achieved simply by blowing the smoke toward the tunnel intake. The smoke particles were sufficiently small (nominally
0.5 μm to 60 μm) and dry that they did not wet any screens or coat any surfaces. The Genie device was somewhat more difficult to implement as it was designed to operate at ambient pressure. Since a compressed air line supplied flow to the jets, it was impossible to force the smoke into it from the exterior. The Genie device was therefore operated inside the air line to eliminate any pressure difference between it and the local ambient air. This was achieved by setting the smoke machine in a sealed plastic canister, and adding it in-line, as shown in Figure 7. Smoke was generated in a normal manner, and mixed with the air supply while passing through the hose and plenum.

With the smoke machine placed in-line between the rotometer and the jet exits, there was concern about smoke adding to the volume flow rate of jet air, and not being measured. Tests with the smoke machine placed upstream of the rotometer showed that the volume flow corresponding to a jet exit velocity of 5.5 m/s increased by less than 1.0% with smoke being generated at full capacity. In fact, the increase may even be less, because the presence of smoke particles would have slightly raised the jet air's density, leading to an overestimate in the rotometer's readings. In this test configuration however, the large pressure drop across the rotometer made it difficult to keep the pressurized plastic canister completely sealed. The smoke machine was therefore returned to its original position.

2.2 Test Conditions — Wind Tunnel

As this study of jets in a crossflow was applied to the discrete hole film cooling of gas turbine blades, certain operating parameters were imposed by the practical configuration of cooling jets. The following sections describe the geometry and flow conditions for the present experiments, some of which were recommended by Pratt&Whitney Canada (Pratt&Whitney Canada, 1993).

2.2.1 Flows

Flow through the jets was set to a Reynolds number of approximately 4700 based on the bulk jet velocity of 5.5 m/s, the jet width, and the viscosity of air at STP. This
value was kept constant throughout the experiment; therefore, the jets could be considered turbulent in all cases. Flow field characteristics of jets in a crossflow are strongly dependent on the momentum ratio as defined by

\[ J = \frac{\rho_{jet} V_{jet}^2}{\rho_{cf} V_{cf}^2} \]  

(Holdeman and Walker, 1977). In this low-speed isothermal experiment, the densities in (1) cancel, and the relevant parameter becomes the velocity ratio \( R \). Three cases of \( R \) were examined: 0.5, 1.0, and 1.5. Throughout the experiment, the bulk jet velocity was maintained at 5.5 m/s; therefore, the crossflow velocities used were 3.67 m/s, 5.5 m/s, and 11.0 m/s.

For the purpose of flow visualization, an additional case corresponding to \( R=0.5 \) and a jet exit Reynolds number of 900 was examined. Therefore, the bulk jet exit velocity was 0.70 m/s, a value approximately one fifth the minimum value used for the LDV measurements. The objective of this case was to observe the characteristics of flow issuing from a laminar or, more likely, transitional jet.

**2.2.2 Measurement Locations — LDV**

The range of measurement locations was carefully selected so that particular aspects of jet-in-crossflow injection could be examined, for example, the jet exit condition, separation in the near field, and interaction between adjacent jets. For each velocity ratio, the boundary layer profile was measured at a position five diameters upstream of the injection point. Measurements were then made on a six by six horizontal grid in the plane of the jet exit. The rest of the measurements were located at various elevations, \( z/D \), ranging from 0.25 to 6.0, and at downstream positions, \( x/D \), of 0, 1, 3, 5, and 8. In the lateral direction, measurements were taken in four planes, namely \( y/D=\{0.0, -0.5, -1.0, -1.5\} \). Therefore, a 3-D region was examined, encompassing one half of the flowfield surrounding a particular jet. If symmetry and periodic boundary conditions are assumed, the measurement scope represents much of the flow field of the six side-by-side jets in the crossflow.
2.2.3 Measurement Locations — Flow Visualization

Video recordings were made for the flow in several 2-D planes. The cross-tunnel planes (yz-planes) investigated were located at \( x/D = \{0, 0.5, 1, 3, 5, 8\} \). In the lateral direction, vertical streamwise planes (xz-planes) corresponding to \( y/D = 0.0 \) and \( y/D = -1.5 \) were examined.

2.3 Recovery Boiler

The recovery boiler experiments were performed in the Pulp and Paper Research Center at the University of British Columbia. Descriptions of the recovery boiler model and of the distribution of flow are provided in the following two sections.

2.3.1 Model Geometry

The primary apparatus consisted of a 1:28 scale model of the #2 recovery boiler located in Kamloops, British Columbia. Its appearance was not unlike a vertical rectangular channel. The model walls were constructed of 16 mm thick plexiglass, so that laser light could be transmitted freely through to the measurement locations. The experiments were designed to represent isothermal flow; therefore, there was no need to account for density effects of cold injection air by implementing Thring-Newby scaling to the air ports. Scaling of all dimensions — including air port shapes — was geometric.

The three levels of air injection were included in the model, as well as the sloped furnace floor, and, for one set of PIV measurements, a simulated smelt bed. The upper section of the furnace model included the bullnose and the heat exchangers. A drawing of the model and a detail of the smelt bed are given in Figures 8 and 9 respectively. Also shown on Figure 8 is the coordinate system used in the present set of experiments. The origin coincides with the back left corner of the boiler floor.

The 174 primary air ports were nearly evenly distributed about the perimeter of the furnace. At the secondary air level, four ports were located on the front and back walls, and five on the left and right. Also included at this level were the two large starter burners on
each of the front, left, and right walls. The tertiary air was distributed in an interlaced fashion, with four ports on the front wall and five on the back.

The liquour guns were not modelled, as they were considered to have little effect on the flow field. This assumption is based on the fact that the volume flux of black liquour during its trajectory through the boiler is typically two to four orders of magnitude less than that of injection air. Momentum exchange between black liquour and injection air is highly variable throughout the boiler, but is considered to be very small except in local regions near black liquour injection.

2.3.2 Flow System

Flow in a recovery boiler is highly turbulent; likewise, so should be the flow in the recovery boiler model. The concept of Reynolds number similarity expresses that turbulence, once created, has large-scale structures which are independent of viscosity, and therefore Reynolds number. This principle was applied to the present experiments, in which the preferred working fluid was water. Based on the viscosity of water at 25°C, the characteristic length scale of the model (ie. the model width), and a practical operating flow rate of approximately 500 L/min, the bulk Reynolds number equals 20000 — a value representative of flow well into the turbulent regime. Therefore, through Reynolds number similarity, flow in the model was considered to represent full-scale isothermal flow, provided that the operating flow rate was on the order of 500 L/min or greater.

Because of the large mass flux of water in the present experiments, a closed-loop flow system was adopted. Water was pumped from a 5700 L supply tank to three 150 mm (i.d.) elevated headers, each of which was designated for a particular level of injection (Figure 10). On the secondary and tertiary levels, a total of 33 lines branched from the respective headers, and supplied water to the individual air ports. Flow to the 174 primary air ports was supplied by 24 lines, each of which fed a group of 7 or 8 ports. The water entered the lower section of the model through the three levels of injection, travelled upward
past the bullnose located on the back wall and heat exchangers, and finally exited the model and followed a return line to the original supply tank.

Flow to each port — or group of ports in the case of the primary jets — was measured by an orifice plate flow meter and regulated with a valve; these were arranged in-line with each of the 57 branches.

2.4 Test Conditions — Recovery Boiler

2.4.1 Flows

Three flow cases were investigated. The first corresponded to a full-scale cold flow run of the Kamloops recovery boiler performed in October 1992. At that time, a particular set of injection air flow rates was selected and a series of mean velocity measurements was acquired at the liquor gun level. The total mass flux of air through the Kamloops boiler was approximately 450,000 kg/hr. In this first test case, the total volume flow rate through the model was set to 570 L/min, and the flow rate through individual ports was scaled accordingly, to match the relative values in the full-scale boiler run. Table 1 below diagramatically lists the volume flow rates and the momentum fluxes at the primary and secondary injection levels. For this flow case, there was no tertiary injection; furthermore, no bed shape was simulated.

The second flow case involved three levels of injection. The total flow rate was 788 L/min with 33.3% of the flow entering the model through each injection level. Again, no bed shape was simulated. Table 2 lists the volume flow rates and momentum fluxes through each port, or group of ports, at the three injection levels. Note that flow through the starter burners on the secondary level was blocked.

The third flow case was identical to the second, but with a bed shape fixed to the boiler floor. Only PIV measurements were acquired here.
Table 1: Flow rates for test case #1. Normal text shows volume flux [L/min]. Italic text shows momentum flux [kg m/s²]. SB denotes "starter burner".
Table 2: Flow rates for test cases #2 and #3. Normal text shows volume flux [L/min]. Italic text shows momentum flux [kg m/s²]. SB denotes "starter burner".
2.4.2 Measurement Locations — LDV

For all three flow cases, measurements were acquired in three horizontal planes. Each plane was divided into a 6×6 grid of rectangular cells with the measurement locations corresponding to the cell centers; therefore, 36 points evenly distributed over the cross section of the model were probed. The lower plane was located at the liquour gun level, or 175 mm above the secondary level. The middle plane was located approximately the same distance (ie. 177 mm) above the tertiary level. The upper plane was located 445 mm above the tertiary level, so as to evenly space the three planes along the boiler's vertical axis. In this thesis, the lower, middle, and upper planes are referred to as levels 1, 2, and 3 respectively (see Figure 8).

2.4.3 Measurement Locations — PIV

For the PIV measurements, the laser sheet was oriented vertically and spanned the boiler model from front to back. The sheet could be translated between the left and right walls of the model, which allowed for the investigation of several 2-D regions. Specifically, the sheet was positioned at certain discrete distances from the boiler left wall, namely — in terms of boiler widths — 1/12, 3/12, 5/12, 1/2 (mid-plane), 7/12, 9/12, and 11/12. With the exception of the mid-plane, these locations matched the coordinates of the rows in the 6×6 LDV measurement grid. Video footage was acquired at three different vertical positions. One captured flow in a plane bounded by the secondary and tertiary levels, the second corresponded to a region above the tertiary level, and the third was located in the upper furnace, encompassing an area about the bullnose.
Figure 4: Open loop wind tunnel

Figure 5: Coordinate system and detail of test section

Figure 6: Detail of jet exit duct
Figure 7: Arrangement of smoke machine within compressed air supply to jets
Figure 8: Kraft recovery boiler model
Figure 9: Detail of smelt bed. All dimensions are in mm.
Figure 10: Schematic of flow system. Not to scale.

A 5700 L supply tank
B pump
C header for tertiaries
D header for secondaries
E header for primaries
F 9 lines to tertiary level
G 24 lines to secondary level
H 24 lines to primary level
J valve
K orifice plate flow meter
L differential pressure gauge
M primary injection level
N secondary injection level
O tertiary injection level
P return line
CHAPTER 3

INSTRUMENTATION

3.1 Laser Doppler Velocimetry — Wind Tunnel

Laser Doppler velocimetry (LDV) is the non-intrusive measurement technique used in this study. This section overviews the basics of LDV operation and the use of LDV in the present experiments.

3.1.1 Background

The operation of LDV is based on the optical properties of two laser beams intersecting at a common focal point. When the beams are transmitted and focussed in this manner, a fringe pattern appears in the volume of intersection. A small particle travelling through this volume will reflect the light from the fringes at a frequency corresponding to the particle's velocity, and this is called the Doppler signal (Figure 11). In this basic setup however, it is impossible to determine whether a velocity is negative or positive. This directional ambiguity may be eliminated if one of the beams in the pair is frequency-shifted. The effect of frequency-shifting is that the fringe pattern no longer appears stationary in the volume of intersection, but moves through it at a speed proportional to the shift frequency. Given that the shift frequency is sufficiently high, a particle will always cross the fringes in the same relative order — regardless of its direction of motion — and the Doppler signal will represent a unique velocity. This signal is sensed by a probe which is sometimes incorporated in the same device that transmits and focusses the beam pair, in which case the mode of signal retrieval is "back-scatter". A dedicated processor analyses the signal and determines the corresponding velocity. Side-scatter and forward-scatter modes are also possible, and are typically considered superior. These modes require that the receiving probe be separate from the transmitting probe. A pair of laser beams is able to measure one component of velocity — that which is in the plane of the beams and perpendicular to the beams' centerline. If three
components of velocity are sought, three pairs of beams, all intersecting at the same point, are required. As success of LDV depends on the existence of suitable particles in the fluid, one must assure that the flow is properly seeded. In water, natural sediment may be sufficient; in air, smoke or a fine liquid spray is usually introduced. Provided the particles faithfully follow the flow, the measured velocities are considered to be accurate. The average rate at which the particles cross the measurement volume and produce valid readings is referred to as the data rate.

3.1.2 Equipment

In the present experiments, a Coherent Innova 7.0 W argon-ion laser paired with a TSI Colorburst model 9201 multicolor beam separator was used as the source for the three pairs of beams. These beams were coupled through fiber optic cables to two probes (TSI models 9831 and 9832), and were focused to a single measurement volume in the test section (Figure 12). The probes also acted to retrieve the Doppler signals, which were transmitted through fiber optic cable to a TSI Colorlink model 9230 photomultiplier, and then to three TSI IFA550 processors. Table 3 below lists selected properties of the beam pairs.

<table>
<thead>
<tr>
<th>Probe #1 green beam pair</th>
<th>Probe #1 blue beam pair</th>
<th>Probe #2 purple beam pair</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lambda$ [nm]</td>
<td>514.5</td>
<td>488.0</td>
</tr>
<tr>
<td>$d_{e_{z}}$ [mm]</td>
<td>2.82</td>
<td>2.82</td>
</tr>
<tr>
<td>$d_{f}$ [µm]</td>
<td>3.73</td>
<td>3.54</td>
</tr>
<tr>
<td>$d_{m}$ [µm]</td>
<td>90.5</td>
<td>85.8</td>
</tr>
<tr>
<td>$l_{m}$ [mm]</td>
<td>1.31</td>
<td>1.24</td>
</tr>
<tr>
<td>$\kappa$ [°]</td>
<td>3.95</td>
<td>3.95</td>
</tr>
</tbody>
</table>

where $\lambda$ = wavelength
$d_{e_{z}}$ = diameter of beam at probe
$d_{f}$ = fringe spacing
$d_{m}$ = diameter of measurement volume
$l_{m}$ = length of measurement volume
$\kappa$ = half angle of beam pair

Table 3: Properties of the beam pairs.
3.1.3 Acquisition and Storage

Acquisition and storage of the raw data was controlled by version 3.53 of FIND — a TSI software package. Program features included user-selectable shift frequencies, coincidence windows, and Doppler signal filters. A signal was accepted if the IFA550 processors counted eight consecutive fringe crossings from a particle travelling through the intersection of each beam pair. The time for eight crossings, $T_8$, was determined by the processor, as well as the time between the current and previous measurement, denoted $T_{M}$, or time between data. This information was transmitted to the PC, and a time trace of $T_8$ was stored on disk. Given the values of fringe spacing and shift frequency, it was possible to later extract velocity traces for each component by the following formula.

$$V = d_f \left( \frac{8}{T_8} \times 1000 - f_s \right)$$

(2)

where

- $V =$ velocity, in m/s
- $f_s =$ frequency shift, in MHz
- $d_f =$ fringe spacing, in $\mu$m
- $T_8 =$ time for eight fringe crossings, in ns

3.1.4 Mode of Operation

One of the purposes of this experiment was to measure not only mean velocity and normal stress, but also shear stress. It was therefore necessary to operate the LDV system in three-component coincidence mode. That is, a measurement was accepted only if all three processors validated a Doppler signal within a user-selected time span, or coincidence window. The size of this window was determined by dividing the diameter of the intersection volume by the approximate fluid velocity, thereby calculating the expected residence time of a particle in the measurement volume. The fluid velocity was obtained from a continuously updated histogram of the 256 most recent velocity readings, as displayed on-screen by the operating software. A window any larger than the one calculated would enable a given measurement to be accepted from more than one particle, thereby increasing the error in the
estimates of shear stress. A smaller window would reduce the probability of obtaining a valid measurement from all three processors, and the data rate would decrease. At this point however, it is impossible to justify methods of correction for unsuitable window sizes. A separate study would be necessary to quantify the effects of window size on the flow statistics. To prevent biases due to window size, a conservative, smaller window was selected at the expense of higher data rates.

3.1.5 Difficulties

LDV has the potential to be a highly accurate measurement technique; however, misuse of the equipment and improper analysis of the data can lead to large errors in measurement.

3.1.5.1 Multiple Realizations

The IFA550 is a free-running processor, and therefore continuously performs a correlation on the incoming signal to determine if a valid Doppler signal is present. If so, an accepted measurement of $T_g$ (and $T_M$) is transmitted to the PC, and the processor is immediately reset to accept further signals. A problem arises when a measurement is accepted, and the corresponding tracer particle remains in the measurement volume, which is entirely possible under normal operation conditions. For example, consider the following conditions

$$f_c = 1.0 \text{ MHz}$$
$$d_f = 3.73 \text{ μm}$$
$$V = 1.0 \text{ m/s}$$
$$d_m = 90.5 \text{ μm}$$

where $V$ is the particle's velocity component in the direction measured by the green beams. By equation (2), $T_g$ is calculated to be 6309 ns. However, if the particle travels the full diameter of the measurement volume, its residence time will equal 90500 ns ($= d_m/V$). It is possible in this case to acquire a maximum of 14 readings ($= 90500/6309$) from the same particle. Typically, slow moving particles reside longer in the measurement volume, and produce a
greater number of multiple realizations. Velocity time traces will therefore contain a disproportionately large number of low velocity readings. When flow statistics are calculated, the use of ensemble averages will yield biased estimates. In the present experiments, multiple realizations were nearly eliminated by selecting a coincidence window roughly equal to the expected residence time. This forced the processors to reset not immediately after $T_s$, but after a given particle was no longer "visible".

3.1.5.2 Beam Trajectory

In the present experiments, vertical velocity was measured by the purple beam pair, which was directed at the test section from the side of the tunnel (Figure 12). Measurements anywhere near the tunnel floor however, were impossible, because light from the lower beam was obstructed by the structures of the tunnel. As near wall measurements were of great interest, this configuration was unacceptable. The most practical solution was to angle the probe downward by roughly $6^\circ$ — a value greater than the beam pair half angle $\kappa$. It was then possible to position the measurement volume anywhere in the field of interest, including locations on the tunnel floor.

3.1.5.3 Alignment With Respect to Coincidence

The fact that coincidence mode was used to simultaneously measure three velocity components at a given location imposed a restriction on the positioning of the probes in that the three pairs of beams were required to intersect at a common point. The blue and green beam pairs were designed to intersect one another, for they were transmitted through a common lens in the first probe. The purple beam pair, however, originated from a second probe and was oriented at approximately $90^\circ$ to the first. Aligning its volume of intersection with that of the blue and green beams was not a trivial matter. The traverse mechanism to which the probes were secured was designed so that the beams from the two probes would intersect; however, small errors in machining and flexibility of the traverses made it impossible to align the beams without any further adjustment. Therefore a system of microadjustments was made possible by securing the probes to the traverse mechanism with adjustable set
screws. The alignment of the probes could then be fine-tuned so that the three beam pairs intersected at a common point.

The pinhole method adopted by Rickards et al. (1993) was used to gauge and correct the misalignment. The method uses the basic principle that a laser beam's intensity displays a Gaussian profile in the radial direction. Therefore, when a laser beam is transmitted through a small hole (e.g. an order of magnitude smaller than the width of the beam), the light power passing through the hole is an indication of how well the beam is centered over the hole. A maximum in power is reached when the beam and the hole are concentric. Figure 13 shows the pinhole unit used to measure the position of the beams in the present experiments. The device was a 25.4 mm tall aluminum block with a top surface inclined at 45°. It housed a 30 μm metal film with a 20 μm pinhole in the center. A photo-resistive silicon sensor was positioned just below the pinhole, and a multimeter was used to measure the sensor's resistance, which decreased inversely with the power of light directed upon it. The device fit snugly in a jet exit so that a securely fixed reference point could exist. With the unit's angled surface oriented to face the three pairs of beams, the probes were aligned to center the intersection of each beam pair over the pinhole. The final result was a set of three beam pairs which intersected at a common point. It is estimated that the focal points of the three beam pairs were within 25 μm of one another. Recall that the diameter of the beams was approximately 90 μm at the focal point (Table 3); therefore, there was still good coincidence despite the minor misplacement of focii.

3.1.5.4 Angular Misalignment

One difficulty associated with acquiring vector measurements is that of accurately aligning the measurement probe with the desired reference axes. This is particularly important when a weak velocity component is being measured in the presence of a large one. For example, consider velocity in a boundary layer, where the streamwise velocity component is dominant. If one seeks the velocity component perpendicular to the wall, the probe must be aligned accurately. Otherwise, the dominant streamwise velocity will map onto
the component being measured. Errors introduced by this type of angular misalignment may be corrected if 1) the angle of misalignment is accurately known, and 2) an assumption or accurate estimate can be made regarding the magnitudes of the two other velocities. In the case of multiple jets issuing into a crossflow, accurate estimates of the complex flow field are not available a priori.

The problem is compounded when cross-correlated terms like shear stresses are sought. If the three probes cannot be aligned precisely normal to one another, a correction needs to be made to each measured velocity component for every accepted measurement at the current location.

Since the two LDV probes in this study were not perfectly orthogonal and were angled at approximately $6^\circ$ to the tunnel floor to allow near wall measurements, corrections were required and were applied to the time traces of raw data following the acquisition process. It was therefore necessary to measure the three angles by which each probe was misaligned with respect to the reference axes. A sample of 10 to 15 measurements of each angle — at various positions in the measurement domain — was acquired to make the corrections and to later evaluate the uncertainty in flow statistics due to angular misalignment. The methods by which the angles in question were measured are described below. $\alpha$, $\beta$, and $\gamma$ refer to the right hand angles about the positive $x$-, $y$-, and $z$-axes respectively. The blue-green probe is denoted by "1", and the purple by "2".

Consider the angle $\alpha_1$. A precise $90^\circ$ wedge, or square, was placed in the tunnel with its wide face facing the tunnel side (Figure 14). With the $y$-traverse, the unshifted green beam was aligned to contact the wedge near its top edge, where it appeared as a reflected ellipse. The elevation of the ellipse center was recorded ($h_1$), as was the position of the $y$-traverse ($y_1$). The beam was then translated, again with the $y$-traverse, until it contacted the wedge near its lower edge. At this position, $h_2$ and $y_2$ were recorded. $\alpha_1$ for the unshifted green beam, could then be determined by
The procedure was then repeated for the shifted green beam, which contacted the opposite face of the wedge, and \( \alpha_{1, \text{shifted}} \) was determined. Finally, \( \alpha_1 \) was calculated as the average of \( \alpha_{1, \text{unshifted}} \) and \( \alpha_{1, \text{shifted}} \). This procedure, or a variation thereof, was applied to the measurement of \( \alpha_1, \beta_1, \alpha_2, \) and \( \gamma_2 \).

The second method of measuring beam misalignment was applied to \( \gamma_1 \) and \( \beta_2 \), and is named the pinhole method. Consider here the angle \( \gamma_1 \). With the pinhole unit firmly secured in the test section, the shifted green beam was centered over the pinhole as described in the previous section, and the positions of the x-traverse (\( x_j \)) and y-traverse (\( y_i \)) were recorded (Figure 15). The unshifted green beam was then translated with the x- and y-traverses until it was centered over the pinhole, and \( x_2 \) and \( y_2 \) were recorded. \( \gamma_1 \) was then determined by

\[
\tan(\gamma_1) = \frac{x_2 - x_1}{y_2 - y_1}
\]

Table 4 below lists the values of the angles and the corresponding measurement uncertainty.

<table>
<thead>
<tr>
<th>Angle</th>
<th>Measured value</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \alpha_1 )</td>
<td>6.26</td>
<td>0.065</td>
</tr>
<tr>
<td>( \beta_1 )</td>
<td>0.51</td>
<td>0.117</td>
</tr>
<tr>
<td>( \gamma_1 )</td>
<td>-0.69</td>
<td>0.076</td>
</tr>
<tr>
<td>( \alpha_2 )</td>
<td>5.95</td>
<td>0.066</td>
</tr>
<tr>
<td>( \beta_2 )</td>
<td>0.65</td>
<td>0.112</td>
</tr>
<tr>
<td>( \gamma_2 )</td>
<td>-0.12</td>
<td>0.048</td>
</tr>
</tbody>
</table>

Table 4: Measured angles of misalignment

For a single measurement of velocity, the measured values — denoted by subscript "m" — are related to the true values by a transformation based on a small angle approximation of a general coordinate rotation, as written below.
\[ U_m = C U \]  \hspace{1cm} (5)

where
\[
U_m = \begin{bmatrix} U_m \\ V_m \\ W_m \end{bmatrix}, \quad U = \begin{bmatrix} U \\ V \\ W \end{bmatrix}, \quad \text{and}
\]
\[
C = \begin{bmatrix}
\cos \gamma_1 \cos \beta_1 & \cos \beta_1 \sin \gamma_1 & -\sin \beta_1 \cos \gamma_1 \\
-sin \gamma_1 \cos \alpha_1 & \cos \gamma_1 \cos \alpha_1 & \cos \gamma_1 \sin \alpha_1 \\
\cos \alpha_2 \sin \beta_2 & -\sin \alpha_2 \cos \beta_2 & \cos \alpha_2 \cos \beta_2
\end{bmatrix}
\]

The known values however, are \( U_m, V_m, \) and \( W_m, \) and equation (5) must be rearranged to
\[
U = C^{-1} U_m
\]  \hspace{1cm} (6)

The transformation matrix \( C \) could easily be inverted numerically to obtain \( C^{-1}, \) but to evaluate the error induced by the measurement of angular misalignment (see section 4.2.2), one needs to invert \( C \) symbolically. The software package Mathematica was used for this purpose. An example of the complexity of equation (6) is shown below by a single element of the matrix \( C^{-1} \).

\[
C^{-1}_{1,1} = \cos(\alpha_1 - \alpha_2) \cos \beta_2 \cos \gamma_1 / \left( \cos \alpha_1 \cos \alpha_2 \cos \beta_2 \cos \gamma_1 + \cos \beta_1 \cos \beta_2 \cos \gamma_1 \sin \alpha_1 \sin \alpha_2 + \cos \alpha_1 \cos \alpha_2 \cos \gamma_1 \sin \beta_1 \sin \beta_2 + \cos \alpha_1 \cos \alpha_2 \cos \beta_1 \cos \beta_2 \sin \gamma_1 + 0.5 \cos \alpha_1 \cos \beta_2 \sin \alpha_2 \sin \beta_1 \sin 2 \gamma_1 + 0.5 \cos \alpha_2 \cos \beta_1 \sin \alpha_1 \sin \beta_2 \sin 2 \gamma_1 \right)
\]  \hspace{1cm} (7)

The magnitudes of the corrections used in the present experiments are apparent in the velocity transformation matrix \( C^{-1} \) below, which was used to recalculate each data measurement accepted by the LDV processor.

\[
C^{-1} = \begin{bmatrix}
0.9999 & 0.0121 & 0.0024 \\
-0.0099 & 0.9946 & -0.1091 \\
-0.0176 & 0.1036 & 0.9941
\end{bmatrix}
\]

3.1.5.5 Near-Wall Measurements

The TSI acquisition equipment was originally configured to operate in backscatter mode. Preliminary measurements showed that this technique was adequate except in the case of near-wall measurements (ie. within 12.7 mm of the floor), at which point the data rate dramatically decreased, in particular for the velocity components corresponding to the
blue-green probe. Visual inspection showed that the flow near the floor was seeded as densely as any other region; therefore, it was concluded that the proximity of the floor was a factor. As confirmation of this, a reasonable data rate was attained at the level of the floor, directly above the jet exit. It is possible that in the case of near-wall measurements, strong reflections were sensed by the probe, and that a valid Doppler signal could not be detected. The problem was eliminated by altering the acquisition equipment to operate in side-scatter mode. By reversing the optical fibre-to-photomultiplier connections, the signal sensed by the purple probe was directed to the green/blue photomultiplier, and vice versa. Reasonable data rates were then attained for near-wall measurements, and were generally higher for all other measurement positions as compared to the back-scatter mode of operation.

3.1.5.6 Seeding

Non-uniform seeding appears in two forms and may create a measurement bias in turbulent flow. The first form occurs when the seeding density is dependent on the local velocity. For example, the flow may be characterized by densely seeded, low velocity pockets. Therefore, the LDV processor will accept more low velocity readings than high, and flow statistics calculated by ensemble averages will be biased. This form of non-uniform seeding may be eliminated by ensuring that seed particles are thoroughly mixed with the fluid before entering the flow domain, as was done in the present experiments. The second form occurs when seeded fluid is introduced to the flow domain through more than one entrance. This occurred in the present jet-in-crossflow situation where flow to both the jets and the crossflow were independently seeded. Although uniform seeding existed at the respective entrances, a difference in seeding density between the two could have lead to a bias in the flow measurements. It was difficult to accurately gauge if the two flow sources were seeded equally; however an examination of the intensity of the laser light reflected by the smoke particles in the near field of the jets sometimes revealed a difference in brightness between jet and main stream air. The seeding rates were then adjusted to minimize this difference, thereby roughly equalizing the seeding densities of the two sources.
3.2 Flow Visualization

LDV measurements represent a point-wise interrogation of a flow field, and therefore do not capture changes in the gross flow with time. Flow visualization is a valuable complement to such a set of data, for it enables this form of information to be observed and recorded.

3.2.1 Methodology

In the present experiments, flow visualization consisted of seeding the jet air with smoke and observing the jets' motion in selected 2-D planes by illuminating the flow field with a narrow sheet of light. This was accomplished by coupling the original laser beam to a single fibre optic cable, and transmitting it to the test section. The beam then passed through an objective and a cylindrical lens, and was spread into a 5 mm wide sheet of bluish light. Since the beam was focussed, the thickness of the sheet was non-uniform. A colimmator could have been positioned ahead of the cylindrical lens to eliminate this characteristic, but the variation in thickness over the flow region under consideration was very small. The light sheet was directed into the tunnel from above and was oriented either parallel or perpendicular to the direction of the crossflow. A Sony Camcorder video camera operating at 30 frames/s was used to film the motion of the jets in the various interrogation planes. Although the resolution of the video camera was less than that of print film, the advantage of recording a time trace of the jet motion proved to be useful in terms of capturing unsteadiness in the flow. With the light sheet oriented parallel to the crossflow, video was shot from the side of the tunnel. In the second orientation, video was shot from downstream. This was accomplished by positioning the camera at the side of the tunnel approximately 1.0 m downstream of the jets, and securing a flat mirror in the tunnel, oriented at of 45° to the crossflow, to reflect the image of the jets toward the camera. The light reflected by the smoke in the plane of the sheet was sufficient for camera shutter speeds of up to 1/250 s. The advantage of using a higher
than standard (1/60 s) shutter speed was that the images of the jets were less smeared, and finer structures were visible.

3.3 Laser Doppler Velocimetry — Recovery Boiler

The recovery boiler experiments were designed to obtain reasonable estimates of the flow characteristics for the three cases under investigation. The flow field was highly complex — due to unevenly distributed injection through over 200 ports combined with sloped floor geometry in the lower furnace — therefore, highly accurate measurements over the coarse measurement grid would not necessarily lead to the extraction of highly useful information. As a result, some of the measures adopted in the wind tunnel experiments were ignored. Conversely, some new measures were taken to account for properties unique to the present experiments. The equipment and method of acquisition and storage were similar to those described in sections 3.1.2 and 3.1.3.

3.3.1 Mode of Operation

The mode of operation in the boiler model experiments was influenced by the physical characteristics of the apparatus and the nature of the information sought. The presence of plexiglass model walls and water as the working fluid caused the laser beams to refract as they were transmitted through these different media. This phenomena could be easily accounted for (see section 3.3.2.1), but not with the level of accuracy needed for the alignment of beam pairs with one another. The LDV system was therefore operated in random mode, which, in contrast to coincidence mode, is used to accept a Doppler signal from a single channel. For example, eight fringe crossings may be detected from the processor associated with the blue beam pair, but not from the green. In random mode, the signal is accepted, and the measurement recorded. Unfortunately, this mode of operation does not permit the measurement of shear stresses, as "simultaneous" measurements of two velocity components are unavailable.
The number of velocity components measured was limited to two. A third component would have required the use of the second probe, but physical and optical obstructions about the model made the implementation of a second probe impractical. Vertical velocity — the dominant component — and one horizontal component were measured with the probe directed toward the model from the left or right side. The probe was supported by an elevated surface, and could freely translate to any horizontal location, to correctly position the measurement volume anywhere on the 6×6 grid. The height of the support surface was variable, and was set for the appropriate measurement level.

In random mode, with no applicable coincidence window, multiple realizations were entirely possible; in fact, these were the norm. On average, a greater number of realizations occurred for lower velocities than high, which induced a significant bias in the velocity statistics. However, it is shown below that multiple realizations may be used to correct the velocity bias associated with turbulent flow. Given the optical properties listed in Table 3, the theoretical number of multiple realizations can be determined as a function of particle velocity. Assuming that the selected frequency shift is 500 kHz, the time for eight fringe crossings (T₈, in [ns]) of the green beam pair is calculated from equation (2) to be

\[ T₈ = \frac{8000}{0.2681V+0.5} \]  

where \( V \) is in [m/s]. If the particle travels the maximum diameter of the measurement volume, its residence (\( T_m \), in [ns]) time is given by

\[ T_m = |d_m/V| = |90500/V| \]  

Therefore, if the processor is reset immediately after each measurement (there does exist a small lag, though it only slightly affects the present reasoning), the total number of realizations \( N_R \) is

\[ N_R = \frac{T_m}{T₈} = \left| \frac{90500}{V} \right| \cdot \frac{0.2681V+0.5}{8000} = 3.03 \frac{V}{|V|} + \frac{5.66}{V} \]  

\[ \]
In the present experiments, the bulk upward velocity was set to 0.055 m/s in one flow case, and 0.077 m/s in the other two. Even with the greatest velocities equalling four times the bulk upward velocity, a reasonable approximation of equation (10) may be made:

\[
N_r = \left| \frac{5.66}{V} \right|
\]  

(11)

Evidently, weak velocities lead to greater multiple realizations than do strong velocities. Calculation of mean and rms velocities by ensemble averaging would result in a bias toward low velocities.

In section 4.1.3, a form of velocity bias, in which higher velocities are overly weighted, will be explained. Provided that the data consists of single-realization measurements, one method of correcting for this second velocity bias is to apply inverse velocity weighting. In the boiler model experiments however, inverse velocity weighting may be ignored, because of the inverse velocity relationship in equation (11). Simply, the bias induced by multiple realizations accounts for the effect of turbulence-induced velocity bias, and the two approximately cancel.

Angular corrections could not be made to the individual measurements because 1) only two components of velocity were measured, and 2) the LDV system was not operated in coincidence mode. Therefore, any misalignment of the probes with respect to the boiler model was not corrected. Nevertheless, this error was considered to be much smaller in this set of experiments, for the probe was not rotated a nominal 6°, as it was in Part I. It was oriented to within 1° of the line perpendicular to the facing model wall.

Generally, the flow did not require seeding, for the sediment which naturally occurred in the water was sufficient to produce a reasonable data rate. At times — for example, during periods of dry weather — water supplied to the 5700 L tank was exceptionally clear, and it was necessary to seed the flow. A fine grey dust, a form of residue from a neighbouring chemical engineering experiment, proved to be suitable for the task.
3.3.2 Difficulties

3.3.2.1 Refraction

It was noted in section 3.3.1 that the laser beams were refracted as they were transmitted through the plexiglass and the water. It was therefore necessary to set the measurement probe to the correct position outside the model based on the measurement locations inside. In the formulations below, air, water, and plexiglass are denoted by "1", "2", and "3" respectively.

Consider a beam of light travelling through air and approaching a plane of plexiglass at an angle $\theta_1$ to the line normal to the plane (Figure 16). It is then transmitted through the plexiglass at an angle of incidence $\theta_2$ before entering water, at which point it is once again refracted, with a final angle of incidence of $\theta_3$. Given the thickness of the plexiglass wall, the separation of the beams at the probe lens ($r_1$), and the indices of refraction $n$ for air, plexiglass, and water, Snell's law may be applied to determine the probe's position $d_1$ as a function of the measurement position $d_v$. First, two relations may be written, one for each change in medium.

\[
\frac{\sin(\theta_1)}{\sin(\theta_2)} = \frac{n_2}{n_1} = \frac{1.5}{1.0} = 1.5
\]  
\[\text{(12)}\]

\[
\frac{\sin(\theta_2)}{\sin(\theta_3)} = \frac{n_3}{n_2} = \frac{1.33}{1.5} = 0.89
\]  
\[\text{(13)}\]

With $\theta_1$ equal to the beam half angle $\kappa$ (= 3.95° from Table 3), $\theta_2$ equals 2.63°, and $\theta_3$ equals 2.97°. Next, three simple trigonometric relations may be written.

\[
\frac{r_3}{d_3} = \tan(\theta_3)
\]  
\[\text{(14)}\]

\[
\frac{r_2 - r_3}{d_2} = \tan(\theta_2)
\]  
\[\text{(15)}\]

\[
\frac{r_1 - r_2}{d_1} = \tan(\theta_1)
\]  
\[\text{(16)}\]
Equations (14) (15) (16) are then combined to obtain the following relation.

\[ d_1 = r_1 - d_2 \tan(\theta_2) - d_3 \tan(\theta_3) \tan(\theta_1) \]  

With the values of \( \theta_1, \theta_2, \) and \( \theta_3 \) as given above, \( r_1 \) equal to 25 mm (ie. half the beam separation), and \( d_2 \) equal to 17.5 mm in the boiler model, one obtains

\[ d_1 = 350.4 - 0.75d_3 \]  

In the present experiments, the relation of equation (18) was used to correctly position the probe outside the boiler model, given any desired position inside.

3.3.2.2 Far-Wall Measurements

Measurements were generally obtained with little complication. An exception occurred for measurement locations near the far wall of the model, in which case the data rate climbed to an unrealistically high value. Although the measurement volume was 35 mm from the wall, it was still close enough for the beams to reflect back toward the probe, and affect the nature of the sensed Doppler signal. Certain areas of the probe's lens were masked in an attempt to eliminate the effect of the reflections, but this proved to be unsuccessful. The final solution was to avoid the problem: one half of the measurements were acquired from the left side of the model; the other half from the right. With this method, the measurement volume never approached the far wall.

3.4 Particle Image Velocimetry

One disadvantage of LDV measurements is that one can acquire data only one position at a time. Although a velocity trace may show variations in time with a particular range of characteristic frequencies, no information is available with respect to the temporal changes in large-scale flow structures, for example, large eddies being convected through the flow field. A solution to this problem is PIV, a measurement technique which retrieves 2-D velocity information in a given plane of a flow field, and possibly a time trace of this motion. A brief discussion of the technique, and how it was applied in the present experiments, is provided in
the following sections. Further information about PIV as applied to recovery boiler modelling is available in Ketler (1993).

3.4.1 Background

The first step involves illuminating a 2-D plane of the flow field, and filming the motion of reflective tracer particles. The particles' positions are then determined for each image in the recorded sequence. This may be done digitally through some form of grey level binarization. For example, image pixels greater than a particular brightness level are considered to be tracer particles, and their positions are stored. The binarized images are then partitioned into a grid of cells, and a particle tracking method (e.g. cross-correlation) is used to determine the average displacement of the particles within each cell between two successive images. This set of displacements is multiplied by the original film's frame rate to determine the velocity field in the illuminated 2-D plane. The process may be repeated for successive steps in time to investigate the temporal distribution of flow velocities.

3.4.2 Equipment

The same 7.0 W argon-ion laser used for the LDV measurements was used for the purpose of PIV. As in the flow visualization section of the wind tunnel experiments, the original laser was transmitted through a cylindrical lens and directed toward the boiler model, thus producing a narrow intense sheet of light. Flow was seeded by polystyrene particles with an average diameter of 400 μm and a specific density of 1.05. Ketler (1993) showed that such particles are suitable for use in a similar recovery boiler model.

3.4.3 Acquisition and Storage

Motion of the particles in the plane of the light sheet was recorded on tape with a S-VHS video camera operating at a standard frame rate of 30 frames/s. Shutter speeds of 1/60 s, 1/100 s, and 1/250 s were used, and the image sequences with a combination of the best lighting properties (i.e. high contrast, bright particles, little blur) were considered for analysis. These sequences were later digitized with a full-motion video capture system and
stored to a dedicated hard drive at a rate of 30 frames/s (real-time) and a resolution of 752×480 pixels. The digitizer was manufactured by Digital Processing Systems and consisted of a PAR animation recorder and TBC-IV time base corrector.

Figure 11: Source of Doppler signal
Figure 12: Optics setup and arrangement of measurement probes with respect to test section
Figure 13: Detail of pinhole device
Figure 14: Method #1 of measuring angular misalignment

Figure 15: Method #2 of measuring angular misalignment
Figure 16: Refraction of laser beam through changes in medium
CHAPTER 4
DATA ANALYSIS

4.1 Velocity Statistics — Wind Tunnel

The calculation of statistics in this experiment was a post-acquisition process, as the data from each measurement position was stored to disc as a time trace of $T_g$. The TSI software package was not suitable for this application for the following reasons: 1) it did not allow for the correction of the angular misalignment, 2) it did not allow for any form of correction to the statistics, 3) it was limited to analysing discrete lengths of the time traces, and 4) it had limited criteria for eliminating "bad" points. As a result of this, the analysis software program, XFORMV20 (Ajersch, 1993), was written to overcome these inadequacies.

4.1.1 Removal of Bad Points

Careful inspection of the time traces of $T_g$ showed that rare but occasional measurements of a nominal zero-velocity in one or more components were accepted. Although this was possible due to the discrete nature of the processors' measurements of $T_g$, it was considered improbable, particularly in regions of high velocity low turbulence flow. Because of these aberrations, all nominal zero-velocity points in the time traces of $T_g$ were omitted in the analysis of the data.

XFORMV20 also included the option of removing velocities which lay outside three standard deviations from the mean. This enabled the analysis to exclude points which were considered strange or unlikely.

4.1.2 Correction of angular misalignment

The LDV probes were not accurately aligned with the axes of the test section, and therefore did not directly measure the three components of velocity $U$, $V$, and $W$ defined earlier in Figure 5. This was one of the main difficulties with the operation of LDV discussed
in section 3.1.5.4. It was shown that for each measurement accepted by the processors, it was necessary to correct the velocity with the transformation matrix of equation (5). XFORMV20 was designed to input the angles of misalignment and calculate the transformation matrix $C^{-1}$. The instantaneous velocities could then be corrected prior to the calculation of flow statistics.

### 4.1.3 Correction of Velocity Bias

With the use of LDV, if flow statistics in turbulent flow are simply calculated by using arithmetic averages, a bias in the statistics will exist (Edwards, 1987). The explanation is that in uniformly seeded flow, the flux of seed particles through a given volume is greater at large velocity than at small velocity. Therefore, turbulence in the flow will lead to a disproportionately large number of high velocity readings in the recorded time trace of velocity. A number of weighted averaging techniques can be applied to correct this error (McLaughlin and Tiederman, 1973), each with its own set of advantages. The technique selected in the present experiments was inverse velocity weighting. The expected value of a general flow statistic $s$ is then calculated by

$$
\langle s \rangle = \frac{\sum_{i} s_i}{\sum_{i} \frac{1}{|\bar{V}_i|}}
$$

where $s_i$ is the contribution to the statistic $s$ from the $i$-th data point and $\bar{V}_i$ is the velocity for that same point.

The expected values of the flow statistics as calculated in the present experiments are defined below. Assuming that the corrections for angular misalignment have been made, we consider a general component of velocity

$$
U_i = U + u_i
$$

where $U_i$ is the instantaneous velocity for the $i$-th data point, $U$ is the mean velocity over $N$ points, and $u_i$ is the fluctuating component of velocity for the $i$-th data point. The expected values are as follows.
Mean velocity:
\[
\langle U \rangle = \frac{1}{N} \sum_{i=1}^{N} \frac{U_i}{|V_i|}
\]
\[
\langle V \rangle = \frac{1}{N} \sum_{i=1}^{N} \frac{V_i}{|V_i|}
\]
\[
\langle W \rangle = \frac{1}{N} \sum_{i=1}^{N} \frac{W_i}{|V_i|}
\]

Normal stress:
\[
\langle u' \rangle = \langle \sqrt{uu} \rangle = \frac{\sum_{i=1}^{N} u_i^2 \frac{1}{|V_i|}}{\sum_{i=1}^{N} \frac{1}{|V_i|}}
\]
\[
\langle v' \rangle = \langle \sqrt{vv} \rangle = \frac{\sum_{i=1}^{N} v_i^2 \frac{1}{|V_i|}}{\sum_{i=1}^{N} \frac{1}{|V_i|}}
\]
\[
\langle w' \rangle = \langle \sqrt{ww} \rangle = \frac{\sum_{i=1}^{N} w_i^2 \frac{1}{|V_i|}}{\sum_{i=1}^{N} \frac{1}{|V_i|}}
\]

Shear stress:
\[
\langle vw \rangle = \frac{\sum_{i=1}^{N} v_i w_i \frac{1}{|V_i|}}{\sum_{i=1}^{N} \frac{1}{|V_i|}}
\]
\[
\langle uw \rangle = \frac{\sum_{i=1}^{N} u_i w_i \frac{1}{|V_i|}}{\sum_{i=1}^{N} \frac{1}{|V_i|}}
\]
\[
\langle vw \rangle = \frac{\sum_{i=1}^{N} u_i v_i \frac{1}{|V_i|}}{\sum_{i=1}^{N} \frac{1}{|V_i|}}
\]

Turbulence kinetic energy:
\[
\langle k \rangle = \frac{1}{2} (\langle u' \rangle^2 + \langle v' \rangle^2 + \langle w' \rangle^2) \tag{20}
\]

4.2 Error Analysis — Wind Tunnel

4.2.1 Measurements of Turbulence

LDV is an accurate, non-intrusive measurement technique, but high levels of turbulence in the flow may lead to significant errors in the computation of velocity statistics. This problem becomes more pronounced with low data density \( N_D \) (Fuchs et al., 1993), which is defined as the number of particle arrivals per integral time scale, or

\[
N_D = \dot{N} T_\lambda \tag{21}
\]

where \( \dot{N} \) = particle arrival rate
\( T_\lambda \) = integral time scale
In the present experiments, an estimate of the integral time scale may be obtained by dividing the jet diameter $D$ by the bulk jet exit velocity $V_{jet}$, which equals 0.0023 s. Based on the existing data rates which ranged from 1 Hz to 400 Hz, the data density was as low as 0.002 and as high as 0.9, and is classified as "low" and "medium" respectively (Edwards, 1987).

Fuchs et al. (1993) used simulation software to examine the accuracy of statistical estimators in terms of the percent error in velocity mean and variance as defined by

$$
\beta_1 = \frac{\langle U \rangle - U}{U} \quad \text{and} \quad \beta_2 = \frac{\langle uu \rangle - uu}{uu}
$$

(22)

where $\langle \rangle$ denotes the estimate of the true value.

With the use of ensemble averaging, it was found that $\beta_1$ increased with the square of the turbulence intensity $\overline{uu}/U^2$, for turbulence intensities below 30%, and that this value represented a maximum likely error in the mean velocity. The use of transit time weighting or arrival time weighting in the calculation of the statistics had the effect of greatly reducing the error; however, $\beta_2$ could still be relatively large. It is important to note that transit time weighting is conceptually similar to the inverse velocity method used in the present experiments.

Fuchs et al. ran a simulation for the parameters listed in Table 5 below. This table also lists typical values of the parameters in the present experiments. It is obvious from a comparison between the two sets of parameters that large differences exists between the present experiments and those of Fuchs et al., and therefore the observations of Fuchs et al. are not directly applicable here. However, what Fuchs et al. does provide is a sense of the magnitude of the bias caused by turbulence, and the level to which this bias may be corrected. With the use of transit time weighting, Fuchs et al. observed that $\beta_1$ did not seem to be a function of $N_D$, and values of this error were as high as 5%. Error in variance was noticeably higher however, with values of $\beta_2$ near -20%. Therefore, even with the use of a reputable
weighting scheme, one must take care not to misinterpret such results by treating them as an absolute truth.

Although Fuchs et al. (1993) used different weighting schemes and simulated different flow conditions than those of the present experiments, the results of the study did demonstrate the level of uncertainty which may be present in turbulent flow statistics. Inverse velocity weighting is a logical method of accounting for the cause of the errors, but errors will undoubtedly remain, the size of which will vary with the local flow conditions. Beyond applying the initial weighting scheme, valid additional corrections would be difficult to support; for example, there would be no justification in substituting -20% for $\beta_z$ in equation (22) to solve for $\overline{uu}$. Because the inverse velocity weighting scheme is unable to thoroughly account for turbulent flow bias, the errors induced by turbulent flow are likely the largest cause of uncertainty in the present experiments.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Fuchs et al. (1993)</th>
<th>Typical values from present experiments</th>
</tr>
</thead>
<tbody>
<tr>
<td>mean velocity, $U$</td>
<td>[m/s]</td>
<td>0.432</td>
<td>5.5</td>
</tr>
<tr>
<td>mean velocity, $V$</td>
<td>[m/s]</td>
<td>0.180</td>
<td>0.5</td>
</tr>
<tr>
<td>mean velocity, $W$</td>
<td>[m/s]</td>
<td>0.134</td>
<td>1.0</td>
</tr>
<tr>
<td>variance, $\overline{uu}$</td>
<td>[m$^2$/s$^2$]</td>
<td>0.189</td>
<td>0.8</td>
</tr>
<tr>
<td>variance, $\overline{vv}$</td>
<td>[m$^2$/s$^2$]</td>
<td>0.158</td>
<td>0.8</td>
</tr>
<tr>
<td>variance, $\overline{ww}$</td>
<td>[m$^2$/s$^2$]</td>
<td>0.170</td>
<td>0.8</td>
</tr>
<tr>
<td>covariance to $x$, $\overline{uv}$</td>
<td>[m$^2$/s$^2$]</td>
<td>-0.032</td>
<td>0.6</td>
</tr>
<tr>
<td>covariance to $x$, $\overline{uw}$</td>
<td>[m$^2$/s$^2$]</td>
<td>-0.062</td>
<td>0.6</td>
</tr>
<tr>
<td>integral time scale in $x$, $T_x$</td>
<td>[ms]</td>
<td>11</td>
<td>2.3</td>
</tr>
<tr>
<td>integral time scale in $y$, $T_y$</td>
<td>[ms]</td>
<td>1.5</td>
<td>2.3</td>
</tr>
<tr>
<td>integral time scale in $z$, $T_z$</td>
<td>[ms]</td>
<td>1.5</td>
<td>2.3</td>
</tr>
<tr>
<td>measurement volume diameter, $d_m$</td>
<td>[$\mu$m]</td>
<td>19</td>
<td>90</td>
</tr>
<tr>
<td>shift frequency, $f_s$</td>
<td>[kHz]</td>
<td>500</td>
<td>2000</td>
</tr>
<tr>
<td>fringe spacing, $d_f$</td>
<td>[$\mu$m]</td>
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<td>3.73</td>
</tr>
<tr>
<td>minimum periods</td>
<td>—</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>particle density, $N_p$</td>
<td>—</td>
<td>0.1-30</td>
<td>0.0023-0.9</td>
</tr>
</tbody>
</table>

Table 5: Parameters used in a simulation of LDV data compared to those of the present experiments.
4.2.2 Uncertainty Due to Angular Misalignment

As it was not feasible to align the two LDV probes with the axes of the test section, the angles by which each probe was misaligned were measured. Therefore, a set of six angle measurements — three for each probe — was obtained, along with the respective variance in each angle. Based on this data, an estimate of the error induced by the uncertainty in the measurement of these angles was made.

Given a function \( T \) of \( k \) random variables \( \Theta_1, \ldots, \Theta_k \), the variance of the function is dependent on the following relation (Bury, 1986)

\[
\text{var}(T) = \sum_{i=1}^{k} \sum_{j=1}^{k} \left( \frac{\partial T}{\partial \Theta_i} \right) \left( \frac{\partial T}{\partial \Theta_j} \right) \text{cov}(\Theta_i, \Theta_j)
\]

(23)

where \( E \) is the expectation operator. If the function in question is a velocity component for a single measurement in time, for example \( U \), and the variables on which it is dependent are the angles of misalignment (ie. \( \alpha_1, \beta_1, \gamma_1, \alpha_2, \beta_2, \gamma_2 \)) then the variance in \( U \) due to the uncertainty in these angles is

\[
\text{var}(U) = \left( \frac{\partial U}{\partial \alpha_i} \right)^2 \text{var}(\alpha_i) + \left( \frac{\partial U}{\partial \beta_i} \right)^2 \text{var}(\beta_i) + \cdots + \left( \frac{\partial U}{\partial \gamma_i} \right)^2 \text{var}(\gamma_i)
\]

(24)

Note that terms involving the covariance of two different angles are assumed to be zero, as there is no reason to believe that the uncertainty in the measurement of one angle is correlated to that of another.

The velocity transformation matrix was first introduced in section 3.1.5.4, and it was shown that each value in a velocity time trace could be corrected by equation (5). If one considers that \( U_m, V_m, \) and \( W_m \) in this equation are measured with reasonable certainty by the LDV system, then the variance in \( U, V, \) and \( W \) is obtained by first determining the partial differential of each element in the matrix \( C^{-1} \) with respect to each of the six angles of misalignment. Each element in the matrix however, consists of many trigonometric terms, and there exist 45 possible partial derivatives (there is no dependence on \( \gamma_j \)); therefore, a
numerical differentiation method was selected to facilitate the task. As the analysis of raw data was performed by the program XFORMV20, the code was modified to incorporate numerical differentiation. Higgin's algorithm (Numerical Recipes in C, 1988) was implemented.

As noted above, equation (5) applies to a single measurement in time. An additional step must be taken to obtain the variance in $U$ over a time trace of measurements. If inverse velocity weighting is ignored, the expected value of $U$ is determined by

$$\langle U \rangle = \frac{1}{N} \sum_{i=1}^{N} U_i$$

where $U_i$ is the velocity of the $i$-th measurement in the trace. The variance in $\langle U \rangle$ is then obtained by

$$\text{var}(\langle U \rangle) = \frac{1}{N} \sum_{i=1}^{N} \text{var}(U_i)$$

Inverse velocity weighting was not included in the derivation above, as it would have added a level of complexity to the calculations of variance. The weighting is considered here to have a second order effect on the variance, and is therefore neglected.

The method outlined above was applied to the derivation of variance for the six flow stresses as well. Higgin's algorithm and the necessary calculations were incorporated into the data analysis software, so that the variance in each measured flow statistic due to the uncertainty in angle measurements could be output.

4.2.3 Particle Tracking

When LDV is used, the assumption is made that the tracer particles accurately follow the flow. However, density differences between particles and fluid can lead to measurement errors. For gaseous flows with relatively heavy solid or liquid particles, Adrian (1991) showed that
\[ |\mathbf{v} - \mathbf{u}| = \frac{\rho_p d_p^2}{36\nu} |\dot{\mathbf{v}}| \]  

(27)

where \( \mathbf{v} = \) particle velocity  
\( \mathbf{u} = \) fluid velocity  
\( \dot{v} = \) particle acceleration  
\( \rho = \) fluid density  
\( \rho_p = \) particle density, 1117 [kg/m\(^3\)]  
\( d_p = \) particle diameter  
\( \nu = \) kinematic viscosity of fluid

provided that \( |\mathbf{v} - \mathbf{u}|d_p/\nu \ll 1 \). The best particles would then be least heavy and very small; however, more reflective and therefore larger particles are more suitable for LDV. The particles used in the present set of experiments ranged in diameter from 0.5 μm to 60 μm (nominal values), although the upper limit is more realistically 10 μm as the particles were in liquid phase and underwent evaporation before entering the test section. Consider an extreme particle acceleration of 300 m/s\(^2\). At STP, the density and viscosity of dry air are 1.2 kg/m\(^3\) and 1.5×10\(^{-5}\) m\(^2\)/s respectively, and the upper limit of slip velocity is calculated from equation (27) to be 0.052 m/s, or 0.9% of the jet exit velocity. It is apparent from this estimate that the particles followed the flow with acceptable accuracy.

### 4.2.4 Measurement Positioning

In the present experiments, a measurement represented not a point in space, but a finite volume which was considered spherical with an approximate diameter of 90 μm. Alignment of the measurement volume center with the tunnel coordinate system was achieved by the pinhole method described in 3.1.5.3. With the pinhole device firmly inserted in a jet exit, the pinhole itself was located nominally 25.4 mm above the tunnel floor. Therefore, with all three beam pairs focussed on the pinhole, a reference point could be found based on the location of lowest sensor resistance. As the focal points of the beams were estimated to be within 25 μm of one another (see section 3.1.5.3), the positioning accuracy could be no better than this. The greatest source of positioning uncertainty was most probably due to mechanical play between the pinhole device and the jet exit. It is estimated that the
uncertainty here was on the order of 100 μm. Considering that the measurement locations nearest to the tunnel floor were 0.25 diameters, or 3.2 mm, this positioning uncertainty was acceptable.

4.3 Flow Visualization Images — Wind Tunnel

The images of the jets presented in this thesis were extracted from the original video footage with a full-motion real-time video capture device. A Digital Processing Systems PAR animation recorder was paired with a TBC-IV time base corrector to digitize video sequences at 30 frames/s and store them to a dedicated hard drive. Individual frames from the sequence could then be exported from this drive to readable Targa format image files. The images in this thesis that represent time averages of a sequence were obtained by numerically averaging each grey scale value of an image pixel array over a range of consecutive Targa files in the given sequence.

4.4 Velocity Statistics from LDV Data — Recovery Boiler

In section 4.1, it was noted that the TSI software — FIND version 3.53 — was not suitable for the analysis of the wind tunnel data. However, in the boiler model experiments, the data was acquired in two-component random mode, and was treated satisfactorily by the FIND program. Angular corrections were deemed unnecessary, and the velocity bias caused by turbulent flow was accounted for by the presence of multiple realizations (section 3.3.1). With random mode sampling, the software adequately managed any length velocity trace, and the problem with "bad" points was no longer apparent. Ensemble averages were used to calculated the mean velocities $U$ and $W$, and the respective fluctuating components $u'$ and $w'$. In the discussion of results, reference is often made to turbulence kinetic energy, $k$. As only two components of velocity were measured, a variation of equation (20) was used. The assumption is made that the unknown horizontal component $V$ is equal to $u'$. One then writes

$$\langle k \rangle = \frac{1}{2} \left( 2\langle u' \rangle^2 + \langle w' \rangle^2 \right)$$

(28)
As a partial verification of the calculated velocities, the net flow rate through each measurement level was calculated by integrating the 36 vertical velocities (those in the 6x6 measurement grid) over the area of the horizontal cross-section. Assuming that each velocity is uniform through the corresponding grid cell, the net flow rate $Q$ is calculated to be

$$Q = 1000 \cdot 60 \sum_{i=1}^{36} V_i A_i = 60000 \sum_{i=1}^{36} V_i \frac{w h}{6 \cdot 6} = 10284 \sum_{i=1}^{36} V_i$$

where

- $Q$ is in [L/min]
- $V_i$ = vertical velocity, in [m/s]
- $A_i$ = area of local grid cell, in [m]
- $w$ = boiler cross section dimension #1, in [m]
- $h$ = boiler cross section dimension #2, in [m]
- $i$ is the grid cell number

Note that wall effects are assumed to be negligible for the flow is highly turbulent and the wall boundary layer is much smaller than the size of the grid cells.

### 4.5 Velocity Statistics from PIV Data — Recovery Boiler

Extensive processing was required after a sequence of images from the raw video footage was digitized and stored to disk. Binarization of the digitized images to extract the locations of valid tracer particles was the first of three processes. The second process involved particle tracking by a cross-correlation technique to determine the velocity field of every successive image pair. Finally, for the purpose of presentation, the sequence of velocity fields could be assembled into an animation, or alternately, a series of time averages.

#### 4.5.1 Binarization

The first process, binarization, was used to determine the existence and location of the tracer particles in each image of the original video recording. For this purpose, the computer program BINARIZE (Ketler and Ajersch, 1994) was written in-house.

Ideally, the particles appear as bright dots on a dark background, and a single grey level threshold is able to distinguish all particles from the background. For example, all image pixels for which the grey level is above, say, 146 — where zero is black and 255 is
white — are labelled as particles, and set to a grey level of 255; all other pixels are set to zero. In practice, signal noise and large variations in background brightness made this simple method unreliable. A threshold suitable for the lower left region of the image sometimes caused the entire background in the upper right region to light up. One solution was to segment the image into a grid of cells, and to use a binarization threshold suitable for each cell. The method of threshold selection is explained below.

Consider a grid cell (64×64 pixels) which contains a number of bright particles against a dark and slightly noisy background, as in Figure 17. In Figure 18, a histogram of the cell's grey levels is plotted. The population of bright pixels appears to be centered about the grey level 140; this value is representative of the tracer particles. The population of darker pixels is not centered about an obvious level, but is scattered between 20 and 120. This represents the background grey levels and the image noise. Selection of a threshold for this cell is fairly easy, and a value of 130 clearly distinguishes the particles from the background. However, elsewhere in the image, a threshold of 130 may be too low, and brighter background noise may inadvertently be picked up. This will not occur if each cell's grey levels are scaled in an appropriate manner. One scaling method offered in Binarize is outlined below. It is applied separately to each cell in the image grid.

1) The median grey level of a given cell is determined (see Figure 18). Because only a small percentage of pixels represent tracer particles, the median grey level of the complete cell is only slightly higher than the median grey level of the cell's background. Hence, the median chosen is a fair estimate of a representative background grey level.

2) All grey levels below the median are set to the median value.

3) The maximum grey level is determined (see Figure 18). This value is typically not much higher than the average tracer particle grey level.

4) All grey levels are scaled such that the new values range from 0 to 255. This is accomplished by the following formula where \( g_0 \) is the original
grey level of a pixel, $g_1$ is the transformed grey level, and $g_{\text{med}}$ is the cell's median grey level:

$$g_1 = 255 \frac{g_0 - g_{\text{med}}}{g_{\text{max}} - g_{\text{med}}}$$

(30)

The above transformation reorganizes each cell's grey levels such that the representative background level is scaled to zero, and the maximum grey level is scaled to 255. The cell-to-cell distribution of grey levels is therefore rendered more uniform, and it becomes possible to select a single binarization threshold suitable for the entire image. The software allowed to user to select the best threshold for a given sequence of images, and to apply slight variations to the above scaling method.

### 4.5.2 Cross-Correlation

This process consisted of segmenting the images into a grid of rectangular cells, and performing a cross-correlation on the corresponding cells of successive image pairs. The image-to-image displacement of particles, and therefore the field of particle velocities, was then determined. A separate computer program, named CORRELAT (Ketler, 1993), was written for this purpose.

A 752x480 digitized image typically contained flow field information within an approximately 600x400 region of interest. In the analysis of the present experiments, the region was subdivided into a 15x10 grid of cells, with each cell measuring 64x64 pixels. Note that the cell dimensions — necessarily $2^N$ pixels tall/wide — lead to the overlap of adjacent cells, the consequence of which was a slight smoothing of the calculated velocity field. Alternately, cells sized 32x32 could have been chosen, but the fourfold loss of data in each cell was considered detrimental.

Given a pair of successive images, a cross-correlation was performed on each cell pair (e.g. lower left cell of image A and lower left cell of image B). The output of each cross-correlation indicated the average trajectory of tracer particles between images. A
displacement, and therefore a velocity, was calculated for each cell pair, the result being a velocity vector field at the given time step. The next pair in the image sequence (e.g. images B and C) was then input for analysis. The cross-correlations were repeated for the new pair, and every successive pair, and a time trace of velocity vector fields was obtained. A description of the analytical methods is provided in Ketler (1993).

4.5.3 Averaging

The vector plots presented in this thesis represent time-averages of the calculated values. To examine the unsteady nature of the flow, successive five second averages were calculated, each by averaging the values in a velocity field over a sequence of 300 images. The mean flow fields presented were obtained by averaging the velocity values over 40 seconds, or 1200 images, of a given sequence.

Figure 17: Example grid cell
Figure 18: Histogram of example grid cell
CHAPTER 5
RESULTS AND DISCUSSION

This chapter comprises a presentation of the results from the wind tunnel and recovery boiler experiments, and is organized in eight sections. The chapter begins with the wind tunnel experiments, and an examination of the boundary conditions of the flow field, as measured by LDV. The next three sections correspond to the flow field in the region about a particular jet in the row. These include LDV measurements of the mean flow and various flow stresses. The fifth section assesses the reliability of the angular misalignment corrections, and examines the symmetry conditions of the row of jets. Next, selected images from the flow visualization are presented and discussed. Finally, the recovery boiler experiments are dealt with in sections seven and eight, which correspond to LDV and PIV measurements respectively.

5.1 Boundary Conditions — Wind Tunnel

5.1.1 Crossflow

At the upstream position x/D=-5, a series of measurements was taken to examine the boundary layer. For the three velocity ratios, profiles of mean streamwise velocity normalized to the set crossflow velocity $V_d$ are displayed in Figure 19. Also shown in Figure 19 are profiles of normalized turbulence kinetic energy, $\sqrt{k}/V_d$. The boundary layer thickness is found to be approximately 2.0D in all three cases. For reference, the mean velocity profile obtained by the one-seventh-power law (for a 2.0D thick boundary layer) is plotted. Agreement between the power law profile and the measured profiles is reasonable. Note that the power law is a suitable approximation for a low Reynolds number turbulent boundary layer; however, in this set of experiments, a trip wire prematurely induces turbulence, thereby generating a velocity profile characteristic of a higher Reynolds number.
turbulent boundary layer. The maximum normalized turbulence kinetic energy in the boundary layer ranges from 0.07 to 0.10. Free stream turbulence is approximately 2% in the cases of R=1.5 and R=1.0, and is moderately less at 1.2% in the case of R=0.5. Turbulence in the free stream is non-isotropic with the magnitude of $u'$ approximately twice that of either $v'$ or $w'$.

### 5.1.2 Jet Exit Without Crossflow

Flow at the jet exit is turbulent as indicated by the contour plot of normalized turbulence kinetic energy, $\sqrt{k/V_{jet}}$, in Figure 20. Values of $\sqrt{k/V_{jet}}$ rise to approximately 0.18 close to the jet duct walls, which is evidence of the generation of turbulence in the duct wall boundary. Toward the center of the jet, this value drops to 0.10, but still indicates that the flow is turbulent, as expected for a jet exit Reynolds number of 4700 and a sharp edged entry to a 6D long duct. The normalized vertical velocity profile, also shown in Figure 20, appears fairly rounded. Given that the entry to the jet duct is sharp-edged, this profile is not unexpected, as the duct length is only 6D and does not allow for the flow to become fully developed.

### 5.1.3 Jet Exit With Crossflow

The flow field at the level of the jet exit is strongly dependent on the jet-to-crossflow velocity ratio $R$. Figure 21 shows the normalized vertical velocity profiles in this plane for the three cases. As expected, the strong jet ($R=1.5$) is least affected by the crossflow while the weak jet ($R=0.5$) is the most deflected. For $R=0.5$, $W/V_{jet}$ on the upstream side is less than 0.2, and on the downstream side rises above 1.7. The profile shape is wedge-like, with a steeper gradient on the upstream half. As the jet strength increases, the flow becomes slightly more uniform, but still exhibits the characteristics described above.

Contours of turbulence kinetic energy at the jet exit, normalized to the bulk jet velocity, $(\sqrt{k/V_{jet}})$ are shown in Figure 22. The region of lowest turbulence kinetic energy in the weak jet lies near the downstream edge and has a value of 0.10. As the velocity ratio
increases, the position of minimum turbulence kinetic energy moves toward the middle of the jet. The magnitude of $\sqrt{k_{\text{min}}/V_{\text{jet}}}$ however, is not sensitive to R, and remains near 0.10 for the strong jet. The region of maximum turbulence kinetic energy is located near the upstream edge of the jet in all three cases. This is expected, for the jet/crossflow interaction is certainly greater near this edge than anywhere else in the jet exit plane, and intermittent penetration of the crossflow into this region would cause fluctuations in velocity, thus elevating $\sqrt{k}$. The magnitude of $\sqrt{k_{\text{max}}/V_{\text{jet}}}$ is sensitive to R, and reaches values of 0.28, 0.26, and 0.24 in the weak, intermediate, and strong jet respectively.

The normalized velocity components in the jet exit plane are shown in the vector plots of Figure 23. Streamwise deflection of the jet is readily apparent, and appears to be most pronounced for R=0.5. Lateral deflection also exists, and increases in magnitude with distance away from the center-plane $y/D=0$. As the velocity ratio increases, the magnitude of the velocity components in the xy-plane decreases, but the trends remain the same.

Ideally, the patterns of Figures 21, 22, and 23 would be perfectly symmetrical about the center-plane $y=0$. The measured values shown here indicate that the symmetry is quite good.

5.2 Mean Velocities — Wind Tunnel

5.2.1 Mean Flow for R=1.5

A series of vector plots showing the mean velocity components in selected xz-planes is shown in Figure 24. The four plots correspond to the standard streamwise planes, namely $y/D=\{0,-0.5,-1.0,-1.5\}$. The center-plane ($y/D=0$) illustrates how the jet is deflected as it issues into the cross stream. The crossflow accelerates over top of the jet as well as between the jets and reaches a maximum normalized streamwise velocity of 0.80 — 19% greater than the mainstream value of 0.67 — in the plane of symmetry between jets at $x/D=1$. 
A small zone of negative flow is seen in the near field downstream of the jet, indicating the presence of 3-D separation. One must not equate this flow field to that of a 2-dimensional jet by labeling this as recirculation, for the flow in this region probably travels the circular path only once. According to Andreopoulos and Rodi (1984), a streamline here follows a spiral path as it approaches the jet center-plane from either side as illustrated in Figure 25. It then curves toward the floor, and follows a path upstream. As it rises to return to the beginning of the loop, it is swept upward into the crossflow by the jet.

In the far field of the jet (x/D>3), a wake structure is evident. Figure 26 shows contours of $U/V_{jet}$ in the standard cross-tunnel planes, which correspond to x/D=\{0,1,3,5,8\}. Between three and eight diameters downstream, fluid in the wake center accelerates from values of $U/V_{jet}$ of 0.1 to over 0.3. The size of the wake — as defined by the velocity isoline $U=90\%V_{cf}$ ($U/V_{jet}=0.6$) — increases over the same distance. What differentiates this flow from cases with higher velocity ratios (R\gg1.5) is that there exists no local maximum in $U/V_{jet}$. Customarily, the location of this maximum is used to quantify the penetration of the jets; however, here this is inapplicable. What is observed in Figure 26 are local minimums in $U/V_{jet}$ which occur somewhere between one and two diameters from the tunnel floor for x/D>3. Perhaps the center of this wake is a better indication of the jet centerline.

The 3-dimensional nature of the flow field is made apparent by the vector plots in Figure 27. These show the two mean velocity components in the standard cross-tunnel planes. At x/D=0, the jet is seen to exit at a normalized velocity greater than unity, as expected from the jet exit conditions described in 5.1.3. A fairly strong lateral component of velocity at positions away from the centerline shows how the crossflow bends around the jet. By x/D=1, one half of the counter-rotating vortex pair (CRVP) is apparent, and its strength decreases with position downstream. At x/D=8, the vortex shape is still clear, with the exception of minor irregularities. This may be an indication of the stability of the CRVP, at least between zero and eight diameters downstream. However, one must keep in mind that
each measurement point was sampled for 30 to 90 seconds, and that variations in the vortex shape and position may occur within this time frame.

5.2.2 Mean Flow for R=1.0

The case of R=1.0 shows strong similarities to that of R=1.5. Vector plots of the velocity components in the standard streamwise planes again show the deflection of the jet at the exit and the acceleration of the crossflow over top and around it (Figure 28). In the plane of symmetry between jets, the crossflow reaches a maximum normalized velocity of 1.08 — 8% higher than the mainstream value.

Back flow exists on the near lee side of the jet, but is limited to a region much closer to the tunnel floor. This is possibly due to the stronger deflection of the jet, which reduces the size of this low pressure region.

Figure 29 shows contours of $U/V_{jet}$ in the standard cross-tunnel planes. An examination of these contours reveals that a wake structure grows with position downstream. The vertical penetration of the wake as defined by the line denoting $U=90\%V_d$ ($U/V_{jet}=0.9$) is less than that for R=1.5 at a given downstream position; however, the widths of the wakes are roughly equal. At both velocity ratios, the wake extends to the $y/D=-1.5$ plane of symmetry by $x/D=8$, indicating that it meets with the wake of the adjacent jet. An examination of $U/V_{jet}$ alone however, does not demonstrate that adjacent jet structures such as the CRVP have merged. For $x/D>3$, a local minimum in $U/V_{jet}$ occurs in the jet center-plane somewhere between 0.5 and 1.5 diameters from the tunnel floor. The value of the minimum increases from 0.2 to 0.5 with downstream position, indicating that the fluid in the wake is accelerating toward to the free stream velocity.

Vector plots of the velocity components in the standard cross tunnel planes are shown in Figure 30 and are seen to strongly resemble those of Figure 27. The vortex center roughly follows the same trajectory as that for the strong jet, and the strength of the respective vortices is comparable. Some difference does occur at $x/D=3$, where the vortex
seems to be localized between $y/D = -0.5$ and $y/D = -1.0$. Another difference is that the downflow in the plane of symmetry between jets is slightly weaker. This may be because the CRVP's of adjacent jets do not interact until farther downstream, and therefore there is more opportunity for shear forces at the vortices' edges to damp them.

### 5.2.3 Mean Flow for $R=0.5$

Vector plots of the normalized velocity components in the standard streamwise planes are shown in Figure 31. It is immediately apparent that the crossflow's effect on the jet is significant. The jet is strongly deflected and is nowhere seen to penetrate the 2.0D thick boundary layer. As in the other cases, there is streamwise acceleration of the crossflow between the jets, but here the maximum normalized streamwise velocity rises only 3% above the mainstream value of 2.0. There is evidence of a small backflow region at $x/D = 1$, but more resolved measurements would be necessary to comment further on its size and structure.

Contour plots of $U/V_{jet}$ are shown in Figure 32, for the standard cross-tunnel planes. Again, a wake structure is apparent. The extent of the wake as defined by $U=90\%V_{et}$, or $U/V_{jet}=1.8$, is much smaller in this case. It seems to spread to $y/D = -1.0$, at which point it merges not with the adjacent jet, but with the boundary layer, identified by horizontal contours.

Vector plots of the velocity components in the standard cross-tunnel planes are shown in Figure 33. The left half of the CRVP is seen to be weaker than in the other cases, with the center of the vortex located between $y/D = 0.0$ and $y/D = -0.5$. There is no downflow in the plane of symmetry between jets, which suggests that the diameter of the vortex is less than 1.5D and that adjacent jets do not merge. The vortex strength decreases with downstream position, and is rendered indistinguishable by $x/D = 8$. Since the jet does not penetrate the boundary layer, the turbulence in this region acts to destroy the large-scale but weak vortex structure.
5.3 Normal Stresses — Wind Tunnel

5.3.1 Turbulence Kinetic Energy for R=1.5

Contours of normalized turbulence kinetic energy, $\sqrt{k/V_{jet}}$, are shown for the standard cross-tunnel planes in Figure 34. Up to $x/D=1$, turbulence levels near $z/D=4.0$ are close to those measured in the free stream at $x/D=-5$. Nevertheless, the influence of the jet is fairly notable, as one can see by following the penetration of the contour line denoting $300\%\sqrt{k_{is}}$, or $\sqrt{k/V_{jet}}=0.04$. This turbulence level is higher than that of the undisturbed free stream level, but still far from that seen at the jet exit. It is used here to determine the extent of the jet's penetration. By $x/D=8$, it reaches a height of 3.8D, which is deeper than one might note by examining contours of $U/V_{jet}$ or vector plots in the yz-plane.

A local minimum in turbulence kinetic energy occurs along the jet center-plane, and approximately coincides with the minimums in $U/V_{jet}$ from Figure 26. As one would expect in a wake, the turbulence level here decreases with position downstream, dropping from 0.15 to 0.10 between $x/D=3$ and $x/D=8$.

A peak in turbulence kinetic energy occurs at approximately $y/D=-1.0$ beyond one diameter downstream, and drops in magnitude from 0.22 to 0.14 over the same downstream range. A comparison of the $\sqrt{k/V_{jet}}$ contours with the $V-W$ vector plots of Figure 27 shows that the peaks in $\sqrt{k/V_{jet}}$ occur close to the edge of the vortex. An explanation is that the shear generated at the edge of the vortex promotes considerable mixing in this region. Also, any instability or unsteadiness in the position of the vortex would appear as an increase in turbulence kinetic energy at its edge, because of the shear layer moving through a fixed measurement point. Another local maximum first appears in the near wake region, occurring 1.25 diameters above the tunnel floor at $x/D=1$, where $\sqrt{k/V_{jet}}$ reaches 0.36. This region is one where the jet and crossflow directly interact, and is possibly characterized by instability and significant shear, thus explaining the presence of high turbulence. This
maximum turbulence decays at downstream positions, but still persists and penetrates 2.5 diameters by x/D=8.

Turbulence seems to spread well in the lateral direction. From x/D=0 to x/D=3, strong gradients in $\sqrt{k}$ with respect to y are evident, which suggests that turbulence has not yet spread to the plane of symmetry between jets. Downstream of this point however, levels of higher turbulence reach y/D=-1.5, suggesting that adjacent jets have merged.

### 5.3.2 Turbulence Kinetic Energy for R=1.0

Some of the trends discussed in the strong jet case also appear in the case of R=1.0. Contours of $\sqrt{k/V_{jet}}$ in the standard cross-tunnel planes, shown in Figure 35, demonstrate the spread of the jet in the vertical and lateral directions. Turbulence kinetic energy far from the tunnel floor is close to that measured in the free stream at x/D=-5, while the contour defining 300%$\sqrt{k}$, or $\sqrt{k/V_{jet}}=0.06$, penetrates deeper into the crossflow with downstream position, though less than in the case of R=1.5. In the lateral direction, the jet seems to spread slower than in the case of the strong jets, and adjacent jets do not seem to merge until x/D=8, at which point contours of higher turbulence (ie. $\sqrt{k/V_{jet}}=0.12$) reach the plane of symmetry between jets.

One no longer observes the local minimums of turbulence kinetic energy which occur along the jet center-plane for R=1.5. *Maximums* along the center-plane do appear, and coincide not with the local minimums of $U/V_{jet}$ in Figure 29, but with a position somewhat farther from the tunnel floor. What was likely represented here is once again the region where the top, or upstream, side of the jet interacts with the crossflow and turbulence is generated in the shear layer. As with R=1.5, the magnitude of the turbulence in this region decreases with position downstream.

The off-center maxima are less obvious in this case, which comes as a surprise, because mean motion in the yz-plane bears strong resemblance to that for R=1.5, as noted in section 5.2.2. Still, these are noticeable, and appear slightly closer to the jet center-plane.
5.3.3 Turbulence Kinetic Energy for R=0.5

An examination of turbulence kinetic energy in the case of R=0.5 shows that the row of weak jets penetrates far less into the crossflow than in the other cases studied. Figure 36 shows a series of contour plots of $\sqrt{k/V_{je}}$ in the standard cross-tunnel planes. The free stream turbulence levels are nearly unaffected outside the 2.0D thick boundary layer, and the 300%$k_{fs}$ contour rises only slightly with position downstream. Therefore, the jet interacts primarily with the turbulent boundary layer, where inviscid dynamics are less dominant.

The turbulence levels in the plane of symmetry between jets are very close to those found directly upstream at $x/D=-5$. The horizontal contours between $y/D=-1.0$ and $y/D=-1.5$ most likely represent the turbulent boundary layer, and indicate that it has remained undisturbed by the motion of the jets. As turbulence in the jet spreads little beyond one diameter in the lateral direction, one concludes that adjacent jets have not merged.

An obvious characteristic in these contour plots is the presence of a local maximum at $y/D=-0.5$ between 0.25 and 0.75 diameters from the tunnel floor. It first appears at $x/D=1$, and its value drops from 0.44 to 0.26 between this position and $x/D=8$. A comparison of the positions of these maxima with the vortices of Figure 33 shows that the maxima are located to the left of the vortices' centers, presumably in a region of elevated shear. Interestingly, at $x/D=8$ where the vortex structure is no longer distinct, the maximum still appears and is most likely the result of advective transport of turbulence from upstream positions.

5.3.4 Isotropy

An examination of turbulence kinetic energy provides valuable information about the turbulent nature of the flow; however, additional information is contained in the individual normal stress terms, which are not always equal. As well, numerical models sometimes assume isotropic turbulence except near the wall, where a turbulence model for
non-isotropic turbulence is used. The effects of these assumptions however, are not entirely clear.

For the purpose of this discussion, only the case of $R=1.5$ is considered. Two normal stress ratios — the $v'$-ratio and the $w'$-ratio — are defined as

\[ \frac{v' - u'}{u'} \quad \text{and} \quad \frac{w' - u'}{u'} \]

respectively. A zero value of both ratios indicates that the flow is isotropic. Figure 37 shows contours of the first quantity, the $v'$-ratio, in the standard cross-tunnel planes. In the wake region of the jet at $x/D=5$, the $v'$-ratio is seen to rise to 0.5, and is representative of the flow at other downstream positions. What this indicates is that $v'$ exceeds $u'$ by up to 50% in the wake, where turbulence in the lateral direction is dominant. In the region of shear on the top side of the jet at $x/D=5$, the ratio drops to -0.3. Again, this is representative of other downstream positions. In this region, the velocity gradient $\partial U/\partial z$ is dominant, and contributes to the production of $u'$. Therefore, the relative deficit in $v'$ seems reasonable.

Contours of the $w'$-ratio are plotted in Figure 38 for the standard cross-tunnel planes. In the jet exit region, the value of this ratio is large, and rises to 1.2. Non-isotropic flow in the jet channel would certainly explain this dominance in $w'$ where the jet issues into the crossflow. For $x/D>3$, this normal stress ratio is mostly negative, but rises above zero in a small region in the wake, as well as far from the tunnel floor ($z/D>3.0$). Maximum and minimum values are 0.2 and -0.4 respectively. The minimum is generally found close to the floor, typical of near-wall flow.

**5.4 Shear Stresses — Wind Tunnel**

Shear stresses are often left unmeasured and unreported because of the lack of available tools. Three-component coincidence-mode LDV, as used here, does allow for these measurements. The results are discussed below.
5.4.1 An Examination of $\overline{uw}$

Consider first the case of $R=1.5$. Figure 39 shows a series of contours of the shear stress $\overline{uw}$ normalized to $V^2_{jet}$ in the standard cross-tunnel planes. In the near jet region of $x/D<3$, there seems to be little large-scale organization in the flow. A refined measurement grid is needed to capture more information here. At downstream positions, $\overline{uw}/V^2_{jet}$ reaches a negative peak far from the tunnel floor. The negative contours define a shape not unlike a crescent above the jet with the concave side facing downward. Negative values occur here because the crossflow far from the wall ($z/D>1.5$) exhibits the characteristics of a boundary layer. That is, $\partial U/\partial z$ is positive and turbulence kinetic energy drops from a high near $z/D=2.0$ to its free stream value farther away. Positive peaks in $\overline{uw}/V^2_{jet}$ appear on the lower bound of the jet, but are weaker in magnitude. Based on Figure 26, $\partial U/\partial z$ is negative in this region.

The case of $R=1.0$ shows similar trends as above. A set of contours in Figure 40 shows the field of $\overline{uw}/V^2_{jet}$ in the standard cross-tunnel planes. For $x/D<3$, no large patterns in $\overline{uw}$ are discernible. Downstream of this point, values of $\overline{uw}/V^2_{jet}$ are negative far from the tunnel floor, and only slightly positive closer to the floor. The crescent shape discussed above appears at $x/D=5$ and $x/D=8$. Interestingly, at $x/D=3$, the crescent is flipped, with the concave side facing upward.

For $R=0.5$, large-scale patterns in $\overline{uw}$ are again not evident until $x/D=3$, at which point a fairly strong negative peak appears (Figure 41). The crescent shape develops by $x/D=5$. The magnitude of the largest negative values is generally much greater than the other two cases for a given position downstream, but this may be a factor of the normalization by $V^2_{jet}$. Since shear stress is produced by the interaction of turbulence with the mean flow, normalization of $\overline{uw}$ by $V^2_{ct}$ might have been more appropriate in the far field where the flow is predominantly in the streamwise direction. Above $z/D=2.0$, the shear stress is virtually zero, confirming that structures of the weak jet do not penetrate the boundary layer.
5.4.2 An Examination of $\overline{uv}$

Beginning again with the case of $R=1.5$, contours of $\overline{uv}/V_{\text{jet}}^2$ in the standard cross-tunnel planes are displayed in Figure 42. Some organization of this shear stress appears to exist by $x/D=1$, and is clearly apparent at all positions downstream of this. Again, the contours form a crescent shaped region; however, here it is located beside the jet, the plotted values are positive, and the concave side faces inward.

Andreopoulos and Rodi (1984) state that the shear stress $\overline{uv}$ is an indication of lateral turbulent mixing. One should then expect to see a correlation between $\overline{uv}$ and the side bounds of the jet. The reason for this is rooted in the free wall jet, a jet which issues perpendicularly from a wall into quiescent fluid and expands in the axial direction. The shear layer circumscribes the jet, and the spread of turbulence is primarily normal to this. Therefore, the spread of turbulence in a deflected jet should occur radially from the jet centerline, with lateral spread occurring near the jet's left and right bounds. In Figure 42, indication of this is apparent where the contours define the crescent shape as noted above.

The case of $R=1.0$ is qualitatively very much like that of $R=1.5$, with the possible exception of the position $x/D=3$, as seen in the contour plots of this shear stress in the standard cross-tunnel planes (Figure 43). Here, values of $\overline{uv}/V_{\text{jet}}^2$ are negative in the region where one might expect them to be positive (i.e. $=1D$ from the floor near $y/D=-0.5$), as they are for $x/D=5$ and $x/D=8$.

For $R=0.5$, contours of $\overline{uv}/V_{\text{jet}}^2$ in the standard cross-tunnel planes are plotted in Figure 44. There is minimal variation in this shear stress above $z/D=1.5$, suggesting again that the jet does not penetrate the boundary layer. Contours do not outline a crescent shape, but still reach a positive peak to the side of the jet. Maximum values drop from 0.050 to 0.025 between $x/D=3$ and $x/D=8$. 
5.4.3 An Examination of $\overline{vw}$

Contour plots showing the measured values of $\overline{vw}/V_{jet}^2$ in the standard cross-tunnel planes are displayed in Figure 45 for the case of $R=1.5$. A region of primarily negative shear stress rises in magnitude to a peak at approximately $y/D=-1.0$, in particular for $x/D>3$. Values of $\overline{vw}/V_{jet}^2$ are generally somewhat less than the other shear stresses at the same locations. This is partly due to the magnitude of the terms contributing to the production of this stress. Andreopoulos and Rodi (1984) state that the shear stress $\overline{vw}$ acts to damp the secondary-vortex motion, and that it is the gradients $\partial V/\partial z$ and $\partial W/\partial y$ that generate this shear stress. These gradients however, are observed to be weaker than those involved in the production of $\overline{uw}$ and $\overline{uv}$, which are $\partial U/\partial z$ and $\partial U/\partial y$ respectively.

A similar set of contour plots of $\overline{vw}/V_{jet}^2$ for the case of $R=1.0$ is shown in Figure 46. Values of $\overline{vw}/V_{jet}^2$ are again negative at far downstream positions; however, the contours at $x/D=3$ do not follow this trend. It would seem that there is some form of inconsistency in the measured flow field in the case of the intermediate jet. Shear stress contours in Figures 40, 43, and 46, and the vector plot of Figure 30 all exhibit a variation in the observed trends at the position $x/D=3$. It was noted in section 4.1.3 that regions of high turbulence are susceptible to error, in particular at low data rates. At $x/D=3$, in this case, the data rates were approximately 1 Hz; therefore, some doubt exists regarding the reliability of the measurements.

Again, a similar set of contour plots of $\overline{vw}/V_{jet}^2$, here for the case of $R=0.5$, is shown in Figure 47, but large-scale trends in this shear stress do not seem to be captured. In this particular case, the resolution of the measurement field is not sufficiently refined, given that the structures of the jet lie much closer to the tunnel floor and are dominated by the boundary layer.
5.5 Verification of Methods — Wind Tunnel

5.5.1 Symmetry Check

The results discussed in section 5.1 through 5.4 correspond to measurements in the region about one side of the single jet EAST1. It is assumed that the flow field is symmetric about the jet center-plane, and represents the other jets in the row with the exception of those closest to the tunnel walls. This section investigates the nature of this symmetry condition by comparing vertical flow profiles at given positions with the corresponding positions across the plane of symmetry between jets (y/D=-1.5).

The first comparison is made at a position one diameter downstream of injection at lateral coordinates equidistant from the plane of symmetry between jets, namely y/D=-0.5 and y/D=-2.5. The second of these two positions is associated with flow from the jet WEST1. Figure 48 displays five flow profiles of the quantities (from left to right) $U/V_{jet}$, $V/V_{jet}$, $W/V_{jet}$, $\sqrt{k}/V_{jet}$, and $\overline{uv}/V_{jet}^2$. The triangles denote measurements at y/D=-0.5; the circles, y/D=-2.5. For the purpose of comparison, the sign of $V/V_{jet}$ for the second position is inverted. Flow at the two positions is evidently similar in nature. Mean streamwise velocity near the jet WEST1 is slightly higher, particularly in the free stream above z/D=2. Profiles of the vertical and lateral velocity components match very well through the range considered. Trends in the turbulence quantities are similar, but individual values between the two positions can differ to some extent.

The second set of positions considered was located three diameters downstream of injection at the lateral coordinates y/D=-1.0 and y/D=-2.0. A set of vertical flow profiles, similar to that of Figure 48, is shown in Figure 49. The streamwise velocity profile at y/D=-2.0 exhibits less of a velocity deficit in the wake than at y/D=-1.0. In the free stream however, values are nearly identical. The two profiles of $V/V_{jet}$ are alike except in the region close to the floor. With respect to the vertical component of velocity, values are nearly equal across the plane of symmetry. The trends in $\sqrt{k}/V_{jet}$ and $\overline{uv}/V_{jet}^2$ between the two
positions are similar; however, as in Figure 48, a difference between corresponding individual values may exist.

Symmetry in the flow field seems to be quite good based on the vertical flow profiles investigated. Differences in the values of corresponding statistics may be attributed to 1) unevenly distributed flow through the six jets, 2) spatial variations in the crossflow velocity, and 3) unsteady flow near the jet exit leading edge, in combination with small jet-to-jet variations in duct and exit geometry.

5.5.2 Misalignment

5.5.2.1 Corrections

Section 3.1.5.4 introduced the velocity transformation matrix $C^1$ used to correct the velocity of each accepted measurement. The magnitudes of the corrections used in the present experiments were listed to provide a sense of the angular misalignment's affect on velocity. Here, a comparison is made of the uncorrected flow statistics with those transformed by the matrix $C^1$ to observe the end affect of misalignment. Figure 50 shows five vertical flow profiles at a downstream position of $x/D=1$ and a cross-tunnel position of $y/D=-0.5$, corresponding to the intermediate jet case ($R=1.0$). This position was arbitrarily chosen; it was thought to represent a typical profile in the present flow field. From left to right, the plotted quantities are $U$, $V$, $W$, and $u'$ normalized to $V_{jet}$, and $\bar{u}v$ normalized to $V_{jet}^2$. The circles and triangles represent the uncorrected and corrected values respectively. The quantities most influenced by the corrections are $V/V_{jet}$ and $W/V_{jet}$, which are seen to change in magnitude on the order of 0.02, or approximately 10% of the maximum values in the given profile. Far from the tunnel floor (ie. $z/D>2$), where the jet's influence is much smaller, $V/V_{jet}$ is corrected to a near-zero value, as expected. The corrections of the streamwise velocity $U/V_{jet}$ are very small, and are not apparent from Figure 50. The same applies for the corrections of $u'/V_{jet}$ and $\bar{u}v/V_{jet}^2$. Since $U$ is the dominant component of velocity in this region, at approximately five times the magnitude of either $V$ or $W$, the small corrections to
are expected. As for the descriptors of turbulence, these are derived from the summation of the instantaneous velocity fluctuations, which are affected much less by the corrections than are the mean values.

A second position in the flow field is examined via the profiles of Figure 51. The same quantities as Figure 50 are plotted here, but for a position eight diameters downstream of injection at y/D=−0.5. The quantities V/V\text{jet} and W/V\text{jet} are once again the most affected by the corrections. In this case, the magnitude of the corrections is on the order of 0.01, or approximately 25% of the maximum values in the given profile.

Although the largest angle (≈6°) by which the probes were misaligned was fairly significant and deliberately imposed, a sense of the importance of correcting flow statistics for any measurable angular misalignment is provided above.

5.5.2.2 Uncertainty

The six angles by which the probes were misaligned were measured with a level of uncertainty, which translates to an uncertainty in the correction of velocities and calculation of the flow statistics. For two arbitrary positions, an assessment of this uncertainty — based on the formulas derived in section 4.2.2 — is made. Figure 52 shows five flow profiles at a position of (x/D,y/D)=(1,-0.5) for the intermediate jet. Plotted from left to right are the corrected values of U/V\text{jet}, V/V\text{jet}, W/V\text{jet}, u'/V\text{jet}, and \overline{uv}/V^2\text{jet}, including error bars which demarcate an expected uncertainty of ±3.0 standard deviations. The error in the streamwise velocity U/V\text{jet}, and in the turbulence quantities u'/V\text{jet}, and \overline{uv}/V^2\text{jet}, is very small, and the error bars, which show a very small range in uncertainty, appear as a single line. The primary reason for the small error levels is that the corrections to these quantities are also very small. The displayed uncertainty in V/V\text{jet} and W/V\text{jet} is on the order of ±0.005, which corresponds to approximately 2% of the maximum values in the given profile. The level of uncertainty is not highly dependent on the magnitude of the value plotted, or on the vertical position.

In Figure 53, which displays a similar set of plots for the position (x/D,y/D)=(8,-0.5), the uncertainty is yet again very small for U/V\text{jet}, u'/V\text{jet}, and \overline{uv}/V^2\text{jet}. For
the other two mean velocities, the uncertainty corresponding to ±3.0 standard deviations is on
the order of ±0.003, or approximately 7% of the maximum values in the profile.

In section 5.5.2.1, the magnitude of the corrections to \( V/V_{jet} \) and \( W/V_{jet} \) decreased by a factor of two between \( x/D=1 \) and \( x/D=8 \). Likewise, in this section, the level of uncertainty in these velocities decreased by a similar amount. One may deduce from this that large corrections are associated with greater uncertainty. If this is so, regions where one component of velocity is obviously dominant — one being in and about the jet exit — may be characterized by large measurement uncertainty.

5.6 Flow Visualization — Wind Tunnel

5.6.1 Velocity Ratio \( R = 1.5 \)

It is found that the penetration is deepest and lateral spread widest for the \( R=1.5 \) jets as expected. An image obtained from time-averaging 30 frames of the video sequence is shown in Figure 54, and corresponds to a cross-tunnel plane at \( x/D=1 \). Also shown is a single frame capture of the center jet. Figures 55 and 56 are similar images of the jets at \( x/D=5 \) and \( x/D=8 \) respectively. At \( x/D=1 \), the CRVP of each jet is apparent, and conforms very well to the corresponding velocity vector plot in Figure 27. Seeded fluid from the jets does not spread to the plane of symmetry between jets, therefore indicating that the jets are not merged. The jets however, do not follow the same trajectory as single jets, for the flow between them has accelerated to 119%\( V_{d} \) and the boundary layer here is much smaller than 2\( D \) (see Figure 26). At \( x/D=5 \), fluid from the jets reaches the plane of symmetry between jets, but individual jets are still discernible. Individual jets at \( x/D=8 \) are nearly indistinguishable. The jets seem to be fully merged, or mixed, but an examination of the velocity vector plot of Figure 27 shows that the CRVP structures are still present. Based on the extent of the illuminated region, jet fluid is present very close to the tunnel floor, and penetrates vertically approximately four diameters into the crossflow.
5.6.2 Velocity Ratio $R = 1.0$

Motion of the jets in the cross-tunnel plane $x/D=1$ is shown in Figure 57. Figures 58 and 59 are similar images of the jet at $x/D=5$ and $x/D=8$ respectively. This intermediate jet case is similar to that of $R=1.5$. The CRVP of each jet is visible at $x/D=1$. At $x/D=5$, individual jets are easily discerned, and these seem to just reach the plane of symmetry between jets. A difference in this case is that the individual jets at $x/D=8$ are still clearly distinguishable, thereby indicating that lateral mixing is somewhat weaker.

5.6.3 Velocity Ratio $R = 0.5$

Motion of the jets in the cross-tunnel planes at $x/D=1$, 5, and 8 is shown in Figures 60, 61, and 62 respectively. The round shape of the CRVP structures is evident in the image at $x/D=1$, but the structures proper (e.g. swirls) are not. The extent of lateral spread at this downstream position is no more than one diameter. At $x/D=5$, the jets appear as blurred circles, slightly flattened on their lower side. They still do not penetrate the 2.0D thick upstream boundary layer. At $x/D=8$, vertical penetration does exceed 2.0D, but only slightly, which is in accordance with the observations of the LDV measurements. Adjacent jets seem to be merged, but only close to the floor where turbulence in the upstream boundary layer may have improved lateral mixing.

5.6.4 Jet Reynolds Number = 900

A sequence of five images is presented in Figure 63, and corresponds to the case of $R=0.5$ and $Re_{jet}=900$. The position of the cutting plane is $x/D=0.5$ — the downstream edge of the jet exit. The CRVP appears in these images, but with an interesting variation. On the left side of the jet, a secondary pair of vortices is visible. This structure disappears by the fourth frame, at which point the jet has a standard appearance. In the last frame, the jet seems to split in half, a trend which persists for five more frames (not shown). After this, a secondary pair of vortices materializes on the right side of the jet. The process continues indefinitely. For the cases of $Re_{jet}=4700$, there was evidence of the same, but with greater
frame-to-frame variation. This difference may be attributed to 1) higher turbulence levels in the jet, or 2) a smaller characteristic time scale caused by a higher convection speed.

These interesting structures, which endure for several frames, are too large to be considered turbulent fluctuations. Their time scale is on the order of five frames or 0.167 s. In comparison, the characteristic turbulent time scale of the system is approximated by dividing the jet exit diameter by the free stream convection speed of 2.2 m/s, and is found to be 0.006 s — a value approximately 30 times smaller than the time scale of the structures. Therefore, what is observed is best described as large-scale unsteady flow structures, possibly Görtler vortices associated with flow curvature.

5.7 LDV Results — Recovery Boiler

5.7.1 Case #1 — Primaries and Secondaries

This case is the one which corresponds to the full-scale cold flow run of the Kamloops recovery boiler. Figure 64 shows a series of contour plots of the mean vertical velocities normalized to the set bulk upward flow, \( W/W_{sb} \), at each of the three measurement levels. The plots are displayed such that levels 1, 2, and 3 are arranged from bottom to top. At the liquor gun level (i.e. level 1), there is evidence of a high velocity core near the back, left region of the boiler. Recirculation, as indicated by negative flow, roughly circumscribes this core, but only appears along the front and right walls because of the core's displaced center. The maximum normalized velocity is approximately 5.5, and the minimum, -2.0; flow at this level is highly non-uniform, as expected. The primaries and secondaries inject high-momentum fluid toward the boiler's center, where opposing jets collide and are redirected in the vertical direction to generate strong up flow. By continuity, regions of weak flow and/or down flow are inevitable. The core's offset position may be attributed to relatively strong flow through the starter burners on the front and right walls, in particular, the two closest to the corner. Combined, these two ports account for 23.6% of the total mass flux of secondary
injection, or 17.0% of the momentum flux. As a result, the penetration of these jets is relatively high, and their momentum shifts the position of the core.

At level 2, "core flow" is no longer apparent, but a region of strong up flow is clearly present at the left and back walls. It is possible that the core seen at the first level continues its trajectory away from the center until it finally encounters the boiler walls. A down flow region is still present, and is slightly weaker with a peak value of less than -1.0. It no longer circumscribes any form of core; in fact, it appears to be a weak reversed core itself, as one may see by the concentric distribution of negative velocity.

At level 3, the flow finally shows evidence of achieving uniformity. A recirculation zone is virtually non-existent, and the velocities in the plane are less than 3.0 times the bulk value, except for the back, leftmost position. There is obviously still a velocity gradient across the boiler, and considering the level's proximity to the bullnose, uniform flow is probably not achieved before the heat exchanger section.

The next set of contour plots shows normalized turbulence kinetic energy, \( \sqrt{k/W_{sb}} \), for each of the measurement levels (Figure 65). At the lowest of these levels (the bottom plot), a peak is evident near the center of the boiler, and has a value of 3.0. Throughout the cross-section, \( \sqrt{k/W_{sb}} \) is generally above 1.2, thus indicating the high levels of turbulence present in the lower region of the boiler. As the secondary jets — as well as those of the primary level — directly interact and mix in the region just below measurement level 1, large values of \( \sqrt{k/W_{sb}} \) are expected. The contour defining a value of 2.2 approximately delineates the core flow region seen in Figure 64. Outside the core, turbulence kinetic energy is lower. This may be explained in terms of the source of the turbulence, namely, the shear layer of each jet and the regions of high velocity gradients between interacting jets. In the boiler, the large array of primary and secondary jets generates turbulence, which in turn is convected toward the boiler center and finally upward with the core. Elsewhere in the flow field, velocity gradients are less than those found in the shear layer of a jet; therefore, turbulence is not as readily generated.
At the middle measurement level, turbulence kinetic energy is more uniformly distributed, with values of $\sqrt{k/W_{sb}}$ ranging from 0.2 to 1.9. Although no central core is evident at this level, there is still a correspondence between high turbulence kinetic energy and the strong up flow present in the back, left region of the boiler.

Measurement level 3 is characterized by a slightly more uniform distribution of turbulence kinetic energy, with values of $\sqrt{k/W_{sb}}$ ranging from 0.8 to 1.6. Evidently, as fluid moves upward through the boiler, the turbulence which was once dominant in the core region dissipates, and values of $\sqrt{k/W_{sb}}$ drop to the present levels.

In Figure 66, a more complete picture of the flow field is presented. The 3-D representation of the boiler shows the two components of velocity measured at the three levels of interest. The right half of Figure 66 shows three top views of the boiler, in which the horizontal velocity vectors are displayed. All velocities are normalized to $W_{sb}$. At the lowest level, flow along the right wall is moving toward the front. Along the left wall, fluid "fans out" from the center (i.e. $+U$ toward the front, $-U$ toward the back) as though the core region impacts the wall and spreads laterally. However, with no measurement of the third component $V$, this impacting motion is but a rational speculation.

At level 2, the patterns in $U$ are roughly the same as at level 1. Fanning occurs along the left wall, and $U$ is positive along the right wall. The central region of the boiler does not show any distinct trends.

At the upper measurement level, the flow apparently develops a clockwise swirl. This is possibly a result of the right-wall, front-side starter burner on the secondary injection level, which accounts for 17.1% of the mass flux, or 14.9% of the momentum flux, of the total secondary injection. This jet may impart swirl in the lower furnace, which reaches a higher level of stability farther up. A number of additional factors certainly contribute to the swirl. In fact, in the second flow case (section 5.7.2), for which the distribution of injection fluid is nearly uniform, a swirling motion is clearly evident at all measurement levels.
5.7.2 Case #2 — Primaries, Secondaries, and Tertiaries

The second test case consists of a more uniform distribution of flow and the addition of tertiary injection. In Figure 67, three contour plots of \( W/W_{sb} \) are shown, one for each of the measurement levels. In the bottom plot, which corresponds to level 1, there is evidence of a central core. Surrounding this core on the front and right walls is a recirculation region wherein the normalized velocity drops to -2.0. On the back and left walls however, there is only evidence of weaker upward flow, and not recirculation. Although primary and secondary injection is nearly uniform and symmetric about both horizontal axes, the mean vertical flow at level 1 is not. Why the mean flow field is skewed is not entirely understood. It has been shown that the case of opposing jets is not a stable configuration (Quick, 1993), and that the flow may fluctuate between two modes. Perhaps the boundary (inlet) conditions of the boiler model are such that a minor imbalance, such as a small surplus in flow from a group of primary injection ports, is sufficient to generate a larger imbalance, thereby causing one flow mode to dominate. There is also a prominent physical asymmetry in the boiler model — the sloped floor. This surface is angled at approximately 6°, with the low side at the back and the high side at the front. The floor's proximity to the primary injection level is certainly a factor in the development of the flow. In combination with minor port-to-port variations in mass flux, this may explain the mean flow field observed at level 1.

At level 2, no down flow is observed. The region of strongest up flow is located toward the front and left walls of the boiler, and the maximum value of \( W/W_{sb} \) is approximately 2.5. Since the rate of tertiary injection from the back is 25% greater than that from the front (five ports vs. four ports), stronger up flow toward the front wall is expected. The fact that the core is located on the left of the boiler may be attributed to the trend observed at level 1, which persists to the current level.

Up flow at level 3 is strongest at the front wall and weakest toward the back, left corner of the boiler. The range in vertical velocities is about the same as at level 2, with the minimum and maximum values of \( W/W_{sb} \) equal to 0.0 and 2.5 respectively. Flow
uniformity is roughly the same as at level 2, although here, one observes higher velocity gradients toward the front, left corner. The core seems to have continued its trajectory toward the front wall, which is not unlike the up flow in case #1, where the core encounters the left wall.

Contours of turbulence kinetic energy normalized to the bulk vertical velocity ($\sqrt{k/W_{sb}}$) are shown in Figure 68, for each of the three measurement levels. At the lowest level, the peak in $\sqrt{k/W_{sb}}$ roughly coincides with the maximum velocity in the central core (level 1, Figure 67) and is equal to 3.6. Again, this is probably due to the convective transport of turbulence from the opposing primary and secondary jets to the mean flow some distance above. Far from the core, the turbulence kinetic energy generally drops, except toward the right wall, where a secondary peak in $\sqrt{k/W_{sb}}$ indicates elevated turbulence in the recirculation zone.

At the middle measurement level, turbulence evidently decays, with a maximum value of $\sqrt{k/W_{sb}}$ equal to 2.4. The trends in $\sqrt{k/W_{sb}}$ are remarkably similar to the trends in $W/W_{sb}$ at the same level (Figure 67), which further suggests that the convective transport of strong jet turbulence is a dominant mechanism in the boiler.

Turbulence kinetic energy at the level 3 is nearly uniform, and values of $\sqrt{k/W_{sb}}$ are approximately equal to 1.0 across the boiler. It would seem that the injection of tertiary fluid aids in the distribution of turbulence. An explanation of this uniformity lies in the flow field generated by the tertiary jets. This is the one location in the boiler where injection ports on opposite walls are interlaced. In contrast to opposed jets, which interact head-on and induce flow instability, interlaced jets maintain their individual structure for a longer trajectory, and are therefore able to convect turbulence toward the far side of the boiler. In addition, the total region of shear between interlaced jets is much greater and better spatially distributed than in the case of opposed jets; therefore, turbulence caused by jet/jet interaction is well distributed.
Figure 69 shows a more complete picture of the flow field, and includes the measured $U$-component of velocity. The plots are arranged similarly to Figure 66, and all velocities are normalized to $W_{sb}$. A first inspection of the flow at each measurement level reveals a counter-clockwise swirl. At level 1, the flow in the horizontal direction is roughly symmetric about the boiler center, with positive $U$ on the left half and negative $U$ on the right. The magnitude of $U/W_{sb}$ is as high as 4.0 in places. One must keep in mind the regions of up flow and down flow, and not misinterpret the pattern in the top view vector plot as a rising vortex; the flow along the right wall is downward and toward the back.

At levels 2 and 3, the swirl motion is still very clear, its intensity decreasing with elevation. Although the tertiary jets appear to alter the distribution of turbulence kinetic energy (discussed above), they do not seem to destroy the patterns in $U$ seen at level 1. Perhaps the swirl in the lower furnace is strong enough that the flow has considerable stability; therefore, the injection of tertiary fluid is not sufficient to generate an imbalance.

### 5.7.3 Verification of Bulk Flows

As a first order verification of the LDV measurements, the total flow through a horizontal cross-section was calculated by summing the individual measured flows through each cell in the 6×6 grid (section 4.4). A volume flow rate was calculated for each of the measurement levels in the two test cases. Table 6 below summarizes the findings.

<table>
<thead>
<tr>
<th>Location</th>
<th>Set bulk flow across the level [L/min]</th>
<th>Measured bulk flow [L/min]</th>
<th>Percent error in measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>level 1, case #1</td>
<td>570</td>
<td>754</td>
<td>+32%</td>
</tr>
<tr>
<td>level 2, case #1</td>
<td>570</td>
<td>641</td>
<td>+12</td>
</tr>
<tr>
<td>level 3, case #1</td>
<td>570</td>
<td>656</td>
<td>+15</td>
</tr>
<tr>
<td>level 1, case #2</td>
<td>525</td>
<td>989</td>
<td>+88</td>
</tr>
<tr>
<td>level 2, case #2</td>
<td>788</td>
<td>841</td>
<td>+20</td>
</tr>
<tr>
<td>level 3, case #2</td>
<td>788</td>
<td>948</td>
<td>+7</td>
</tr>
</tbody>
</table>

Table 6: Measured vs. set bulk volume flow rate
The flow rates obtained from the LDV measurements are seen to be consistently high, with an alarming 88% error at level 1 in case #2. The general disagreement may be attributed to several factors, as listed below.

1) The measurement grid is rather coarse and may not well represent some of the lower velocity regions.

2) Turbulence levels, in particular at level 1, are high, and may lead to significant errors in flow statistics. Correspondingly, multiple realizations may not have sufficiently countered the turbulence-induced velocity bias.

3) Operation of the LDV data acquisition equipment with less than extreme care may have lead to a systematic filtering of signals corresponding to low velocity measurements.

It would therefore be wise to consider the results of the lowest measurement level with certain caution. At higher elevations, the error is not as significant, and probably has little affect on the information retrieved from the data with respect to the observed trends and large-scale patterns in the flow field.

5.8 PIV Results — Recovery Boiler

5.8.1 Case #1 — Primaries and Secondaries

One 40 second segment of video footage is analyzed for this case — that corresponding to a vertically-oriented plane midway between the left and right walls at the level of the bullnose. In Figure 70, a vector plot of the $U$- and $W$-components of velocity is shown, as viewed from the left side of the boiler. The plot represents the average flow field over 40 seconds. Flow is very slow-moving near the front side, and upward on the back, with the bullnosed redirecting fluid toward the boiler center. The maximum velocities in this back-central region reach approximately 0.8 m/s or 1.4 times the set bulk velocity. Recirculation is evident near the front wall in the lower region of the image. It is interesting that this would
occur so far up the boiler, for by this point, the flow should be reaching some form of uniformity. However, a re-examination of the $W/W_s$ contour plots of Figure 64 shows that recirculation is present even at level 3 where the fluid velocity drops slightly below zero near the front wall. Therefore, what is seen in Figure 70 is a continuation of the trends from lower elevations. Note that the upper LDV measurement level is approximately 0.7 boiler widths below the base of the bullnose, and therefore lies slightly beyond the lower border of Figure 70.

5.8.2 Case #2 — Primaries, Secondaries, and Tertiaries; without bed

Two regions are analyzed for this test case. The first is located at the level of the bullnose; the second, above the tertiaries. Figure 71 shows a 40 second average of the normalized velocities in the 2-D region about the bullnose. As in Figure 70, the view is from the left side, but here the plane is located 0.25 boiler widths from the left (facing) wall. As compared to case #1, the flow patterns are roughly opposite. Velocity is up along the front wall, and has a maximum magnitude of approximately 0.11 m/s, or 1.4 times the set bulk velocity. Flow is much weaker toward the back, but there is no evidence of recirculation. Again, the flow field seems to be a continuation of the trends from lower levels. Recall the contour plots of Figure 67, in which recirculation virtually disappears by level 2, and flow is fairly uniform at level 3 with the exception of stronger up flow along the front wall. The same is observed in the lower region of Figure 71.

The second region of interest is bordered on the bottom by the tertiary injection ports and spans vertically approximately 0.9 boiler widths. The plane is located 0.25 boiler widths from the left wall. Figure 72 shows a 40 second average of the velocities in this plane. At this level, the flow is characterized by regions of recirculation and moderate velocity gradients. As the tertiary jets are located just below the region of interest, the dynamics of the flow are fairly complicated and are not easily explained. A second set of vector plots, shown in Figures 73(a) through (e), is somewhat more revealing. The view is
the same of that of Figure 72, but each plot corresponds to the average motion over a five second span. Specifically, the sequence of figures is as listed in Table 7 below.

<table>
<thead>
<tr>
<th>Figure</th>
<th>Averaging time span [s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Figure 73(a)</td>
<td>0 - 5</td>
</tr>
<tr>
<td>Figure 73(b)</td>
<td>5 - 10</td>
</tr>
<tr>
<td>Figure 73(c)</td>
<td>10 - 15</td>
</tr>
<tr>
<td>Figure 73(d)</td>
<td>15 - 20</td>
</tr>
<tr>
<td>Figure 73(e)</td>
<td>20 - 25</td>
</tr>
<tr>
<td>Figure 73(f)</td>
<td>25 - 30</td>
</tr>
</tbody>
</table>

Table 7: Sequence of figures for 5 second averages

In Figure 73(a), a large region of counter-clockwise recirculation is seen to dominate the flow. Relatively strong downward velocities along the back wall are present, and up flow is prominent throughout the central region. Over Figures 73(b) and 73(c), the original recirculation zone disappears, and a clockwise vortex becomes perceptible near the front wall, in the lower region of the plot. In Figure 73(d), negative velocities are present toward the upper part of the back wall, and these increase in magnitude over Figures 73(e) and 73(f). The last two figures show similarities to the very first, with a counter-clockwise recirculation region dominating the flow. In addition, the clockwise vortex reappears near the front wall. It is apparent from these plots that the flow just above the level of tertiary injection is highly unsteady. Velocity reversals are common, and large-scale flow patterns change with time.

5.8.3 Case #3 — Primaries, Secondaries, and Tertiaries; with bed

This section discusses data from a repeat of case #2, but with an arbitrary bed shape positioned on the boiler floor. Figure 74 shows a vector plot of the velocities normalized to $W_{sb}$ in a measurement plane located 0.25 boiler widths from the left wall. Like Figure 72, the plot’s lower border corresponds to the level of tertiary injection, and the velocities represent the average fluid motion over 40 seconds. The average flow field differs significantly from that of case #2. Up flow is strongest in the central region, and a zone of recirculation appears near the front wall. The maximum observed velocities are comparable to
those in Figure 72, but occur elsewhere. Based on the observations of cases #2 and #3, the addition of the bed shape has a significant effect on the mean flow field, as expected. Flow in the lower furnace, particularly at the primary injection level, is undoubtedly altered by the bed. In case #2, with no bed, interaction between jets is considerable because of the opposed configuration of primary injection ports. In case #3, with the bed in place, primary jets are immediately redirected upward at an angle of approximately 45°. A core of up flow is probably still generated, but because the jets are not directly opposed, the location and intensity of the core may be more constant. At the secondary and tertiary injection levels, the jet/crossflow interactions are certainly dependent on the existing core, and the flow develops into what is observed in Figure 74; mean velocity trends are unique to this case.

Figures 75(a) through 75(f) represent a sequence of vector plots showing the normalized velocities in the current measurement plane. The six plots are similar to that of Figure 74, but represent consecutive 5 second averages of the fluid motion. Interestingly, the fluid motion does not appear to change much over the six time periods. As in the 40 second average, Figures 75(a) through 75(f) all indicate strong up flow in the central region and recirculation near the front, and the velocity magnitudes are fairly constant over time. The center of the clockwise recirculation zone shifts very little from average to average. Figures 75(a) and 75(e) do indicate a slight variation in the upper region of the measurement plane, where $U$-velocities are notably positive, as though the recirculation zone begins lower in the boiler. The presence of the bed apparently leads to a much more steady flow condition in the region investigated. The reason for this possibly lies in the altered trajectory of the primary injection fluid, which eliminates the instabilities inherent to an opposed jet configuration.
Figure 19: Boundary layer profiles of $U/V_g$ and $\sqrt{k}/V_g$

Figure 20: Jet exit condition without crossflow. Left: $W/V_{jet}$, Right: $\sqrt{k}/V_{jet}$
Figure 21: Contours of vertical velocity at jet exit, $W/V_{\text{jet}}$

Figure 22: Contours of turbulence kinetic energy at jet exit, $\sqrt{k}/V_{\text{jet}}$
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Figure 28: Vector plots of velocities in xz-planes, \( V/V_{jet} \) (R=1.0)
Figure 29: Contours of $U/V_{jet}$ in yz-planes (R=1.0)

Figure 30: Vector plots of velocities in yz-planes, $V/V_{jet}$ (R=1.0)
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Figure 32: Contours of $U/V_{jet}$ in yz-planes (R=0.5)

Figure 33: Vector plots of velocities in yz-planes, $V/V_{jet}$ (R=0.5)
Figure 34: Contours of $\sqrt{k/V_{jet}}$ in yz-planes (R=1.5)

Figure 35: Contours of $\sqrt{k/V_{jet}}$ in yz-planes (R=1.0)
Figure 36: Contours of $\sqrt{k/V_{\text{jet}}}$ in yz-planes (R=0.5)

Figure 37: Contours of a normal stress ratio in yz-planes, $(v'-u')/u'$ (R=1.5)
Figure 38: Contours of a normal stress ratio in yz-planes, \((w' - u')/u'\) (R=1.5)

Figure 39: Shear stress \(\overline{w}/V_{jet}^2\) in yz-planes (R=1.5)
Figure 40: Shear stress $\overline{uw}/V_{jet}^2$ in $yz$-planes (R=1.0)

Figure 41: Shear stress $\overline{uw}/V_{jet}^2$ in $yz$-planes (R=0.5)
Figure 42: Shear stress $\bar{u}v/V_{jet}^2$ in $yz$-planes ($R=1.5$)

Figure 43: Shear stress $\bar{u}v/V_{jet}^2$ in $yz$-planes ($R=1.0$)
Figure 44: Shear stress $\frac{\bar{u}v}{V_{jet}^2}$ in yz-planes (R=0.5)

Figure 45: Shear stress $\frac{\bar{w}w}{V_{jet}^2}$ in yz-planes (R=1.5)
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Figure 47: Shear stress $\overline{vw}/V_{jet}^2$ in yz-planes (R=0.5)
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Figure 51: Effect of corrections for angular misalignment. O uncorrected values, Δ corrected values (x/D=8, y/D=-0.5, R=1.5)
Figure 52: Uncertainty in flow statistics due to misalignment. Δ corrected values, bars show ±3.0 standard deviations (x/D=1, y/D=-0.5, R=1.0)

Figure 53: Uncertainty in flow statistics due to misalignment. Δ corrected values, bars show ±3.0 standard deviations (x/D=8, y/D=-0.5, R=1.0)
Figure 54: Image of jets in yz-plane at x/D=1. Left: 2 second "exposure", Right: single frame (R=1.5). Scale is denoted by 1.0D marker.

Figure 55: Image of jets in yz-plane at x/D=5. Left: 2 second "exposure", Right: single frame (R=1.5). Same scale as Figure 54.

Figure 56: Image of jets in yz-plane at x/D=8. Left: 2 second "exposure", Right: single frame (R=1.5). Same scale as Figure 54.
Figure 57: Image of jets in yz-plane at x/D=1. Left: 2 second "exposure", Right: single frame (R=1.0). Same scale as Figure 54.

Figure 58: Image of jets in yz-plane at x/D=5. Left: 2 second "exposure", Right: single frame (R=1.0). Same scale as Figure 54.

Figure 59: Image of jets in yz-plane at x/D=8. Left: 2 second "exposure", Right: single frame (R=1.0). Same scale as Figure 54.
Figure 60: Image of jets in yz-plane at x/D=1. Left: 2 second "exposure", Right: single frame (R=0.5). Same scale as Figure 54.

Figure 61: Image of jets in yz-plane at x/D=5. Left: 2 second "exposure", Right: single frame (R=0.5). Same scale as Figure 54.

Figure 62: Image of jets in yz-plane at x/D=8. Left: 2 second "exposure", Right: single frame (R=0.5). Same scale as Figure 54.

Figure 63: Image sequence of jet at x/D=0.5, time increasing by 1/30 s for each frame from left to right (Re=900, R=0.5)
Figure 64: Contour plots of $W/W_{sh}$. Top: level 3, middle: level 2, bottom: level 1.
Figure 65: Contour plots of $\sqrt{k/W_\phi}$. Top: level 3, middle: level 2, bottom: level 1
Figure 66: Three-dimensional view of two vector components ($V/W_{sb}$), and vector plots of $U/W_{sb}$.
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Figure 69: Three-dimensional view of two vector components ($V/W_\theta$), and vector plots of $U/W_\theta$. 
Figure 70: Vector plot of velocities in PIV measurement plane at level of bullnose. Case #1, 40 second average, $V/W_{sb}$

Figure 71: Vector plot of velocities in PIV measurement plane at level of bullnose. Case #2, 40 second average, $V/W_{sb}$
Figure 72: Vector plot of velocities in region above tertiary injection. Case #2, y=104 mm, 40 second average, \( \frac{V}{W_{sh}} \).
Figure 73: Sequence of six vector plots of velocities in region above tertiary injection. Case #2, consecutive 5 second averages, $V/W_{sb}$
Figure 74: Vector plot of velocities in region above tertiary injection. Case #3, y=104 mm, 40 second average, $V/W_{sh}$. 
Figure 75: Sequence of six vector plots of velocities in region above tertiary injection. Case #3, consecutive 5 second averages, $V/W_b$
CHAPTER 6
CONCLUSIONS AND RECOMMENDATIONS

An investigation was conducted to study the complex flow in the region about a row of six square jets issuing into a uniform crossflow, and to examine the characteristics of the flow in a Kraft recovery boiler. In the first set of experiments, jet-to-crossflow velocity ratios (R) between 0.5 and 1.5 were considered, to cover a range pertinent to film cooling of gas turbine blades by discrete hole injection. Measurements of the mean velocities and six flow stresses were acquired by three-component coincidence-mode laser Doppler velocimetry, and were complemented by a set of flow visualization experiments. In the recovery boiler experiments, a 1/28 scale model was used to represent the flow conditions in the #2 boiler in Kamloops, British Columbia. Two components of velocity and two normal stresses were acquired by LDV, and large-scale, low-frequency changes in the flow were captured by particle image velocimetry. The findings are summarized below.

6.1 Wind Tunnel Experiments
The vertical velocity across the jet exit plane was non-uniform, particularly at low values of R, as expected. The upstream third of the exit plane was characterized by high turbulence kinetic energy, possibly generated by intermittent intrusion of cross-stream air into the jet duct.

In the near field, velocity gradients were fairly large, which led to high levels of turbulence kinetic energy. A region of backflow, observed near the tunnel floor on the lee side of the jet, increased in size with R, and was considered to represent 3-D separation. At a position one diameter downstream of injection, formation of a counter-rotating vortex pair was already evident. There was little large-scale organization of the shear stresses in this region. Detailed information here would require the use of a finer measurement grid.
Farther downstream (ie. beyond \( x/D=1 \)), a streamwise velocity deficit appeared in the jet center-plane, but decreased in magnitude with downstream position. The formation observed was not unlike that of a wake, and spread laterally and vertically as it continued downstream. Turbulence kinetic energy levels were typically high in this wake, as well as in the region of shear on the top side — or upstream side — of the jet. Up to \( x/D=8 \), the counter-rotating vortex pairs were very distinct, except in the case of \( R=0.5 \), where turbulence in the boundary layer hastened the destruction of these large-scale structures.

Shear stresses exhibited trends which provided insight into the nature of turbulence production and mixing for this particular flow configuration. An examination of individual normal stresses revealed that the flow was notably non-isotropic throughout the flow field.

In the case of \( R=0.5 \), flow statistics varied very little beyond the elevation \( z/D=2.0 \), which indicated that the jets did not penetrate the 2.0D thick free-stream boundary layer. This was confirmed by flow visualization video footage, in which smoke from the jets was nowhere seen to rise above \( z/D=2.0 \). Flow visualization also showed that the mixing of jets with one another and with crossflow air improved dramatically with \( R \). In the case of \( Re=900 \), an unsteady, low frequency, asymmetric vortex pair was observed, and may have represented instability arising from streamline curvature. It was not captured in any way by the measurements.

The measurements in the present set of experiments provided information about the general flow field in the region about a row of jets; however, certain question were left unanswered and new questions were raised. For example, how large is the separation region on the lee-side of the jet, and what is its influence on film cooling effectiveness? It would be useful to further investigate the cases of the present experiments — in particular, \( R=0.5 \) and \( R=1.0 \) — while devoting special attention to the near-field of the jets and to the near-wall region. A further step would be to measure the distribution of heat transfer rates from the plate to determine local film cooling characteristics.
Secondly, with the development of better turbulence models, and with the phenomenal increases in computer power in this age, the field of computational fluid dynamics (CFD) is approaching a level at which numerical simulations can be applied as a practical tool. The data acquired in the present set of experiments provides a useful milestone by which the progress of CFD may be assessed. It is therefore recommended that high-accuracy data, such as that acquired here, be used as a validation tool, and that CFD models be refined until they are able to satisfactorily duplicate these experimental results.

6.2 Recovery Boiler Experiments

Mean flow in the Kamloops recovery boiler model was seen to be non-uniform and at times, unsteady. Turbulence was generally very high in the lower regions of the boiler, but dissipated as it was convected upward.

In the first test case, injection through the primaries and secondaries was set to represent a cold flow experiment performed on the actual boiler. In the lower furnace, particularly at the liquor gun level, local velocities climbed to several times the set bulk velocity, and down flow, or recirculation, was significant. There existed a core of up flow, but it was shifted from the boiler center toward the left wall. At higher elevations the trends seen in the lower furnace were still evident, but less intense. The core region became attached to the left wall, with recirculation down the right. Even at the highest measurement level, recirculation was apparent. Turbulence kinetic energy dropped from a maximum of $3.0W_{ab}$ at the liquor gun level to a nearly uniform level of $1.0W_{ab}$ near the bullnose. The slanted boiler floor and the uneven distribution of fluid through the secondaries was considered to be a large factor in the non-uniform flow characteristics observed.

A second set of measurement was acquired for a distribution of flows in which one third of the total mass flux originated from each of the three injection levels, and flow through the ports on each of these levels was uniform. The mean flow field however, again showed characteristics of up flow on one side and recirculation on the other. LDV measurements
showed that a vertically rising core was approximately coincident with the boiler center at the liquour gun level; however, recirculation was apparent only near the right and front walls. The maximum vertical velocity was $5.5W_{sb}$ and the minimum, $-2.0W_{sb}$. In the one horizontal direction probed, flow was strong and positive on the left half of the boiler and negative on the right, as though a swirling motion dominated the flow in the horizontal plane. At the middle measurement level, the swirling trend continued, but the original core seemed to have been destroyed by the nine high-mass-flux tertiaries. As the ports at this level were numbered five on the back wall and four on the front, a new region of strong up flow was generated near the front wall. Near the bullnose, both the new core and the swirl from lower elevations persisted. Although the mean flows in this case were significantly different from those of case #1, the turbulence levels were comparable at corresponding elevations; for example, uniform and decayed turbulence ($\sqrt{k/W_{sb}} = 1.0$) was observed in the upper furnace for both cases.

PIV was used to compare the mean and changing flow fields in the region above the tertiaries of one case which included a smelt bed with one which did not. The uniform flows of case #2 were used. Without the bed, a 40 second average of the fluid velocities showed that the mean flow was up and toward the front, and there was recirculation near the upper part of the back wall. With the bed, up flow was dominant in the center and back regions and there was recirculation along the front wall. The mean flow alone however, did not reveal anything of great value, but a sequence of 5 second averages of the fluid velocities did. In the case without a bed, the region of strongest up flow shifted in direction and the recirculation zone disappeared and reappeared. It was clear that were large-scale structures fluctuating at a low frequency. In contrast, in the case with a bed, the mean flow varied very little between 5 second averages. There was a change in direction in the upper part of the measurement window, but it was more subtle than the fluctuations noted in the previous case. As the presence of the bed was the only difference between the two cases, it was deemed to be a significant factor in the development of the flows. With the bed in position, the primary jets were no longer opposed, but were redirected upward to form an apparently steady core.
Finally, a general recommendation regarding the direction of future recovery boiler research is offered. It has been shown that the arrangement of opposed jets may lead to unsteady flow conditions — in this study, flow conditions which are considered sensitive to small changes in the input flow rates. In a Kraft recovery boiler, the mass flux of combustion air is not controlled with research-level accuracy; therefore, it is possible that boiler performance suffers from the adverse effects of minor imbalances. There seems to be little purpose in modelling and computing flows which are strongly dependent on unrealizable input accuracy. In light of this, future research should be directed toward the study of steady flows, so that predictable input conditions leading to consistently efficient operation may be recommended.
REFERENCES


Pratt and Whitney Canada, 1993, private communication.


APPENDIX A

The data from the wind tunnel experiments is available on the enclosed diskette. Included are: mean velocities, normal stresses, and shear stresses, as determined by the inverse-velocity-weighting data analysis technique. The table below summarizes the contents of the diskette.

<table>
<thead>
<tr>
<th>Filename</th>
<th>Size [kb]</th>
<th>Contents</th>
</tr>
</thead>
<tbody>
<tr>
<td>READ .ME</td>
<td>3002</td>
<td>• an explanation of how the data is organized in the *.DAT files</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• an explanation of the coordinate system used in the wind tunnel experiments</td>
</tr>
<tr>
<td>JETSR15 .DAT</td>
<td>44661</td>
<td>• data for the test case of R=1.5</td>
</tr>
<tr>
<td>JETSR10 .DAT</td>
<td>42337</td>
<td>• data for the test case of R=1.0</td>
</tr>
<tr>
<td>JETSR05 .DAT</td>
<td>42341</td>
<td>• data for the test case of R=0.5</td>
</tr>
<tr>
<td>EXITR15 .DAT</td>
<td>5187</td>
<td>• data in the plane of the jet exit for the test case of R=1.5</td>
</tr>
<tr>
<td>EXITR10 .DAT</td>
<td>5187</td>
<td>• data in the plane of the jet exit for the test case of R=1.0</td>
</tr>
<tr>
<td>EXITR05 .DAT</td>
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<td>• data in the plane of the jet exit for the test case of R=0.5</td>
</tr>
<tr>
<td>EXITNOCF .DAT</td>
<td>5187</td>
<td>• data in the plane of the jet exit when no crossflow was present</td>
</tr>
</tbody>
</table>

Table A.1: Contents of data diskette