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MEASUREMENT OF HEAT AND MOMENTUM EDDY DIFFUSIVITIES IN RECIRCULATING LMFBR OUTLET PLENUM FLOWS

by
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June, 1978

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ABSTRACT

MEASUREMENT OF HEAT AND MOMENTUM EDDY DIFFUSIVITIES
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An optical technique has been developed for the measurement of the eddy diffusivity of heat in a transparent flowing medium. The method uses a combination of two established measurement tools: a Mach-Zehnder interferometer for the monitoring of turbulently fluctuating temperature and a Laser Doppler Anemometer (LDA) for the measurement of turbulent velocity fluctuations. The technique is applied to the investigation of flow fields characteristic of the LMFBR outlet plenum. The study is accomplished using air as the working fluid in a small scale Plexiglas test section. Lows are introduced into both the 1/15 scale FFTF outlet plenum and the 3/80 scale CRBR geometry plenum at inlet Reynolds numbers of 22,000.

Measurements of the eddy diffusivity of heat and the eddy diffusivity of momentum are performed at a total of 11 measurement stations. Significant differences of the turbulence parameters are found between the two geometries, and the higher chimney structure of the CRBR case is found to be the major cause of the distinction. Spectral intensity studies of the fluctuating electronic analog signals of velocity and temperature are also performed. Error analysis of the overall technique indicates an experimental error of 10% in the determination of the eddy diffusivity of heat and 6% in the evaluation of turbulent momentum viscosity. In general it is seen that the turbulence in the cases observed is not isotropic, and use of isotropic turbulent heat and momentum diffusivities in transport modelling would not be a valid procedure.

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NOMENCLATURE

C_p	Specific heat ($\text{kJ/kg}^\circ\text{C}$)
F	Computational function (dimensions as specified)
Re	Reynolds number (dimensionless)
T	Temperature ($^\circ\text{C}$)
T'	Temporal fluctuation of temperature ($^\circ\text{C}$)
U	Horizontal velocity component (m/sec)
V	Vertical velocity component (m/sec)
d_l	Laser beam diameter (mm)
d_m	LDA measuring volume diameter (mm)
f_D	Doppler frequency (Hz)
$\bar{l}$	Characteristic turbulence length (mm)
l_m	LDA measuring volume length (mm)
m	Order of interference (integer)
n	Index of refraction (dimensionless)
t	Time (sec)
u'	Temporal fluctuation of horizontal velocity component (m/sec)
v'	Temporal fluctuation of vertical velocity component (m/sec)
$\underline{x}$	Position vector (m)
x_i	Dependent computational variable (dimensions as specified)
x_j	j th coordinate of position vector (m)
α	Thermal diffusivity (m^2/sec)
$\epsilon_{H,i,j}$	Eddy diffusivity of heat, second rank tensor, (m^2/sec)
$\epsilon_{M,i,j}$	Eddy diffusivity of momentum, second rank tensor (m^2/sec)
θ	Angle ($^\circ$)
λ	Laser wavelength ($6.328 \times 10^{-7} \text{m}$)

ν	Kinematic viscosity (m^2/sec)
ρ	Density (kg/m^3)
τ	Resolution time (sec)
ϕ	Angle of LDA beam intersection ($^\circ$)
ω	Frequency (Hz)
$-$	Mean value
$< \quad >$	Flow ensemble average

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Chapter 1

INTRODUCTION

1.1 Definition and Scope of Work1.1.1 Problem Proposition

The turbulent interchange of heat and momentum which occurs in the outlet plenum of a nuclear reactor where the exiting coolant mixes before flowing out of the vessel determines the thermal and mechanical stresses which the structural members in that region must endure. Therefore it is clear that accurate understanding and predictive ability regarding these phenomena are essential for a sound engineering design. The physical phenomena driving the momentum and energy exchanges are molecular processes and so-called "eddy" processes. The molecular mechanisms are well understood, and accurate predictive analyses of their characteristics are available. Unfortunately, in the highly turbulent regime of a nuclear reactor coolant flow, the mixing modes are dominated by the less understood eddy exchange processes. The flow parameters which embody the eddy effects are the eddy diffusivity of heat, ϵ_H , and the eddy diffusivity of momentum, ϵ_M . The eddy diffusivity of heat in particular determines how efficiently thermal mixing progresses and hence determines the thermal gradients of the flow which in turn determine the character of the thermal stress field

in the structural components. The thermal stresses are of concern during normal operating conditions but are crucially important in predicting the behavior and structural reliability of components during thermal transient situations.

Mathematically, the eddy diffusivity of heat is defined as

$$\epsilon_{H_{i,j}} = \langle T(\underline{x},t) V_i(\underline{x},t) \rangle / \partial T(\underline{x},t) / \partial x_j, \quad (1.1)$$

where $\langle \rangle$ denotes a flow ensemble average. This expression originates from the conservation of energy equation. As can be observed from the defining equation, accurate evaluation of the parameter requires a true mapping of both the time-varying temperature and velocity fields and their cross correlation product. The intrinsic difficulty in attaining an accurate monitoring of these properties arises from the rapid temporal fluctuations present in the turbulence and the inability of most measurement devices to follow these changes.

1.1.2 Method of Investigation

The purpose of this investigation is to measure directly the velocity and temperature fluctuations in the recirculating flow regime which is characteristic of flow in the outlet plena of liquid metal fast breeder reactors (LMFBR's). The modelling scheme employed uses a two-dimensional air flow in a Plexiglas scale model test cell coupled to an optical measurement system. The scope of the work includes

measurements in both the steady state and flow upset conditions. The optical measurement system is basically the combination of two proven experimental tools, one sensitive to temperature fluctuations and the other capable of detecting temporal velocity components.

Optical systems have many advantages over mechanical probe temperature sensors and velocimeters. The foremost benefit is the non-interference quality of the optical devices. All other measuring sensors need to be physically placed in the flow field in order to operate. This intrusion causes local flow perturbations in the immediate neighborhood of the probe which are subsequently measured even though they are not indigenous characteristics of the flow. In an effort to minimize these interference effects, mechanical probes are made as small as possible and hence experience limited structural integrity especially in high stress situations. Furthermore, not until recently have temperature probes been developed which can begin to respond faithfully to the high frequency nature of the mixing.

The system utilized in this work has two major subdivisions. The temperature measurements are carried out using a Mach-Zehnder interferometer [1]. The arrangement is similar to that developed by Bennett and Golay [2]. The instrument defines a measuring volume of 1.25 mm^3 and has been shown to be able to follow signals as rapid as 8 kHz. It is important to note as was pointed out by Bennett and Golay that the

system time response is a function of the photodetector employed and could therefore be modified in order to enhance frequency response. The output of the temperature monitoring system is a DC analog voltage which is nearly linearly proportional to the temperature fluctuations.

The velocity measuring apparatus is a Laser Doppler Anemometer (LDA). The basic operating principle of the instrument is the measurement of the Doppler frequency shift of light which has been scattered from particles entrained in the flow. Therefore, if it can be assumed that the particles are moving with the flow, the measured particle velocity will be identical to the fluid velocity. The laser anemometer also has the qualities of non-intrusion into the flow and can follow the velocity fluctuations accurately. The measuring volume defined by the LDA is roughly 0.5 mm^3 . The correlation measurements necessary to evaluate the eddy diffusivities are derived by coupling these systems in two ways. First, the two "light probes" are aligned such that they define nearly the same measurement zone. (It is noted previously that the interferometric system defines a region nearly three times as large as that for the velocity measurement system.) The optical alignment provides simultaneous monitoring of the two fluctuating fields. Secondly, the output DC analogs of the two systems are combined using a turbulence processor which is a small analog computer capable of performing simple arithmetic operations on high

frequency input signals.

The data presented illustrate the information acquisition capability of the system and demonstrate methods by which these experimental observations can be translated into a better understanding of turbulent mixing and more accurate calculative methods in predicting the associated flow parameters. The obvious shortcoming of this technique is its inapplicability to direct use when studying a liquid metal or any other opaque fluid. However, the information acquired using transparent fluid modelling as that employed in this endeavor provides useful insight into the actual situation. Furthermore, this system does possess direct applicability when applied to the study of transparent reactor coolants such as water or gas.

1.2 Previous Work

Measurement of heat transfer parameters using both optical and other means has been extensively performed and presented in the literature and a brief survey of some of the more relevant investigations is now presented. Most directly related to this work is the previously referenced investigation of Bennett and Golay. Their efforts led to the successful application of an interferometric temperature measurement technique to the study of temperature fields characteristic of LMFBR outlet plenum geometries. Also closely tied to this work is that of Chen and Golay [3]

who employed an LDA system coupled with numerical analysis in order to improve turbulence models used in analyzing LMFBR outlet plenum flows. Chen used a Plexiglas test cell and a water flow in the study and the work was confined to isothermal flow situations. Also of note are the investigations of Novendstern, Ruse and Budden [4] and Lorenz, Howarth and Novendstern [5] who employed numerical methods and conventional mechanical probe sensors in the evaluation of flow mixing characteristics during steady state and transient (particularly reactor trip) situations. For the experimental modelling they employed a three-dimensional outlet plenum scale model and a water flow.

Methods of measuring ϵ_H of liquid metals have been limited largely to techniques in which values of the parameter are inferred from the measurement of more attainable parameters and other known physical properties. The foremost weakness in this sort of investigative scheme is the initial abandonment of measuring directly the true velocity temperature correlation term $\langle V(\underline{x},t)T(\underline{x},t) \rangle$ which necessarily leads to a degree of approximation and further loses contact with the actual physical processes of interest. In place of directly determining the multiplicative correlation term, the following identity is employed:

$$q(\underline{x})/\rho C_p = (\alpha + \epsilon_H)(-\partial T(\underline{x})/\partial x), \quad (1.2)$$

which when rearranged yields:

$$\epsilon_H = -[\alpha + \frac{q(\underline{x})}{\rho C_p} (\frac{\partial T(\underline{x})}{\partial x})]. \quad (1.3)$$

As can be seen from Eq. (1.3), the parameters needed to infer a value for ϵ_H are the heat flux as a function of position, thermal molecular diffusivity and an exact map of the mean temperature field in the flow in order to calculate the thermal gradient. The first requirement restricts such schemes to simple geometrical configurations while an accurate value for α demands an exact knowledge of the fluid's state properties as a function of both time and position. Such measurements have been performed for both circular ducts using a sodium flow [6] and mercury in an annular flow [7]. In both of these efforts, the proper monitoring of the temperature field and the maintenance of a uniform heat source proved to be formidable tasks.

Monitoring liquid metal flows especially when high frequency turbulence parameters are to be measured is a difficult problem. The major points of difficulty are the competing demands on a probe to provide both an accurate high frequency response (which infers small physical size) and the considerable structural integrity in the extremely corrosive environment characteristic of liquid metals. The most reliable instruments in the present state of the art employ stainless steel thermocouples for temperature measurements and electromagnetic flowmeters [8] for velocity studies. Both

of these types of instrument have very limited (low) frequency response and are most accurate when time-averaged quantities are desired. A promising approach in the measurement of temperature variations in liquid metals is the use of electrical parameter models which can relate local variations in electrical conductivity to thermal fluctuations [9].

When alternative fluids are employed a degree of approximation is introduced but a great advantage is gained in the improved instrumentation and larger available data base. The employment of interferometry in the investigation of thermal hydraulic phenomena as well as LDA type systems are well established and documented methods when transparent fluids are used [10,11,12]. In the area of non-optical instruments, thermocouples of extremely small size and high accuracy have been developed. One of the most accurate probes available can detect temperature variations as small as 1°K with a frequency response of roughly 5 kHz [13]. It is important to note that the range of accurate frequency response of mechanical probes are inversely proportional to the probe sizes. The frequency response values stated are the upper limits of the mechanical probes due to fabrication difficulties in designing such probes which are inherently fragile. Thus, an important advantage of optical devices in addition to their high frequency and non-interference qualities is that they do not encounter difficulties related to probe structural integrity and durability.

Finally, the evaluation of ϵ_H for certain special situations has been attempted using basic principles coupled with semi-empirical correlations. The most fruitful approach in this regard is to relate ϵ_H to ϵ_M which has been evaluated with greater accuracy via a fixed constant or constitutive relation based on various geometrical, heat transfer and hydrodynamic parameters exemplified by Reynolds or Von-Karman analogies [14,15]. The optical means employed in this experiment can be employed in the augmentation of these developments. In fact, the coupled interferometer/LDA package can directly measure both $\langle V_i(\underline{x},t)T(\underline{x},t) \rangle$ and $\langle V_i(\underline{x},t)V_j(\underline{x},t) \rangle$ which are the stochastic terms needed to evaluate accurately the ratio of ϵ_H to ϵ_M [16].

Chapter 2

MEASUREMENT SYSTEM

2.1 Overview of Technique

2.1.1 Physical Principles

The operating principle of both the temperature and velocity systems is based on the same physical phenomenon, that is the interference interaction of coherent electromagnetic waves. Therefore, though the application and operating procedures for the two techniques seem quite different, they can be both classified as interference pattern formation optical techniques. This class of optical procedures is contrasted with the other major category--image formation. In fact, laser anemometry was an outgrowth of the older and more established field of interferometry. Nevertheless, while both systems utilize the same observable physical phenomena, their components are necessarily different due to their independent goals.

The interferometric investigation of temperature is based on the functional dependence of the index of refraction on a material's state properties. As is expected from everyday experience these dependencies are of a very small absolute magnitude, and actual observation of such changes can be accomplished through either the introduction of very severe state variations or in the development of ultra-sensitive measure-

ment systems. With the functional dependencies of the refractive index of air being of the order of $10^{-5}/\text{psi}$ and $10^{-6}/^{\circ}\text{C}$ for pressure and temperature changes, respectively, it is clear that the creation of significant absolute changes is nearly impossible. Therefore, since total variation is difficult to achieve, differential techniques become more applicable. In devising such a differential system it is also crucial to ensure that the desired functional dependence is orders of magnitude more significant than the other dependencies. Therefore, in this investigation the experiment was designed in order to maximize temperature variations and minimize pressure changes.

While the fringe patterns central to the temperature measurements are formed outside the subject flow when the two optical paths of the interferometer are recombined, the characteristic pattern of the laser velocimeter is formed at the measuring point in the flow. The creation of the fringe pattern in this particular LDA configuration is accomplished by focusing two intersecting laser beams at the desired spatial location in the flow. The laser anemometer utilizes light scattered by particles in the flow as they travel through the imposed interference pattern. As is explained by the basic theory, the character of the scattered light is a direct product of the particle transit velocity. Therefore, the velocity of the particle which caused the scattering event can be ascertained when the shifted frequency is analyzed.

A more detailed explanation is presented later, but from this brief description three major requirements become evident. First, the subject flow and flow conduit must be translucent. Secondly, the flow must contain a significant number of particles which must be large enough to act as significant scattering centers and yet be small enough to follow the flow including the severe fluctuations present in the turbulent eddies. And, finally, a data processing system of an optico-electronic nature must be employed in order to discern a velocity or analog parameter from the produced scattered light characteristics.

2.1.2 System Output

Since the desired parameter is the multiplicative correlation $\langle V(\underline{x},t)T(\underline{x},t) \rangle$, it is clear that the two subsystems introduced must be mated in order to attain this time averaged parameter. The combination is facilitated by obtaining both system outputs as DC analog voltages. The DC signals are mated in a fashion that will not distort their character. This is accomplished through the use of an analog unit termed a turbulence processor which is subsequently described. In the sections to follow, the measurement system introduced is discussed in detail, and the exact experimental environment including the test cell, flow circuit and auxiliary features are described.

2.2 Interferometric Temperature Measurement

2.2.1 Use in Heat Transfer Analysis

The Mach-Zehnder interferometer is a valuable tool in the measurement and visualization of heat transfer processes

in air flows. As previously elucidated the optical device does not penetrate the flow, but there is an additional desirable feature of this particular configuration. The interferometer when used as a differential refractometer as is the case in this work possesses very little thermal inertia and is capable of nearly instantaneous response. Since the system is nearly identical to that of Bennett and Golay, only a brief review of the basic system operation is presented and the reader is referred to the original work for a more complete analysis. In addition, changes made in the original configuration are discussed and described.

2.2.2 Physical Description of Temperature System

The Mach-Zehnder interferometer which is the most widely used type of interferometer in heat transfer studies produces a fringe pattern for which fringe lines (minima of the electromagnetic scattering pattern) are analogs of isotherms. The incident coherent light beam which in this case originates from a He-Ne laser is initially split into equally intense perpendicular beams. The two normal rays are directed along prescribed paths using optically flat front surface mirrors and are finally recombined again using a 50/50 beamsplitter. (A 50/50 beamsplitter is an optically coated wedged prism which allows 50% of the incident light to be transmitted while 50% is reflected at a right angle to the original beam.) The paths travelled by the intermediate split beams need not be of identical geometrical length due to the high degree of inherent light source coherency. The interaction of the recombined

beams are a product of the two optical (not geometrical) paths taken. The optical beam paths are determined by the refractive environment through which they pass and after recombination, the interference mode is determined by:

$$\oint n(\underline{x}) d\underline{x} = m \frac{\lambda_0}{2} \begin{cases} m = \pm 0, 2, 4, 6 \dots & \text{constructive} \\ & \text{interference} \\ m = \pm 1, 3, 5, 7 \dots & \text{destructive} \\ & \text{interference} \end{cases} \quad (2.1)$$

For example, if the value of this path integral was $\lambda_0/2$, the two beams would experience total destructive interference, and if the optical components were perfectly aligned and stationary in regards to a common reference frame, no light would be observed.

Fig. 2.1 presents a schematic diagram of the interferometer. There are three basic component groupings. The first is the light source and the beamsplitter mounted directly in front of it. The source is a 50 mW He-Ne laser which drives both the interferometer and the LDA. The beamsplitter divides the beam into two beams, one which impinges directly onto the LDA optical transducer and the other which is directed via an additional mirror into the four optical components of the temperature system. The interferometer consists of two mirrors and two 50/50 beamsplitters. There are additional "optical components" which must be noted, and they are the Plexiglas walls of the test cell. The effect of these walls cause minor

FIGURE 2.1: ISOMETRIC VIEW OF MACH-ZEHNDER INTERFEROMETER

L - Laser, B - Beamsplitter, M - Mirror, D - Detector

and basically negligible degradation of the overall product fringe pattern. It is further noted that the optically coated fused silica beamsplitters were not used in the original work, and that their utilization in this work leads to a significant optimization in the use of available laser light. In fact, a detailed analysis shows that though half the laser power is introduced to the interferometer in the current arrangement, the intensity of laser light eventually focused on the photodetector is 45% greater than that of the original configuration. Fig. 2.2 illustrates the improvement.

The third subassembly of the system is the output intensity detector which consists of a simple double convex glass lense which focuses the recombined beam onto a photodiode electronic circuit. Fig. 2.3 is a schematic diagram of the detection circuit. The photodiode possesses a verified frequency response of 8 kHz and a probable true response of over 10 kHz. The choice of photodiode was based on durability and economy. More sensitive components are available. A detailed analysis of optical inaccuracies such as test cell wall non-uniformity, uncompensated optical beam lengths and distortion due to Schleioren effects are presented in the original work.

2.2.3 System Capabilities

Some important features of the temperature analog are now reviewed. The analog output does not include the mean temperature of the fluid due to the large phase angle introduced by the uncontrollable heating and cooling of the Plexi-

ORIGINAL DESIGN

NEW DESIGN

FIGURE 2.2: COMPARISON OF ORIGINAL INTERFEROMETER TO MODIFIED DESIGN

M - Mirror, B - Beamsplitter, D - Detector

FIGURE 2.3: TEMPERATURE ANALOG DETECTION CIRCUIT

glas walls. While the output signal does contain a baseline DC component, this voltage is unrelated to fluid temperature but is actually a magnification of less than ideal fringe contrast. The shortcoming of the system is that an additional and perhaps less accurate means of monitoring the average temperature must be employed. In this work a thermocouple is used to measure the temperature at the various measurement stations in order to allow proper evaluation of the various fluid properties which are involved in the calculation of desired moduli such as Reynolds number. Since the linearity of the measurement system is most significantly determined by the centering of the interference pattern upon one fringe, the time during which one fringe does not drift appreciably is a crucial parameter. The drifting of the pattern is caused by heating of the test cell walls and by external vibrations. Therefore, data acquisition periods are limited to roughly sixty seconds in order to allow for constant monitoring of fringe alignment.

2.2.4 Sources of Error

The temperature variation to which the system is sensitive is 33°C (60°F). This parameter is a function of both the laser's wavelength and the test cell internal thickness as can be seen from Eq. (2.1). The system is initially aligned such that one fringe centered about its half maximum is observed. The initial alignment compensates for the presence of the test cell walls and any other systematic dissimilarity between the

interferometer's two optical legs. Therefore, once the beams are aligned any shift in the fringe must be a product of the temperature fluctuations in the cell. Since the interference path integral is limited to a value of $\lambda_0/2$, the temperature change (termed upset) the configuration can detect is uniquely determined since both the optical path length and laser wavelength are constants. Therefore, the change in the index of refraction is a direct product of the temperature change. As an illustration, consider utilizing a light source with a wavelength half that of a He-Ne laser and a test cell internal width of half that of the actual cell, the resultant detectable temperature upset is exactly the same as in the former case.

The system accuracy is determined by the degree to which the fringe shift is a product of the temperature difference between the two legs of the interferometer. Other driving forces of fringe movement are any other differences in optical paths introduced into the experiment. Aside from the test cell characteristics which have been considered, the other major source of inaccuracy is the lack of rigidity of the other optical components. This is an important consideration since any vibration of the optics will introduce a time varying change in the optical path lengths which are spurious in regards to the temperature measurement. To control this effect, certain preventative steps are taken. First, it is clear that even if the optical mounts possessed very limited stability, if all sources of vibration are eliminated, the components will

not move. Though complete elimination of vibrational sources is unattainable, the measurements have been performed in a basement during quiet house in order to reduce environmental vibration.

Unfortunately, the experimental configuration itself contains the strongest and highest frequency vibration source, the air blower. Though the experimental set up is detailed in a later section, it is noted that the configuration is designed with vibration reduction as a principle design goal. In addition to experimental location, the optical components were secured in a rigid fashion to an optical bench. The optical bench design centered upon the need to eliminate any high frequency vibrational noise (> 1 kHz) since those frequency ranges begin to approach the turbulence frequency regime of interest. Therefore, when vibrations could not be damped, the vibrational frequency was changed to a lower value by modifying the optical bench structure.

2.3 Laser Doppler Anemometry

2.3.1 Physical Principles

The underlying physical phenomena which allows coherent light sources to be used as a means of measuring velocity is the Doppler shift, the apparent frequency changes detected by a stationary observer measuring the frequency of a moving source. This shift phenomenon is an observable quality of all wave systems. The utilization of this physical mechanism

has been an important part of astronomical and communication devices for many years, but its application to velocimetry was proposed in 1964 by Yeh and Cummins who measured fully developed water flow in pipes.

There are myriad combinations of optical and electronic components which will create a usable laser velocimeter. However, three general modes of operation can be delineated as reference beam, dual scatter (differential Doppler mode) and dual beam. The reference beam mode which was used by Yeh and Cummins employs two beams of markedly different intensities--a powerful scatter beam and a weak reference. The reference beam which intersects the scatter beam at the measurement point is directed into a photodetection arrangement which measures the frequency shift. The dual scatter or differential differs from the other two in that the initial beam is not split but directed into the flow. The light scattered from the beam is monitored at two symmetric locations, and the recombination of the two waves allows measurement of the Doppler induced interference. Finally, there is the dual beam or fringe mode which is the configuration employed in this study. The incident laser beam is split into two equally intense beams which are directed to an intersection point in the flow. In the volume of this intersection an interference pattern is established. As a particle passes through the pattern, the scattered light intensity undulates due to the fact that the particle is passing through alternately light and dark regions.

The rate of intensity fluctuation is directly proportional to particle velocity. There is also an associated amplitude variation in the intensity due to the assumed Gaussian intensity distribution of the laser beam.

Each mode of operation possesses inherent advantages and disadvantages. The dual scatter method with its simplicity of alignment is especially useful in applications where alignment is difficult. However, the dual scatter mode uses a very small amount of collected scattered light and signal levels are quite low necessitating both powerful lasers and high flow seed concentrations. The reference beam mode also has good applicability in situations where high seeding level is possible and further can be used in a back scatter mode which allows the measurement of solid object velocities. These conditions are mostly encountered in liquid flows. The dual beam system chosen in this work possesses the best signal to noise ratio, is easiest to use and most importantly in this situation has the lowest flow seed requirements. The subsequent discussion of LDA measurements is limited to dual beam analysis.

The relationship between the observed frequency and the particle velocity is:

$$|U| = \frac{f_D \lambda_o}{2 \sin \left(\frac{\phi}{2} \right)} \quad (2.2)$$

As Eq. (2.2) illustrates the only parameters needed for complete

determination of the velocity are the wavelength of the light source and the angle of beam intersection. The laser anemometer in this simple configuration measures the velocity component normal to the unsplit beam and coplanar with the beam intersection. Further, the Doppler frequency of a particle traversing the intersection in one direction is exactly the same as that of a particle travelling in the opposite direction. In short, a 180° directional ambiguity exists, and the system in its basic form is insensitive to flow reversals. In addition to this intrinsic drawback, when investigating turbulent flows, the temporal variations around the mean flow are important parameters. Therefore, it is clear that an additional modification needs to be introduced in order to use a laser velocimeter in the study of turbulence structure.

The technique used to alleviate these weaknesses is frequency shifting. In the dual beam mode the fringe pattern in the measurement volume is stationary. If one of the beams experience a frequency shift before intersection, the interference pattern would appear to be moving; that is, the fringes move in a parallel or antiparallel direction to the measured flow. The important effect of this change is that the frequency shift associated with zero particle velocity is no longer zero but is equal to the frequency of the artificially shifted beam. Movement of the particle in the same direction as that of the fringe pattern will lower the measured shift and vice versa. Thereby shifting one beam by a high frequency

(on the order of MHz), the problems of directional ambiguity and undetectable flow reversal is conquered. Further in turbulence studies frequency shifting is used to "focus" the system on the spectral regime of the fluctuations of interest. Frequency shifting is accomplished through the use of an optico-acoustic Bragg cell. Fig. 2.4 illustrates these principles.

The final component of an LDA system is a frequency tracking device which converts the photodetector output into the velocity or some other useful analog. Since the particles (flow seed) which act as scattering centers are of both variable size and density, the photodetector output is both of varying amplitude and discontinuous. In addition, the signal contains spurious components including undesired noise stemming from stray reflections and electronic imperfections. Therefore, the frequency tracker must have the ability to both process the desired signal and reject the noise.

2.3.2 Description of Velocity System

The laser Doppler anemometer used in this investigation possesses two basic categories of components--optical modules and electronic devices. While it is clear that the two component classes are intensively interconnected, the system is most clearly explained using these delineations and illustrating the interconnections when they arise.

The most logical approach in describing the system is

BEAM INTERSECTION

INTERFERENCE PATTERN IN MEASURING VOLUME

FIGURE 2.4: LASER DOPPLER ANEMOMETER PRINCIPLES IN THE DUAL BEAM MODE

to follow the laser beam's path once it has been divided between the interferometer and the LDA. The beam incident to the transmitting optics assembly is approximately 25 mW. The unit splits the beam into two beams which are focused at the desired measurement zone. The beamsplitter is actually a single glass prism which transduces the original beam into two parallel beams displaced 25 mm from the original but remaining coplanar. While the beam division is variable, an even split is used in dual beam operation. The beamsplitter can be rotated 360° thereby allowing measurement of any direction. The split beams are then directed into a Bragg cell which introduces a frequency shift of as much as 40 MHz on one beam. This unit is powered and regulated by a separate unit. The two beams then pass through a focusing lense with a focal length of 108 mm and a beam intersection angle of 15.1° .

As discussed above, the beam intersection is a small volume containing an interference pattern. The zone of sensitivity is 0.5 mm^3 which is roughly 50% of the temperature sensitive volume. The fringe spacing is calculated to be 0.0024 mm.

The scattered light is detected by a photomultiplier which is powered by a high voltage source. The focusing of the photomultiplier on the beam crossing is crucial since monitoring another area such as just one of the beams will cause erroneous data. The photomultiplier assembly is the

major interconnection between the optical and electronic components.

The output of the tube is then connected via coaxial cable to the frequency shifter control unit. Before this signal is provided as input to the device, a unique system interfacing component is utilized. Since the photomultiplier is not matched to the other devices which are produced by a different manufacturer, its input is not compatible with the remainder of the electronics. Specifically, the tube output is in the form of an anode current while the receiving modules demands a DC voltage. Therefore a transimpedance amplifier is introduced to alleviate the difficulty. In addition to normalizing the signal, this device also provides a point at which to monitor the photomultiplier output to ensure its integrity. The control unit is also connected to the Bragg cell. The output of the unit is then coupled to the tracker. The frequency tracker is a combination of these systems: a tracking filter which eliminates detectable noise, a frequency-to-voltage converter and a sampling and hold circuit. These three features are necessary due to the noisy discontinuous nature of the input. The quality of data is mostly determined by the flow seed. A detailed listing of the equipment and settings used is presented in Appendix A.

2.3.3 Flow Seeding

The flow seeding scheme determines to a significant

extent the abilities of a laser anemometer. The first requirement is that there are enough particles in the flow to cause scattering events with a sufficient rate as to allow proper operation of the detection system. Secondly, in order that the data be accurate the particle must be able to follow the flow including the torrid eddy circulation

While water and some other liquids possess a sufficient natural contaminant level to sustain LDA measurements, most gases must be artificially seeded. In the air flow of this work, the air source is atmospheric and the natural particulate concentration is quite insufficient.

The design of a seeding system and the choice of a suitable flow seed is not a trivial task. The system finally developed consists of a makeshift fluidized bed utilizing microscopic plastic spheres as the seed. While this system is discussed below in greater detail, a brief review of other systems and seeds tried are presented as a guide to future investigators. It is noted at the outset of this review that the insufficiency of some of these attempts is not a product of the alternative's intrinsic weakness but is often due to the constraints created by the particular experimental configuration.

The first particle tested was ordinary tobacco smoke injected into the flow via the air blower intake, but this scheme is inadequate for many reasons, most significant of which is that the high volume flow rate dictated the use of

large amounts of smoke which seemed beyond the capacity of conventional sources. The second seed alternative is powder. The most negative aspect of this seed is that it adheres to the test section walls rendering them completely occluded in a matter of 15 seconds. Also injecting the powder into the blower, which deposition upon the heating element filaments and long term contamination can cause heater failure. The final seed tested and that subsequently adopted consists of plastic microballoons, which are basically hollow plastic spheres with an average diameter of roughly 5 μm . These spheres (the product name is Phenolic Microballoons) have the attractive features of good size, regular density distribution and tolerably low adherence to the test cell walls. The seed does nevertheless cloud the walls, and frequent cleaning of the internal faces is necessary during measurement operations.

Besides deciding upon a proper seed, a usable seed injection system must be devised. The creation of a pressure differential via a reduced area in the air hoses failed because the apparent suction created is too weak. Also, introducing the particle prior to the heater unit is unadvisable because of observed high attrition rates through the heater. The system that has proved successful involves using a fluidized bed injection scheme. A fluidized bed is basically a sealed reservoir of particles through which a gas flow

is passed. If the gas flow rate is great enough, the particles are entrained in the flow in an analogous fashion to vapor bubbles in a liquid. The seeded flow is then directed into the main flow circuit at a convenient location. The system has two advantages: the seed injection and particle entrainment is quite uniform, and the seeding rate can be varied by regulating the incipient gas flow. The scheme uses a glass cannister partially filled with particles. An air flow is passed through the bottle using compressed air as the source. The seeded air flow which exits from the top of the bottle is then directed via a polyvinyl hose into the ambient flow leg of the main flow circuit.

2.3.4 System Capabilities

The output of the LDA is in the form of a DC voltage which is a linear analog of the velocity being tracked. Even though the data rate is actually discontinuous, data rates on the order of 10^4 /second are treated as being continuous.

Since the output signal represents all components of the overall velocity and spectral regime, the system output can be used to attain many parameters including mean flow, temporal fluctuations and multiplicative correlation terms such as $\langle u_i u_j \rangle$ and $\langle u_i T \rangle$. The acquisition of the various parameters is accomplished by using the proper combination of data analysis equipment.

While the optical arrangements to measure mean flow and temporal components are described previously, the configu-

ration needed to measure Reynolds stress has not been mentioned. Actually, the arrangement is straightforward. If the beam intersection plane is oriented $+45^\circ$ and -45° off-normal to the two orthogonal Cartesian axes, the difference of the squares of these two respective measurements will yield the analog of $\langle u_i' u_j' \rangle$. (The parameter $\langle u_i' u_j' \rangle$ will henceforth be noted as $\langle u'v' \rangle$.) Actually, as can be seen in Fig. 2.5, the relationships obtain:

$$\begin{aligned} |\underline{A}|^2 &= \frac{1}{2} (u'^2 + 2u'v' + v'^2) \\ |\underline{B}|^2 &= \frac{1}{2} (v'^2 - 2u'v' + u'^2) \end{aligned} \quad (2.3)$$

and subtracting these terms yields:

$$|\underline{A}|^2 - |\underline{B}|^2 = \frac{1}{2} \langle u'^2 + 2u'v' + v'^2 - u'^2 + 2u'v' - v'^2 \rangle = 2 \langle u'v' \rangle. \quad (2.4)$$

Thereby it is seen that utilizing this method coupled with removing the average velocity components (DC terms) of the system output the desired cross correlation term is obtainable.

While the analog voltage output is a convenient form to use in electronic data analysis, there is always the need to monitor the actual numerical values of velocity magnitudes. The velocity is related to the frequency tracker output in a linear fashion, and conversion is accomplished utilizing the equation:

$$|\vec{A}| = \frac{1}{\sqrt{2}} (u' + v')$$

$$|\vec{B}| = \frac{1}{\sqrt{2}} (v' - u')$$

FIGURE 2.5: $\langle u'v' \rangle$ MEASUREMENTS USING A ONE COMPONENT LDA SYSTEM

$$\bar{V} \text{ (m/sec)} = \text{Output (Volts)} / \left(\frac{\text{Volts}}{\text{MHz}} \right) \left(\frac{\text{MHz}}{\text{m/sec}} \right) \quad (2.5)$$

where the terms in the denominator of the right hand side are determined as follows. The ratio of voltage to frequency is set by an adjustment on the tracker. The value selected is determined by the range of velocities present. The frequency-to-velocity unit ratio is a product of the optical geometry employed. The relationship which determines this parameter is:

$$f_D = [2\bar{V} \sin(\frac{\phi}{2})] / \lambda_0. \quad (2.6)$$

In this work $\phi = 15.1^\circ$ and $\lambda_0 = 6328 \times 10^{-8}$ cm and the conversion is:

$$\begin{aligned} f_D / V &= \frac{\text{MHz}}{(\text{m/sec})} = \left[\frac{1}{10^6} \times 2 \times \sin\left(\frac{15.1}{2}\right)^\circ \right] / 6.328 \times 10^{-7} \\ &= 0.415. \end{aligned} \quad (2.7)$$

As an illustration, an output voltage of 2 volts represents a velocity of 24.1 m/sec assuming a setting of 0.2 volt/MHz.

2.3.5 Sources of Error

The laser velocimeter is a very accurate measurement system with a substantial advantage over other anemometers in that it requires no calibration. The dual beam mode in addition possesses good signal-to-noise ratios at relatively low seeding concentrations. The system however is not perfect, and its major inaccuracy stems from what is termed frequency broadening. Frequency broadening is the general

term used to describe the changes caused in the frequency structure of the optical signals due to phenomena independent of velocity fluctuations. There are three subdivisions of frequency broadening. The effect of finite transit times of particles passing through the measuring volume is termed finite transit time broadening. This problem stems from the fact that since both the measuring volume is small and the transit period is discontinuous, spectral analysis of the signal has inherent resolution problems. Imperfections in the optical components and laser beam intensity nonuniformity yields optical imperfection broadening. Though this error source can be minimized by careful maintenance, it can never be eliminated. Finally, if the velocity is not uniform across the sensitive volume the velocity gradient will cause particles traversing the measuring zone at different locations to have different velocities. Since the frequency analyzers cannot distinguish these spatial variations from the true temporal fluctuations, additional changes of frequency are created. Designing the system in a manner compatible with minimizing the frequency broadening problems is a necessary facet of laser anemometry, and this constraint is part of the design criteria of this experiment.

2.4 Integrated Measurement System

2.4.1 Optical Dual Alignment

The ability of this mensuration method to measure the

correlation term $\langle u'T \rangle$ and hence to evaluate the eddy diffusivity of heat is due to the coincidence of both measuring volumes. In order that the measuring volumes be the same, both optical probes must be trained on the same region. Ideally, the most accurate way to attain the correlation functions is to have the measuring volumes be identical and infinitely small. The small size would decrease spatial flow variations across the region. First, as has been discussed, the shapes and magnitudes of these two volumes are intrinsically and unalterably different. There is little motivation to alter this situation since it introduces little inaccuracy in the overall technique due to the fact that the narrowness of the test section and the boundary layer of the turbulent flow field allow the assumption of temperature uniformity across the cell. Secondly, the interferometer beam cannot be directed to pass directly through the LDA dual beam crossing. The reason for this is more subtle than the first situation and stems the nature of the LDA system. The intersection of a third beam with the two probe beams of the anemometer consequently creates new and unwanted interference patterns in the same area as the desired LDA fringes. The presence of the additional fringe patterns causes spurious frequencies to be seen by the photodetector. This occurs because particles passing through the secondary fringe patterns also scatter light but with a frequency not indicative of the particle

velocity. Therefore, the interferometer is aligned such that it passes through the fluid a full beam width away from the LDA intersection. The degree of approximation introduced by not monitoring exactly the same point in the flow is assumed to be negligible since the behavior of the flow area separated by a distance of 0.5 mm (one beam width) is identical in any measurable sense.

In addition to the first order optical dual alignment described, there exists a second area of optical mating. The two subsystems have the same coherent light source which is equally divided between the two sets of apparatus. While this seems to be a trivial point, it is noted that serious consideration must be given to constructing a dual alignment system where multiple redirections of laser light and other sources of misalignment are to be minimized. The system herein described was not set up originally in its final form. The configuration evolved as it was sought to minimize these stated problem areas.

2.4.2 Electronic Mixing

Once the light probes emerge and their signals are converted into analog voltages, they must be correlated by some accurate electronic method. It is important to reiterate that both DC analogs are linear which greatly simplifies signal multiplication. Nevertheless, special care must be taken due to the high frequency nature of the signals. Therefore, simple schemes such as connecting the outputs to two voltmeters

and multiplying the transcribed values leads to gross errors.

Since proper evaluation of the desired parameters requires electronic information processing capable of monitoring severe temporal variations, a turbulence processor is used. This unit further has the ability to remove any constant or DC voltage components of the input signals in order to isolate the time dependent elements which are to be correlated. A filter is also placed on the input temperature signal which eliminates all low frequency (< 200 Hz) components since the content of the signal below that frequency is predominantly noise created by unavoidable vibration in the system.

To illustrate the final output of the device and hence values of $\langle u'T' \rangle$ or $\langle u'v' \rangle$, consider the following case. Suppose input signals are being analyzed with their DC components filtered out, therefore an output of C volts² from the processor is translated into a value of $\langle u'T' \rangle$ as follows:

$$\langle u'T' \rangle = C \times S_T \times S_V \quad (2.8)$$

where

$$S_T = \# \text{ } ^\circ\text{C/volt}$$

$$S_V = \# \frac{\text{m}}{\text{sec}} / \text{volt}.$$

Using the mathematical nomenclature already established, the final system output can be written as:

$$C = \text{analog} \left[\frac{1}{\tau} \int_0^\tau U T d\tau \right] = \begin{cases} \text{analog} [u'T' + (\bar{U} \bar{T})] & (i) \\ \text{analog} [u'T'] & (ii) \end{cases} \quad (2.9)$$

where (i) → DC coupling
(ii) → AC coupling.

Fig. 2.6 presents a block diagram of the electronic arrangement.

2.4.3 Accuracy

The numerical calculation of experimental error is postponed until after the data analysis portion of this work, but a brief review of the error magnitudes involved in the overall system is presented. The accuracy of the interferometric system is ~5% when all the precautions outlined in 2.2 are employed. The 5% deviation is a product of uncontrollable variations in optical path length. The LDA measurement of velocity fluctuations does not contribute any systematic error since any inaccuracy of the time varying components is not expected to be correlated. There is inaccuracy in any mean velocity measurements, but calculations presented later show them to be less than 5%. Finally, the turbulence processor possesses an unverified manufacturer's accuracy of $\pm 2\%$. The data analysis section illustrates the errors concurrent with data acquisition methods and calculational procedures.

2.5 Experimental Arrangement

2.5.1 Environment and Auxiliary Facilities

The experiments were performed in the basement of an MIT building. The necessity of locating the experiment in a basement area originates from the extreme sensitivity of the interferometer to vibration. The location is fairly satisfactory for the measurements, but care must always be taken to

FIGURE 2.6: BLOCK DIAGRAM OF ELECTRONICS INVOLVED IN CROSS CORRELATION MEASUREMENTS

minimize the effect of external vibration. The chief sources of outside vibration are traffic, machinery and air pumps in the building. The course of action taken to counteract their presence is to choose a location as distant as possible from heavy machinery and the street and to perform all data acquisition during quiet hours (during nights or weekends). In contrast to the interferometer, the LDA is relatively insensitive to vibration and generally creates few extraordinary demands when locating an experiment. Even with the precautions taken, certain sources of incessant vibration remained and these are the chief inaccuracy sources in the temperature system. The room itself had not originally possessed sufficient electric power and was refit with improved lighting and three independent 20 amp circuits.

2.5.2 Flow Circuit

The flow circuit is shown schematically in Fig. 2.7. As can be observed, the basic features are a 1/4 horsepower "squirrel cage" type air blower, flow heater, Plexiglas test cell and a filter system joined together by rubber hoses of varying shapes and lengths. A more detailed component description is now given. The air blower is a standard rotary compressor with capacitor start. The heater is both a flow divider and heat source. The heater is a parallelepiped shaped box built of asbestos board in which a kitchen toaster is placed. Above the toaster, between it and the flow inlet level, there is a baffle system which creates the resistance to flow necessary

FIGURE 2.7: SCHEMATIC DIAGRAM OF FLOW CIRCUIT

to accomplish the desired flow division. The result is two outlet flows, one at ambient conditions and the other heated. The temperature of the ambient flow leg is 27°C while that of the heated flow is $\sim 71^{\circ}\text{C}$. The conduit connecting the heater and air blower is a 6.35 cm O.D. hose. The outlets of the heating unit flow into 5.08 cm rubber hoses with good insulating properties. The ambient flow tube has an aperture which receives a polyvinyl tube which contains the flow seed. The air flow of the seed tube is roughly 6% of the ambient flow. The hoses are then directed into a cylindrical assembly which rearranges the flow such that the cannister outlet consists of an annular conduit with the ambient flow contained in the inner zone and the heated flow in the surrounding region. This annular arrangement is then attached to the test section which is described below. Finally, the two exiting jets of the test cell are directed via hoses into a crude filter system which utilizes a standard ventilation system filter. The purpose of this filter is to avoid the ejection of flow seed into the laboratory environment for the protection of both the experimenter and the electronic components.

2.5.3 Optical Bench

The basic optical bench used is identical to that used by Bennett and Golay, and a detailed description of it can be found in that work. Briefly, the bench consists of two wide-flanged iron beams which rest upon pedestals composed of concrete blocks. The bench is secured to its supports by large

adjustable C-Clamps. In addition, two shock absorbers consisting of wooden support members and compressed foam rubber and a number of concrete blocks are employed to both damp out some vibration and moreover disrupt the higher fundamental vibration modes. The overall weight of the structure is 450 kg.

Though the bench is crude and more elaborate and expensive benches would significantly decrease the vibration problem thus allowing more convenient experimental location, it does have some redeeming advantages. First, its overall design is focused on the needs of the particular experiment, particularly the bench allows the test cell to be positioned between the two sets of optical components constituting the interferometer. Secondly, its modular construction makes the addition of the LDA related equipment fairly simple. Finally, the bench's rather open construction lends itself to easy storage of various power and control cables and other auxiliary devices.

2.5.4 Improvements

Fig. 2.8 shows an overhead view of the optical bench with the additional optical support surfaces added in this work in addition to the schematic layout of the various optical components. The laser rests on a solidly constructed bench 1.9 m long which is structurally independent of the optical bench. It is aligned perpendicular to the wide-flanged beams of the optical bench. The original configuration used by Bennett and Golay had the laser positioned on the optical

FIGURE 2.8: EXPERIMENTAL CONFIGURATION

B - Beamsplitter, M - Mirror

bench, but this is not well-suited to the combined measurement system. Initially, it was attempted to stow the laser on one of the lower flanges of an iron beam and through a series of custom built mirror mounts redirect the beams to the level of the upper flange and into the optical components. The source of difficulty and subsequent abandonment of this arrangement is that before the laser light is directed into the backface of the LDA transducer it has experienced a total of five redirections and angular changes. The multiple reflections render the alignment of the entering beam in a straight (normal to the plane surface of the optical assembly backface) trajectory virtually impossible thereby causing serious misalignment. In addition, the multiple reflections off of the imperfect mirror surfaces scattered more than 20% of the initial laser light before it reached the LDA optics. The new configuration successfully solves these problems.

Additional renovations are present in the optical bench. The new position of the light source coupled with the need to split the beam before it entered the LDA assembly calls for the addition of two extensions of the upper flange on the side closer to the laser. The first small platform consisting of a 0.95 cm thick aluminum plate is securely fastened to the bench and is used for the support of the beamsplitter shown in the figure. The second addition which is identical serves to support the redirecting mirror mount which aligns the interferometer beam. The fastening of these plates is performed with

careful consideration paid to avoiding the addition of new areas of vibration. All other optical devices are secured to sturdy mounts and fastened to the bench using metal clamps. The test cell itself sits on an independent support structure constructed of angle iron and wooden blocks which allow for the translation of the cell to accomplish changes in measurement stations. The result of this arrangement is that changing measurement locations does not involve moving the optics.

2.6 Test Cell

2.6.1 Physical Description

A schematic representation of the experimental test section is presented in Fig. 2.9. The acrylic unit has a variable internal geometry with two modelling configurations. The right half of the sketch illustrates the 1/15 scale ANL (Argonne National Laboratory) FFTF outlet plenum, and the left side shows the 3/80 CRBR scale modelling.

The assembly has an outer width of 2.54 cm and an internal width of 1.27 cm. It consists of two peices, a 1.905 cm base plate from which a 1.27 cm depression is machined out in a pattern consistent with the modelling, and a 0.64 cm top plate. The two sections are bolted together with 0.32 cm bolts placed roughly 7.62 cm apart around the perimeter of the cell. Further, a rubber gasket is placed around the outer boundary in order to insure a leak-tight arrangement. The test cell is made in a modular form in order that its internal faces can be cleaned since the continual deposition of flow seed on

the walls causes occlusion. In fact, any clouding causes deleterious scattering of laser light, but a certain level is accepted as unavoidable.

As stated above, the test cell utilizes a variable geometry scheme. This is accomplished through the positioning of Plexiglas pieces at desired locations. These additions consist of two large blocks to change the overall external expanse of the flow section, two smaller blocks to vary the outlet nozzle structure and two pair of narrow struts which model the chimney structure of the above-core internals. The modular additions are secured to the cell with small screws which penetrate the outer boundary. The ability to disassemble also allows this variable geometry option. Besides increasing the scope of the data, the changeable internal structure also allows for direct comparison of results from the same experimental set-up.

2.6.2 Flow Characteristics

Though the flow characteristics of the geometry are the subject of this report and detailed discussion of it is presented in later sections, a brief qualitative description of the pattern is now presented as it pertains to the test cell construction. The entrance region consists of three entering channels of flow isolated from each other by 0.635 cm channel walls. The 2.54 cm outer channels contain the heated flow while the 5.08 cm inner channel contains the ambient seeded flow. This arrangement enhances the thermal mixing

properties of the entrance region. At steady state conditions the entrance Reynolds number is about 22,000. Since the inlet flow geometry is fixed, changes in Reynolds number are accomplished through the use of a more powerful blower or of a lower bulk temperature.

The internal width is twice that of the original test section. As discussed earlier, this results in a smaller measurable temperature upset. Another second order effect occurs due to the increased internal span. At velocities present in the original cell questions arose as to whether a laminar sub-layer spanned a significant percentage of the open channel in low flow regions. With the additional width and the presence of flow directing chimneys, the significance of sub-layer growth is reduced.

Chapter 3

DATA ACQUISITION

3.1 System Output

3.1.1 Temperature Velocity Correlations

The numerical values of the cross correlation terms $\langle u'T \rangle$ and $\langle v'T \rangle$ are acquired in the following fashion. The output of the turbulence processor is connected to a digital voltmeter from which numerical values are transcribed by hand. The input gains of the processor are set at values which produce useful output signals. The data accumulation rate was roughly one transcription per second. Enough data were taken to provide a reasonably good statistical base for the measurements. This is accomplished by acquiring data until the standard deviation of the readings approach the asymptotic value presented on the maps below.

The variations listed on the maps presented are indications of the relative data fluctuation at particular locations. Significant degradation in data constancy is noted in the flow regions distant from the inlet and chimney regions and the most plausible explanation of this phenomena is that it is caused by the higher and more erratic occlusion observed at these stations. As previously detailed, this occlusion leads to signal deterioration in both systems. Though the absolute values of the measurements are set by the system parameters mentioned, their dimensions are (length x tempera-

ture) x inverse time.

3.1.2 Reynolds Stress Correlations

The measurement of the analog of the $\langle u'v' \rangle$ term is also acquired through the use of the turbulence processor which is used as both an amplifier and high pass filter eliminating all DC components of the input signal. As is the case in the temperature velocity correlations, a digital voltmeter is used to attain numerical values.

3.2 Measurement Stations

The measurement stations used in this investigation are shown in Fig. 3.1. It is observed that the area of prime interest is centered about the central region. The motivation in the selection of the measurement positions is two-fold, but the strongest contributing factor is the increasing difficulty in acquiring data in regions distant from the inlet. The reason for this data acquisition degradation is due to the fast and nearly complete occlusion of the test cell in these areas due to low flow seed deposition. The product deposition is minimized but a baseline rate must be accepted since a particular lower bound seeding rate is needed to insure the integrity of the velocity measurements. In addition, the narrow width of the test cell which is required to embody a reasonable temperature upset aggravates the situation.

The limitations which this situation introduces are not as severe as might be thought, and the explanation of this ties

FIGURE 3.1: MEASUREMENT STATIONS

into the second aspect motivating the station selection. It is observed in this work and was observed in the original work that the temperature fluctuation as a function of time weakens dramatically in areas away from the inlet flow. Therefore, monitoring areas around the chimneys suited the requirements of the experiment in the realm of the $\langle u'T' \rangle$ and $\langle v'T' \rangle$ results.

3.3 FFTF Data

3.3.1 $\langle v'T' \rangle$ Measurements

Measurements of the $\langle v'T' \rangle$ analog in the FFTF geometry are presented in Figs. 3.2 and 3.3 for the measuring stations indicated. The frequency shift employed is 10 MHz and the turbulence processor settings are equal input gains with AC coupling. Fig. 3.2 is a full scale map while Fig. 3.3 presents a representative time history plot of the data taken. Significant decreases in magnitude can be observed at increasing distance from the inlet (as is expected intuitively). Complete analysis of the measurements are presented later. Finally, noticeable variational increases (signal fluctuation about a mean as a function of time) which are discussed above are observed in the non-chimney regions.

3.3.2 $\langle u'T' \rangle$ Measurements

The $\langle u'T' \rangle$ analog data are taken under identical flow conditions as the $\langle v'T' \rangle$ measurements. The same locations are monitored using the same electronic mixing. Fig.

FIGURE 3.2: FULL SCALE MAP OF $\langle v'T' \rangle$ ANALOG IN FFTF GEOMETRY
(Arbitrary Units)

FIGURE 3.3: DATA TIME HISTORY OF $\langle v'T' \rangle$ ANALOG MEASUREMENTS
IN FFTE GEOMETRY

3.4 presents a full scale map of the data while Fig. 3.5 gives a representative sampling of data time histories. Three observations are noted. First, the absolute magnitude of the multiplicative correlations are uniformly smaller than the corresponding $\langle v'T \rangle$ terms. Second, the trend observed in the previous results is reversed in that the magnitude increases with distance from the inlet. Finally, while higher occlusion rates in the non-chimney region causes increased data variation (note position F), the chimney regions also have relatively high variational rates.

2.3.3 $\langle u'v' \rangle$ Measurements

The measurement of the $\langle u'v' \rangle$ analog is undertaken utilizing two different flow situations. Data indicative of situations of no thermal mixing, that is, all flow inlets held at the ambient temperature and with thermal mixing where the inlet conditions are identical to the $\langle v'T \rangle$ measurements are presented. Figs. 3.6 and 3.7 present maps of the Reynolds stress terms while Figs. 3.8 and 3.9 present representative data histories of the measurements at the points indicated.

Two interesting features which are discussed in the analysis chapter are noted. The values of the Reynolds stress terms in the chimney region during temperature upset conditions are higher than those under ambient conditions. A corollary remark to this observation is the convergence to common values observed at measurement stations far from the inlet where the thermal mixing effects are decaying away. Second, higher data

FIGURE 3.4: FULL SCALE MAP OF $\langle u'T \rangle$ ANALOG IN FFTF GEOMETRY
(Arbitrary Units)

FIGURE 3.5: TIME HISTORY OF $\langle u'T' \rangle$ DATA IN FFTF GEOMETRY

FIGURE 3.6: FULL SCALE MAP OF $\langle u'v' \rangle$ ANALOG WITHOUT
INLET TEMPERATURE UPSET IN FFTF GEOMETRY
(In Arbitrary Units)

D' $0.013 \pm 8\%$
4"
D $-0.249 \pm 3\%$

E
 $-0.161 \pm 3\%$

C
 $-0.089 \pm 2.4\%$

F
 $0.043 \pm 6.9\%$

B
 $0.050 \pm 3\%$

AMBIENT

AMBIENT

FIGURE 3.7: FULL SCALE MAP OF $\langle u'v' \rangle$ ANALOG WITH
INLET TEMPERATURE UPSET IN FFTF GEOMETRY
(Arbitrary Units)

FIGURE 3.8: DATA TIME HISTORY OF $\langle u'v' \rangle$ ANALOG MEASUREMENTS
IN FFTF GEOMETRY WITHOUT INLET TEMPERATURE
UPSET (Arbitrary units)

FIGURE 3.9: TIME HISTORY OF $\langle u'v' \rangle$ MEASUREMENTS IN FFTF GEOMETRY WITH INLET TEMPERATURE UPSET (Arbitrary Units)

variation is noted in the non-chimney regions in both inlet situations with the area above the chimney experiencing the worst conditions.

3.3.4 Temperature Temporal and Spectral Characteristics

The fluctuating nature and spectral quality of the temperature at the various measurement stations are discussed. The general conclusions of the original work are reaffirmed in that the temperature fluctuations are very severe in the inlet regions while they become relatively calm as the distance from the inlet increases. Also the frequency structure of the various points shows distinct qualities in that where the fluctuation is more severe in absolute rate so too are the fundamental frequencies higher.

Figs. 3.10 to 3.14 present representative scans of the temperature signals at stations B, C, D, E and F in the FFTF geometry with the respective coordinates indicated. Variations on the order of 4000-5000 °C/sec are observed at position B while at station F maximum fluctuation intensities of 500°C/sec are observed but are in fact rare with the average fluctuation being about 50°C/sec.

The spectral structure of the temperature field are also measurably distinct. Figs. 3.15 to 3.19 present plots of the relative frequency intensities representative of the data observed at the flow points. In addition, Figs. 3.20 and 3.21 illustrate the background noise frequency structure observed at points C and D. Each of the spectral traces

FIGURE 3.10: T' SCAN AT STATION B IN FFTF
GEOMETRY

FIGURE 3.11: T' SCAN AT STATION C IN FFTF
GEOMETRY

FIGURE 3.12: T₁ SCAN AT STATION D IN FFTF
GEOMETRY

FIGURE 3.13: T' SCAN AT STATION E IN FFTF GEOMETRY

FIGURE 3.14: T' SCAN AT STATION F IN FFTF
GEOMETRY

FIGURE 3.15: T' FREQUENCY SPECTRUM AT STATION B
IN FFTF GEOMETRY

FIGURE 3.16: T' FREQUENCY SPECTRUM AT STATION C
IN FFTF GEOMETRY

FIGURE 3.17: T' FREQUENCY SPECTRUM AT STATION D
IN FFTF GEOMETRY

FIGURE 3.18: T' FREQUENCY SPECTRUM AT STATION E
IN FFTF GEOMETRY

FIGURE 3.19: T' FREQUENCY SPECTRUM AT STATION F
IN FFTF GEOMETRY

FIGURE 3.20: T' NOISE FREQUENCY SPECTRUM AT STATION C IN FFTF GEOMETRY

FIGURE 3.21: T' NOISE FREQUENCY SPECTRUM AT STATION D IN FFTF GEOMETRY

are presented with a reference zero frequency trace.

The maximum significant frequency observed in the chimney region is between 1-2 kHz as can be seen in Fig.

3.16. In contrast, the upper bound of significant frequencies at position E is much lower. It must be noted that the scans provided are only illustrative and no information can be accurately drawn from the detailed spectral intensities present. In other scans made under exactly the same conditions, the same general structure is observed, but particular peaks can appear noticeably translated in frequency or can disappear entirely. The noise spectrum plots indicate that the noise levels further from the inlet become more severe. This is due to the aforementioned sporadic reflections caused by the seeding particles. These high frequency noise traces become most significant at points such as D and E far from the inlet.

3.3.5 Velocity Spectral Structure

The general observation is made that the measurable frequency structure of the turbulent velocity components capable of being monitored by this system are different from those of the temperature data in that much higher intensities are observed at frequencies in the 5 - 15 kHz range at various locations. The frequency intensity traces presented for the FFTF flow configuration have mixed scaling of both linear and logarithmic abscissa coordinates, and careful note of the labelling must be taken when analyzing the plots.

Also as in the case in the temperature data only general trends can be faithfully ascertained since specific maxima locations are not consistently observed. The major reason for this lack of clarity is rooted in the discontinuous nature of the LDA frequency tracker output which is caused by the sources of innaccuracy previously elucidated. Figs. 3.22-3.27 present representative frequency scans while Figs. 3.28-3.30 represent sample noise scans at various measurement stations.

Similar tendencies as those seen in the temperature frequency data are observed, but significant differences are also seen. The chimney zone positions have much higher upper frequency bounds in their spectra in general than those stations in the outlying regimes. For example, measurements at position B indicate that significant intensities exist in the area of 5 kHz while the upper bound observed in regions represented by position F are on the order of 1.5 kHz. It is noted from Fig. 3.27 that the spectral density is skewed to a lower frequency band. The noise traces in general indicate the excellent signal to noise characteristics of the laser anemometer in the dual beam mode. However, it is observed that positions closer to the inlet such as station B have relatively higher noise levels with more intense frequency structure. The cause of this phenomenon is thought to be stray flow seed particles of larger than normal size (agglomerates) which scatter inordinately large amounts of light and lead to spurious photomultiplier signals.

FIGURE 3.22: v' FREQUENCY SPECTRUM AT STATION B IN FFTF GEOMETRY

FIGURE 3.23: v' FREQUENCY SPECTRUM AT STATION C IN FFTF GEOMETRY

FIGURE 324: v' FREQUENCY SPECTRUM AT STATION D
IN FFTF GEOMETRY

FIGURE 3.25: v' FREQUENCY SPECTRUM AT STATION D' IN FFTF GEOMETRY

FIGURE 3.26: v' FREQUENCY SPECTRUM AT STATION E
IN FFTF GEOMETRY

FIGURE 3.27: v' FREQUENCY SPECTRUM AT STATION F
IN FFTF GEOMETRY

FIGURE 3.28: v' NOISE FREQUENCY SPECTRUM AT STATION B IN FFTF GEOMETRY

FIGURE 3.29: v' NOISE FREQUENCY SPECTRUM AT STATION D' IN FFTF GEOMETRY

FIGURE 3.30: v' NOISE FREQUENCY SPECTRUM AT STATION E IN FFTF GEOMETRY

Figs. 3.31 to 3.36 are sample spectra of the u' frequency structure in the FFTF geometry. Figs. 3.37 and 3.38 are representative noise spectra. Though some trends mentioned above when analyzing the corresponding data for the vertical velocity components are observed in these figures, some important differences do occur.

The low frequency nature of the velocity in the major area of recirculation is evidenced. In fact, fluctuation frequencies above 1kHz are not observed. Also the noise frequency scans taken at positions C and E in the FFTF geometry exhibit the same low levels found in the other velocity data. Different from the v' results is the fact that while higher frequency bands are observed in the chimney region, the slow decay of the higher frequencies as a function of distance found in the v' data is not observed, and in fact the opposite situation exists. While upper bound frequencies at position B are roughly 12 kHz, the upper bound observed at C is 13.5 kHz and that of D is above 15 kHz. This characteristic of the horizontal temporal component is indicative of the flow pattern. It is in the upper chimney and above chimney regions where the flow begins to turn markedly off-vertical and also experiences a narrowing or funneling effect.

3.4 CRBR Data

3.4.1 < $v'T'$ > Measurements

As is detailed above, the inlet condition for the

FIGURE 3.31: u' FREQUENCY SPECTRUM AT STATION B
IN FFTF GEOMETRY

FIGURE 3.32: u' FREQUENCY SPECTRUM AT STATION C
IN FFTF GEOMETRY

FIGURE 3.33: u' FREQUENCY SPECTRUM AT STATION D
IN FFTF GEOMETRY

FIGURE 3.34: u' FREQUENCY SPECTRUM AT STATION D'
IN FFTF GEOMETRY

FIGURE 3.35: u' FREQUENCY SPECTRUM AT STATION E
IN FFTF GEOMETRY

FIGURE 3.36: u' FREQUENCY SPECTRUM AT STATION F
IN FFTF GEOMETRY

FIGURE 3.37: u' NOISE FREQUENCY SPECTRUM AT STATION C IN FFTF GEOMETRY

FIGURE 3.38: u' NOISE FREQUENCY SPECTRUM AT STATION E IN FFTF GEOMETRY

cross correlation measurements in the CRBR outlet plenum geometry is identical to that employed in the FFTF investigations. The only changes made are the addition of various Plexiglas blocks in order to model the CRBR geometry. The frequency shift employed and various input gains are identical to those used in obtaining the FFTF data. Fig. 3.39 is a full scale map of the observed $\langle v'T \rangle$ analog data while Fig. 3.40 illustrates a sample data history plot.

Two particular features of the data are noted. Higher data variation is observed in the CRBR than at the FFTF positions. In addition, while the observed feature of lower variation in the chimney region repeats itself, the absolute magnitude of the variations are quite dissimilar in most cases. Secondly, the effect of the taller chimney structure in the CRBR case is observable in the relative magnitudes of the correlative analog values.

3.4.2 $\langle u'T \rangle$ Measurements

Figs. 3.41 and 3.42 are a full-scale map of the measured $\langle u'T \rangle$ analog and a representative data histogram respectively in the CRBR geometry. As is observed in the FFTF data, the overall magnitudes of the $\langle u'T \rangle$ terms are uniformly smaller than the $\langle v'T \rangle$ data. In fact, the largest ratio is found at D with a value of less than 0.60 while other locations are consistently lower. The trend of increasing value proportional to distance from the inlet is again seen, but the change is less noticeable than in the FFTF

FIGURE 3.39: FULL SCALE MAP OF $\langle v'T \rangle$ ANALOG IN CRBR GEOMETRY
(Arbitrary Units)

FIGURE 3.40 : DATA TIME HISTORY OF $\langle v'T' \rangle$ ANALOG IN CRBR GEOMETRY

FIGURE 3.41: FULL SCALE MAP OF <u'T'> ANALOG IN CRBR GEOMETRY
(Arbitrary Units)

FIGURE 3.42: DATA TIME HISTORY OF $\langle u'T \rangle$ ANALOG IN CRBR GEOMETRY

case. Finally, the characteristic of low variation in the chimney region is seen as contrasting with the FFTF results.

3.4.3 <u'v'> Measurements

As is the case with the FFTF <u'v'> data, measurements are taken under the two flow conditions of entirely ambient flow and thermal upset conditions. Figs. 3.43 and 3.44 are maps of the values ascertained without and with an incipient temperature upset, respectively. Representative data traces are presented in Figs. 3.45 and 3.46. Higher data variation in the CRBR <u'v'> data is noted.

As is the case in the FFTF flow, the temperature upset seems to increase the Reynolds stress in the chimney regions but not as significantly as in the FFTF situation. In fact, at some positions, the inverse effect is observed but to a much smaller degree. The effects show the influence of the higher temperature on the shear and slip behavior of the flow due to the increased density differentials. Nevertheless, as is seen with the FFTF data in regions distant from the inlet, values converge to identical magnitudes. Also, as is true in the other geometry, a change in sign occurs at various positions. Finally, the ever present occlusion induced data variations are observed in the locations far from the entrance/chimney region of the test cell.

3.4.4 Temperature Temporal and Spectral Characteristics

Figs. 3.47 to 3.52 are representative traces of the

FIGURE 3.43: FULL SCALE MAP OF $\langle u'v' \rangle$ ANALOG IN CRBR GEOMETRY WITHOUT INLET TEMPERATURE UPSET (Arbitrary Units)

FIGURE 3.44: FULL SCALE MAP OF $\langle u'v' \rangle$ ANALOG WITH INLET TEMPERATURE UPSET
IN CRBR GEOMETRY
(Arbitrary Units)

FIGURE 3.45: TIME HISTORY OF $\langle u'v' \rangle$ ANALOG IN CRBR GEOMETRY WITHOUT INLET TEMPERATURE UPSET (Arbitrary Units)

FIGURE 3.46: DATA TIME HISTORY OF $\langle u'v' \rangle$ ANALOG IN CRBR GEOMETRY WITH INLET TEMPERATURE UPSET (Arbitrary Units)

temporal nature of the temperature field at the prescribed measurement stations in the CRBR geometry. Similar results to the FFTF data are observed. For example, the steepest peaks in Fig. 3.48 represent absolute fluctuation rate of roughly $6000^{\circ}\text{C}/\text{sec}$ at position C which is 10cm above the inlet while at position E the maximum variations observed are measured to be less than $300^{\circ}\text{C}/\text{sec}$ which is less than 6% that of the value at C. An additional observation is that the temperature fluctuations are more severe at stations F and G than at E even though G in particular seems to be in the area of least temperature upset. However, the differences are slight when compared with values obtained in the chimney region.

The relative spectral intensities found at the flow points are presented in Figs. 3.53 to 3.58, and the results are consistent with physical intuition and the previously noted tendencies of the FFTF data. The upper bound frequencies of significant intensity are inversely proportional to the distance from the entrance region. The spectrum at B, for example, shows significant structure in the 4.2 to 4.5 kHz range while that of C is bounded by approximately 3.0 kHz and that of positioned D is bounded by 1.5 kHz with the bulk of characteristic frequencies (over 60%) falling below a level of 1 kHz. This characteristic of reducing fluctuation intensity is observed at all other stations. It is again noted that the fine structure such as the 500 Hz spike at position E is not significant and subsequent measurements

FIGURE 3.47: T' SCAN AT STATION B IN CRBR GEOMETRY

FIGURE 3.48 : T' SCAN AT STATION C IN CRBR
GEOMETRY

FIGURE 3.49: T_i SCAN AT STATION D IN CRBR
GEOMETRY

FIGURE 3.50: T' SCAN AT STATION E IN CRBR
GEOMETRY

FIGURE 3.51 : T' SCAN AT STATION F IN CRBR GEOMETRY

FIGURE 3.52: T' SCAN AT STATION G IN CRBR
GEOMETRY

FIGURE 3.53: T' FREQUENCY SPECTRUM AT STATION B
IN CRBR GEOMETRY

FIGURE 3.54: T' FREQUENCY SPECTRUM AT STATION C
IN CRBR GEOMETRY

FIGURE 3.55: T' FREQUENCY SPECTRUM AT STATION D
IN CRBR GEOMETRY

FIGURE 3.56: T' FREQUENCY SPECTRUM AT STATION E
IN CRBR GEOMETRY

FIGURE 3.57: T' FREQUENCY SPECTRUM AT STATION F
IN CRBR GEOMETRY

FIGURE 3.58: T' FREQUENCY SPECTRUM AT STATION G
IN CRBR GEOMETRY

at the location proved the observed peak in Figs. 3.56 to be an anomaly.

3.4.5 Velocity Spectral Structure

The spectral characteristics of the temporal vertical velocity component, v' , are presented in Figs. 3.59 to 3.63 and two representative noise traces illustrating the situation at positions A and F are shown in Figs. 3.64 and 3.65. As is the FFTF result, the velocity frequency spectra is higher than the temperature spectra.

The chimney region is again the area of greatest frequency maxima with the upper bound frequencies of 20-25 kHz observed at stations B and C. An interesting observation can be made in the comparison of Figs. 3.59 to 3.60 and 3.61 in that the structure at A is skewed to lower regimes than the variations observed at B and C and this fact is discussed later when the analysis of the apparent increase in $\langle u'v' \rangle$ from A to B is undertaken. Other than that observation, the plots mirror closely the aforementioned FFTF data. Peculiar to the CRBR case is the higher chimney and its effect on the frequency structure of the velocity at point D. Finally, while only a representative scan is presented for position F in Fig. 3.63, the observed results at E and G are found to be similar in that upper bound frequencies of above 2 kHz are not observed.

Representative spectral measurements of u' are presented in Figs. 3.66 to 3.71 and sample noise frequency plots for

FIGURE 3.59: v' FREQUENCY SPECTRUM AT STATION A
IN CRBR GEOMETRY

FIGURE 3.60: v' FREQUENCY SPECTRUM AT STATION B
IN CRBR GEOMETRY

FIGURE 3.61: v' FREQUENCY SPECTRUM AT STATION C
IN CRBR GEOMETRY

FIGURE 3.62: v' FREQUENCY SPECTRUM AT STATION D
IN CRBR GEOMETRY

FIGURE 3.63: v' FREQUENCY SPECTRUM AT STATION F
IN CRBR GEOMETRY

FIGURE 3.64: v' NOISE FREQUENCY SPECTRUM AT STATION A IN CRBR GEOMETRY

FIGURE 3.65: v' NOISE FREQUENCY SPECTRUM AT STATION F IN CRBR GEOMETRY

positive C and F of the CRBR geometry are presented in Figs. 3.72 and 3.73. Analysis of these plots show that they clearly mirror the FFTF results. Significant degradation of turbulence intensity as evidenced by low-upper bound frequencies are observed in the outer chimney region. This is especially so at position F where a comparison of the true spectrum with noise spectrum indicates scarcely any high frequency (above 1 kHz) components of the signal. The decrease is more marked than in the FFTF geometry.

The increasing turbulence intensity of the horizontal velocity component as a result of flow reduction in the upper chimney region is again seen in comparing the spectrum observed at B (Figs. 3.66) and that observed at D (Fig. 3.68). The cut off frequency at B is 10 kHz while significant spectral structure of D extends up to 15 kHz with an increase in magnitude indicating a substantially higher power spectral density in the upper chimney regime. Finally the noise plots exhibit high, low amplitude quality down into the low frequency levels.

3.5 Time Averaged Flow Conditions

3.5.1 FFTF Geometry

The time averaged flow conditions in the test cell when used in the FFTF outlet plenum geometry are now reviewed. The flow pattern observed in this work as ascertained from velocity measurements and flow visualization studies is in good agreement with the results of the isothermal work. Qualitatively the

FIGURE 3.66: u' FREQUENCY SPECTRUM AT STATION B
IN CRBR GEOMETRY

FIGURE 3.67: u' FREQUENCY SPECTRUM AT STATION C
IN CRBR GEOMETRY

FIGURE 3.68: u' FREQUENCY SPECTRUM AT STATION D
IN CRBR GEOMETRY

FIGURE 3.69: u' FREQUENCY SPECTRUM AT STATION E
IN CRBR GEOMETRY

FIGURE 3.70: u' FREQUENCY SPECTRUM AT STATION F
IN CRBR GEOMETRY

FIGURE 3.71: u' FREQUENCY SPECTRUM AT STATION G
IN CRBR GEOMETRY

FIGURE 3.72: u' NOISE FREQUENCY SPECTRUM AT STATION C IN CRBR GEOMETRY

FIGURE 3.73: u' NOISE FREQUENCY SPECTRUM AT STATION F IN CRBR GEOMETRY

symmetric (about the centerline) streamlines deviate slightly from a perfectly vertical direction in the chimney region and then proceed into a 180° turn as the fluid travels to the outlets. The position where the streamline changes slope is located 12.5 cm off the centerline and 10 cm below the upper side of the cell. The major area of recirculation is located on the outside of the chimneys and is a countercurrent flow with vortices approximately 7.5 cm from the chimney outer edge and 17.8 cm below the lower cell boundary. The areas directly below the boundary at the centerline and extreme corner positions appear to be areas of flow stagnation.

Table 3.1 presents results of velocity measurements of the mean flow at the three chimney region measurement stations chosen for this work. The convention used is that V represents the vertical component and U the horizontal component. Also listed along with the absolute magnitude of the vector is the angle of the vector as measured from the vertical axis. The observations made above are illustrated by these results. The increasing magnitude with distance from the inlet also indicates flow stagnation beginning in the upper centerline regimes.

Since the interferometric temperature system is unable to monitor the absolute value of the temperature at a location, a thermocouple is employed to detect the temperature at the measurement stations and Table 3.2 is a listing of the readings taken.

TABLE 3.1 Mean Velocity Data in Chimney Region of FFTF

<u>Position</u>	<u>Distance above inlet</u>	$\underline{V}(\frac{m}{sec})$	$\underline{U}(\frac{m}{sec})$	$\sqrt{u^2+v^2}$	$\beta(^{\circ})$
B	5.1 cm	11.8	0.3	11.8	0
C	10.2 cm	12.6	.8	12.7	8.1
D	17.8 cm	3.6	11.4	26.2	25.7

TABLE 3.2 Average Temperature in FFTF Geometry

<u>Position</u>	<u>°C</u>	<u>°F</u>
B	57.22	135.00
C	57.12	134.81
D	56.88	134.39
E	48.91	120.03
F	36.51	97.71

3.5.2 CRBR Geometry

The time averaged velocity and temperature fields encountered in the CRBR geometry are presented. As is the case with the FFTF measurements, the general patterns observed match nearly identically with previous investigations. For the case of the higher chimney structure of the CRBR geometry, the streamline trajectory remains more significantly vertical in orientation in the centerline region and the direction reversal is sharper due to this effect and the narrower non-chimney region of the geometry. The slope change position is located roughly 10.2 cm off the centerline and 17.8 cm from the upper boundary. The major recirculation area is found again at the outer side of the chimneys but due to the narrower geometry and different exit configuration the vortex is positioned lower than in the FFTF situation. It is located 7.6 cm from the chimney outeredge and 7.6 cm above the lower test cell boundary. Also stagnation or low flow conditions are observed in the upper and lower corners of this geometry.

Table 3.3 shows the measured mean velocity vector in the chimney region in the same format as Table 3.1. The less severe redirection of the vertical flow due to the higher chimney and decreased middle region stagnation are noted. Table 3.4 indicates mean temperature measurements at the measurement stations used for the $\langle u'T' \rangle$ and $\langle v'T' \rangle$ data.

TABLE 3.3: Mean Velocity Data in Chimney Region of CRBR Geometry

Position	Distance Above Inlet	$V(\frac{m}{sec})$	$U(\frac{m}{sec})$	$\sqrt{u^2+v^2}$	$\beta(^{\circ})$
B	5.1 cm	12.0	0.2	12.0	0
C	10.2 cm	12.2	0.8	12.2	3.8
D	17.8 cm	12.3	1.0	12.3	4.6

TABLE 3.4: Average Temperature in CRBR Geometry

<u>Position</u>	<u>$^{\circ}C$</u>	<u>$^{\circ}F$</u>
B	56.54	133.78
C	56.46	133.63
D	56.31	133.35
E	42.57	108.62
F	40.87	105.56
G	43.30	109.94

3.5.3 Inlet and Outlet Conditions

The inlet flow conditions during FFTF and CRBR operation are identical since no flow condition is altered when the modelling is changed. As is detailed above, the entrance region consists of three rectangular channels - a central channel with the ambient flow of 24°C with dimensions of 5.1 cm x 1.27 cm and two outer ducts with a heated flow of 71°C with inner dimensions of 2.5 cm and 1.27 cm. The inlet ducts are separated by 0.64 cm of plexiglas. The mean inlet velocity is 15.4^m/sec giving rise to an inlet Reynolds number of 22,000. Since the inlet turbulent kinetic energy is not measurable in this system, the turbulent kinetic energy at station B in both geometrics are presented as a basis for modelling the inlet region. The respective values for the FFTF and CRBR geometrics are 0.0944 m²/sec² and 0.1060 m²/sec². Variations in the method used to calculate Reynolds number such as the use of a detailed velocity integration to establish mass flow rate change the calculated value by a maximum of 450 or 2.5%. Since it has been found that the inlet conditions significantly determine the nature of the turbulence observed in the outlet plenum geometry, a velocity profile of the inlets during isothermal and temperature upset operation is presented in Fig. 3.74. The velocity profiles are nearly identical except for the increased velocity caused by the density changes introduced by the higher temperature of the air.

FIGURE 3.74: INLET VELOCITY PROFILE

The outlet velocity profile is also noteworthy. A small but measureable recirculation regime exists in the upper corner of the geometries' exists and in fact this zone causes a minor suction to occur at the upper outlet region. Hot wire anemometer data of the FFTF outlet is presented in Fig. 3.75

3.6 Data Availability in Other Regions

Though it is clear from previous discussion that due to the higher and more erratic occlusion behavior of outlying test cell locations the experimental technique loses its applicability in these regions, a sample data point in this regime is now discussed. The purpose of the investigation of this position is to attain an order of magnitude estimate of the correlation terms and to compare this value to the typical value heretofore presented. The location chosen is in the FFTF flow geometry and is located at the height of the chimney and 6.4 cm from the side vertical boundary of the test cell. The parameters measured are $\langle v'T' \rangle$ and $\langle u'v' \rangle$ using the same techniques employed in the other data acquisition.

The most notable feature of the measurements is the significantly higher data variation in this region with the measurement of the $\langle v'T' \rangle$ correlation term in particular. The values obtained at this station for $\langle v'T' \rangle$ and $\langle u'v' \rangle$ respectively are $0.100 \pm 47\%$ and $0.38 \pm 13\%$. The value

FIGURE 3.75: FFTF OUTLET VELOCITY PROFILE (m/sec)

for the $\langle v'T \rangle$ multiplicative correlation is less than 20% that observed at any of the other measurement stations. The $\langle u'v' \rangle$ result is of the same order of magnitude as the other non-chimney values. The severe data variation of the velocity-temperature term is evident.

IV Analysis

4.1 Evaluation of the Eddy Diffusivity of Heat4.1.1 Calculation of ϵ_H from Measurements

The eddy diffusivity of heat is calculated from the acquired data using the following equation:

$$\epsilon_{H,x_i} = \frac{\alpha_T \times \alpha_V \times \langle v'_i T' \rangle}{G_T \times G_V \times G_D \times \partial T / \partial x_i} \quad (4.1)$$

where α_T = conversion of volts to $^{\circ}\text{C}$

α_V = conversion of volts to m/sec

G_T = gain of turbulence processor operating on temperature signal

G_V = gain of turbulence processor operating on velocity signal

G_D = gain of voltmeter operating on input correlation signal

$\partial T / \partial x_i$ = temperature gradient ($^{\circ}\text{C}/\text{m}$).

The various gains are set by select settings on electronic mixing equipment. The constant α_V is evaluated from the

geometry of the LDA configuration and has a value of 12.05 m/sec/volt. The constant α_T is obtained from the interferometric contrast observed during temperature measurement. The multiplicative correlation terms are the as-recorded data presented in Section 3. Finally, the temperature gradients at each position are approximated by a difference equation of the form

$$\frac{\partial T}{\partial x} \approx \frac{T_i - T_{i'}}{x_i - x_{i'}} \quad (4.2)$$

The separation distance between x_i and $x_{i'}$, is 1.27 cm and a thermocouple is used to evaluate the temperatures.

Appendix B contains a complete listing of the conversion constants and signal gains used in each evaluation.

4.1.2: Temperature Gradients in FFTF Geometry

Using the technique outlined above, the temperature gradient at each measurement station is evaluated. Both the $\partial T / \partial x$ and $\partial T / \partial y$ terms are measured since both the vertical and horizontal component of eddy diffusivity are evaluated. The significant difference between the horizontal and vertical gradients in the chimney region should be noted as this difference leads to significant differences in the absolute values of $\epsilon_{H,x}$ and $\epsilon_{H,y}$.

4.1.3 $\epsilon_{H,x}$ in the FFTF Geometry

Fig. 4.1 presents a map of the calculated values of $\epsilon_{H,x}$ at the measurement stations of the FFTF outlet plenum geometry.

TABLE 4.1: Temperature Gradients in FFTF Geometry

Position	$\partial T / \partial x$ ($^{\circ}\text{C} / \text{m}$)	$\partial T / \partial y$ ($^{\circ}\text{C} / \text{m}$)
B	59.65	2.08
C	78.16	2.57
D	86.39	3.06
E	90.50	244.1
F	277.51	244.1

TABLE 4.2: Temperature Gradients in the CRBR Geometry

Position	$(\partial T / \partial x)$ ($^{\circ}\text{C} / \text{m}$)	$(\partial T / \partial y)$ ($^{\circ}\text{C} / \text{m}$)
B	26.74	1.64
C	26.74	1.84
D	4.11	2.04
E	127.53	33.46
F	133.70	32.70
G	55.54	31.93

FIGURE 4.1: EDDY DIFFUSIVITY OF HEAT IN FFTF GEOMETRY (X-COMPONENT) (m^2/sec)

The values range from a low of $.0005 \text{ m}^2/\text{sec}$ at station F to a maximum of $.0077$ at station E. A continuous increase is observed as a function of distance from the inlet at the chimney stations B, C and D. This indicates an increasing turbulence intensity in the u' turbulence component since concurrent with these changes is a decrease in turbulent temperature fluctuation. Therefore, it can be concluded that the increasing turbulence intensity of the horizontal vertical component dominates the decreasing thermal intensity. The maximum value of $\epsilon_{H,x}$ at station E represents a ϵ_H/α ratio of 2.62. The large difference between positions E and F indicate that in the flow configuration E is in the main streamline regime while F is clearly in the recirculation region discussed previously.

4.1.4 $\epsilon_{H,y}$ In the FFTF Geometry

Fig. 4.2 is a map of the calculated values of $\epsilon_{H,y}$ in the FFTF geometry. The absolute magnitudes are dramatically greater than corresponding values of $\epsilon_{H,x}$. The values range from a minimum of $.0009 \text{ m}^2/\text{sec}$ to a maximum of $.2569 \text{ m}^2/\text{sec}$. These higher magnitude observations indicate the concurrence of turbulence intensity of the v' and T' fluctuating components. This type of behavior is expected when the geometry of the inlet region is considered. The minimum value location of station F reaffirms the conclusion that the area of recirculation is monitored at that point. A monotonic

FIGURE 4.2: EDDY DIFFUSIVITY OF HEAT IN FFTF GEOMETRY (Y-COMPONENT)
(m^2/sec)

decrease in the eddy diffusivity magnitude is seen as a function of distance from the inlet indicating complimentary degradation of turbulence intensity in the two correlated components. The maximum value station at B has a ϵ_H/α ratio of 83.1 indicating the predominance of eddy transfer processes in the chimney regime. The depressed value of $\epsilon_{H,y}$ at position E tempers the conclusion that station E is in the major streamline zone and may indicate that it is actually in a transitional flow position which is effected by both the main flow and the recirculation phenomena.

4.1.5 Temperature Gradients in the CRBR Geometry

Using the previously elucidated technique, the thermal gradients at the measurement station of the CRBR geometry are evaluated. Table 4.2 presents a listing of the measured parameters. Besides the smaller vertical gradients compared to horizontal gradients also seen in the other geometry, an interesting effect is evidenced at station D with a measured $\partial T/\partial x$ of 4.11 °C/m. This is significantly lower than other values and points out the effect of the taller chimney structure in that at the top of the chimney regime a fairly uniform temperature field is established.

4.1.6 $\epsilon_{H,x}$ In the CRBR Geometry

The calculated values of $\epsilon_{H,x}$ are presented in Fig. 4.3 in the CRBR situation. Similar magnitude results to the FFTF

FIGURE 4.3: EDDY DIFFUSIVITY OF HEAT IN CRBR GEOMETRY (X-COMPONENT)
(m^2/sec)

results are obtained with the notable exception of station D. In general the values obtained in the chimney region are higher than the FFTF data and the reverse is true in the zones outside the chimney structure where consistently lower values are obtained. This result indicates the change in position of the recirculation vortex in the CRBR geometry since the values obtained at stations, E, F and G indicate that all three locations are controlled by recirculation effects as opposed to interaction with the main stream. The maximum value of $.0818 \text{ m}^2/\text{sec}$ at station D corresponds to a ϵ_H/α ratio of 26.5 and which is indicative of the fully developed turbulent flow conditions caused by the chimney structure. This value is nearly 11 times larger than the value calculated at B only 7.6 cm upstream.

4.1.7: $\epsilon_{H,y}$ In The CRBR Geometry

Fig. 4.4 presents a map of the values of $\epsilon_{H,y}$ calculated from the data measured in the CRBR outlet plenum geometry. The range of values run from a minimum of $.0052 \text{ m}^2/\text{sec}$ to a maximum of $.2225 \text{ m}^2/\text{sec}$. The mapping shows identical characteristics to that presented for the FFTF geometry. The concurrence of turbulent intensity of v' and T' is evidenced by the monotonically decreasing values obtained as a function of distance from the inlet. The significantly lower values measured at all non-chimney locations reinforce the previous indication that due to the higher chimney structure the recirculation zone spans a significantly greater flow area

FIGURE 4.4: EDDY DIFFUSIVITY OF HEAT IN CRBR GEOMETRY
(Y-COMPONENT)

(m²/sec)

and further that the existing flow from the chimney region is much more jet-like in nature than that of the FFTF configuration. The dominance of eddy transfer processes in the realm of energy transport in the chimney region is evidenced in the ϵ_H/α ratio at station B having a value of 72.1. Even the recirculation region the minimum value of this ratio observed at the measuring station is 1.7 indicating that despite the turbulence decay in the region, the turbulent energy exchange represents 63% of the total energy transport.

4.2 Evaluation of the Eddy Diffusivity of Momentum

4.2.1 Calculation of ϵ_M From Measurements

The value of ϵ_M in the desired units is obtained from the following expression:

$$\epsilon_{M,xi} = \frac{(\alpha_v)^2 \times \langle u'v' \rangle}{G_v \times G_D \times \frac{\partial \bar{U}_j}{\partial x_i}} \quad (4.3)$$

where α_v = conversion of volts to m/sec

G_v = gain employed on turbulence processor input

G_D = gain employed on voltmeter input

$\partial \bar{U}_j / \partial x_i$ = velocity gradient ($^1/\text{sec}$)

The explanation of the various gains and conversions is given in section 4.1.1. The velocity gradient was evaluated in a similar fashion to the temperature gradient except the LDA system was employed in the velocity measurements. The separation between measurement points used in the evaluation of the gradient is also 1.27 cm. The values of the gains and conversions

are listed in Appendix B.

4.2.2 Velocity Gradients in the FFTF Geometry

Table 4.3 presents a listing of the measured velocity gradients in the FFTF flow geometry. The sign (positive or negative) is assigned on the basis of a right-handed two dimensional Cartesian coordinate axes pair. It is seen in the evaluation of ϵ_M that the measured sign of the variation is consistent with the signs of the multiplicative correlations observed at the respective measurement points. The velocity field is the clearest indicator of the flow regimes encountered at each point and the conclusions drawn above are reinforced. Of particular note is position D where the highest gradients are observed and are indicative of the redirection of the flow occurring at that position.

4.2.3 $\epsilon_{M,x}$ In the FFTF Geometry

Fig. 4.5 is a map of the measured $\epsilon_{M,x}$ values obtained in the FFTF geometry under inlet temperature upset conditions. The values are calculated under these conditions to allow the evaluation of ϵ_H/ϵ_M which is presented in a later section. As is observed the momentum diffusivity map possesses less severe variation as a function of position than the heat diffusivity map. The values range from a minimum of $.0091 \text{ m}^2/\text{sec}$. The values observed at stations E and F further indicate the different flow fields characteristic of the two locations. The maximum value station E represents a ϵ_M/ν ratio of 16.4 while that of the minimum value location is 4.4. This indicates that

TABLE 4.3: Velocity Gradients In the FFTF Geometry

Position	$\frac{\partial V}{\partial x}$ ($^{\circ}/\text{sec}$)	$\frac{\partial V}{\partial y}$ ($^{\circ}/\text{sec}$)
B	+29.53	+15.75
C	-41.11	-92.91
D	-125.98	-144.36
E	-21.46	-26.38
F	+21.46	+26.38

TABLE 4.4 Velocity Gradients in the CRBR Geometry

Position	$\frac{\partial V}{\partial x}$ ($^{\circ}/\text{sec}$)	$\frac{\partial U}{\partial y}$ ($^{\circ}/\text{sec}$)
B	+9.84	+3.93
C	-6.23	-2.93
D	-2.62	-1.3.
E	+73.23	+13.58
F	-54.28	-30.30
G	-25.85	-55.38

FIGURE 4.5: EDDY DIFFUSIVITY OF MOMENTUM IN FFTF GEOMETRY (X-COMPONENT)
(m^2/sec)

the turbulent momentum exchange processes dominate at all measurement locations and, in particular, in the recirculation regime where the highest turbulent decay is expected, the eddy exchange processes account for over 81% of the total transport. Finally, the increasing value of Reynolds stress as a function of distance from the inlet previously observed is again evidenced in the $\epsilon_{M,x}$ calculations.

4.2.4 $\epsilon_{M,y}$ In the FFTF Geometry

The calculated values of $\epsilon_{M,y}$ in the FFTF configuration are given in Fig. 4.6. The magnitudes are uniformly higher than corresponding $\epsilon_{M,x}$ values listed above. The difference however is not as great as that observed in the comparison of the eddy diffusivities of heat. In addition, the uniformity of the momentum exchange field is again observed. No general trend is observed as a function of distance from the inlet but the measurements at stations E and F are additional pieces of evidence in the conclusion that the flow at station F is predominated by recirculation zone effects. The diffusivity values have a range of $.0229 \text{ m}^2/\text{sec}$ and to $.0964 \text{ m}^2/\text{sec}$. These correspond to ϵ_M/ν ratios of 11.1 to 44.6. The turbulence dominance is again evidenced. Further, the eddy exchange processes in the chimney region in particular account for 97% of the momentum transport in the vertical direction and at station B account for over 98% of the exchange. Therefore, it is clear that neglecting the molecular diffusivities in

FIGURE 4.6: EDDY DIFFUSIVITY OF MOMENTUM IN FFTF GEOMETRY (Y-COMPONENT)
(m^2/sec)

modelling the turbulent momentum interchange introduces less than 5% error in the chimney region.

4.2.5 Velocity Gradients in the CRBR Geometry

Using the laser anemometer and simple difference techniques detailed above, the velocity gradient field of the CRBR outlet plenum geometry is estimated. The calculated values are presented in Table 4.4. The uniformity of the higher chimney region of the CRBR is again evidenced in the mild gradients measured at positions B, C and D. The sign convention employed is a right-handed Cartesian coordinate system.

4.2.6 $\epsilon_{M,x}$ In the CRBR Geometry

Fig. 4.7 is a full scale map of the calculated $\epsilon_{M,x}$ values at the CRBR measurement stations. Greater variance is observed in this geometry as is evidenced by the value range of $.0030 \text{ m}^2/\text{sec}$ to $.4451 \text{ m}^2/\text{sec}$. The area of maximum eddy momentum exchange is clearly the upper chimney region where the value of $\epsilon_{M,x}$ corresponds to an ϵ_M/v ratio of 206.9 which represents a turbulent contribution to momentum exchange in the x-direction of 99.5%. The average value of ϵ_M/v in the chimney region is 117.7 while that of the non-chimney stations is 5.93. Therefore, significant turbulence decay occurs once the flow exits the chimney region. Finally, a monotonic increase in $\epsilon_{M,x}$ is observed as a function of distance from the inlet in the chimney region. This is identical to the trend seen in the FFTF measurements.

FIGURE 4.7: EDDY DIFFUSIVITY OF MOMENTUM IN CRBR GEOMETRY
(X-COMPONENT)

(m^2/sec)

4.2.7 $\epsilon_{M,y}$ In the CRBR Geometry

Fig. 4.8 presents the calculated $\epsilon_{M,y}$ values corresponding to data measured in the CRBR geometry. The uniformly larger magnitudes of this vertical exchange parameter as compared to the horizontal exchange is observed as it was in the FFTF configuration. Distinct from the FFTF data, a monotonic increase in magnitude as a function of distance from the inlet is observed. The position of maximum value is station D with a magnitude of $.8901 \text{ m}^2/\text{sec}$ and the minimum occurs at G with a value of $.0084 \text{ m}^2/\text{sec}$. The equivalent ϵ_M/ν ratios at the two positions are 413.4 and 4.2. The mean ϵ_M/ν ratio of the vertical transfer mechanisms is 264.7 in the chimney region, which corresponds to a turbulent dominance of 99.6%. Finally, while the magnitude ranking of the non-chimney stations changes between the $\epsilon_{M,x}$ and $\epsilon_{M,y}$ measurements, the absolute value in both cases are on the order of 4% of the chimney regime data.

4.3 Calculation and Evaluation of ϵ_H/ϵ_M

4.3.1 $(\epsilon_H/\epsilon_M)_x$ In the FFTF Geometry

The dimensionless ratio of eddy diffusivity of heat to eddy diffusivity of momentum is the inverse turbulent Prandtl number and represents a comparison of the eddy exchange character of heat compared to that of momentum. It is of particular importance in the proper analysis of complex turbulent flow fields since in many cases the direct evaluation of ϵ_M is possible and a value of ϵ_H is inferred by analogy.

FIGURE 4.8: EDDY DIFFUSIVITY OF MOMENTUM IN CRBR GEOMETRY
(Y-COMPONENT)

(m^2/sec)

 TABLE 4.5 $(\epsilon_H/\epsilon_M)x$ In the FFTF Geometry

<u>Position</u>	<u>$(\epsilon_H/\epsilon_M)x$</u>
B	.119
C	.065
D	.211
E	.227
F	.055

 TABLE 4.6 $(\epsilon_H/\epsilon_M)y$ In the FFTF Geometry

<u>Position</u>	<u>$(\epsilon_H/\epsilon_M)y$</u>
B	2.665
C	3.071
D	1.743
E	.014
F	.039

In most turbulence models the relationship between ϵ_H and ϵ_M embodied in the parameter E is either set at a constant value or stated as a function of the Prandtl number. It is evident from the data presented that such simple schemes are inadequate in complex flow situations. Table 4.5 presents the tabulated value of the ratio at the measurement stations of the FFTF inlet plenum geometry. The mean value of the ratio is .135 but as can be seen the use of this average value at any of the measurement locations would introduce errors of 12 to 68%.

4.3.2 (ϵ_H/ϵ_M) In the FFTF Geometry

Table 4.6 presents the calculated ratios of the eddy viscosity and eddy thermal diffusivity in the vertical direction in the FFTF flow configuration. The most significant difference between these data and the horizontal ratio is the fact that in the chimney regions the value of the ratio exceeds unity and this is never observed in the horizontal results. In addition, this tendency is for the most part not observed in the CRBR data except for one measurement station.

From the observation of the ratio values and their corresponding positions it is seen to be very inaccurate to describe the ratio in terms of an average constant ratio. The clearly defined differences of the ratio at respective measurement locations when the two components are compared are indicative of the fundamentally different turbulence characteristics of

the u' and v' temporal components.

4.3.3 $(\epsilon_H/\epsilon_M)_x$ In the CRBR Geometry

The ratio $(\epsilon_H/\epsilon_M)_x$ is presented in Table 4.7 similar trends to those seen in FFTF results are observed. First, the ratio never exceeds a value of unity and in fact has a range almost identical to that of the FFTF results. The use of an average ratio value is also very inaccurate in this situation since an employment of the mean value of .111 at each location would introduce an average error of over 68%. It is interesting to note that the ratio peak value of .267 occurs at station E which has been shown to be in the recirculation region.

4.3.4: $(\epsilon_H/\epsilon_M)_y$ In The CRBR Geometry

The results of the $(\epsilon_H/\epsilon_M)_y$ calculations in the CRBR geometry are significantly different from the FFTF results in that the departure of values to magnitudes greater than unity is not observed except at station B and at that station the value is 1.163 as compared with 3.071 at station D in the FFTF configuration. This difference indicates significant distinction between the flow fields and points to an area where turbulence modelling must be more exact. Table 4.8 presents the ratio value for the CRBR case. As can be seen the use of an average value of the ratio such as the arithmetic mean will introduce significant error. A monotonically decreasing trend is also observed as a function of distance from the inlet in the chimney region.

TABLE 4.7 $(\epsilon_H/\epsilon_M)_x$ in the CRBR Geometry

<u>Position</u>	<u>$(\epsilon_H/\epsilon_M)_x$</u>
B	.101
C	.031
D	.184
E	.267
F	.034
G	.050

TABLE 4.8 $(\epsilon_H/\epsilon_M)_y$ In the CRBR Geometry

<u>Position</u>	<u>$(\epsilon_H/\epsilon_M)_y$</u>
B	1.163
C	.302
D	.099
E	.297
F	.247
G	.619

4.3.5 Average Values of (ϵ_H/ϵ_M)

It is useful to determine the average ratio of ϵ_H/ϵ_M at the various positions in order to detect indications as to where the greatest turbulence modelling difficulties appear. Table 4.9 presents such a list of tabulized values. The simple arithmetic mean of the x and y values of (ϵ_H/ϵ_M) are used. The variance is markedly greater in the FFTF geometry and further, the geometry possesses a higher overall flow averaged ratio. It can be concluded from this table that while the use of a constant or simple Prandtl number functional relation for the calculation of the ratio in the FFTF geometry is not required such an application in regard to the CRBR flow field may be appropriate for support of this hypothesis, the use of the average value of .283 in the CRBR geometry introduces an average error of 60% as opposed to well over 100% in the FFTF geometry. Further refinement of the modelling may be made in prescribing an average ratio for the chimney and non-chimney regimes respectively. This modelling scheme when applied to the presented data introduces the following error magnitudes: 51% in the CRBR geometry and 29% in the FFTF configuration. Nevertheless, it is clear from this discussion that it can be concluded that the use of a constant turbulent Prandtl number model is inapplicable and more detailed modelling must be employed.

4.4 Spectrum Measurements

Analysis of the spectral intensity data presented in

 TABLE 4.9 Average Values of (ϵ_H/ϵ_M) In Both Geometries

<u>Geometry</u>	<u>Position</u>	<u>(ϵ_H/ϵ_M)</u>
FFTF	B	1.392
FFTF	C	1.568
FFTF	D	.977
FFTF	E	1.21
FFTF	F	.047
FFTF	Average	.821
CRBX	B	.632
CRBR	C	.167
CRBX	D	.142
CRBR	E	.282
CRBR	F	.141
CRBR	G	.335
CRBR	Average	.283

Section 3 illustrates that the frequency structure of a turbulent flow field can be a useful measurement tool in the modelling of turbulence. A comparison of eddy diffusivities calculated above and RMS signal fluctuations show a direct correlation. In fact careful study of the spectrum measurements lead to the same qualitative conclusions deduced from the detailed measurement and calculation of the eddy diffusivities. The most important result of the spectrum measurements is the universal characteristic of the outlet plenum geometry to exhibit less turbulence decay in momentum exchange than in heat exchange. This is seen from significant upper bound velocity frequencies of 5-10 kHz in the non-chimney regions of both geometrics while temperature fluctuations in those regimes barely approach 1 kHz and are mostly less than 500 Hz. In addition, the measurement of velocity fluctuation frequency spectra give good indication of the developing nature of the flow field as is evidenced by measurements at station D in the FFTF geometry where the significant degree of flow reduction is mirrored in increased frequency levels.

The upper bound frequency can also be related to the turbulence length scale characteristic of the flow. By equating the conduction and convection terms of heat exchange the following relationship is derived:

$$\bar{l} = \left(\frac{2\pi\alpha}{w_c} \right)^{1/2} \quad (4.4)$$

where $\bar{l}$ = characteristic length
 w_c = upper bound frequency

Using the properties of air at 50°C and an upper bound frequency of 15 kHz for velocity, a characteristic length of 1.1 mm is calculated. The corresponding heat exchange length scale is 1.9 mm based on a cutoff frequency of 5 kHz. Therefore, by utilizing experimental data as to the upper bound frequency of another coolant flow such as sodium in an LMFBR a characteristic turbulence length may be calculated. The relationship between the air measurements and the modelled flow could then be used in turbulence scaling and in estimating the magnitude of turbulence effects herein described.

4.5 Error Analysis

4.5.1 Reproduceability

Data reproduceability of the measurement technique is of high quality but two independent sources of inaccuracy must be monitored to insure measurement integrity. In the interferometric temperature system, the voltage output is assumed to be a linear analog. The linearity assumption is based on the initial alignment of the system in a manner

such that the product interference pattern contains only one fringe which is focused on a half maximum. This alignment utilizes the middle range of the $\cos^2$ type intensity function which is approximately linear. Great care is taken in monitoring the vibrational characteristics of the optical bench and optical path lengths in order to maintain the prescribed configuration. Unfortunately, every few minutes during a data run the fringes shift due to unavoidable environmental disturbances which cause a loss in linearity and reproduceability. Therefore constant monitoring of the interferometric alignment is incorporated into the prescribed experimental procedures.

In addition to the sensitivity outlined above, the laser anemometer can also be a source of data distortion. As has been detailed, the data rate and hence velocity signal validity is a direct product of the quality and quantity of flow seed. The signal processor of the LDA has a lower limit as to data rate in order to follow the turbulent flow field dutifully, and if the data rate (which is linearly proportional to seed rate) drops below this validity plateau, the data becomes spurious and cannot be treated as a continuous signal, which is an underlying assumption of the correlation measurements. Therefore seed injection rates are maintained at levels high enough to insure proper output data continuity. The motivation in keeping seeding rates as low as possible is significant; however, since excessive test cell occlusion and saturation conditions of the electronic processing systems due to

excessive data rates must be minimized. Incorporating these limitations into the measurement procedures establishes good data reproducibility which has an average deviation of $\pm 2\%$.

4.5.2 Error Estimation

The purpose of this section is to identify and estimate the errors involved in the calculation of the eddy diffusivities of heat and momentum. Assuming that the sources of error are multiple and independent the theory of compounding errors is applied. Further the error terms are assumed to be symmetric about a zero deviation. These assumptions applied to the basic theory, allows the square of the error to be defined by the equation:

$$\Delta \epsilon = \sum_{i=1}^m \left(\frac{\partial F}{\partial x_i} \right)^2 (dx_i)^2 \quad \text{where } \Delta \epsilon = \text{error in } \epsilon \quad (4.5)$$

$$\epsilon = F(x_1, x_2 \dots x_m).$$

The eddy diffusivity of heat is calculated from the measured correlation analogs as follows:

$$\epsilon_{H,x} = \frac{\alpha'_v \times \alpha'_T \times \langle v'T' \rangle}{\frac{\partial T}{\partial x}} \quad \text{where } \alpha'_v = \text{velocity unit conversion} \quad (4.6)$$

$$\alpha'_T = \text{temperature unit conversion}$$

(The horizontal value is used here as an illustration). The equation can be cast in the general form:

$$\epsilon_H = x_1 x_2 x_3 x_4 \quad (4.7)$$

and using the derived equation for the square of the error, the following expression results:

$$\frac{\Delta \epsilon_H}{\epsilon_H} = \left\{ \left[\frac{\Delta x_1}{x_1} \right]^2 + \left[\frac{\Delta x_2}{x_2} \right]^2 + \left[\frac{\Delta x_3}{x_3} \right] + \left[\frac{\Delta x_4}{x_4} \right] \right\}^{1/2} \quad (4.8)$$

In order to evaluate this equation, the four percentage error terms must be estimated. Since x_1 and x_2 relate to α'_v and α'_T which are unit conversion terms, a value of 100% accuracy is assigned to these parameters. The estimation procedure used in evaluating the temperature gradients embodied in the x_4 term is assigned an accuracy of $\pm 5\%$ due to errors in thermocouple positioning and microvoltmeter accuracy. The $\Delta x_3/x_3$ term is the most complex since it involves the compounding of several sources of error. The identified sources of inaccuracy are the temperature system, laser anemometer, turbulence processor, voltmeter, data variance, and the transcription of data. The temperature system error is estimated to be $\pm 5\%$ which comes about from an analysis of the fringe pattern stability as a function of time. Reproduceability studies indicate an LDA accuracy of $\pm 3\%$ in regards to velocity measurements. The variation is chiefly due to the frequency broadening induced by the imperfection of the seeding scheme. The turbulence processor has a stated but unconfirmed manufacturer's accuracy of $\pm 2\%$. The voltmeter has a similar accuracy of $\pm 0.5\%$. The error

assigned to the visual transcription procedure is 1% due to the care taken when data was recorded. In addition, the correlation data has an average variance of $\pm 5.7\%$. Using these estimations the following calculational error is calculated:

$$\frac{\Delta \epsilon_H}{\epsilon_H} = \left[(0)^2 + (0)^2 + [(.05)^2 + (.03)^2 + (.02)^2 + (.01)^2 + (.01)^2 + (.057)^2] + (.05)^2 \right]^{1/2} = 9.7\% \quad (4.9)$$

This calculation is conservative and overestimates the actual error since it assumes that the errors of the the temperature and velocity systems are completely correlated in the multiplicative correlation analogs. If the optimistic assumption of complete non-correlation of errors is made, the error estimate drops to a value of 5.5%. Therefore it can be concluded that the actual error is bounded by 9.8% and 5.5%.

The eddy diffusivity of momentum is calculated using the following relation:

$$\epsilon_{M,x} = \frac{(\alpha' v)^2 \times \langle u'v' \rangle}{\partial U_x / \partial y} \quad (4.10)$$

which has the general form

$$\epsilon_M = x_1 x_2 x_3 \quad (4.11)$$

In the case of the $\langle u'v' \rangle$ analog measurements, the errors involved in the LDA detection of u' and v' are assumed to be

completely uncorrelated and therefore the sources of inaccuracy in the x_2 term are reduced to the turbulence processor, voltmeter, data variance and data transcription. In addition the x_3 term embodies the accuracy of the velocity gradient estimation. All values have been estimated above except for the velocity gradient accuracy which is assigned a value of $\pm 3\%$ which is the overall LDA accuracy previously discussed and the average data variance which is 4.8% . Using these assumptions, the following error estimation is made:

$$\frac{\Delta \epsilon_M}{\epsilon_M} \left\{ [0]^2 + [(.02)^2 + (.01)^2 + .01^2 + (.041)^2] + (1.03)^2 \right\}^{1/2} \\ = 6.1\% \quad (4.12)$$

V. Conclusions and Recommendations

5.1 Conclusions

The optical technique developed in this work is proven to be an accurate method for the evaluation of the eddy diffusivity of heat of a transparent flowing medium. Further, upon using the proper electronic data analysis equipment, the Reynolds stress, and hence, the eddy diffusivity of momentum is measured in the same experimental environment. The overall calculational accuracies of the eddy diffusivities of heat and momentum are shown to be $\pm 10\%$ and $\pm 6\%$ respectively.

Spectral analysis of the analog electronic signals is performed, and shown to be a good predictive tool in the study of the turbulent recirculating flow field. The measurements indicate that the velocity field is of a greater turbulence intensity than the temperature field at all measurement stations. Differences in the horizontal and vertical velocity components are evidenced in the spectral analyses.

The measurement system is incapable of attaining accurate data in low flow regimes due to the pronounced occlusion of the test cell walls by the flow seeding particles. All measurements indicate that most significant temperature oscillations occur closet to the inlet at locations tractable by the system.

Evaluation of ϵ_H and ϵ_M show significant anisotropic tendencies in regard to the flow direction with the $\epsilon_{H,y}$ values having magnitudes many times those of the $\epsilon_{H,x}$ terms. Such anisotropic behavior is not observed as strongly in the map of eddy diffusivity of momentum values. Analysis of the difference show that while the multiplicative correlation values are similar in all cases, there are significant differences in the character of the temperature gradient in the x and y directions. It is further noted that the departure from isotropy observed in the eddy diffusivity of momentum data arises from the "momentum upset" introduced at the inlet due to the density induced-increased slip conditions caused by the differential heating of the inlet jets.

The ratio of ϵ_H/ϵ_M calculations indicate that a complex relationship between parameters exists, and it is concluded that modelling the ratio as a constant or as a simple function of Prandtl number is not valid. A more detailed model taking into account the departure from isotropic turbulence should be employed.

The most significant difference between the observed FFTF and CRBR outlet plenum flow fields results from the higher chimney structure of the latter geometry. A more uniform temperature field is found in the taller chimney region as is evidenced by milder temperature gradients. Second, the upper region of the taller chimney exhibits unique behavior due to the fact that it is the only regime of either geometry which

is not influenced by hydrodynamic or thermal entrance length effects. Of particular note is the decrease in anisotropy of ϵ_H at this location. The predominance of the structure in the CRBR geometry makes the flow path to the outlets more restrictive and causes a larger recirculation region to exist. The outlet of the chimney can be successfully modelled as a vertical jet in the CRBR geometry while in the FFTF configuration significant flow redirection occurs at the chimney height. Finally, the chimney regimes in both geometrics experience a much greater turbulence intensities than the other flow regions as is evidenced in Table 5.1.

5.2 Recommendations

In the area of experimental procedures, a solution to the occlusion problem needs to be found in order to allow a complete mapping of the geometry. The approach to solving this dilemma is either in finding a better seed particle or in devising a more efficient seed injection system or both. A more uniform seeding system will also reduce data variation.

The data acquisition technique should be upgraded as to eliminate transcription errors and to achieve more uniform data history. An analog or digital electronic arrangement is suggested as a suitable alternative. The optical bench which determines the vibrational sensitivity of the interferometer should be upgraded in order to allow a more liberal measurement schedule and relieve the location limitations heretofore present in the apparatus.

TABLE 5.1: $\bar{\epsilon}_{H/\alpha}$ and $\bar{\epsilon}_{M/v}$ In Both Geometries

<u>Geometry</u>	<u>Position</u>	<u>$\epsilon_{H/\alpha}$</u>	<u>$\epsilon_{M/v}$</u>
FFTF	B	41.8	26.0
FFTF	C	21.9	17.2
FFTF	D	15.8	15.2
FFTF	E	1.5	29.8
FFTF	F	0.3	8.3
CRBR	B	37.4	62.1
CRBR	C	32.1	201.4
CRBR	D	27.6	310.1
CRBR	E	1.1	5.1
CRBR	F	1.2	10.1
CRBR	G	1.1	6.6

In the realm of analytical and experimental investigations, the most intriguing questions involve the departure from directional isotropy in the eddy diffusivities and the establishment of a useable model in the valuation of the ratio of ϵ_H/ϵ_M at all measurement locations.

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Appendix A: Equipment List

1. Coherent Light Source
 - 1.1 Spectra Physics Model 125A Helium-Neon Gas Laser
(50 mW)
2. Laser Doppler Anemometer
 - 2.1 TSI (Thermo-Systems, Inc.) Model 910-2 Transmitting Optics using Model 917 Focusing Lense
 - 2.2 TSI Model 982-2 Frequency Shift Optical Unit
 - 2.3 DISA Model 55LI2 Photomultiplier with High Voltage Source at 1800 Volts (Negative Polarity)
 - 2.4 TSI Custom Design Transimpedance Amplifier
 - 2.5 TSI Model 985 Frequency Shift Supply and Mixer
 - 2.6 TSI Model 1090 Signal Processor
3. Data Analysis Equipment
 - 3.1 DISA Model 52-B25 Turbulence Processor using AC Coupling and $G_A = G_B = 10 \sqrt{10}$
 - 3.2 DISA Model 55D35 RMS Voltmeter
 - 3.3 TSI Model 1076 Digital Voltmeter
 - 3.4 Hewlett Packard Model 141B Storage Oscilloscope
 - 3.5 Nelson Ross Model 235 Plug-in Spectrum Analyser
 - 3.5 High Pass Filter (200 kHz) For Temperature Signal

Appendix B:

Factors Used in Eddy Diffusion Calculations

1. FFTF Calculations

	$\epsilon_{H,x}$	$\epsilon_{H,y}$	$\epsilon_{M,x}$	$\epsilon_{M,y}$
α_T	8.33	8.33	-	-
α_V	12.05	12.05	12.05	12.05
$G_T \times G_V$	100	100	-	-
G_V	-	-	$10\sqrt{10}$	10
G_D	1	3.16	1	1

2. CRBR Calculations

	$\epsilon_{H,x}$	$\epsilon_{H,y}$	$\epsilon_{M,x}$	$\epsilon_{M,y}$
α_T	8.33	8.33	-	-
α_V	12.05	12.05	12.05	2.05
$G_T \times G_V$	100	100	-	-
G_V	-	-	$10\sqrt{10}$	$10\sqrt{10}$
G_D	1	3.16	1	1