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STUDY OF FLUID FLOW DURING DIRECTIONAL SOLIDIFICATION OF H_20-NH_4Cl USING A PARTICLE DISPLACEMENT TRACKING TECHNIQUE

A Thesis

Presented for the

Master of Science

Degree

The University of Tennessee, Knoxville

Ram Sivakumaran

December, 1994

DEDICATION

This thesis is dedicated to
my Parents
and to
my Brother

ACKNOWLEDGMENTS

I am greatly indebted to my major professor Dr. Mary Helen McCay for all her guidance, encouragement, and support given to me at every stage during the successful completion of this project.

I wish to thank Dr. T. Dwayne McCay, Dr. Roger Crawford, and Dr. John Hopkins for serving on my thesis committee. The valuable comments and suggestions they made have significantly contributed to the quality of this work, and is greatly appreciated.

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ABSTRACT

The fluid flow during directional solidification of NH_4Cl-H_2O was studied using a Particle Displacement Tracking (PDT) technique. The study applied orthogonal multiple-plane microscopic particle tracking and automated digital analysis to construct quantitative, three-dimensional velocity fields within regions of particular interest. The structure of jetting convection and fluid velocities were determined.

One experiment condition was selected: Temperature Gradient, G = 15°C/cm, Cooling Rate, CR = 60°C/hr. The duration of the experiments were 35 minutes. Two runs (designated Run 1 and Run 2) were analyzed using this technique.

Typical flow velocities during Run 1 ranged between 0.3 and 0.5 mm/s. Overall flow activity in the all-liquid region at time, t = 5 min, was observed to be minimal. The flow activity then sharply increased until t = 10 min. It continued to increase at a lesser rate reaching the peak at t = 20 min, the flow activity was seen to decrease gradually until the end of the run, t = 35 min.

Towards the end of Run 2, at approximately t = 35 min, a jet occurred. A jet is characterized by a channel of liquid, originating from the mushy zone, which travels upward and out of the mushy zone into the all-liquid region, with velocities within the channel being much greater than the velocities of the surrounding fluid. The surrounding liquid, in general, is found to travel downward, opposite in direction to the jet. The jet diameter was between 1.5 and 2 mm. Typical jet upward flow velocities ranged from 1 to 2.5 mm/s, with the central core of the jet exhibiting the highest velocity. The jet velocity radially decreased away from the core. The activity level at t = 35 min of the flow with the jet was observed to be greater than the activity of the flow without the jet.

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NOMENCLATURE

CR	Cooling Rate (°C/hr)
G	Temperature Gradient (°C/cm)
i	Row index in an image array
j	Column index in an image array
T_{bf}	Cuvette Bottom Final Temperature (°C)
T_{bi}	Cuvette Bottom Initial Temperature (°C)
T_{tf}	Cuvette Top Surface Final Temperature (°C)
T_{ti}	Cuvette Top Surface Initial Temperature (°C)
V	Total velocity vector (mm/s)
V	Magnitude of the total velocity vector - Speed (mm/s)
V_x	X-velocity component (mm/s)
V_y	Y-velocity component (mm/s)
V_z	Z-velocity component (mm/s)
S	Normalized summation of the magnitude of the total velocity vector (speed), summed over the entire interrogation area (mm/s)

I. INTRODUCTION

Convection plays an important role in the solidification of metal alloys, and hence the study of convective fluid flows is important in determining the various characteristics associated with solidification processes. Convection causes such effects as material segregation and the formation of channels and jets. These effects are undesirable since they tend to degrade material strength, along with other material properties. Hence, the understanding of convection related phenomena is essential for the implementation of solidification processes that are free of defects.

In this study, the directional solidification (growth direction is from bottom to top) of H_2O-NH_4Cl is observed. H_2O-NH_4Cl is chosen as the test solution, since its behavior is close to that of a metal alloy with the added convenience of being transparent. The transparency allows observation of the various phenomena associated with convection within the alloy during solidification.

In solidification of alloys, solute redistribution can initiate convective flows within the solution. Typically, one constituent of the liquid phase is preferentially incorporated into the solid phase, which creates a liquid interface near the solidification front whose density is different from that of the bulk liquid. For many alloys, the density of this liquid is less than the bulk liquid density, and hence upon rejection of this liquid from the solid-liquid mushy zone (due to perturbations or disturbances), the liquid tends to rise causing convective motion.

Particle tracking techniques have been applied to study convective fluid flow motion in previous studies. However, few studies have quantified fluid velocity fields. Most of these studies have dealt with quantifying velocities in a two-dimensional field.

In this study, the Particle Displacement Tracking (PDT) technique is used at multiple planes in two orthogonal directions to arrive at quantitative composite three-dimensional velocity fields that characterize the flow field during several regimes of solidification. A particular region within the test cuvette that includes the liquid-solid interface region and the liquid region above the interface is observed continuously starting at a time just before solidification is initiated, and ending at a time just after solidification is terminated. The convective flow above the liquid-solid mushy zone is studied through several solidification stages (e.g., initial interface breakdown, formation of channels and jets, etc.). The objective of this study is to demonstrate the utility of the three-dimensional PDT technique for this particular study by characterizing fluid motion for several flow regimes during directional solidification.

II. BACKGROUND

2.1 PIV Vs PDT

Particle Displacement Tracking (PDT) is a relatively new flow visualization and quantification technique that has evolved from the widely used technique of Particle Image Velocimetry (PIV) (Adrian, 1989).

In this section, a brief overview of the PIV technique is given, followed by a short discussion of the advantages the PDT technique has over PIV. The remainder of the section outlines some of the PIV and PDT related work conducted by other researchers thus far.

In the PIV technique, a cross section of a seeded flow is illuminated by means of a strong light source (typically, that of a laser, whose beam is sent through a cylindrical lens to produce a light sheet). The laser is pulsed for a required length of time, and the time separation between pulses is controllable and known. During the pulsing, the in-plane positions of particles entrained in the flow at two or more instances in time are recorded onto a photographic plate (i.e., at the first laser pulse, the particles in the plane of the light sheet are recorded, then, after a known period of time, during which the particles have moved, a subsequent laser pulse illuminates the plane of reference capturing the displaced particle locations on the same film). The pulsing of the light source may be achieved by pulsing the laser, using a shutter or a chopper between the light source and the recording apparatus, or by scanning the laser beam through the cross-section of the flow by means of a rotating or vibrating mirror. Subsequently the photographic image is processed region by region to measure the displacement of particles from the first to the subsequent

exposures, and hence producing an instantaneous velocity vector map of the entire plane in the flow field. From the instantaneous velocity vector fields, derivative quantities (e.g., vorticity, rate of strain), and integral quantities (e.g., circulation, fluxes) can be calculated. (Adrian, 1989; Buchhave, 1992; Bjorkquist, 1990; Molezzi, 1992; Wernet, Sept. 1990, Aug. 1991)

Analysis of an image is performed by subdividing the image into smaller interrogation zones, and then applying one of the many techniques available to each of the zones. Typically three methods are used to determine the displacement information from the images: (i) two-dimensional Fast Fourier Transform of the fringe spacing and direction of Young's fringes resulting from the interference patterns created by the particles illuminated by the interrogation laser beam, (ii) direct two-dimensional auto correlation of the PIV image, and (iii) probability analysis of the displacement information on the PIV image (Buchhave, 1992; Bjorkquist, 1990). Bjorkquist used a method of data validation in which each vector in the vector field is compared with the average of the neighboring vectors for a tolerance. If tolerance is not met, the vector is considered bad and is removed from the field, and is not used for the subsequent averaging process. This method may be carried out for several passes.

Although PIV provides high precision estimates of velocity (accuracy $\pm 1\%$), processing of the images is tedious and time consuming, in the order of hours (Wernet, Sept. 1990). In addition, Buchave outlines the following technical characteristics associated with PIV: (i) PIV requires small scattering particles at high concentration in the flow. The ideal particle size would be one that will accurately follow the flow, at the same time scattering enough light to create a particle image that is of sufficient quality. (ii) The ability to resolve small spatial velocity scales, which depend on good spatial resolution. Good

spatial resolution is obtained when the measurement volume is small (i.e., the laser sheet thickness times the interrogation area is small). (iii) PIV requires low measurement noise and signal dropout.

PDT has a number of advantages over PIV. PDT uses all electronic acquisition and processing systems, and hence, no chemical processing of photographic plates is necessary. The added hindrance of photographic plate breakage, and cataloging and storage of plates is eliminated. Due to system integration and due to the fact that there is no media conversion required, a single computer can be used to perform all the processing jobs, adding to the simplicity of the PDT technique over the PIV technique. In general, no operator intervention is required in the data reduction phase, provided the obtained images are relatively free of background noise and the particles are well illuminated. In the event that they are not, the contrast of the image has to be modified such that little or no noise is retained, while preserving the particles. The drawbacks of the PDT technique are: (i) low resolution of available CCD cameras limits the spatial resolution of the obtained image, (ii) false identification of velocity vectors in regions of small displacement and high particle concentration, and (iii) due to the maximum framing rate allowed by the video camera (typically 1/60 to 1/30 second), extremely high speed flows cannot be studied, since a particle could move out of the area being analyzed between consecutive frames.

2.2 Previous Work

In 1991, Trolinger et al., used holographic PIV to observe and quantify minute convective currents during crystal growth. Their objective was to compare this flow field with the flow field when solidification occurs in space aboard the International

Microgravity Laboratory I (IML-I) which was scheduled to fly in 1992. The microgravity environment of space reduces the gravity driven convection, resulting in diffusion becoming the dominant mechanism of material transport. Polystyrene spheres were used as the seed material, and ranged in size from 300-600 μm. The flow field was illuminated by a HeNe laser, and multiple exposure holograms were used for the analysis.

Buchhave (1992) reports of another group namely, K. Hinsch, H. Hinrichs, G. Kuhfahl, and P. Meinlschmidt, who have successfully used a holographic PIV system to record 3-D flow configurations. They accomplished this by taking advantage of depth discrimination based on a multiple reference beam hologram, in which, different planes in the flow field are recorded using different reference beams on the same hologram.

Arroyo et al., 1992, at Ciudad Universitaria studied a 3-D Rayleigh-Bernard convective flow in a box. They accomplished three-dimensionality of the results by combining PIV measurements in 15 parallel fluid planes. By combining all the in-plane vectors from the 15 planes, out of plane vectors were calculated by numerical processing based on the integral form of the continuity equation. They used a 5mW HeNe laser (light sheet of thickness less than 150 μm), with pulse separation of 100 ms. Data was reduced using fringe analysis. The investigators were able to visualize and quantify a phenomenon that was not identified earlier when similar flows have been analyzed using 2-D techniques. The final flow structure displayed four vortex rolls separated by three non-flow surfaces, instead of the two vortex rolls reported previously using 2-D techniques. In addition, each roll was observed to have a double helical configuration. Flow from the wall to the mid region was through the inner helix, and flow from the mid region to the wall was through the outer helix.

The majority of the work in which PDT has been successfully applied to various flow situations has been done by Wernet at the NASA Lewis Research Center.

In 1990, 1991, Wernet, together with Pline, investigated a counter-rotating vortex flow by employing the PDT technique. A cylindrical reservoir with silicone oil, seeded with 50-60 μm alumina particles was used where a tubular heater drives a toroidal convection cell flow. The cross-section was observed to have two counter-rotating convection vortices. The experiment was a preliminary ground test study of the NASA Surface Tension Driven Convection Experiment (STDCE), which was to be flown on a future shuttle mission. A 5 mW HeNE laser was used to project a light sheet of 1 mm thickness. Five video fields were obtained at a time interval of 1/60 sec., using an EPIX 4-MEG video frame grabber, installed in a 80386 PC, with a Weitek 3167 co-processor. The PDT technique resolved over 1100 velocity vectors. The reported accuracy of the centroid locations of the particles were ±0.5 pixels. The technique is applicable to velocities less than 20 cm/sec. The total processing time was 11 sec/data set. (Wernet, Aug. 1990, Sept. 1990; Wernet and Pline, 1991).

Wernet, Aug. 1991, then applied the technique successfully to measure high speed gas velocities, where the flow was from a nozzle, where velocities varied from 0.1 m/s to as high as 150 m/s. Here, he used a continuous wave, 18 W argon-ion laser. The flow was seeded with 1 μm polystyrene latex spheres. The flow was recorded via a single intensified, gated CCD camera with RS-170 video CCD chip. An 80386 PC with the EPIX 4-MEG frame grabber was used. Vector maps were displayed 40 seconds after data acquisition was completed. As before, 2-D velocity vector fields of the flow were produced.

Prior work conducted at the Solidification Physics (CAST) Laboratory at UTSI had incorporated another particle tracking method that used solutions seeded with particles for flow visualization. In this method, several images were frame grabbed by the computer at known time intervals, and information from all the images were superimposed onto a single image. By noting the initial and final positions of a particular particle in the composite image, the distance traveled by the particle was easily determined. Since the total time between the first and the last image were known, the speed of the particle was easily estimated. The direction (angle) of the particle is also determined from the initial and final pixel locations of the particle. Although this method allowed for determination of velocities of particles, it was tedious and time consuming, since every single particle in the image needed to be manually processed on an individual basis.

The PDT technique used in this study essentially uses the same logic for velocity determination as the one used in the above mentioned study, only the determination of velocity vectors is carried out in an automated fashion, such that all particles are processed simultaneously in a fashion that requires no human intervention. The technique is outlined in detail in Section 3.3.

2.3 Present Study

Although some investigators have used PIV successfully to study and quantify three-dimensional flows (e.g., see, Trolinger, 1991; Buchhave, 1992 (using a holographic PIV system); Arroyo, et al., 1992 (by superimposing velocity vector fields from several fluid planes, and then applying continuity), this author is not aware of any work reported in the literature where PDT has been successfully implemented to obtain 3-D information.

In this study an attempt is made to successfully apply the all-electronic PDT technique to obtain 3-D information about fluid flow during solidification of a transparent metal model (H_20-28wt%NH_4Cl) which solidifies dendritically. The PDT technique was chosen since it is a natural extension of the particle tracking method used in previous CAST studies. The PIV technique was not considered because of the same reasons outlined in the earlier section, especially the elimination of the need to process photographic plates, the reduction in total processing time, and system integration and simplicity. Another important factor in choosing PDT for this particular study was that all the necessary system hardware elements were readily available in the laboratory (e.g., microscopic cameras, VCR, computer with a frame grabber board, etc.). Only the software needed to be modified and customized to accommodate for the existing hardware.

The technique used for Particle Displacement Tracking in this study is based on the technique developed by Wernet (1990, 1991) at NASA Lewis Research Center. However, the hardware used by Wernet is in many ways different from the hardware used in this study. The major difference is the frame grabber board used for acquiring and digitizing image frames from the video tape. The software used in this study is based on Wernet's, however it incorporates additions and changes to account for the specific hardware used at UTSI, and to account for the phenomenon studied. A detailed description of the PDT technique is provided in Section 3.3.

The flow field in a specific interrogation volume above the mushy zone (the region where the material is not completely solidified and contains both solid and liquid) is studied during directional solidification. Growth direction is from bottom to top, as the bottom

surface of the cuvette is maintained at a lower temperature than the top. The interrogation volume is constituted in the following manner: The field of view of each camera (at a magnification of 1) is approximately 6.5 mm (width) by 4 mm (height). Two-dimensional information at seven planes separated by a distance of 0.5 mm is gathered in two orthogonal directions. All fourteen planes from both orthogonal directions are then combined. The locations of the planes are chosen such that the centers of the fourth plane in both directions coincide. The resulting interrogation volume is 6.5 X 6.5 X 4 mm.

The interrogation volume is fixed (throughout the entire run) at a certain height above the mushy zone (typically at 0.5 mm), such that fluid flow in that same region is observed through the complete solidification period. During solidification, as the mushy zone interface moves upward, the interrogation volume is also moved such that the distance between the mushy zone and the bottom of the interrogation volume is unchanged. This is done by translating the table that contains the cuvette assembly the appropriate vertical distance. Information is gathered within a period of time at distinct time intervals during the course of a solidification run, and the vertical table adjustment is carried out just prior to the beginning of each of the time periods analyzed.

The data gathered in the interrogation region over the period of solidification is analyzed to characterize the flow field at the various stages of solidification.

Typically, jets occur during solidification of the H_2O-NH_4Cl system. A jet, as referred to in this study, is an approximately cylindrical column of fluid (typically 1 - 1.5 mm in diameter) that traverses vertically in an upward direction with fluid speeds on the order of 1 - 2.5 mm/s, surrounded by liquid that traverses downward at velocities an order of

magnitude less than the jet (typically 0.1 - 0.5 mm/s). The interrogation region for a jet is chosen in a similar fashion as described earlier, only centered on the jet. Figure 2.1 shows a typical picture of a jet during directional solidification of H2O-NH4Cl, obtained using a central dark ground method.

The flow is seeded with Duke Scientific polystyrene spheres with mean diameter 50.1 $\mu m \pm 0.3\ \mu m$. The density of the polystyrene spheres is 1.05 g/ml. The density of H_2O-28%NH_4Cl is 1.0767 g/ml. This results in the seeded particles being approximately neutrally buoyant in the test liquid. These particles follow the trajectory of the neighboring fluid. The PDT technique is based on tracking these particle trajectories over a period of time to establish the flow direction and magnitude at points within the interrogation area.

The flow visualization and data gathering technique itself is slightly different from the techniques used in typical PIV/PDT systems. Most studies have used a laser to illuminate a finite plane across the fluid field, thereby being able to record the movement of particles in that plane. Due to optical limitations, the smallest thickness of an achievable light sheet is typically between 0.5 and 1.0 mm. If the phenomenon being observed is at least an order of magnitude greater than the light sheet thickness, then a light sheet with the above mentioned thickness could be considered to represent a "plane", despite the fact that it has a finite thickness. In our study, a typical jet diameter is about 1.5 mm. Hence, it is not easily possible to illuminate several planes across a jet, preferably at intervals of 0.5 mm. A more demanding limitation is the ability to move the light sheet to various locations within the region of observation at various times. Therefore, a laser was not used to illuminate the flow field. Two bright fiber optic white light sources were used

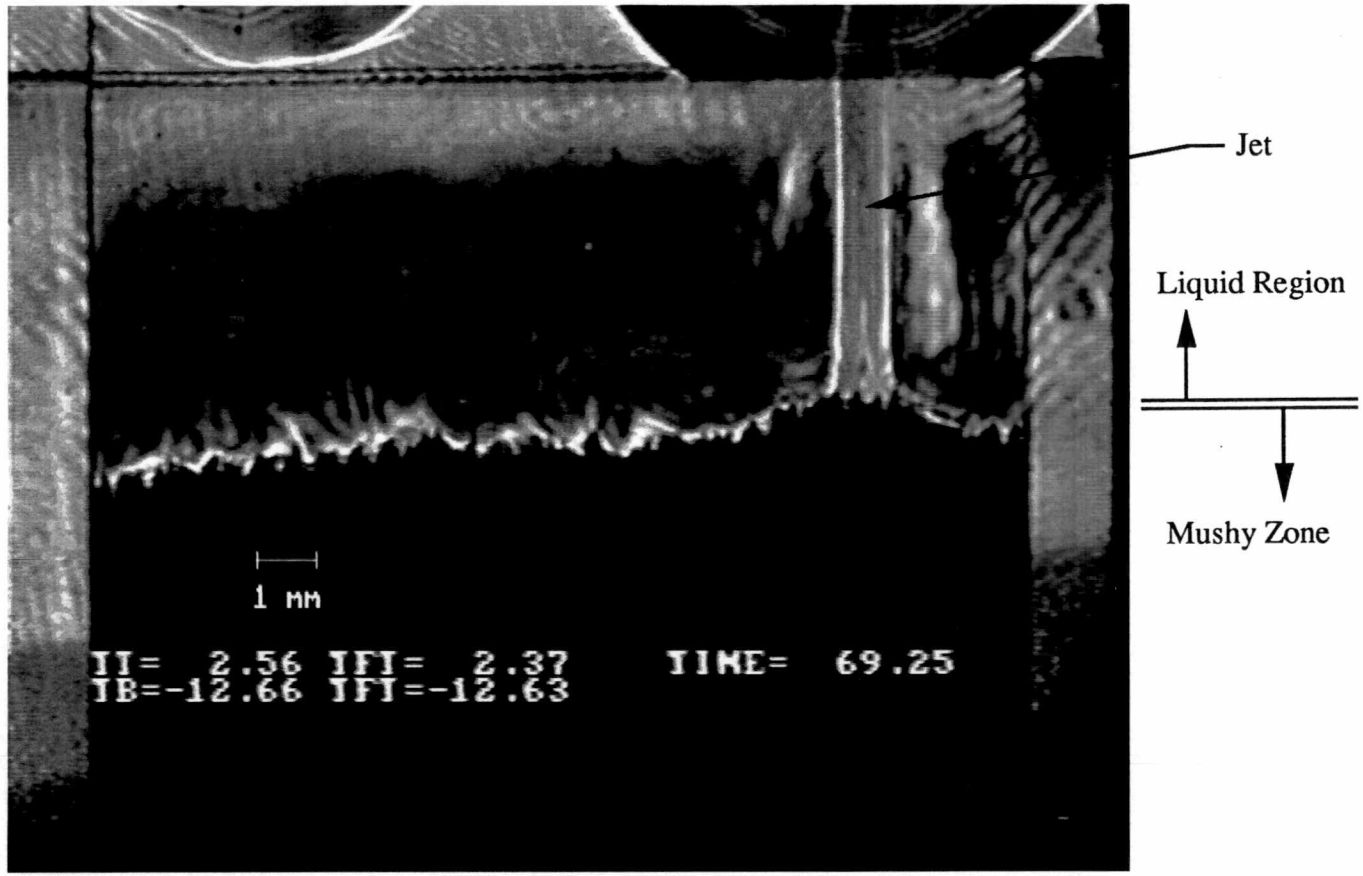


Figure 2.1 A typical jet during directional solidification of H2O-NH4Cl, obtained using a Central Dark Ground Method

instead. To account for capturing events at several planes across a jet separated by about 0.5 mm, microscopic cameras with short depths of focus were used.

The depths of focus of the cameras are approximately between 0.5 and 0.6 mm. Hence, by moving the camera back and forth with respect to the flow field, at intervals of 0.5 mm, particle motion at planes separated by 0.5 mm is captured. The movement of the cameras is not automated, but is carried out manually by moving the translators on which the cameras are mounted on with the aide of built-in micrometers screw gages. The movement of the camera from one location to the other is carried out gradually, however, the data of the flow filed is video taped only at distinct locations, separated by 0.5 mm. Typical time to collect the information is approximately two minutes.

Three-dimensionality in this study is achieved in the following way. Particle motion is recorded in several planes across the interrogation region in two orthogonal directions, and the PDT technique is applied to each of the planes to generate a 2-D velocity vector plot of each of the fields. Then, the information from all the planes is appropriately superimposed to generate a 3-D plot, where the velocity profile will be evident.

The resulting 3-D information is one that depicts the qualitative characteristics of the flow field, but only gives an average representation of quantitative information. The information at different planes throughout the flow field is obtained at successive times and not instantaneously. Hence the continuity equation cannot be applied (since the mass flow or volume flow will differ over time), and out-of-plane velocities cannot be calculated. However, since information is gathered in two orthogonal directions, the out-of-plane velocity in one direction will correspond to the in-plane velocity in the other direction.

III. EXPERIMENTAL STUDY

3.1 Experimental Layout

The experiments were performed in the Solidification Physics (CAST) laboratory at the Center for Laser Applications (CLA), at the University of Tennessee Space Institute.

As shown in figure 3.1, the experimental arrangement consisted of a cuvette assembly, two microscope/camera assemblies (placed orthogonal to each other, one facing the front face of the cuvette and the other the side face), a camcorder, and two fiber optic white light sources (Cole-Palmer Instrument Company, Fiber-Lite, model 9745-00). The white light lamp illuminates the interior of the entire cuvette for enhanced visualization and video-taping of particle motion. The signals from the two cameras and the camcorder are transmitted by coaxial cables via a video mixer and a computer to a VCR, which is programmed to record the sequence of events during a test. The VCR is connected to a TV monitor, which allows for real-time viewing of the solidification process during a test. The temperatures and cooling rates of the top and bottom surfaces of the cuvette are controlled through a PC. The signals from the PC are amplified by an operational amplifier unit, while a power source provides the necessary power to maintain the appropriate temperatures.

Cuvette Assembly

A quartz cuvette with inside wall dimensions of 8mm x 12mm x 16 mm and wall thickness of 2 mm is used. The cuvette is sandwiched between two slotted, thin copper plates. The copper plates are in contact with two Thermo Electric Devices (TEDs). High-conductivity thermal paste is used in the contact regions of the cuvette, the thin copper plates, and the TEDs for enhanced thermal uniformity. The TEDs are in contact with two copper temperature baths, one on top and the other on the bottom

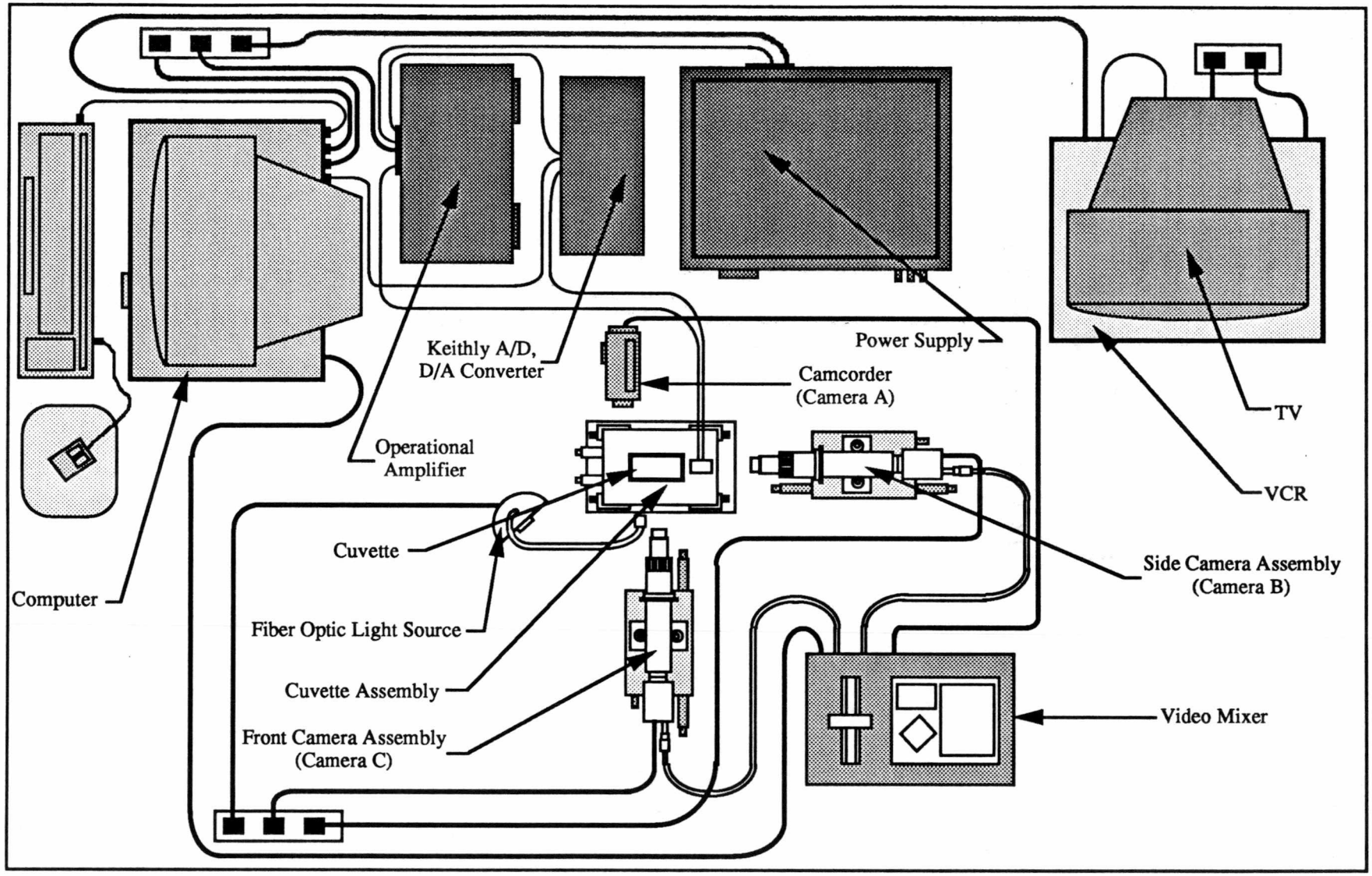


Figure 3.1 Schematic of experimental set-up

(see Figure 3.2). Again, thermal paste is applied in the contact zones to maintain efficient conductivity. Tubes carrying coolant liquid (typically water) from a Cole-Palmer Polystat refrigerated recirculator (model 01283-02) are connected to internal channels within the copper temperature baths. The temperature of the coolant is controllable through the recirculator, and is typically set at 10°C. This action is required when running tests at low temperatures. The temperature baths are held in place by two set-screws that are connected to four supporting trusses placed at each end of the bath. Two Omega Engineering, K-type thermocouples are imbedded within slots, one in each of the thin, slotted copper plates. These record the outside cuvette wall temperatures and transmit the data back to the computer for corrective and or modification measures, as required. The above-mentioned apparatus is mounted on to an NRC model 270 lab jack that can be translated in the Z-direction. The lab jack is attached to two NRC model 100 magnetic instrument bases.

Microscope/Camera Assembly

A Watec WAT-902 high sensitivity camera was attached to an Edmund Scientific Zoom Microscope, model P39-708. The components are secured to a Newport Research Corporation (NRC) model 270 lab jack by means of a bracket (see Figure 3.3). The lab jack can be translated in both Z-directions (i.e., along and opposite to the direction of dendritic growth). The lab jack is placed on a NRC series 460A 2-D translator that permits camera movement both in the X and Y directions (i.e., lateral movement from the left edge to the right edge of the cuvette, and forward movement from the front end to the back end of the cuvette). The translation is carried out by hand, and accurately controlled with the help of two sets of micrometer screw gauges (Metric units). In the case of the front camera/microscope assembly, the 2-D translator is directly secured to a NRC model 200 magnetic instrument base. However, in the case of the side camera a NRC model 440 1-D translator, with micrometer screw gages

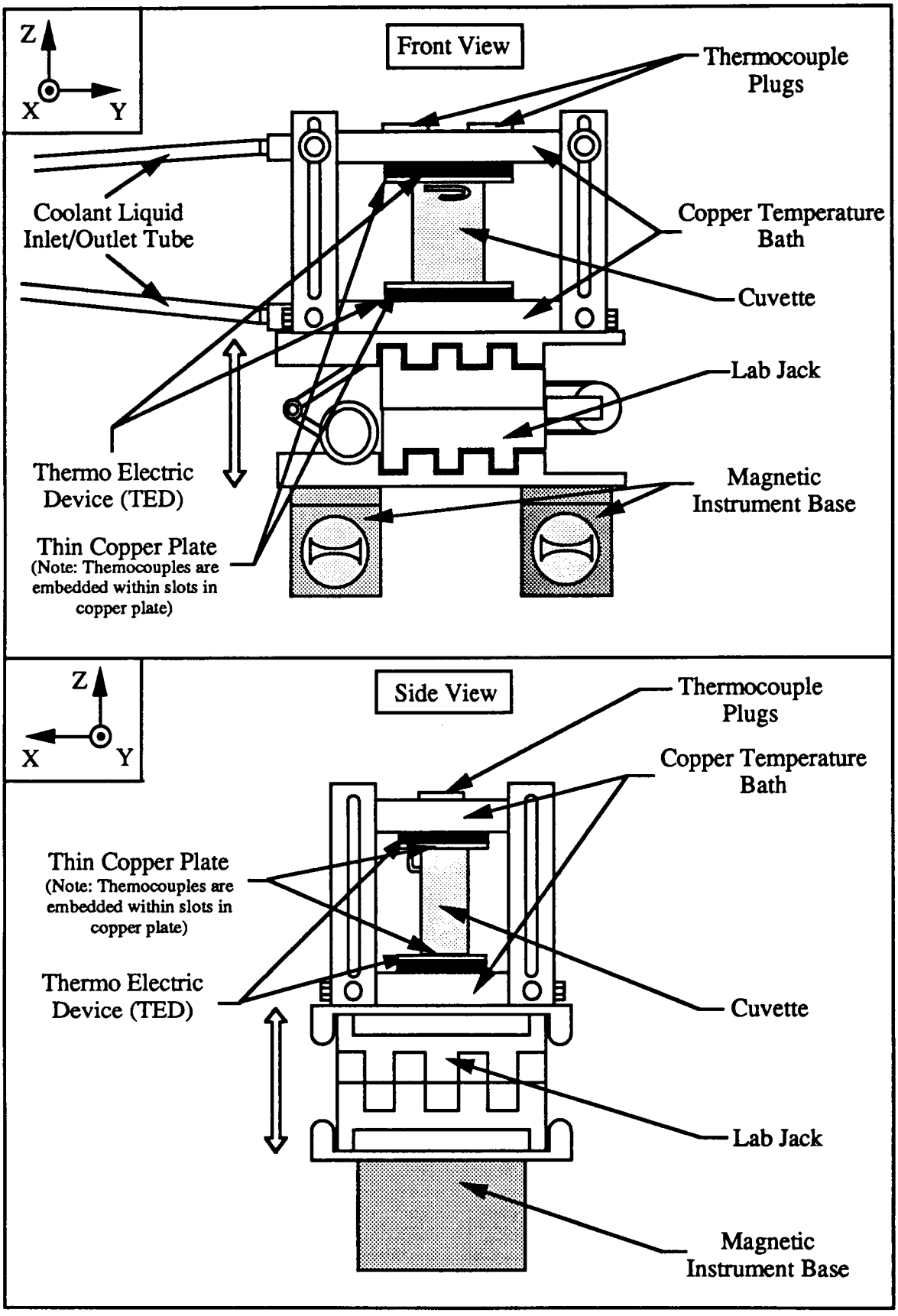


Figure 3.2 Schematic front and side views of cuvette assembly

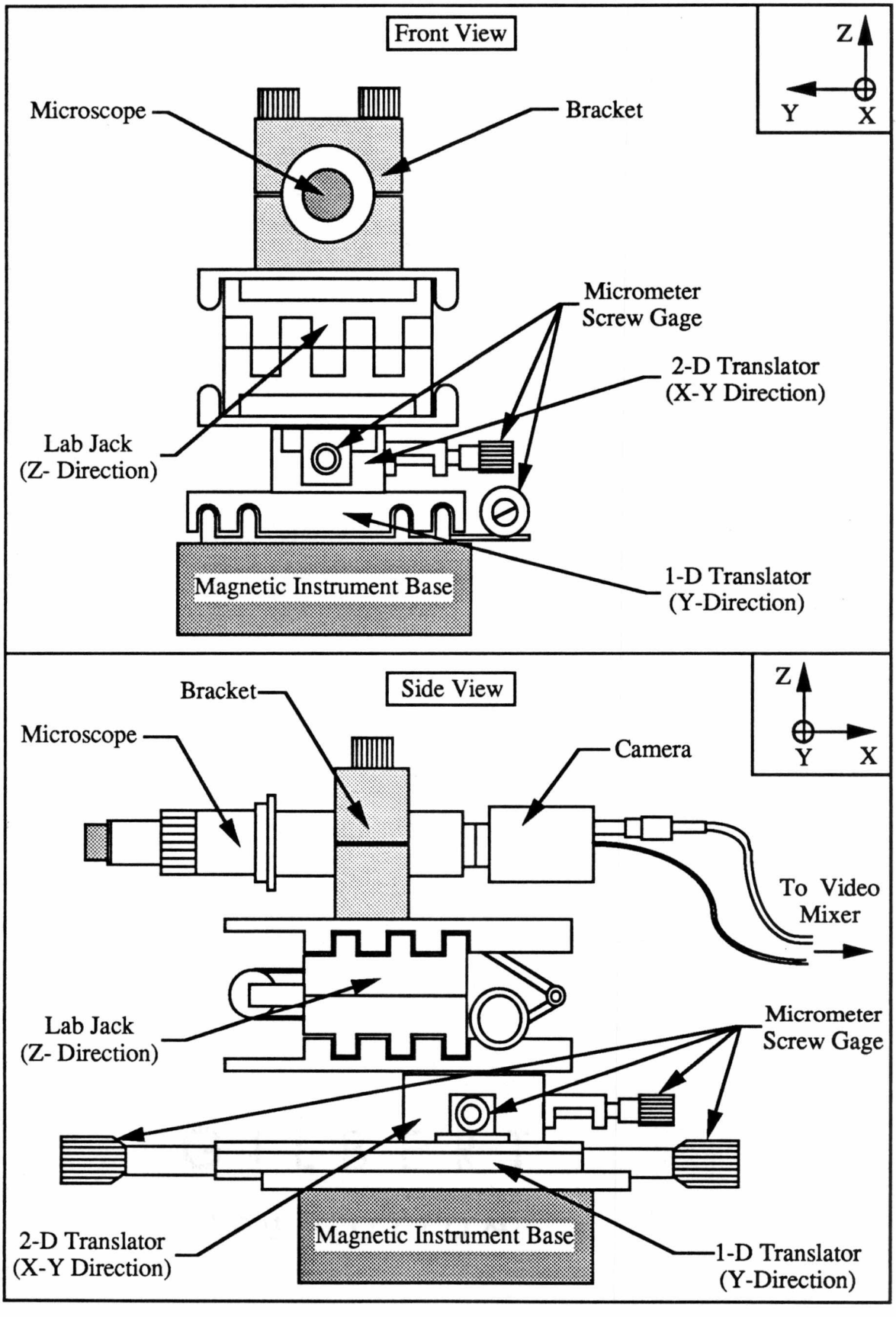


Figure 3.3 Schematic front and side views of camera assembly

(English units), is attached between the 2-D translator and the magnetic base (as shown in Figure 3.3). The 1-D translator moves in both Y-directions. The reason for the added 1-D translator for the side assembly is that, although the 2-D translator can be traversed to map out the entire cuvette in the X-direction, in the Y-direction it can only be made to traverse a portion of the cuvette (due to the rectangular shape of the cuvette).

Both the front and side cameras are connected to a video mixer. The video mixer is connected to a PC video overlay card and this is connected to a VCR. The VCR output is displayed on a video monitor. With the use of the video mixer, the desired camera (front, side, or the camcorder) can be selected at any given time. However, at any given time, only a particular region in the cuvette can be observed either from the front or the side, but not both.

Camcorder

A General Electric Camescope (model CG 805) camcorder is installed across the back face of the cuvette. The purpose of the camcorder is to record the interface height at any given time. A millimeter scale is attached to the edge of the back wall of the cuvette. The camcorder is focused such that the millimeter scale and the cuvette are within its field of view. As the interface grows, the height of the interface is easily determined by reading the division on the scale corresponding to the edge of the interface. The camcorder is directly connected to the video mixer.

Video Mixer

A Videonics digital video mixer (model MX-1 NTSC) is used to control the camcorder and the side and front microscopic cameras (i.e., cameras A, B, and C respectively). The video mixer enables the user to select either one of the microscopic cameras (front - camera C, or side - camera B) or the camcorder, at any given time, such that the information from the

selected camera will be transmitted to the VCR for recording purposes. In a typical experiment, at appropriate times, camera A is first selected to record the interface height at that point in time. Then cameras C and B are selected respectively. In each of the latter cases, the events at several parallel planes are recorded.

The video mixer sends information from the particular camera selected at any given instant in time to the computer.

Computer

A Wells-American 286 PC is used to run a computer program that controls the various test parameters via user inputs through a keypad. The parameters that may be specified are the initial and final temperatures of the top and bottom TEDs, and the cooling rates for the top and bottom temperatures.

An ADDA Technologies, Inc. VGA-AVer Pro-2.0 video overlay card is used to overlay text generated by the computer on the video signal from the video mixer. The following quantities are displayed via the overlay card continuously, throughout the entire duration of each experiment: (a) Time elapsed since the beginning of the run, (b) Prescribed temperatures of the top and bottom TEDs (these are determined by the computer, based on initial user input of the temperature gradient, and the cooling rate), (c) Actual temperature of the top and bottom TEDs (as sensed by the thermocouples), and (d) Temperature differential between prescribed and actual. The overlay capability allows for accurate determination of important quantities such as the beginning and ending time of each of the flow regimes.

The output (i.e., the video imagery plus the information from the video overlay card) from the computer is then transmitted to the VCR for video taping. The information is also

transferred from the VCR to the TV monitor, so that real time viewing of the events is made possible.

Data Acquisition System

A Keithley Series 500 data acquisition and control module was used to perform digital-to-analog and analog-to-digital conversions, so that information from the thermocouples can be conveyed to the computer, and vice versa.

Analog temperature information from the thermocouples is sent to the Keithly module, which then converts the information to a digital signal. This digital signal is then carried to the computer. After determining the required action that is needed based on information from the thermocouples, the computer sends the "response" digital signal to the Keithly module. The Keithly, in turn, converts the signal to analog and transmits it to an operational amplifier, a voltage step-up device that amplifies the signal from the Keithly and powers the TEDs. The operational amplifier is powered by a power supply (see below). The resulting temperature changes are measured by the thermocouples. This interactive sequence of events among the mentioned components is carried through the entire period of a run.

Power Source

The purpose of the power source is to provide the necessary energy to maintain specified temperatures for the top and bottom surfaces of the cuvette. A Power Ten, Inc. model 3300D-2030, 115V power supply is used for this purpose.

Figure 3.4 (a) is a flow-chart outlining the energy supply and data transmission command hierarchy. Figure 3.4 (b) shows the data gathering/visualization flow-chart.

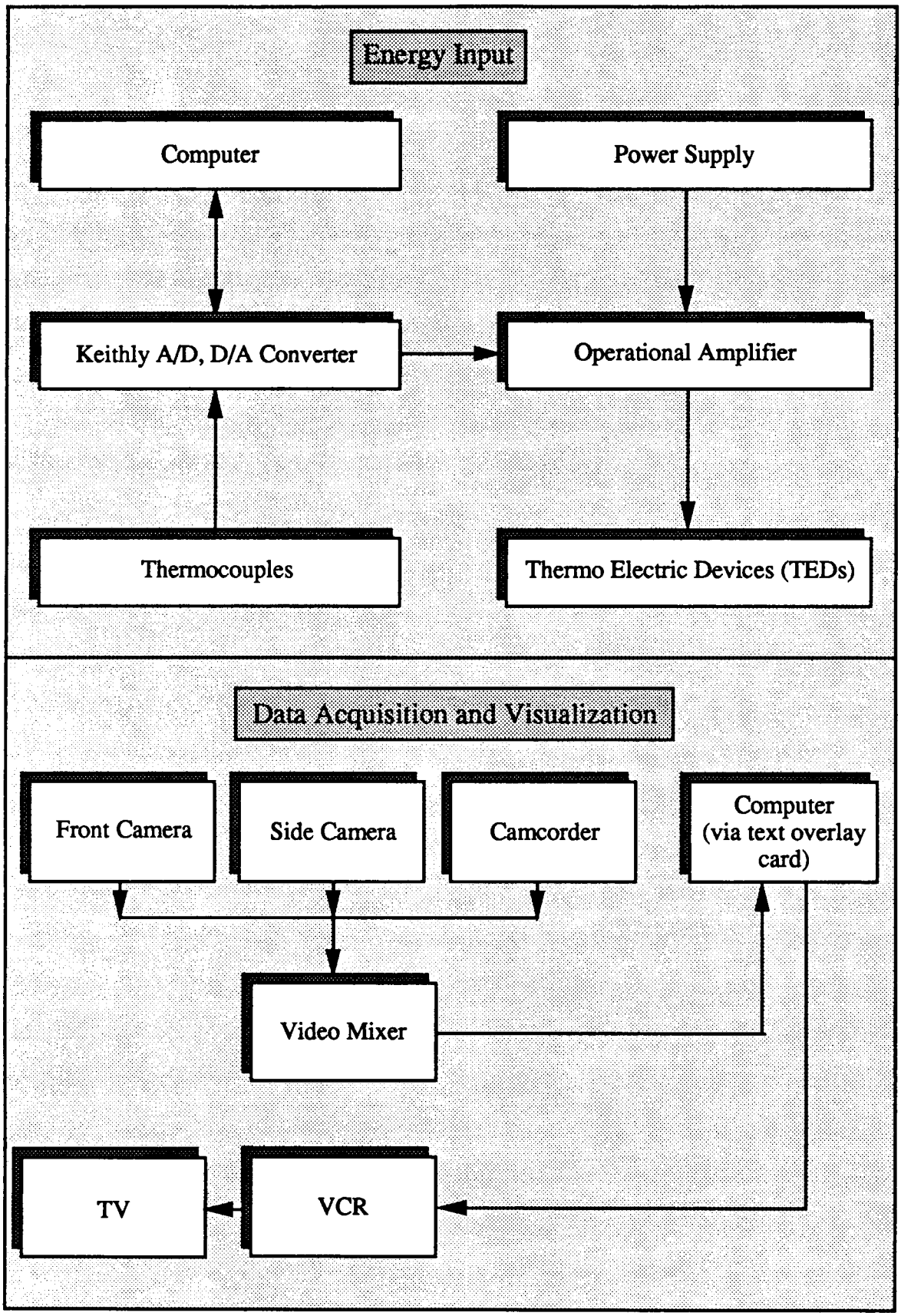


Figure 3.4 Energy supply and data acquisition flow-charts

3.2 Experimental Procedure

In this investigation H_2O-wt28%NH_4Cl was unidirectionally solidified dendritically. The growth direction is from bottom to top. The general objective, as explained in Section 2.3, is to characterize the flow field above a particular region on the interface at various times throughout the growth period.

The implementation of the directional solidification method in this study was carried out in the following manner: Initially, the top and bottom faces of the cuvette are maintained at different temperatures, based on the prescribed temperature gradient (typical temperature gradients are 5, 10, and 15 °C/cm). The top temperature (T_t) is higher than the bottom temperature (T_b), so as to induce a preferred growth direction from bottom to top.

It is desirable to achieve both a uniform temperature gradient and a homogeneous mixture of solute throughout the cuvette. Although a uniform temperature gradient is achieved fairly quickly after setting the initial top and bottom temperatures, achieving homogeneity in the solution takes longer; hence the top and bottom temperatures are maintained at the prescribed levels for a period of time which is referred to as a gradient hold. A typical gradient hold time of 60 minutes is used in experiments reported herein. The gradient hold period also helps the solution to come to a static equilibrium, characterized by the absence of fluid motion.

Following the gradient hold period, the top and bottom temperatures are ramped down at identical rates to conform with Bridgman growth conditions, and hence to maintain a constant cooling rate throughout the cuvette (typical cooling rates are 60 °C/hr). Ramping

down of temperatures initiate the solidification process. Figure 3.5 graphically depicts the sequence of events during a typical run.

The cooling rates are applied until the prescribed top and bottom temperatures are reached. After the final temperatures are achieved, the top and bottom faces are held at these constant temperatures for an extended period of time and the experiment continued subject to whether or not there are jets present at the particular location of observation.

Beginning at the "ramp-down" period, the flow field in a particular X, Y, Z location within the cuvette is observed. This is done until the end of the "ramp down" period, at the following times: 5, 10, 15, 20, 25, 30, and 35 minutes. As time passes and the interface grows, the flow field above the same X- and Y- location is observed, however the Z-location is progressively increased, keeping pace with the growth of the interface.

As mentioned before, the H_2O-NH_4Cl solution is seeded with nearly neutrally bouyant microsphere particles for the purpose of flow visualization. During fluid motion, each particle will move in the direction of its neighboring fluid; hence, by observing particle motion, fluid flow motion is characterized.

Videotaping of the events is initiated towards the end of the gradient hold period, and is continued through the ramp-down period. If jets prevail beyond the ramp-down period, the videotaping is continued into the post ramp-down period until jets cease to exist. Essentially then, fluid motion during a run is recorded and stored on video tape for post experiment processing using the Particle Displacement Technique described in Section 3.3.

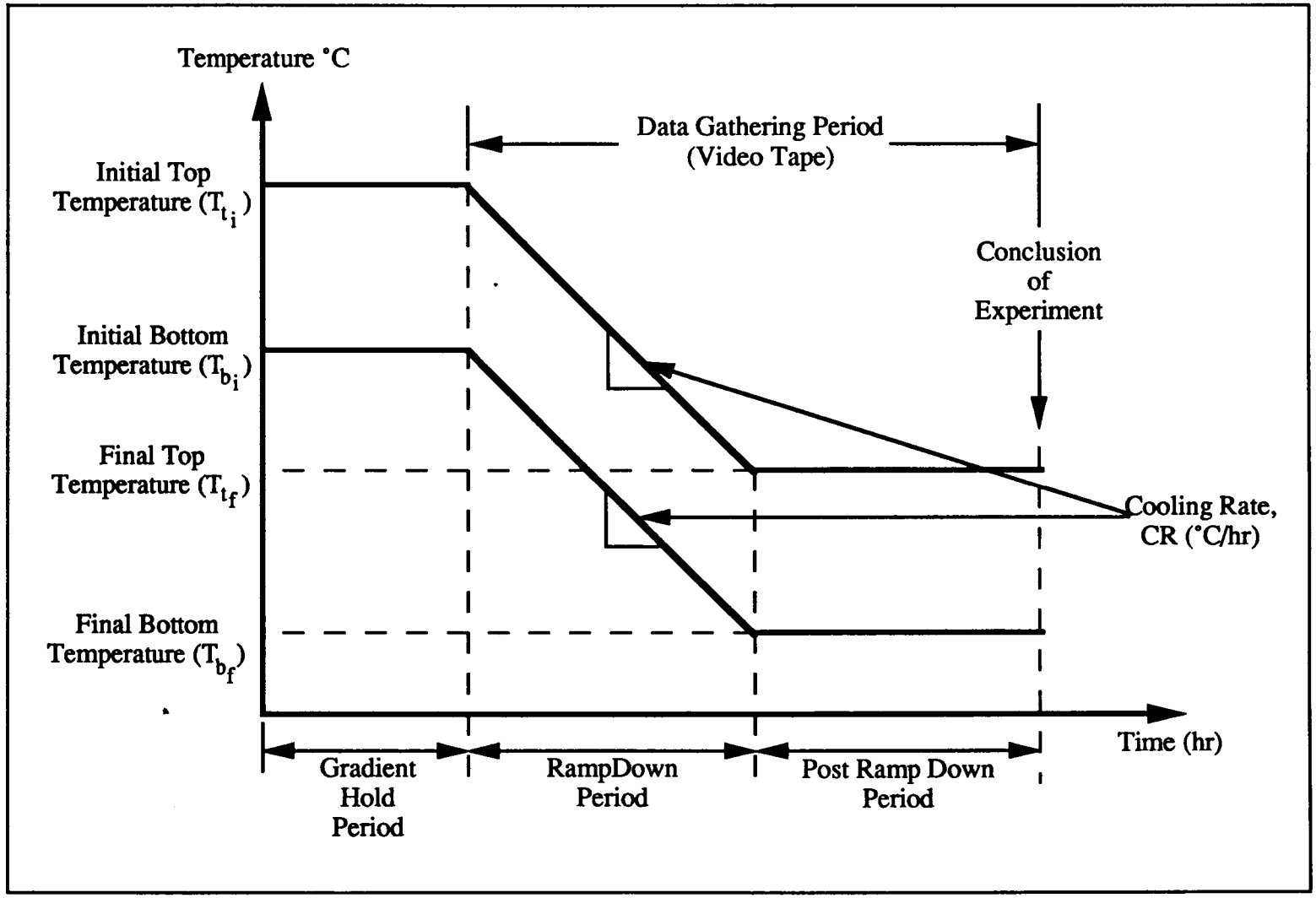


Figure 3.5 Sequence of events during a typical directional solidification experiment

The experiment is typically concluded as soon as the final temperatures are reached, unless continuous jet formation is observed, in which case termination occurs after the jet ceases to exist.

3.3 Particle Displacement Tracking Technique

The Particle Displacement Technique (PDT) is used to measure velocity fields.

The procedure was carried out here, using recorded video data, and a frame grabber board installed in a PC. Essentially, a VCR records the set of events as captured by the microscopic camera. The frame grabber is used to extract a sequence of frames originally recorded on the video tape. Finally, the PDT technique is applied by using successive frames already captured by the frame grabber. Note that the procedure of digitizing the analog signal from the video tape may be carried out at a later time after the experiment is over. This reduces the complexity of applying the PDT technique, giving the experimenter more time to devote to other details as required by the specific experiment.

The PDT technique uses a sequence of five digitized images to determine the direction and magnitude of particles in a flow field. Data reduction is carried out in two stages: (a) Determining particle centroid location, (b) Tracking the particle displacement.

First, the five video fields are modified in a series of steps that enhance the quality of the data contained in the fields. The process includes reduction of background noise and generation of a new image that contains the geometric centers of all particles. The centers are coded with a pixel of intensity 256 (white). The background (i.e. all locations on the image except for centroid locations) is set at zero intensity (black). Details of this procedure are given in Section 4.2.

The five video fields are analyzed individually to determine the location of each particle in each field. Initially, the intensity values from the 1st field (image) are stored in an array. Then, a threshold intensity value is picked so as to eliminate the background noise in the image (i.e., the threshold intensity is set at zero, resulting in the intensity values of particles being greater than zero). The search for particles is carried out in a row-by-row fashion, beginning at the top left corner, and ending at the bottom right corner. In each row the search proceeds from the left most pixel to the right most.

The search for particles involves identifying pixels whose intensity values are greater than the threshold. During the search, when such a pixel is located, a clockwise boundary following algorithm is used to estimate the centroid location of the particle. The algorithm essentially does the following: Immediately after the detection of the non-zero intensity pixel, the pixel to the immediate right is examined for its intensity value. As long as adjacent pixels to the right have non-zero intensity values, the search proceeds in a left to right manner. If no further non-zero pixels are located to the right, the search direction is switched to one of top to bottom. The intensity values of pixels directly beneath the current pixel are examined until a zero intensity pixel is encountered. At this point, the search is directed from right to left, and subsequently, after similar criterion for pixel intensity is met (as discussed above), the search proceeds from bottom to top, returning to the very first non-zero intensity pixel. This identifies the boundaries of the particle. Now, the geometrical center of the detected particle, based on the region encompassed within the identified boundary is stored in a file. This denotes the centroid location of the particle.

Next, all identified non-zero pixels are set to an intensity value of zero. This measure is taken so as to avoid redetection of the same particle during a subsequent pass. The search will now proceed from the location where the initial non-zero pixel was located (Note that

this particular pixel, along with other detected non-zero pixels, all have a zero value now). The search is carried out from left to right, row by row. The above described process is undertaken until the whole image is searched for all existing particles. This procedure of identifying particle boundary, and locating the centroid is carried out for each of the other four images.

All the centroid locations from Image 1 are encoded with amplitudes 2^1. Similarly, amplitudes of Image 2 are encoded as 2^2. Next, one composite image is generated that contains the time-history displacements of all the particles from all the Images 1-5. Hence all particles in the composite image with intensity 2^1 correspond to the first field, with intensity 2^2 to the second field, and so on.

At this stage, the task of tracking particle displacement is initiated. A circular search region of user defined radius (typically 4 pixels) around each of the 2^1 intensity particles is established. Next, particles with 2^2 intensity are searched within this region. This would correspond to the location of the particle, at an instant Δt since the time of the first field (i.e., Δt is the time difference between successive fields). An appropriate Δt has to be determined based on the relative velocities of the particles associated with the particular phenomenon under scrutiny. The minimum Δt is 1/60 of a second. Technically there is no upper limit for the amount of Δt. Based on initial observations, for this study (i.e., to observe jets effectively and determine their velocity profiles to a good degree of accuracy), a Δt of 1/30 sec. was used. This corresponds to examining every consecutive video frame.

Now, within the search region there exists a possibility that there maybe more than one 2^2 particle. At this juncture, the "best" 2^2 particle needs to be identified. All particle intensities are assumed to have approximately a Gaussian distribution. A maximum likelihood examination is carried out based on particle image standard deviation and particle

width. After locating the "best" 2^2 intensity particle within the search region, the angle and distance between the 2^1 and 2^2 intensity particle is determined. These quantities, then, are used to project the centroid locations of the 3, 4, and 5 intensity particles (corresponding to the third, forth, and fifth fields, respectively). At each successive location (i.e., at each field), the search for the particle is carried out within a circle of radius (or tolerance) specified by the user, the maximum being ±3 pixels. That is, the computer will look for the particular particle at every location surrounding the initially projected location. For example, if the user defined tolerance is ±2 pixels, a square region 5 pixels by 5 pixels centered at the original projected location will be searched for the particle. If particles do exist in the projected regions in Fields 3-5, then the tracking process is successfully concluded. However if particles of 2^3, 2^4, 2^5 are not present in the respective projected regions in Fields 3-5, then the initially determined 2^2 particle is not the correct 2^2 particle, and hence, the second "most probable" particle within the search region is analyzed as described above. If all available 2^2 particles within the search region lead to projections that do not correspond to the appropriate 2^3, 2^4, 2^5 particles, then, the displacement tracking for that particular 2^1 particle is abandoned, and the procedure is applied to the next 2^1 particle. In the event that a 2^1 particle has been tracked through all five fields, the velocity vector of the particle is determined based on the locations of the particles in Fields 1 and 5 (i.e., based on particles with 2^1 and 2^5 intensity). The direction of the velocity vector is the direction between the location of the 2^1 and the 2^5 intensity particle, and the magnitude of the velocity is simply the distance between 2^1 and 2^5 intensity particle, divided by $4\Delta t$. Each velocity vector will hence have three sets of information associated with it: (a) the x and y pixel locations (tail of the velocity vector), (b) the x and y components of the vector, (c) the magnitude of the x and y components.

Finally, by superimposing the velocity vector fields from each plane, in both directions, a composite 3-D depiction of the flow field is arrived at. This is graphically displayed in the

form of a 3-D graph. Note, that since events at various planes are recorded at different times, and since no mass conservation has been accounted for, the resulting 3-D profile of the flow field is an "average" profile.

3.4 Case Studied

Solidification experiments were carried out using an H_2O-28wt%NH_4Cl solution seeded with 50.1 μm ±0.3 μm particles. The particles constitute 0.005% by weight of the total solution. The test conditions for the case considered in this study is outlined in Table 3.1.

Table 3.1 Directional solidification conditions used in this study

Temperature Gradient, G (°C/cm)	Initial and Final Bottom Temps. (°C)	Initial and Final Top Temps. (°C)	Cooling Rate, C (°C/hr)
15	22,-14	67,31	60

Several preliminary solidification runs were carried out for various conditions (i.e., for different values of temperature gradient and cooling rate). A set of "more favorable" conditions for the observance of jets were arrived at based on key factors gathered during each of the above mentioned runs. Predictable, repeated occurrence of jets and consistent approximate time and duration of jet occurrence were among the key factors considered.

The G = 15 °C/cm, CR = 60°C/hr condition was picked for the above mentioned reasons and because the run itself is fairly short (a little over 30 minutes). This allowed for repeating the experiment with ease and in a short period of time.

Since the success of the PDT technique largely depends on the clarity of the video frames (i.e., a clear distinction between the intensities of the particles and the background - ideally the background should be as dark as possible with minimum noise, while the particles have to be as light as possible), the lighting of the cuvette becomes important. The lighting should not only be bright enough, but also be fairly uniformly distributed throughout the cuvette. The uniform distribution is important for effective contrast modification (to achieve a fairly "noise-free" background). The experiment was repeated many times, and the run with the "best" lighting condition was picked for the PDT analysis.

During the experiment, each camera records the events at several parallel planes separated by a distance of 0.5 mm, and covering a total distance of 3.5 mm (i.e., 7 planes in each direction). Since the two cameras are positioned orthogonal to each other, the resultant picture is one in which we have two sets of parallel planes at 90° to each other, with both planes intersecting each other in the center of the interrogation region. This is graphically depicted in Figure 3.6. Particle motion in each plane is analyzed using the PDT software. The velocity profiles from each plane (from both cameras) are superimposed to form a composite 3-D velocity profile picture that depicts the nature of the flow field.

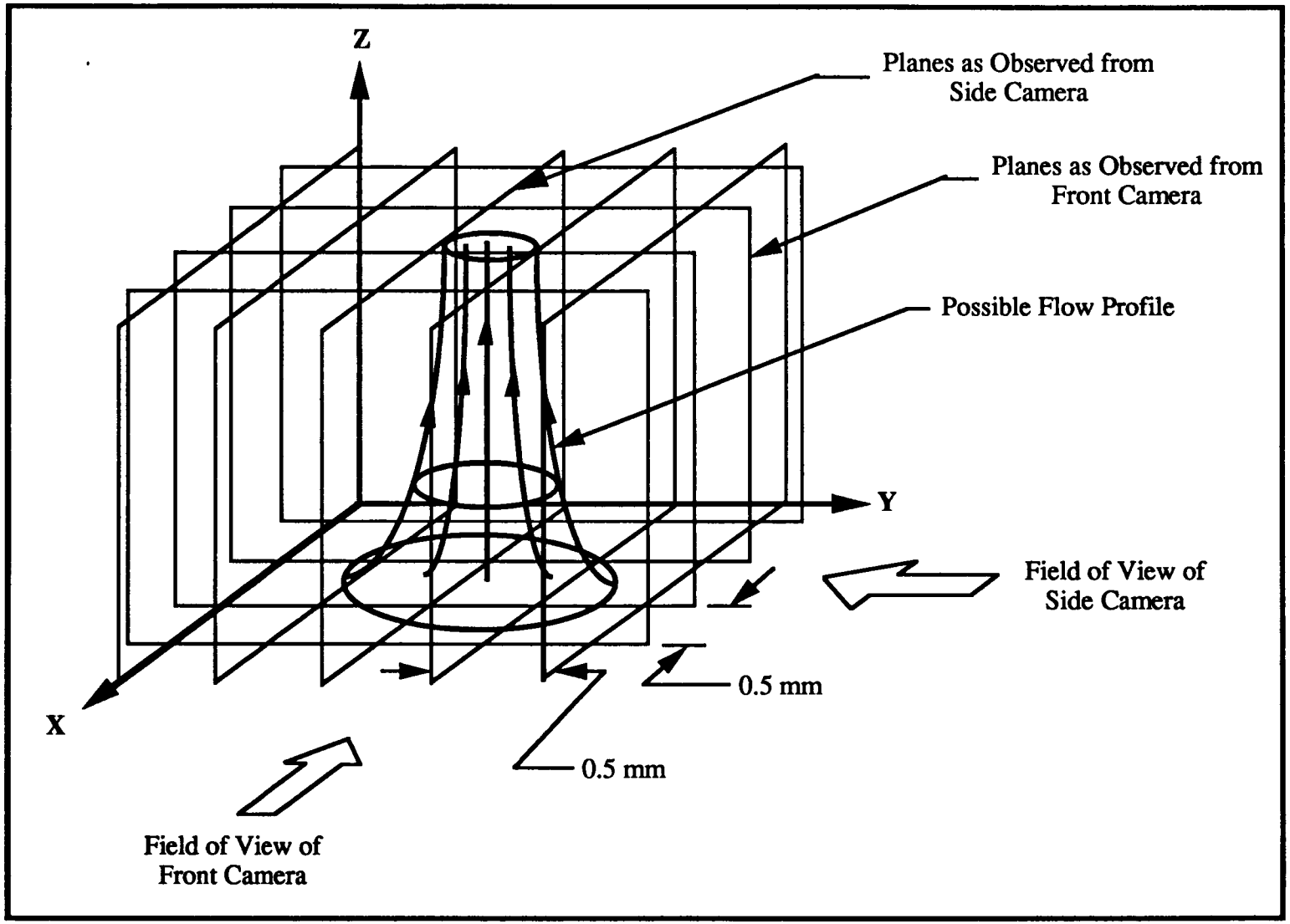


Figure 3.6 Schematic of typical orthogonal "planes" used for PDT analysis

IV. DATA REDUCTION USING PDT SOFTWARE

4.1 Information on the Software

The PDT algorithm used in this study is derived from an earlier algorithm developed by Wernet (see Wernet, 1990). Modifications to the algorithm were made to accommodate for the different computer hardware.

The original software was obtained from the Computer Software Management and Information Center (COSMIC), sponsored by NASA. COSMIC operates in the interest of information exchange among government, industry, and academia.

The COSMIC software was written exclusively to operate with the hardware at NASA Lewis. It has several subroutines that accomplish various tasks associated with PDT. Among the routines are those associated with data acquisition, data reduction, and graphical data analysis. The data reduction routines were modified for this study. The data acquisition routines were discarded, due to the difference in hardware used in the NASA and CAST set-ups. Similarly, the graphical data analysis routines were not used either because of the non-availability of the graphic interface module and associated libraries used at Lewis, namely, the Media Cybernetics HALO professional graphics system. Since tasks of data acquisition and graphical data analysis are essential parts of the PDT process, these were carried out using different systems, methods, and software that are readily available and implementable at the laboratory. These procedures are discussed in the following two sections.

4.2 Procedure

During an experiment, particle movement is observed through two orthogonally placed high resolution cameras attached to microscopes. The observed particle motion is recorded by a VCR (Panasonic AG-1830) onto a VHS tape at a framing rate of 30 frames/sec. Subsequently, the video tape is taken to an image processing set-up that has the following configuration: The System is centered around a 80386 PC fitted with a Data Translation DT-2862 frame grabber board. One of the inputs to the computer is from an optical disc recorder (Panasonic TQ-3031F), which in itself is connected to receive signals from a VCR (Sony SLV-373UC). The output signal from the computer is sent to a monochromatic video monitor (Vicom). A schematic representation of the data gathering and image processing configuration is shown in Figure 4.1.

The information from the video at the appropriate times (e.g., 5, 10 min, etc.) is recorded onto an optical disc via the optical disc recorder. Since the framing rate on the video tape is 30 frames/sec, frames recorded on the optical disc recorder also have a time difference of 1/30 sec. between consecutive frames. Next, five consecutive frames in each relevant sequence of events is frame grabbed (individually), digitized, and stored in five of the sixteen available buffers on the frame grabber board. Each buffer is capable of storing 512 x 512 pixel images (8 bits/pixel). The 8-bit format translates to an image with resolution of 256 gray-scale levels.

The grabbed images are interlaced in a fashion such that 8-bit frame grabber first writes the information to every other row, totaling 256 rows, and then writes the remaining 256 rows, completing the 512-row image. The small time lag involved in the above mentioned process of writing the two sets of 256 rows sometimes produces images

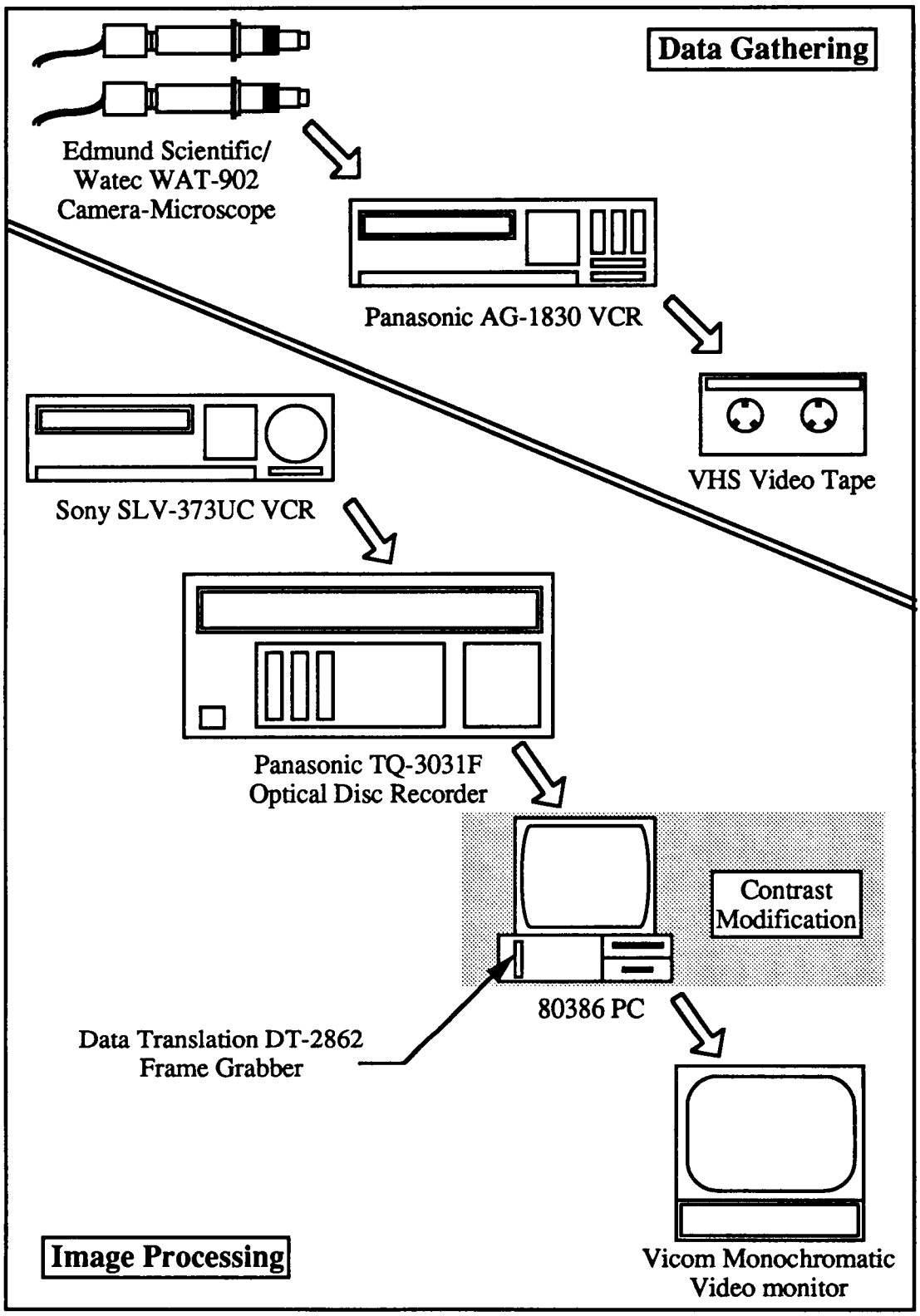


Figure 4.1 Schematic of data gathering and image processing configuration

where some of the particles appeared to be split. This caused difficulty in successfully using the PDT software, therefore a simple program was written to split each image (frame) into two different fields, where the first field contained all the odd-numbered rows, and the second all the even-numbered. Consequently, the two split fields were analyzed using the PDT software.

Next, each of the five frames is inspected for background noise (such as out-of focus particles, and noise resulting from light reflected from the interface and cuvette wall), and particle clarity. If there is a significant amount of background noise, a contrast modification is performed on each of the five frames to filter the background noise and to enhance particle visibility. The process of contrast modification aims at achieving images with background intensity of zero (black), and particle intensity of values greater than zero. The highest possible value of a non-zero intensity pixel is 255, corresponding to white. The contrasting is done by expanding pixel intensities from a narrower range (e.g., 50 to 200) to a large range (from 0 to 255). This action gives all pixels that have intensity values below 50 a value of zero (black) and all pixels that have intensity values above 200 a value of 255 (white). This process may be carried out over several passes until desirable intensity levels in the image are reached, where background noise is eliminated as much as possible, while preserving as many particles as possible.

After contrast modification, the program *cent.for* is used to further enhance the images to facilitate smooth operation of PDT. This program essentially identifies all the particles in the image, and based on a user input threshold value, retains appropriate particles, determines the centroid location each particle, writes the location as one white pixel (256) on a black background (0). This results in an image that contains all the centroid

locations, with each location characterized by one pixel instead of the group of pixels from the original image. The detailed procedure follows:

The array of pixels in an image is inspected in a left to right manner, starting at the top left hand corner and finishing at the bottom right hand corner of the image. Upon encounter of each pixel, the intensities of all eight surrounding pixels are examined. The difference in intensity values between each pair of opposite pixels is computed (i. e., the difference between the pixel on top and bottom of the original pixel, the difference between the pixel on the left and right, and the difference between the two pairs of diagonal pixels). The differences are then summed and compared with a user input threshold. If the sum is greater than the threshold, the particular pixel is converted to white, otherwise the pixel is made black. This information is written to another array. The program then scans the second array in a fashion similar to the first, and identifies the top left hand corner (determining i-min and j-min location), and the bottom right hand corner of a particle. It then determines the geometric center of the particle in the following manner. The sum of the differences between the individual i-locations of each white pixel and i-min is divided by the number of white pixels to arrive at the i-centroid location. Similarly, the j-centroid location is determined using the j-pixel locations.

After establishing the centroid locations, a window is defined for all the images, within which further analysis will be performed. The window is defined such that it excludes the portion of the image that encompasses both the interface and the video overlay graphics.

Two computer programs were written for data reduction, based on similar routines developed by Wernet (1990). The first program *fpart.for* , identifies the boundaries of all

particles in all five frames and then determines the centroid locations, and writes this information from all five frames to one time-history file. Particles from the different frames are coded with different intensities so that they can be identified with their respective frames (see Section 3.3). The second program, *gvel.for*, sets up a search region around each of the particles from the first frame, within which it looks for a possible particle from the second frame. Based on the particles from the first and second frames, the locations of particles in the third, fourth and fifth frames are projected. If the projected particles are identified either at the projected locations or at adjacent locations based on a user input tolerance of $\pm n$ pixels, the program writes the magnitude and direction of the velocity vector to a file. If the particles are not identified at the appropriate projected locations, the initially identified particle from the second frame is not the correct particle. The program then looks for another second-frame particle and again carries out the above mentioned process (see also Section 3.3). Two flow charts outlining the algorithm for *fpart.for* and *gvel.for* are presented in Figures 4.2 and 4.3 respectively.

The graphical data analysis section is carried out independent of COSMIC routines written to perform the similar task. Instead, a graphing software package developed by Amtec Engineering, *Tecplot*, is used to generated 2-D plots of velocity vectors in each plane, and subsequently a composite 3-D plot.

An interpolation procedure using Tecplot is performed on the 2-D data. Two interpolation techniques usable in Tecplot are discussed briefly. The first of the two techniques is inverse-distance interpolation. In this technique, each data point is averaged with its respective neighbors (i. e., the closer a data point is to a neighbor, the greater its weighting function). The weighting function is defined as $w = D^{-n}$, where D is the

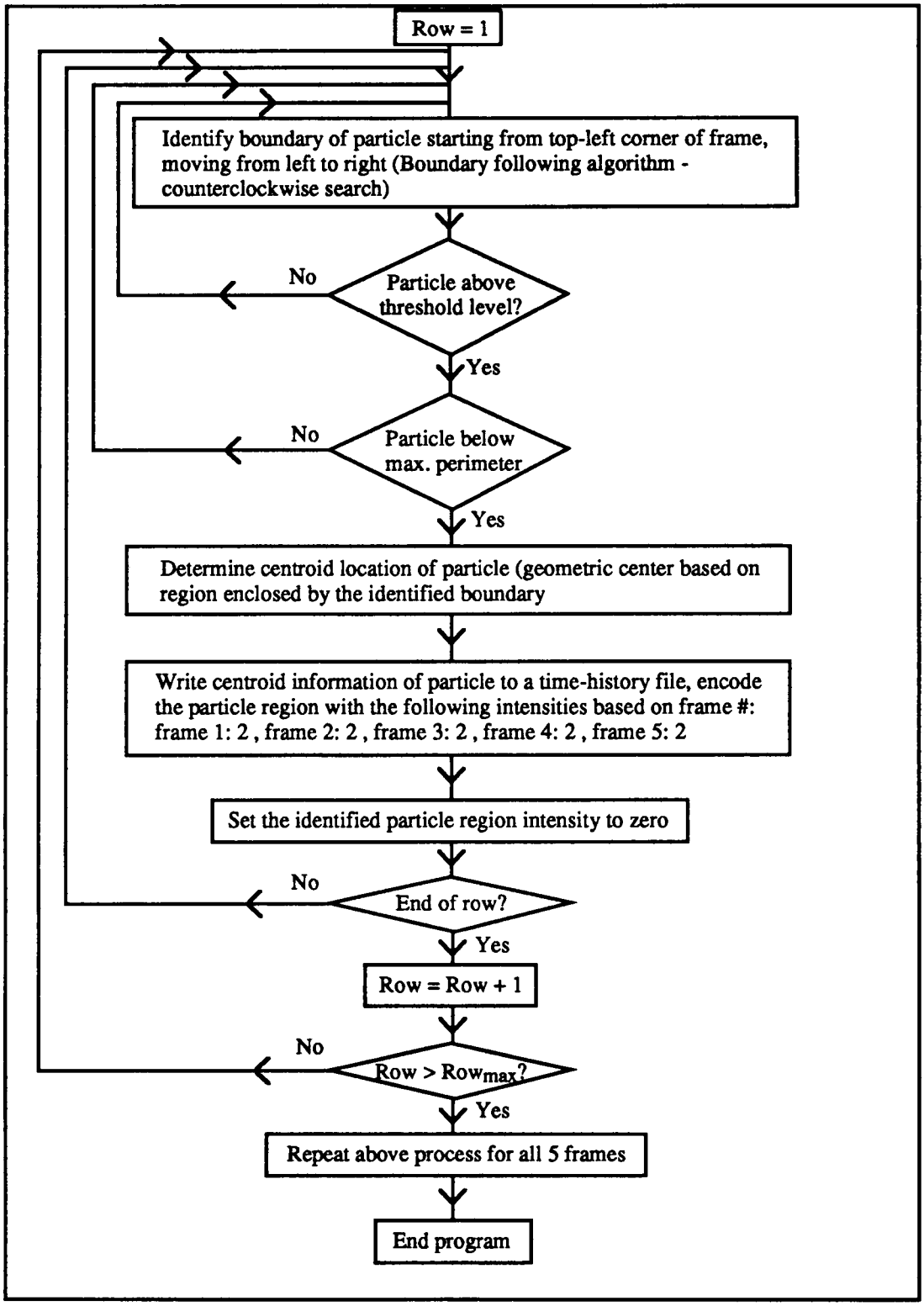


Figure 4.2 Flow chart for FPART.FOR

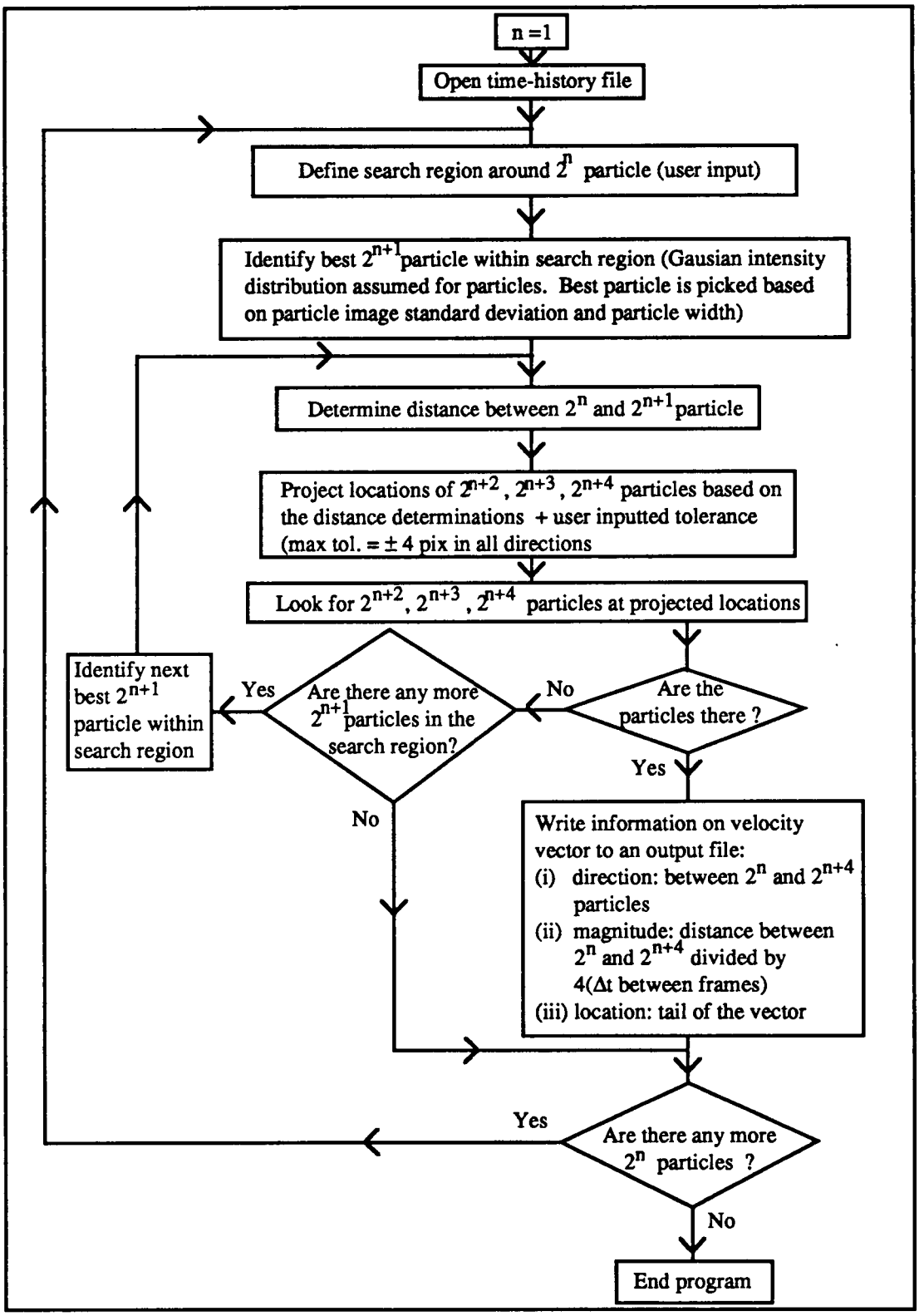


Figure 4.3 Flow chart for GEVEL.FOR

distance between a data point and its neighbor, and n is the exponent, and varies between 2 and 5. (Tecplot User's Manual, 1993). The second technique is Kriging interpolation. Kriging works like inverse-distance interpolation, only the algorithm is more complex and generally produces superior results. For further details, the Tecplot manual recommends the publication by Davis (1986).

Finally, vector maps of consecutive planes in both orthogonal directions are superimposed, using Tecplot, to produce a three-dimensional plot of the velocity distribution in the entire region under scrutiny. The three-dimensional plotting process also involves interpolation, where the two sets of 2-D planes are interpolated into a 3-D field.

The complete procedure to successfully apply the PDT technique is summarized below for easy reference:

(1) Record relevant data from video tape to optical disc.

(2) Grab five images from optical disc and store in computer buffer. (Note that based on the relative fluid flow speeds, the time between each of the five frames must be determined - e.g., for higher speed flows (jet), every consecutive frame may be grabbed, while for lower speed flows (fluid surrounding jet), every fourth frame may be grabbed).

(3) Write images stored in computer buffer to individual image files.

(4) Split each image file into two different image files using the program IMGMOD. (Note that the first image file will contain all the odd numbered lines, while the second will contain all the even numbered lines. As a result, the vertical dimension of the original image file is halved. Either the first or the second

modified image file may be used, however care must be taken in being consistent for all five original images).

(5) Using the program CONT, modify the contrast of each new image file such that an acceptable level of background noise reduction is achieved. (Note that all five images must be modified at exactly the same contrast levels).

(6) Using the program CENT, modify all image files. (Note that an appropriate threshold value needs to be inputted by user).

(7) Run the program FPART. (Note that the user must specify the following: (i) maximum particle size, (ii) coordinates of the rectangular area to be analyzed, (ii) threshold level).

(8) Run the program GVEL. (Note that the user must specify the following: (i) search radius, (ii) displacement tolerance (maximum tolerance: $\pm$ 4 pixels), (iii) framing rate).

(9) Inspect the output file to see if sufficient velocity vectors have been determined, if not, repeat process from Step 6, specifying a different threshold value for CENT. Steps 6 through 9 is an iterative process that needs to be carried out until optimum results are obtained.

(10) Repeat Steps 1 through 9 for all fourteen planes.

(11) Using TECPLOT perform the following:

- (i) Generate 2-D velocity vector maps for all fourteen planes.
- (ii) Perform an interpolation for each of the fourteen velocity maps (Inverse-Distance or Kriging)
- (iii) Place all interpolated velocity maps in appropriate locations relative to one another within a volumetric 3-D zone.
- (iv) Perform a 3-D interpolation (Inverse-Distance or Kriging) within this zone to obtain the final 3-D velocity plot.

Some requirements for the successful application of the PDT technique are discussed next. To get a good representation of the velocity distribution in a field, it is essential to have an adequate number of visible particles within the plane of view. Therefore, every effort is made to seed the test section with sufficient particles, and since poor lighting can also affect the visibility of some particles and their capture by the cameras, providing appropriate lighting during an experiment is essential. Another cause for lack of visible particles is excessive contrast modification. Care must be taken not to "lose" any particles while trying to eliminate background noise.

A source of velocity vector errors arises because of out-of-plane motion of particles. This will result in a particular particle being visible in one or more frames while disappearing in other frames. This technical limitation in applying PDT is governed by the particular flow. Thus in its current state PDT cannot be applied to flows with a strong out-of-plane velocity.

Another source of error arises due to the five frames considered being at too large a time interval from each other. If for instance, the flow characteristics are such that a particle originating in the bottom of an image travels to the top of an image in a time interval less than that between the first and the last of the five frames, then the particle will not be visible in the last few frames. This will result in the PDT program being unable to determine the velocity vector for that particular particle since its existence could not be accounted for in the last frames. Hence, it is extremely important to select intervals between frames based on the general characteristics of the flow. It might even be necessary to use different frame intervals to analyze different portions of a single image (an example of this is when the image has a jet within which the particle velocity may be several times larger than the velocity of particles surrounding the jet). Finally, it should

be noted that due to the limitation of the best achievable framing rate (30 frames/sec), only flows whose mean velocity is such that a particle will travel only part of the image in 1/30 sec can be considered. Flows with greater mean velocities cannot be quantified using the PDT set-up used in this study.

Provided the above mentioned requirements are satisfied, the PDT software will produce a map of velocity vectors representing the flow field under consideration. Tecplot visualization analysis software is then used to display the velocity vector information on a 2-D plot. Typically, such a vector field will display a few vectors whose directions and magnitudes are atypical when compared to vectors in their immediate neighborhood. These are falsely identified vectors and need to be "removed" from the field. This process is done manually, by comparing the vector with the actual five images used in the PDT. That is, the justification for removing a vector is based on successfully identifying that there is no such vector in the original frames grabbed from the video tape that has both the correct direction and magnitude. The correct direction is quite easily determined by displaying the five frames successively on the video monitor (i.e., by "looping" the five frames). However, determining the correct magnitude is more involved. The magnitude is determined by dividing the distance traveled by the particle in pixels by the total time difference between the first and the fifth frame in seconds. The value is then converted to mm/s based on the camera magnification used. If there is no indication, upon review of the actual images, that there exists a particle describing a motion whose direction and magnitude (speed) are similar to that of the suspected falsely identified vector, this vector is removed from the field.

V. RESULTS AND ANALYSES

5.1 Prelude

Essentially two runs with the same test conditions are reported herein. Both experiments were performed at a temperature gradient, G = 15°C/cm, and at a cooling rate, CR = 60°C/hr. The initial top and bottom temperatures, respectively, were 67 and 22°C, and the final top and bottom temperatures, respectively were 31 and -14°C. This resulted in a duration of 35 minutes for the ramp-down period. Both experiments were subject to a gradient hold period of 60 min. The results are presented in tabular and graphical forms, as appropriate.

In Run 1, as mentioned previously, a specific region within the cuvette was chosen before the commencement of the run, and the flow field within this region was observed throughout the entirety of the solidification period. Valuable information was gathered after reduction of data using PDT, as presented in Section 5.3. However, a jet did not occur within the predetermined region of observation. Since characterization and quantification of a jet was a goal for this study, Run 2 was carried out to incorporate a jet in the analysis. In the latter case, the region of interrogation was defined after the occurrence of a jet. The jet began at approximately 90 seconds before the end of the ramp-down period ($t \approx 33.5$ min), and continued into the post-ramp-down hold period for a total time of 10 minutes.

During Run 1, the lateral position of the front camera was fixed at 6.5 mm from the inside left edge of the front cuvette face, and the longitudinal movement was centered at 4.5 mm from the inside front face. The camera was moved longitudinally from 3 mm to 6 mm

from the inside front face, at intervals of 0.5 mm, thereby capturing events in seven distinct planes. The corresponding locations of the side camera were as follows: The camera was fixed laterally at 4.5 mm from the inside edge of the front cuvette face. The side camera moved longitudinally from 5 mm to 8 mm from the inside left edge of the cuvette, the center being at 6.5 mm. Again, seven distinct planes were considered at intervals of 0.5 mm. Figure 5.1 graphically shows the relative positions of cameras for Runs 1 and 2.

5.2 Results at Various Stages of Applying the PDT technique

In this section, the results at various stages of the application of PDT are presented. The results are presented in graphical form, chronologically, beginning with the raw digitized image and ending with the final 3-D plot of representative velocity vectors. Two examples are considered; the data gathered at front plane #5, at a time of 15.76 min for Run 1, and the data gathered at side plane #3, at a time of 35.71 min for Run 2 (jet).

Consider first the data from Run 1. Figure 5.2 shows the raw digitized 512 X 512 pixel image frame grabbed from the video tape. This image has interlaced information, where 256 odd numbered lines were first written, followed by the other 256 even numbered lines after a time lag. As discussed earlier, since this produced split images of particles, the image was regenerated using the program IMGMOD, such that only the odd lines are considered. This image, with intensity values ranging from 0 to 255 is shown on the top portion of Figure 5.3. The image shown on the bottom portion of Figure 5.3 is essentially the same as the top image, except that contrast modification has been performed to reduce background noise. The image was modified at contrast levels of 41 and 224. Essentially, all pixel values in the left image that were below 41 were set at 41, and all pixel values

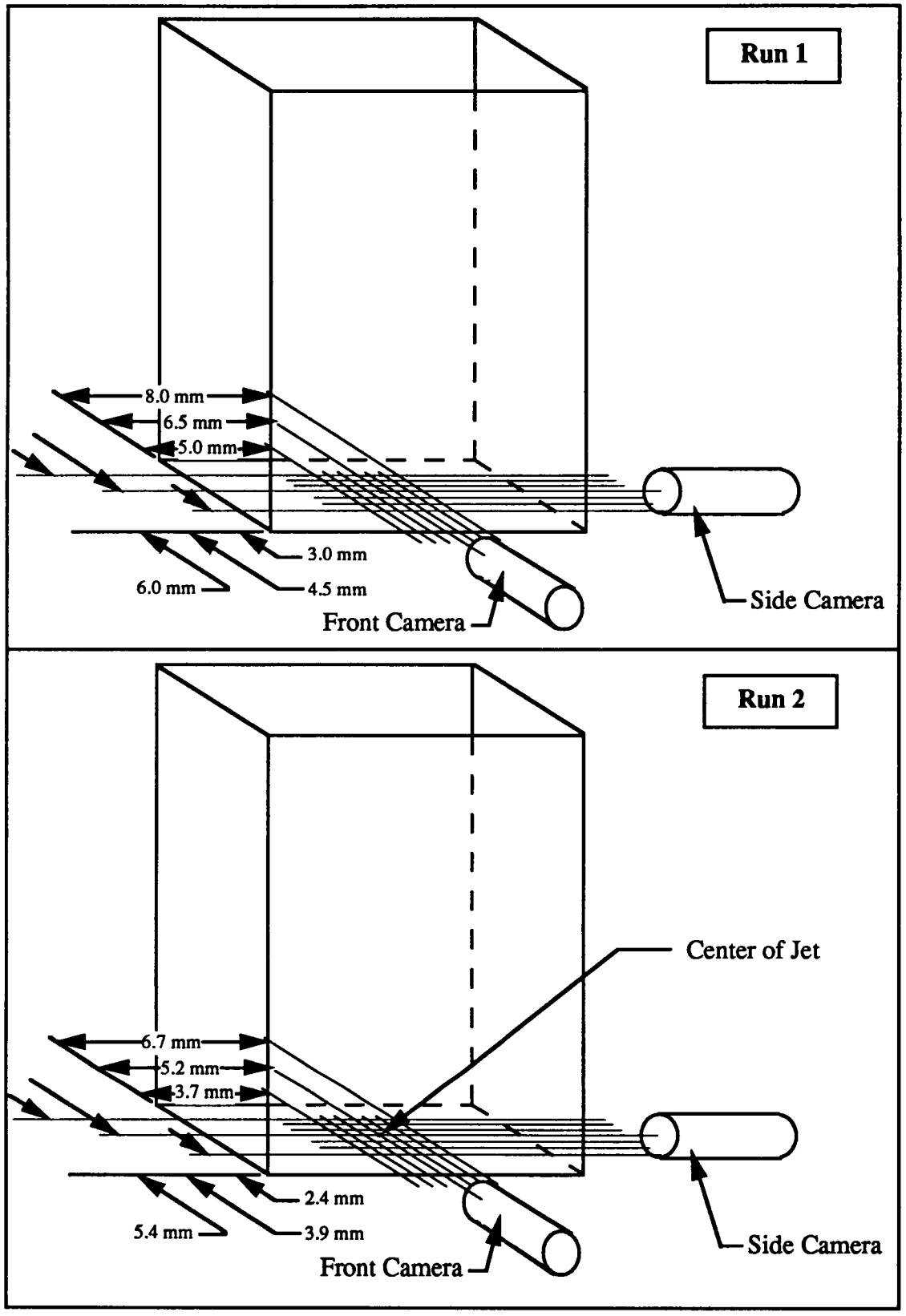


Figure 5.1 Relative positions of front and side cameras during Runs 1 and 2

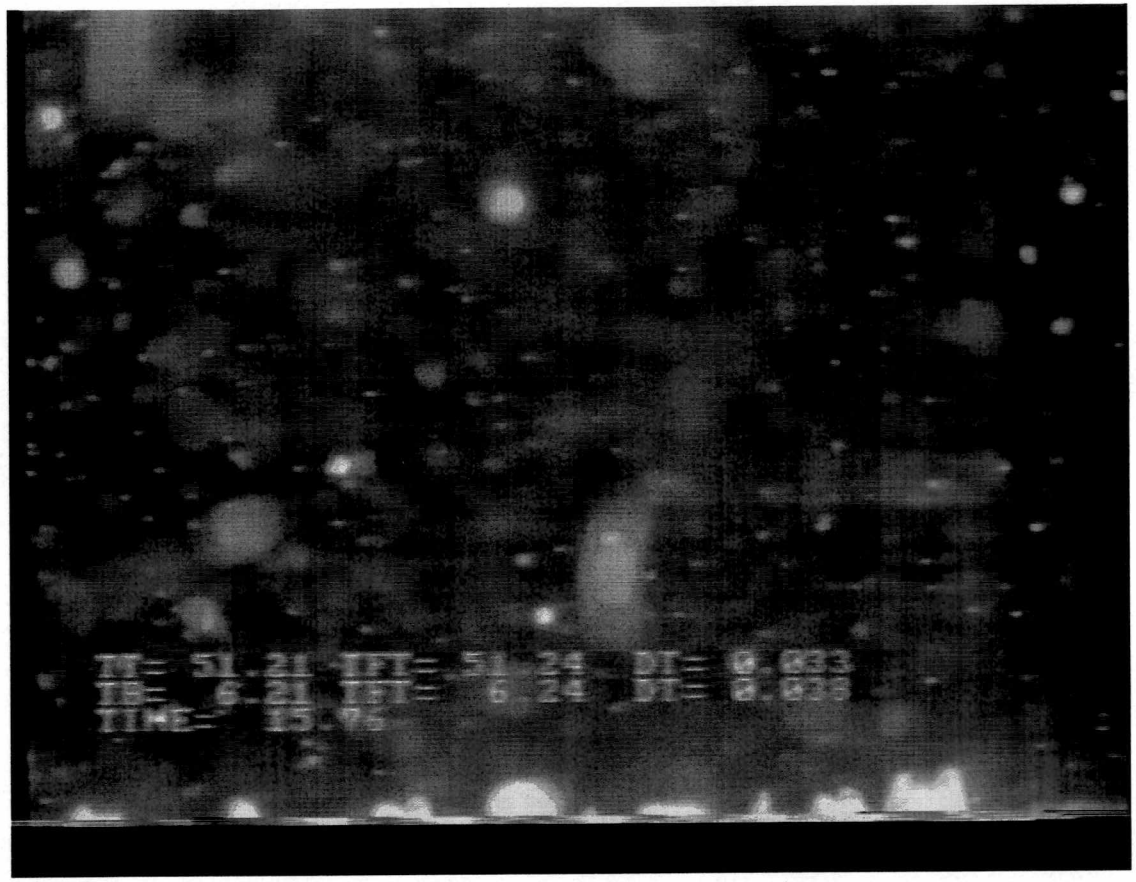


Figure 5.2 Unmodified digitized image at t = 15.76 min, plane 5, front camera, G = 15°C/cm, CR = 60°C/hr, Run 1

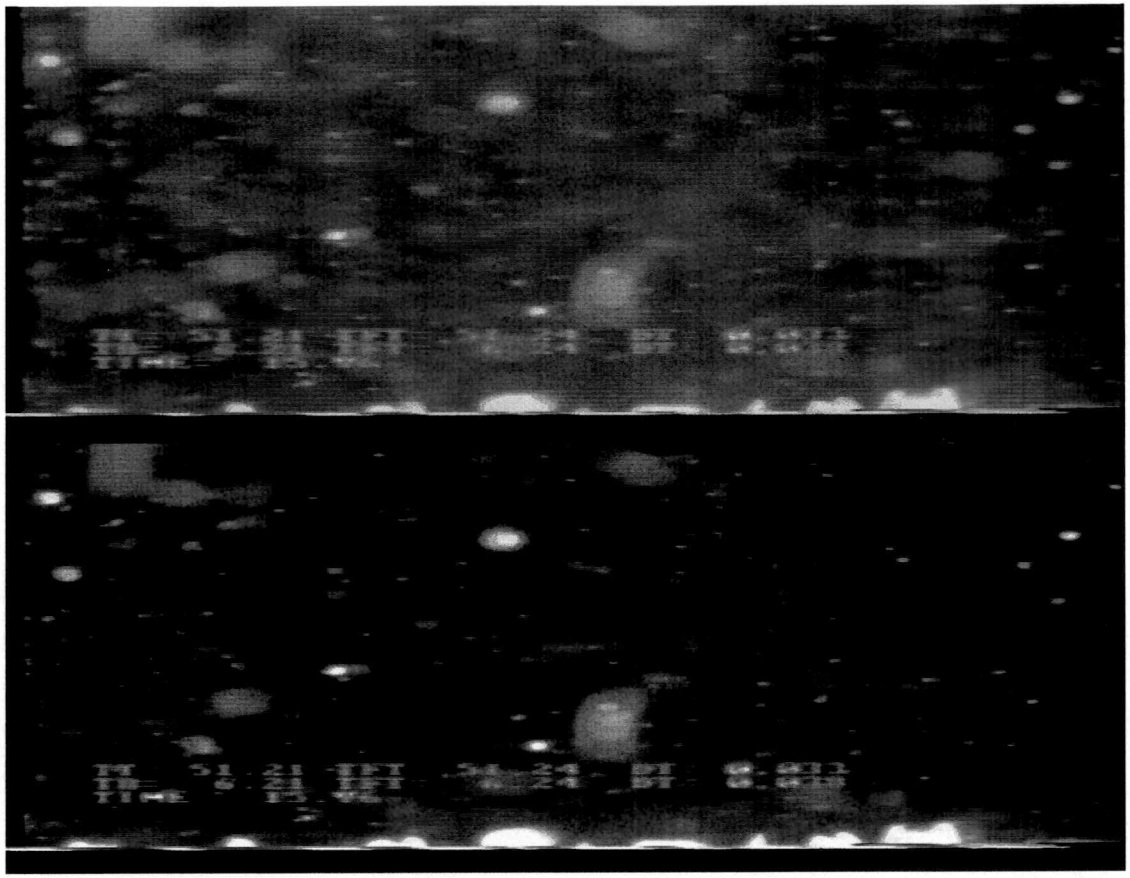


Figure 5.3 Images after interlace modification, with contrast modification (bottom) and without contrast modification (top), plane 5, front camera, G = 15°C/cm, CR = 60°C/hr, Run 1

above 224 were set at a value of 224. The contrast levels were carefully chosen such that, while eliminating background noise as much as possible, no particle information was lost.

The next step was to use the program CENT, to locate the centroid of each particle in the image, and write that information to another image file. (The program CENT was written by Brent W. Blaha, Graduate Research Assistant , CLA, The University of Tennessee Space Institute). The centroid locations are indicated by white pixels, with the background black, hence the intensity values in the new image are either 255 or 0. The threshold level for CENT was set at 85. The image processed using CENT is shown on the bottom of Figure 5.4, with the unprocessed image shown on the top for easy comparison. It is evident from both images that each white pixel in the right image corresponds to the centroid of a particle in the left image. Some bright spots from the left image have not been identified in the right image, since the intensity values of these spots were below the user defined threshold.

Four other images similar to the one discussed above, separated at time intervals of 2/15 sec are processed in the above fashion. The program FPART is then run using the five images to determine particle centroid locations relative to the 512 X 512 array. The window of interest was set as follows: The top left hand corner was set at i =0, j = 0, and the bottom right hand corner was set at i = 510, j = 180. Note that j = 180 corresponds to the location 0.75 mm above the mean interface. This distance is kept fixed throughout the entire experiment.

Next, the program GVEL was executed to determine velocity vectors. The user inputted search radius was 4 pixels. A tolerance of 3 pixels in all directions was specified.

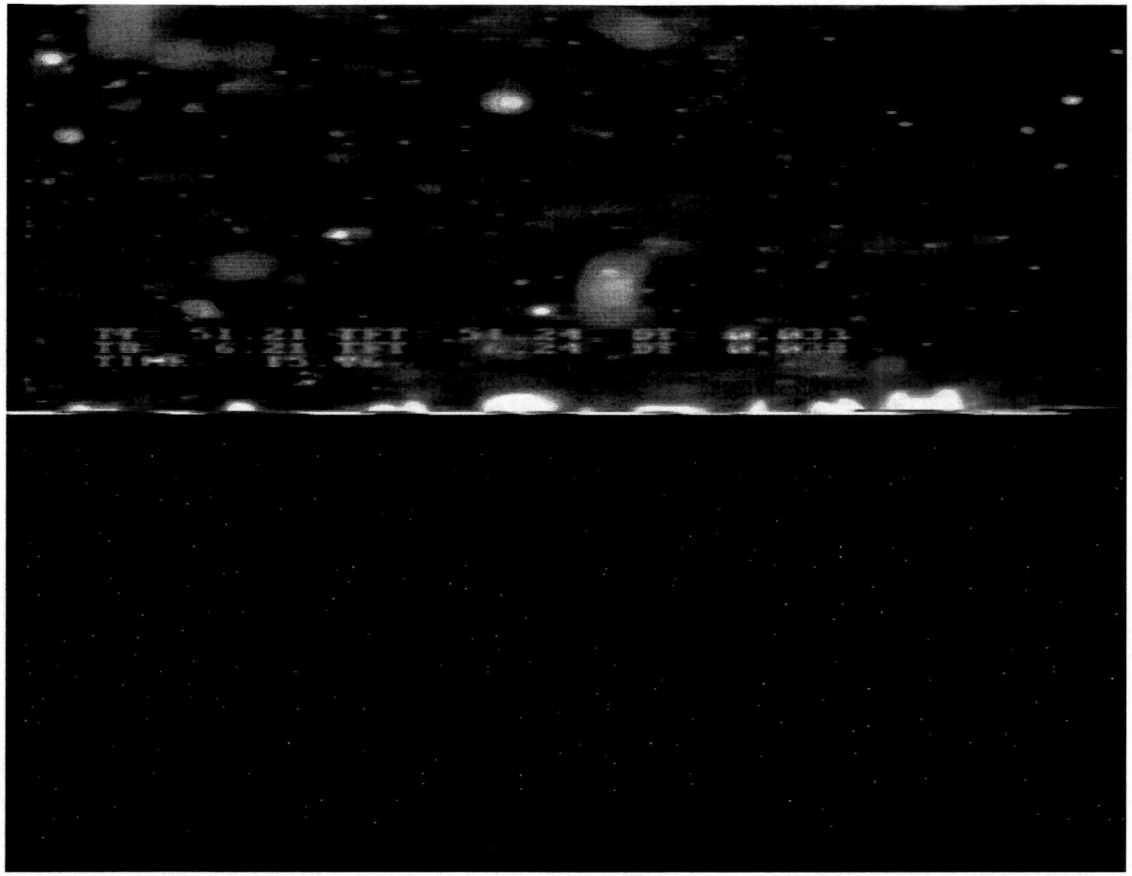


Figure 5.4 Comparison of image files, processed with CENT (bottom), and unprocessed (top), plane 5, front camera, G = 15°C/cm, CR = 60°C/hr, Run 1

Every fourth frame from the optical disc was considered, given the earlier mentioned time interval of 2/15 sec between frames. This procedure was carried out twice to generate two sets of data. The two sets of data (i. e., two sets of five frames) were used to generate two sets of raw velocity vectors. The two sets were then combined to produce one composite vector map. This action was taken to maximize the number of identified raw vectors and to produce a raw vector map that had a good distribution of velocity vectors that cover the entire map. This minimized the areas within the map that were void of velocity vectors. A total of 82 velocity vectors were identified. Figure 5.5 shows the vector map generated by Tecplot, showing all 82 raw velocity vectors. The above described procedure was carried out for the seven front planes and the seven side planes.

Consider now, information from Run 2. In this case, the flow characteristics of the jet and the surrounding fluid are characterized, and since the flow velocity of the jet is much greater than the surrounding fluid, an extra step is incorporated in the reduction procedure to capture both information about the jet and the surrounding fluid.

Two sets of images were processed individually. One set consisted of images separated at a time interval of 1/30 sec. This captured the faster moving particles characterizing the jet. The other set consisted of images separated at 1/6 sec, and captured the slower moving particles, that of the surrounding liquid. The raw velocity vector maps generated by the set of images with the lesser (1/30 sec) and the greater (1/6 sec) time interval are shown in Figures 5.6 and 5.7, respectively. In the case of 1/30 framing rate, 8 velocity vectors were identified, and in the case of 1/6 framing rate, 78 velocity vectors were identified. Comparison of Figures 5.6 and 5.7 illustrates the great difference in magnitude of the velocity vectors (jet flow and non-jet flow).

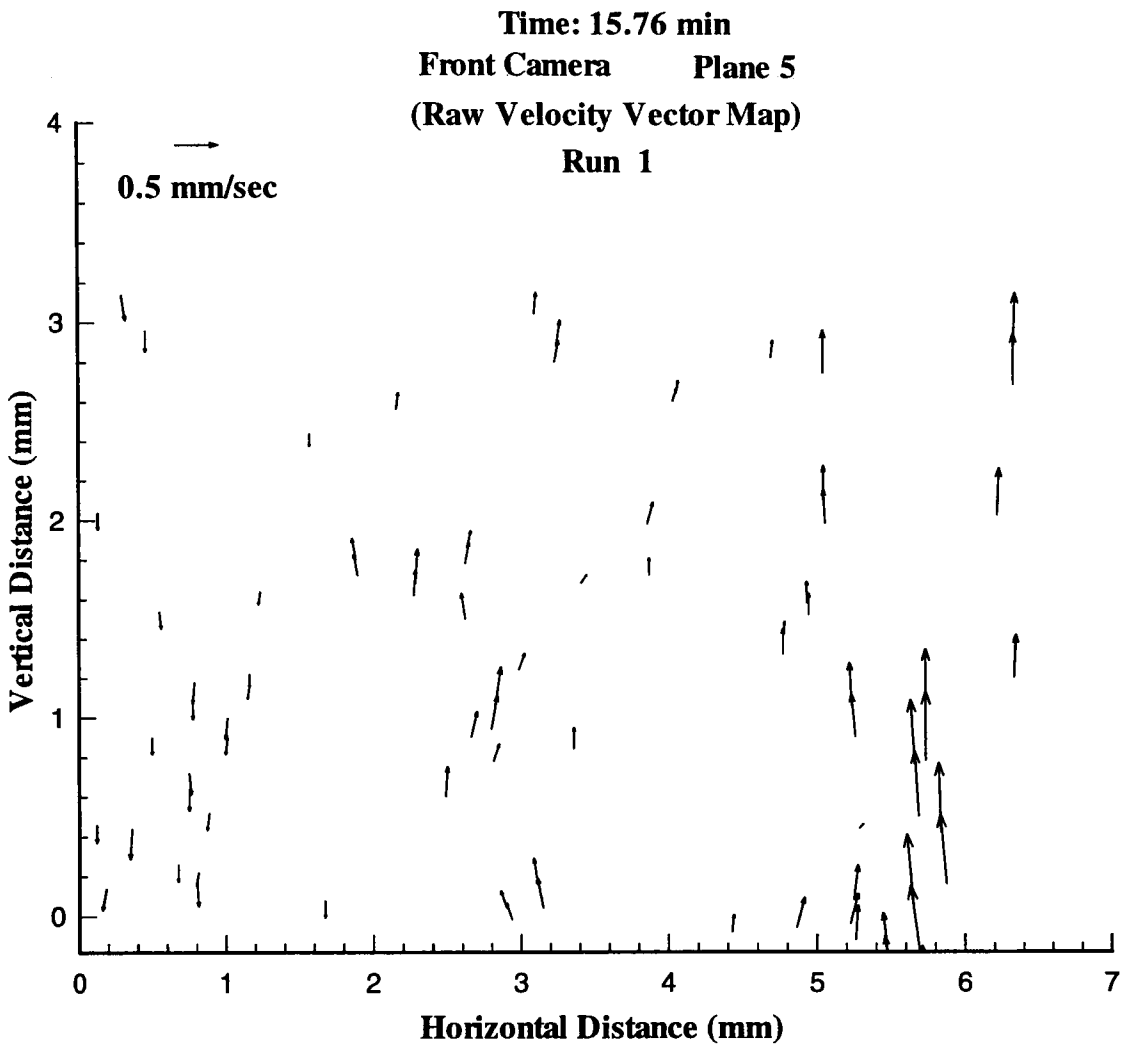


Figure 5.5 Raw velocity vector map, t = 15.76 min, plane #5, front camera, G = 15°C/cm, CR = 60°C/hr, Run 1

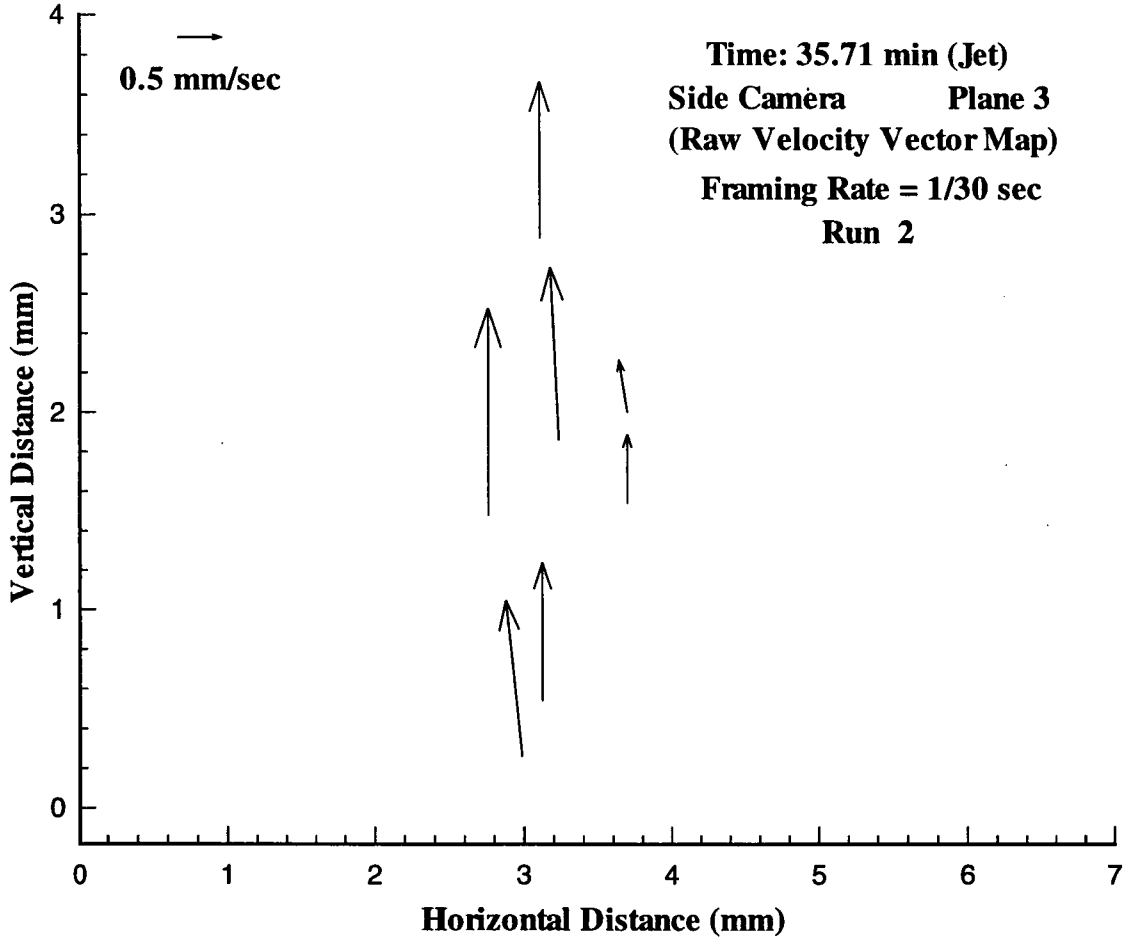


Figure 5.6 Raw velocity vector map, t = 35.71 min (jet), plane #3, side camera, framing rate 1/30 sec, G = 15°C/cm, CR = 60°C/hr, Run 2

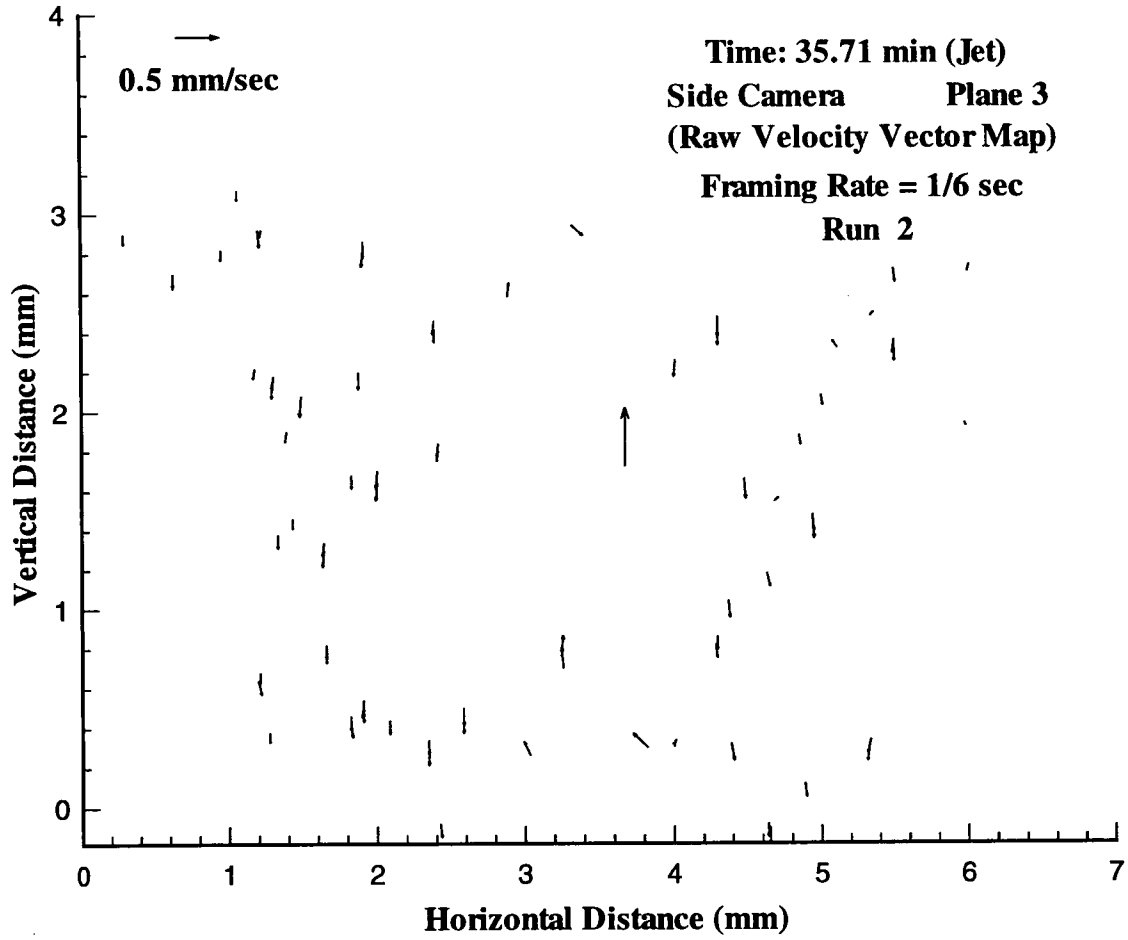


Figure 5.7 Raw velocity vector map, t = 35.71 min (jet), plane #3, side camera, framing rate 1/6 sec, G = 15°C/cm, CR = 60°C/hr, Run 2

Subsequently, both velocity maps are combined and a 2-D Kriging interpolation is performed on the raw data within Tecplot. Figure 5.8 shows the interpolated vector map. This procedure is carried out for all fourteen planes. The final step in the data reduction involved placing the fourteen planes at the appropriate location relative to one another, within a volume of 6.4 X 6.4 X 3.4 mm, and performing a 3-D Inverse-Distance interpolation within the volume. The interpolated 3-D volume is shown in Figure 5.9.

5.3 Results from Runs 1 and 2

In this section, results from Run 1 are presented followed by those from Run 2. Some observations and comments on the results are included in the latter part of this section. In the concluding segment of this section, numerically computed values (using the obtained results) of the overall flow activity throughout the entire run are presented.

Consider Run 1. Representative raw velocity vector maps obtained at various times throughout the entire run are presented. Specifically, the velocity maps at each of the center planes (Plane 4) in both orthogonal directions (front and side) are presented at t = 5, 10, 15, 20, 25, 30 and 35 minutes. As mentioned in Section 5.2, the raw velocity vectors displayed in the vector maps were obtained by applying the PDT technique twice at each of the planes for each of the times (i.e., by using the technique on two sets of five consecutively frame grabbed images). This increased the number of identified velocity vectors and improved the vector distribution throughout the map. Figures 5.10, 5.12, 5.14, 5.16, 5.18, 5.20, and 5.22 show the raw velocity vectors on the front center planes (Plane 4), at t = 5, 10, 15, 20, 25, 30, and 35 minutes, respectively. Similar plots for the side center planes are shown in Figures 5.11, 5.13, 5.15, 5.17, 5.19, 5.21, and 5. 23 for t = 5, 10, 15, 20, 25, 30, and 35 minutes.

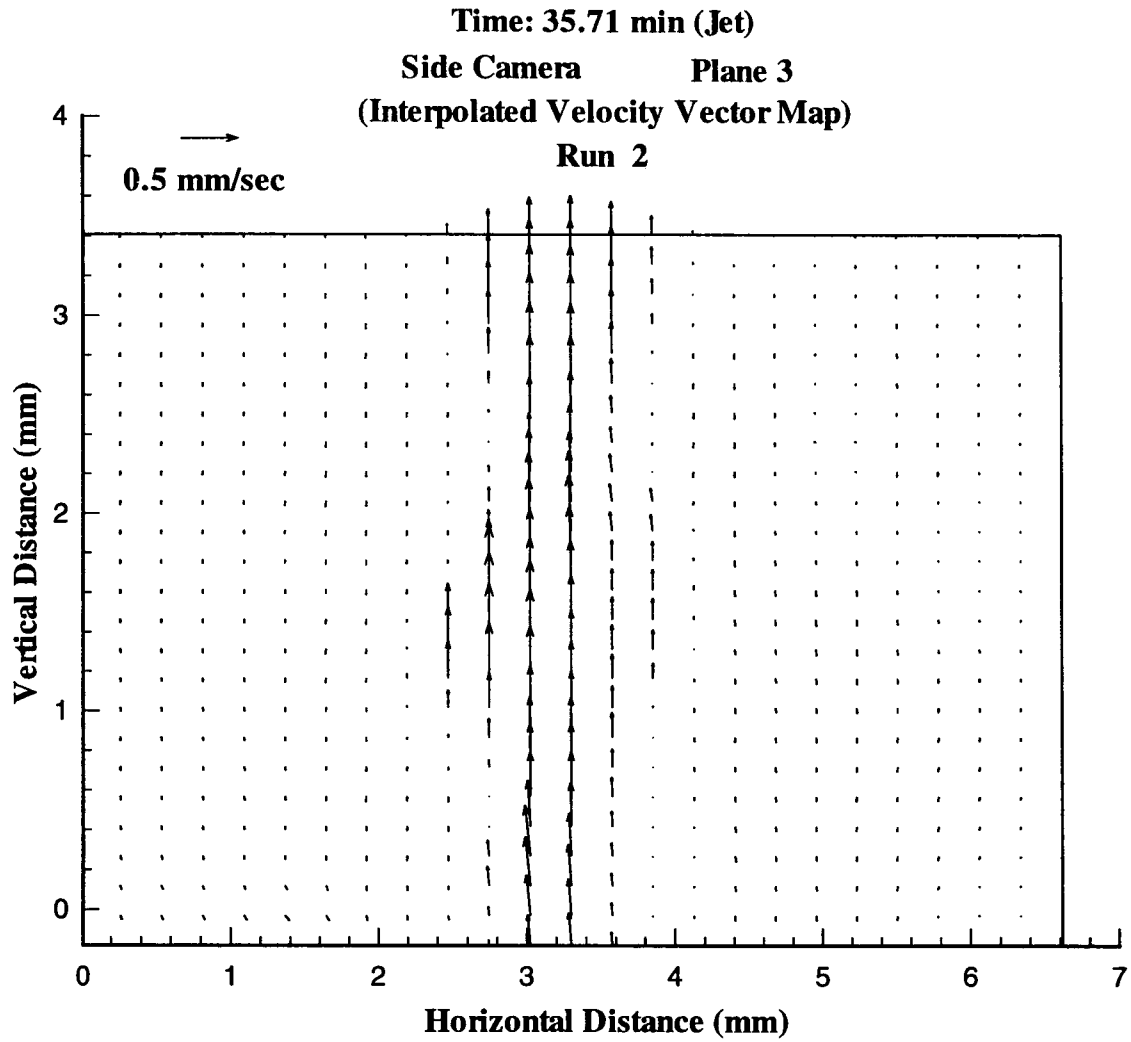


Figure 5.8 Interpolated velocity vector map, t = 35.71 min (jet), plane #3, side camera, G = 15°C/cm, CR = 60°C/hr, Run 2

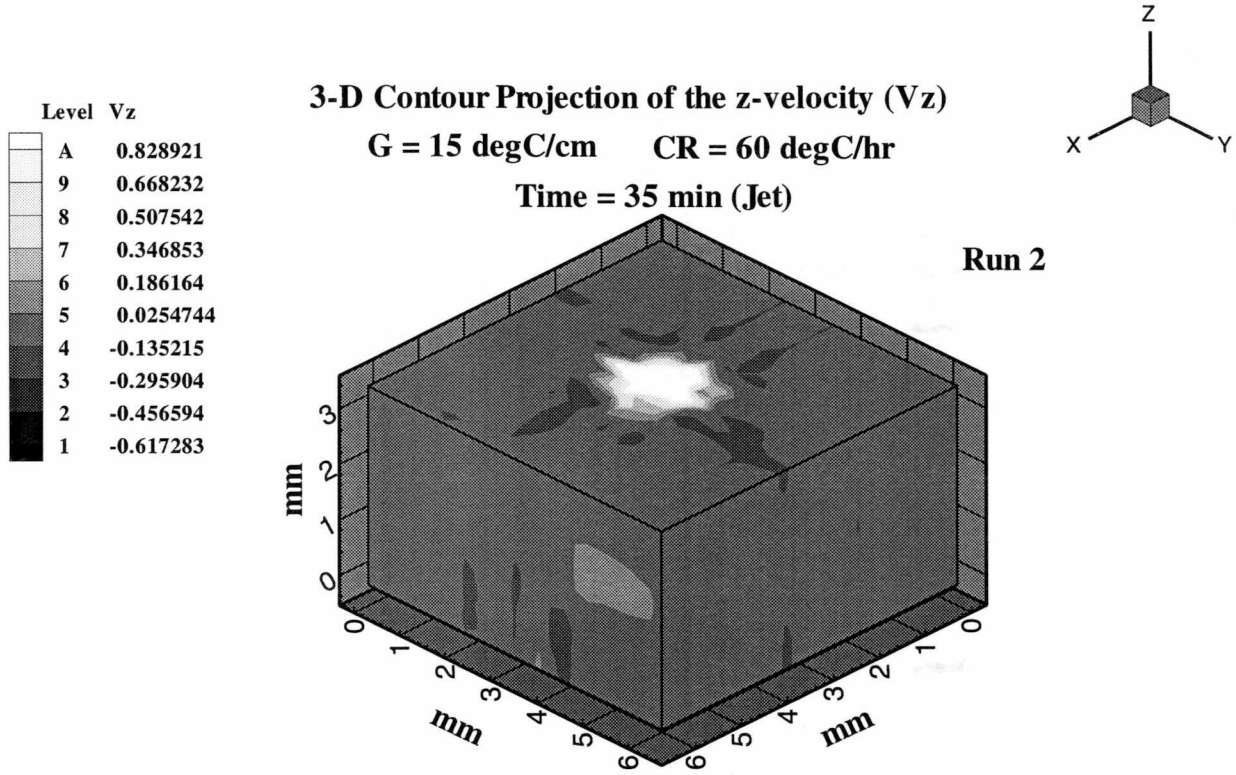


Figure 5.9 Interpolated 3-D contour plot of the Z-velocity, Vz, t = 35 min (jet), G = 15°C/cm, CR = 60°C/hr, Run 2

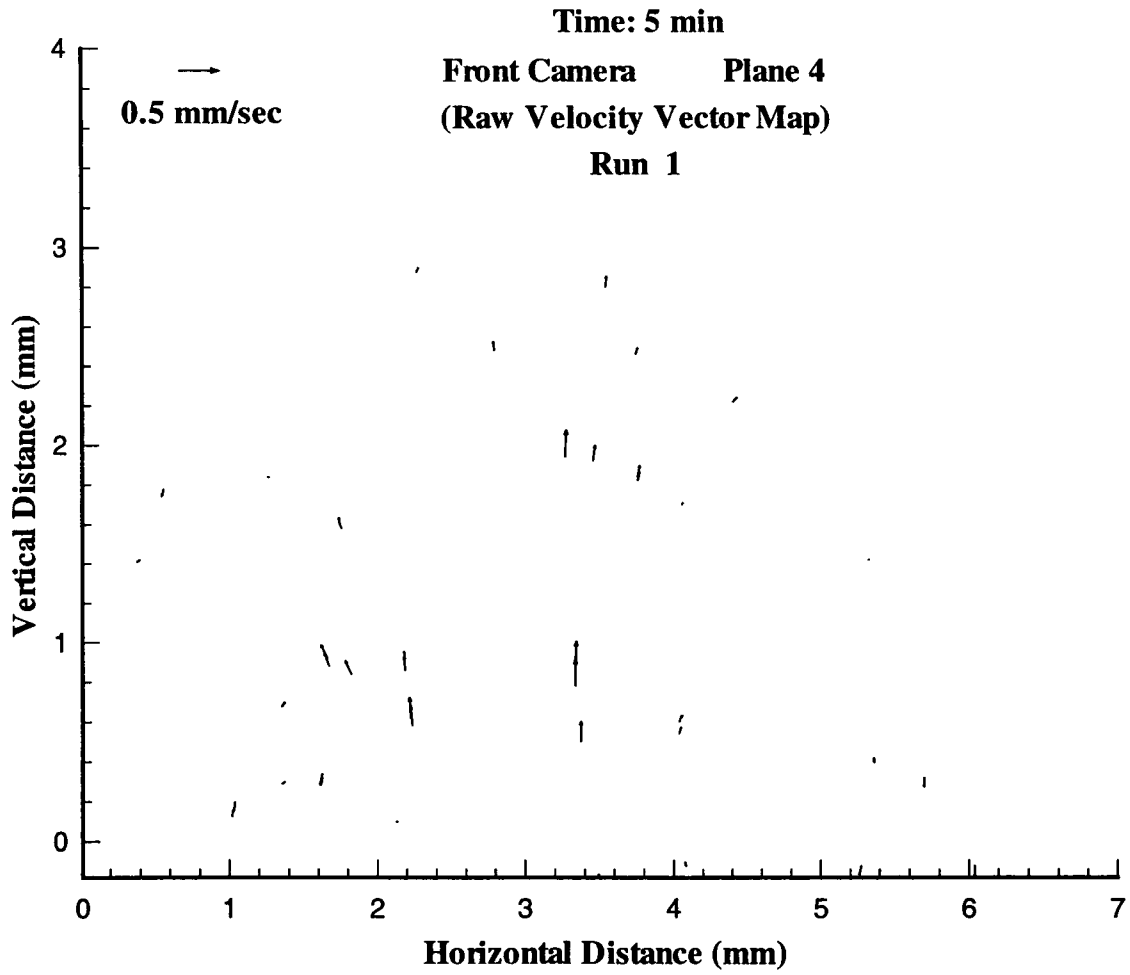


Figure 5.10 Raw velocity vector map, front Plane 4, t = 5 min, G = 15°C/cm, CR = 60°C/hr, Run 1

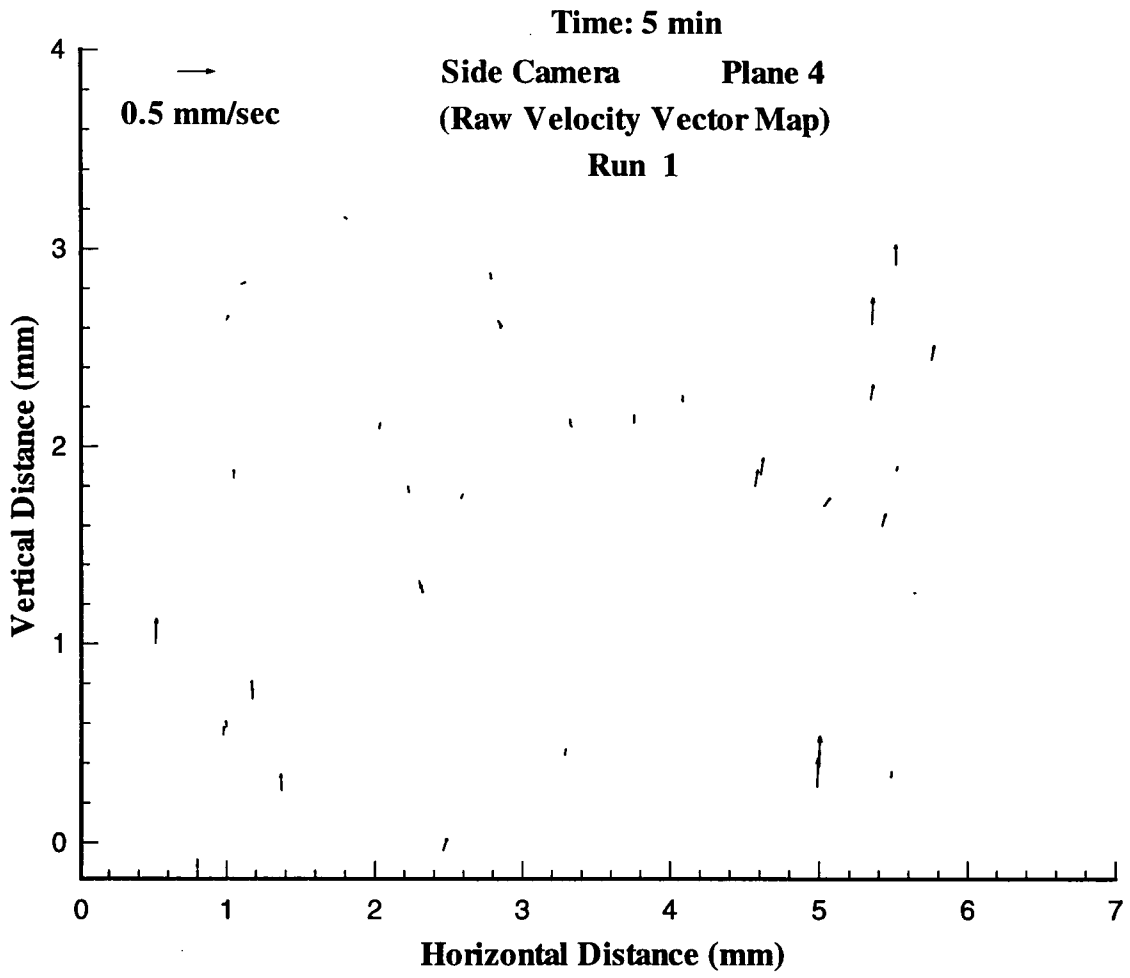


Figure 5.11 Raw velocity vector map, side Plane 4, t = 5 min, G = 15°C/cm, CR = 60°C/hr, Run 1

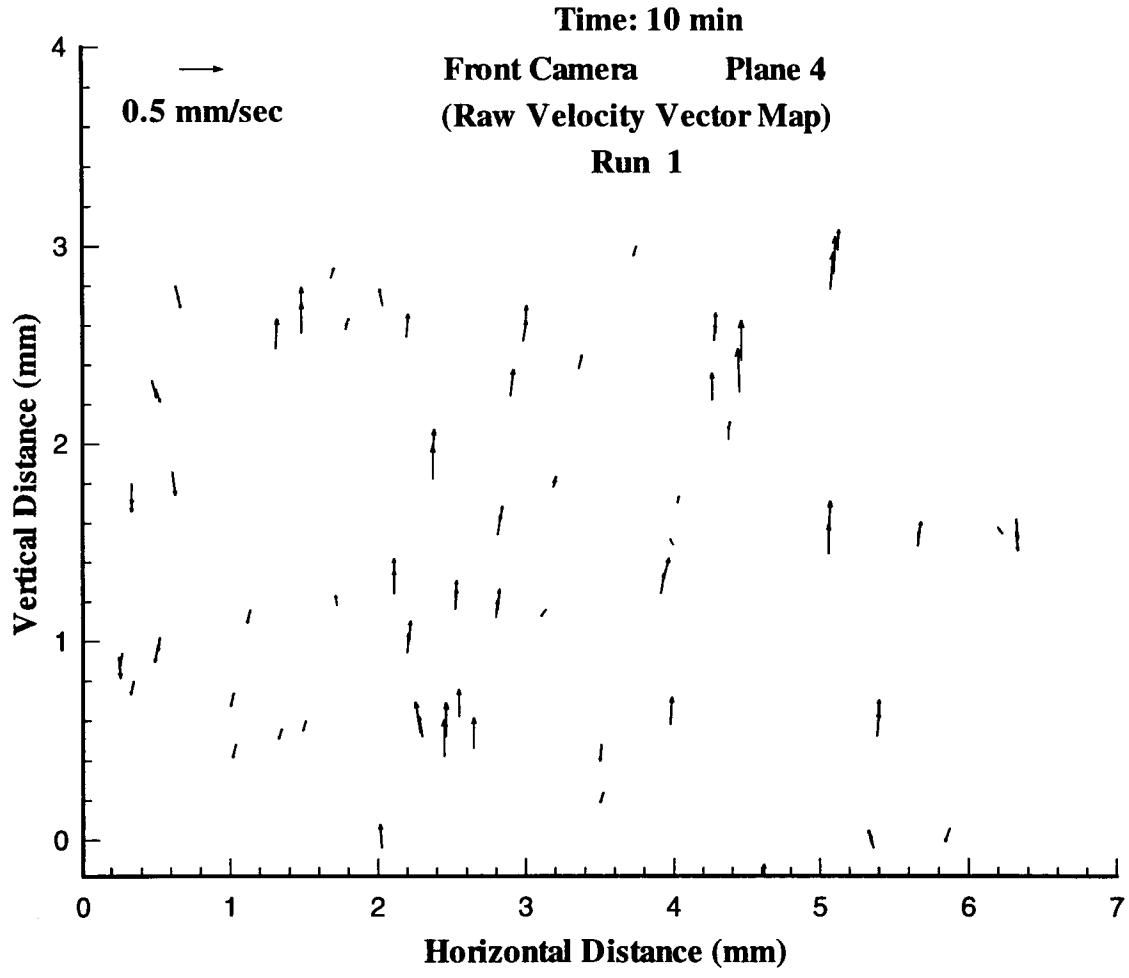


Figure 5.12 Raw velocity vector map, front Plane 4, t = 10 min, G = 15°C/cm, CR = 60°C/hr, Run 1

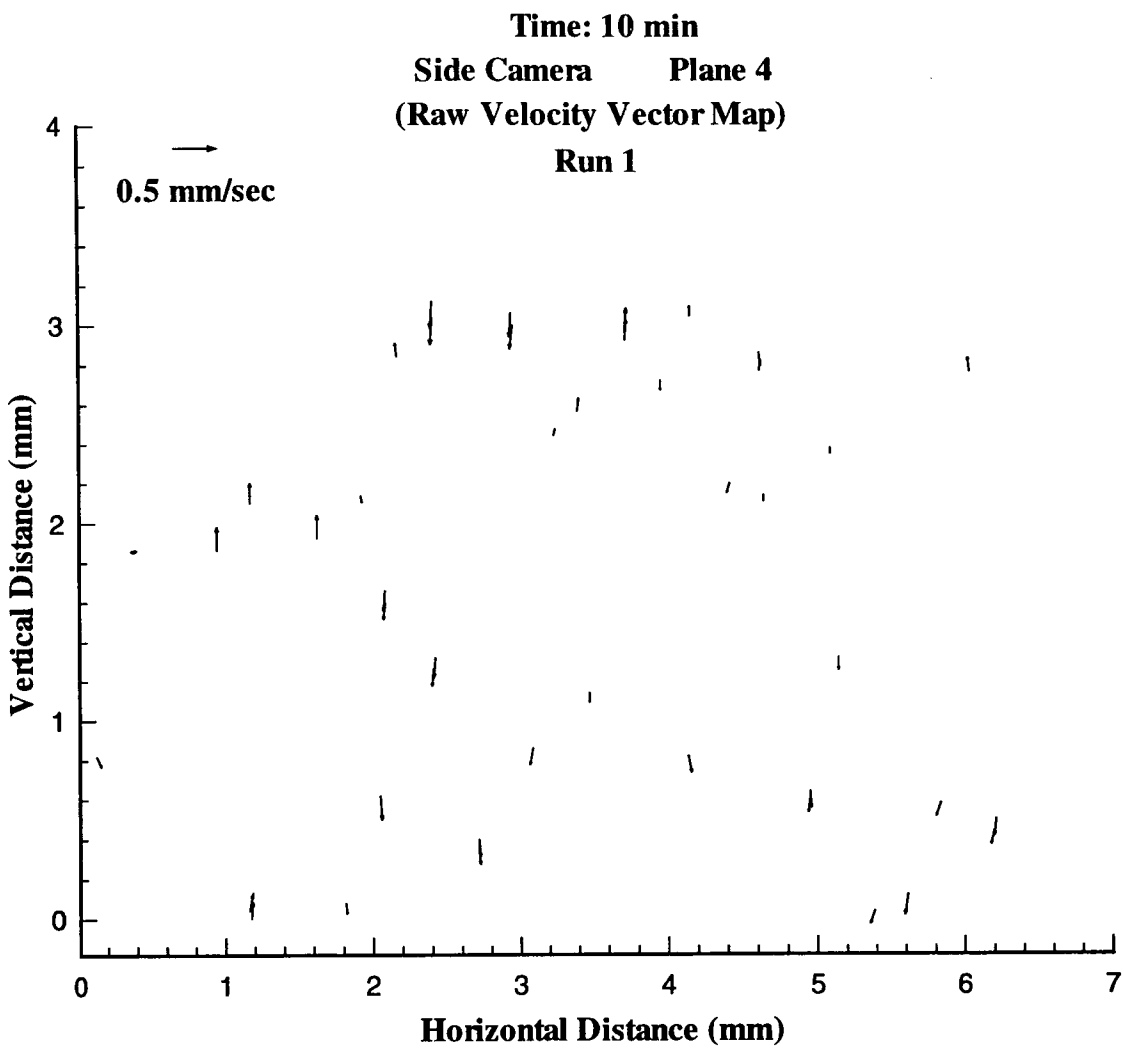


Figure 5.13 Raw velocity vector map, side Plane 4, t = 10 min, G = 15°C/cm, CR = 60°C/hr, Run 1

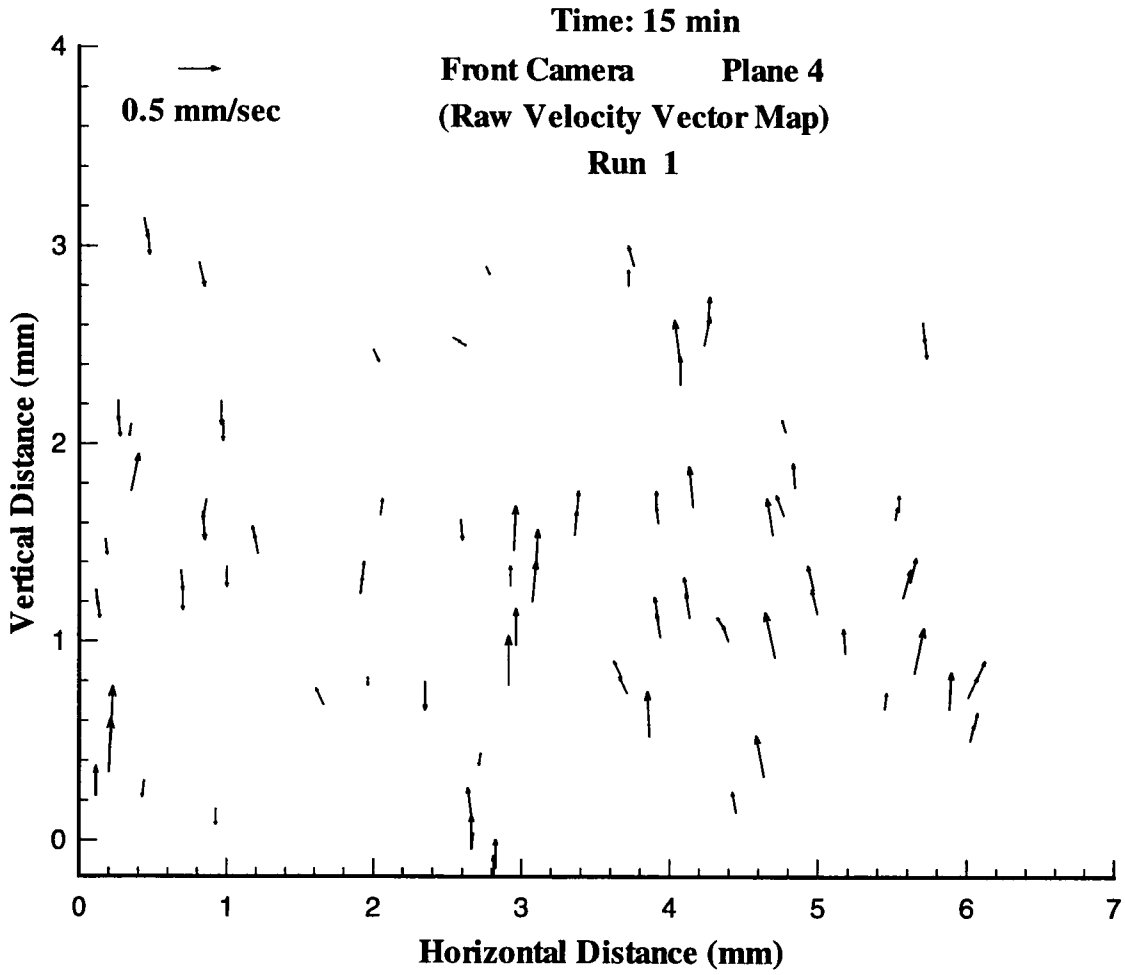


Figure 5.14 Raw velocity vector map, front Plane 4, t = 15 min, G = 15°C/cm, CR = 60°C/hr, Run 1

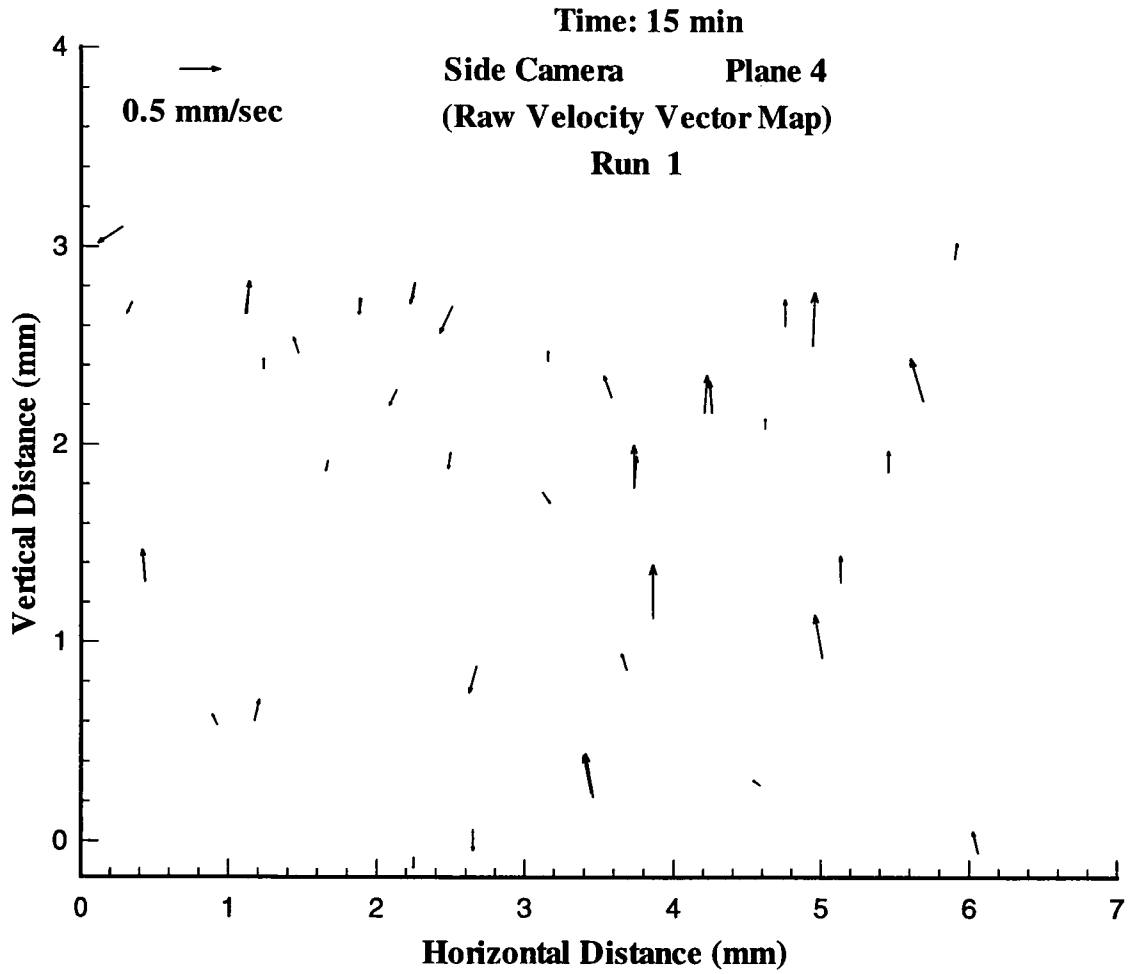


Figure 5.15 Raw velocity vector map, side Plane 4, t = 15 min, G = 15°C/cm, CR = 60°C/hr, Run 1

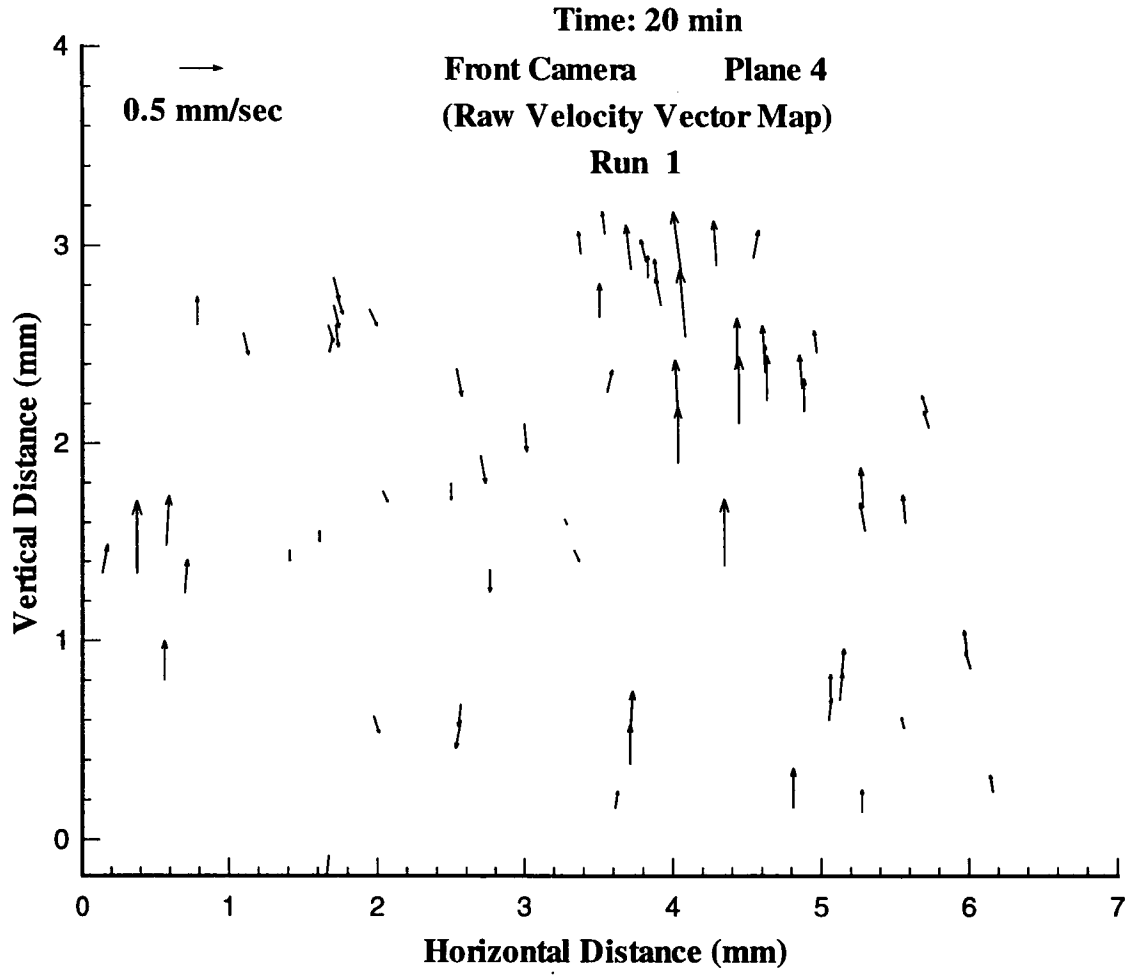


Figure 5.16 Raw velocity vector map, front Plane 4, t = 20 min,
G = 15°C/cm, CR = 60°C/hr, Run 1

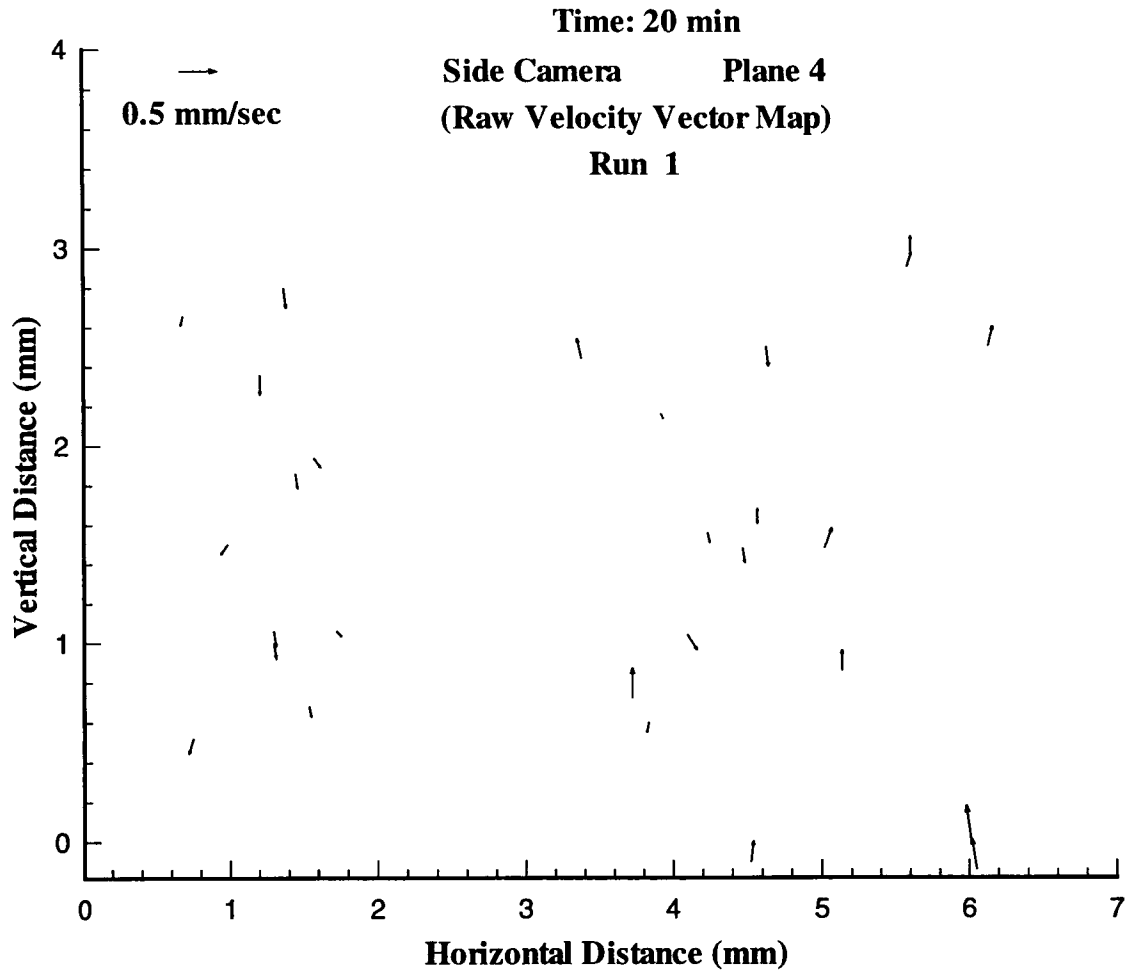


Figure 5.17 Raw velocity vector map, side Plane 4, t = 20 min, G = 15°C/cm, CR = 60°C/hr, Run 1

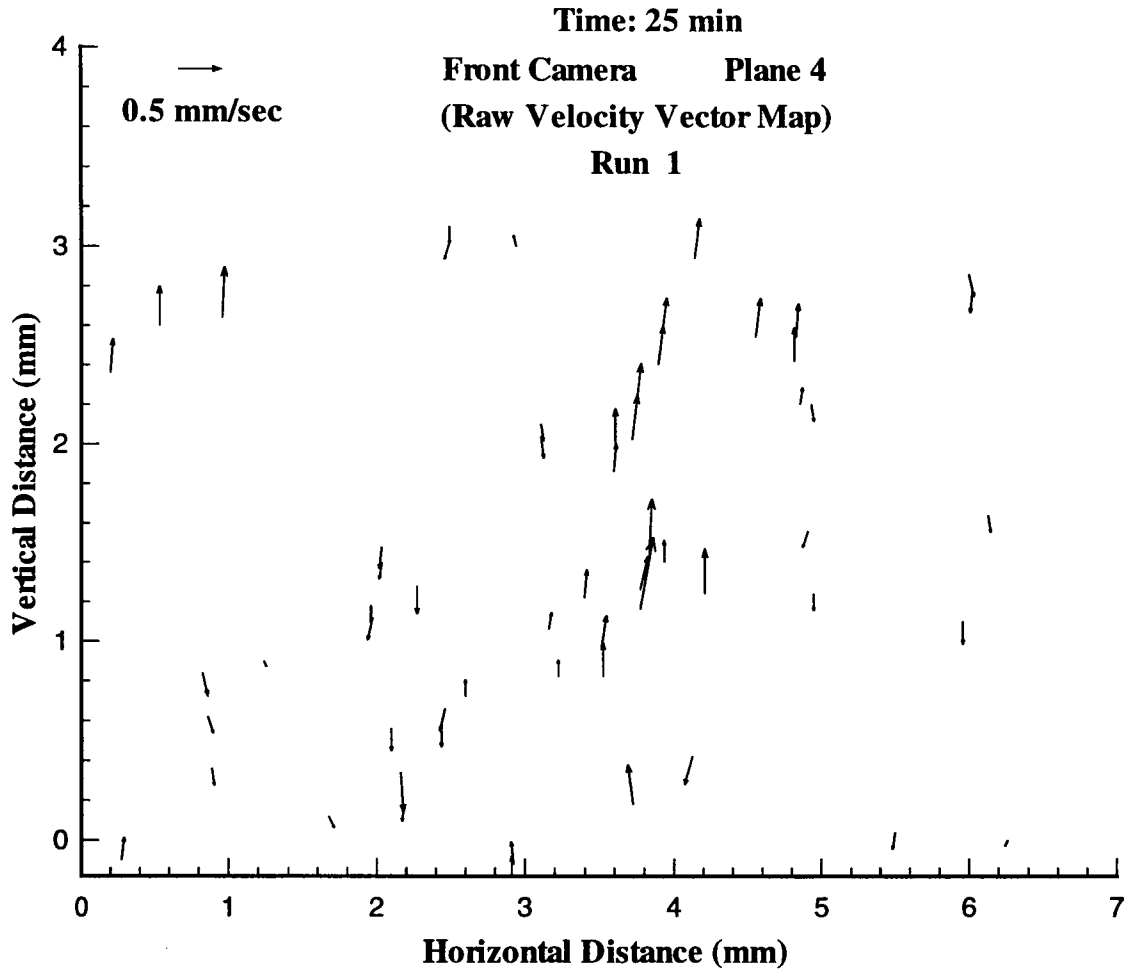


Figure 5.18 Raw velocity vector map, front Plane 4, t = 25 min, G = 15°C/cm, CR = 60°C/hr, Run 1

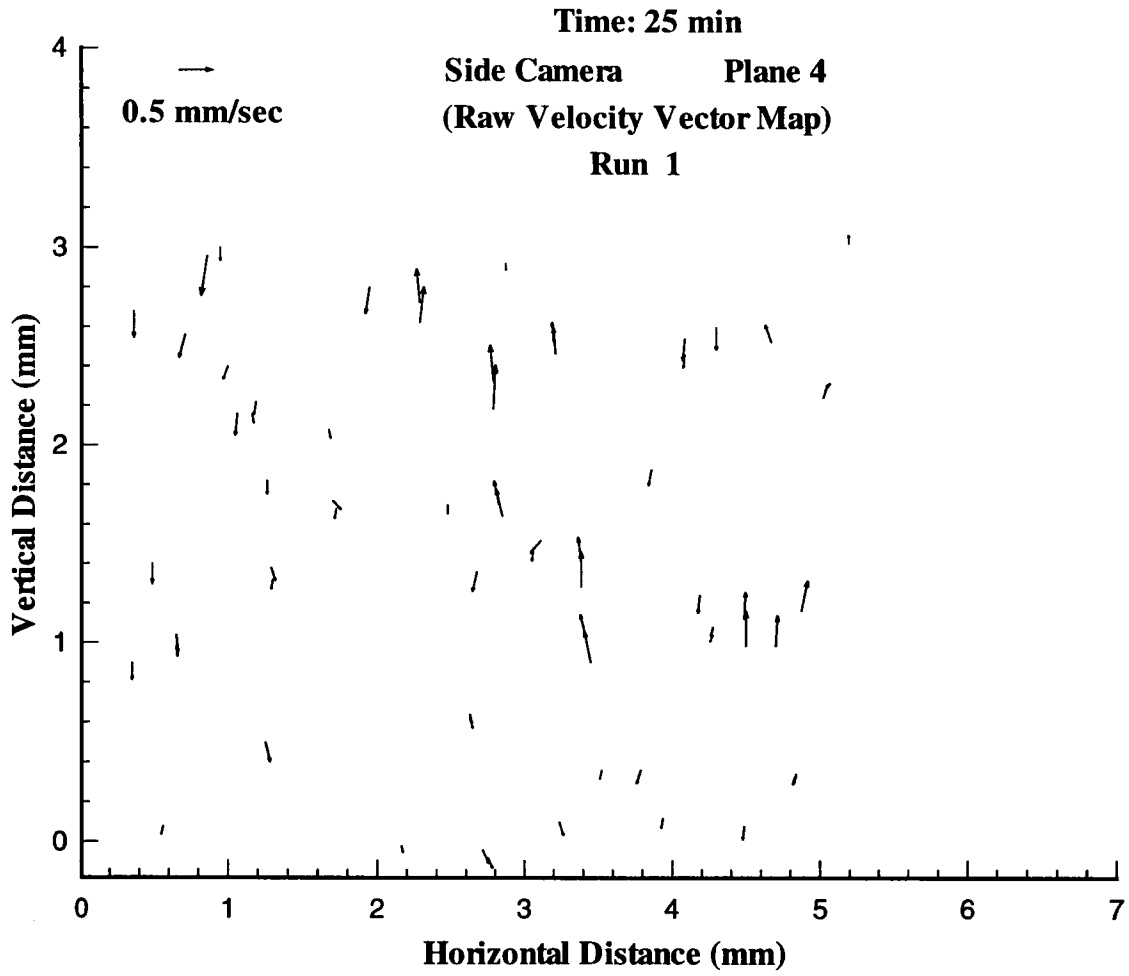


Figure 5.19 Raw velocity vector map, side Plane 4, t = 25 min, G = 15°C/cm, CR = 60°C/hr, Run 1

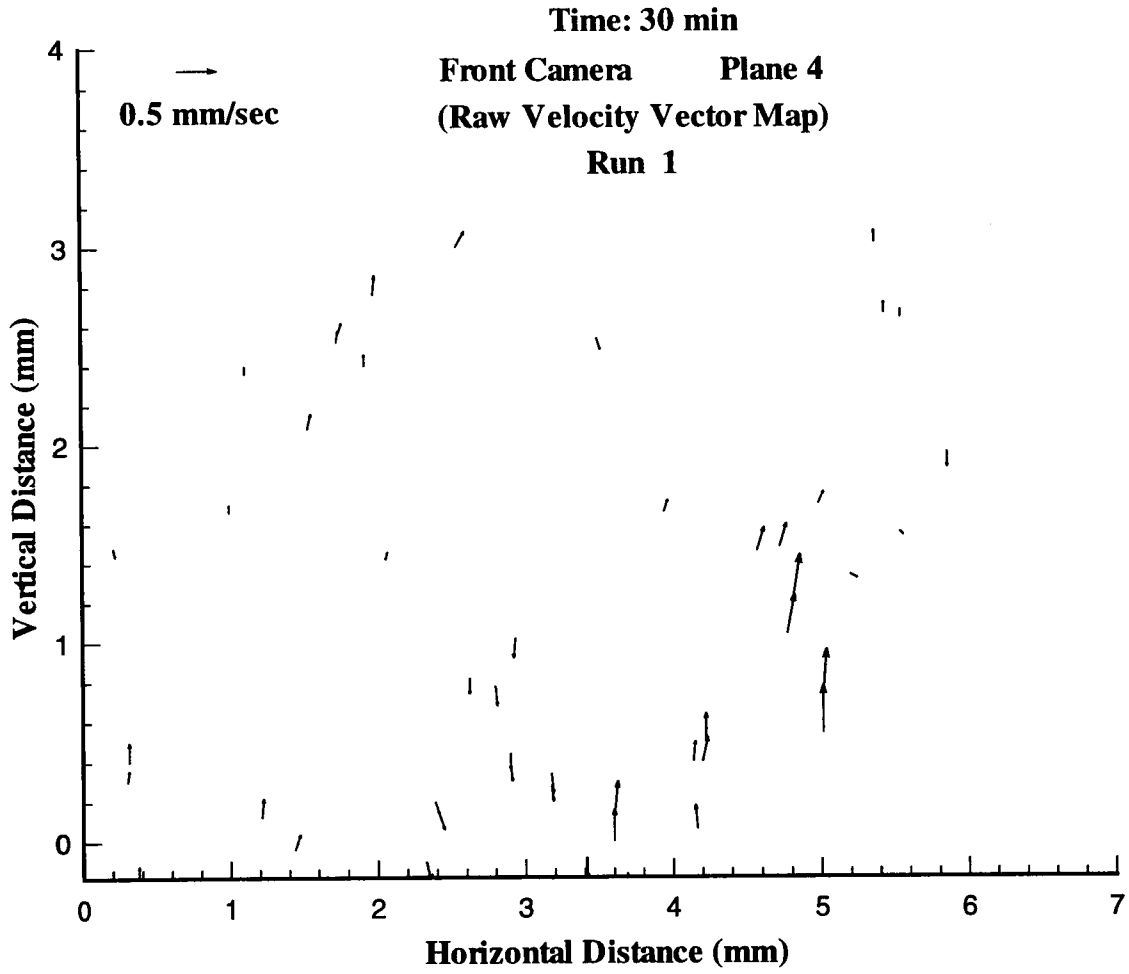


Figure 5.20 Raw velocity vector map, front Plane 4, t = 30 min, G = 15°C/cm, CR = 60°C/hr, Run 1

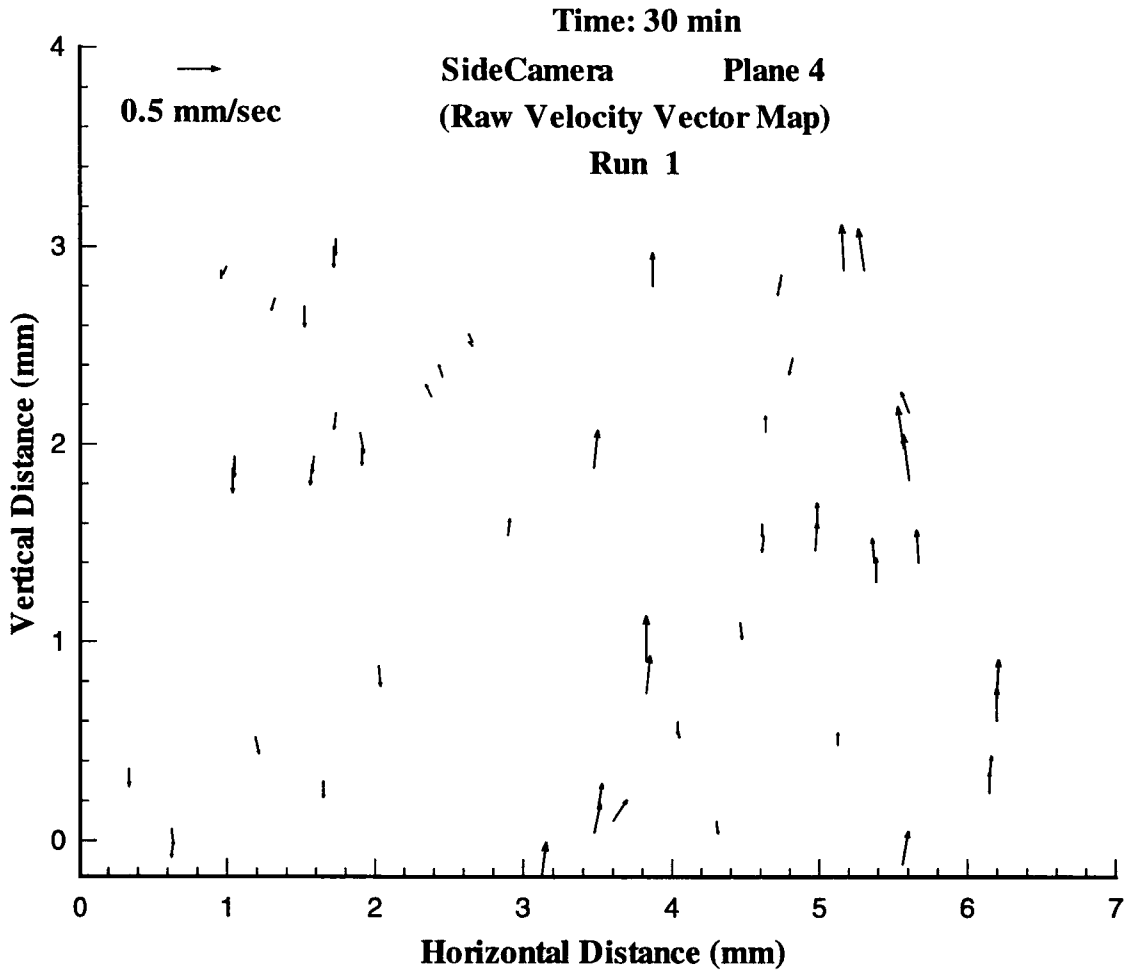


Figure 5.21 Raw velocity vector map, side Plane 4, t = 30 min, G = 15°C/cm, CR = 60°C/hr, Run 1

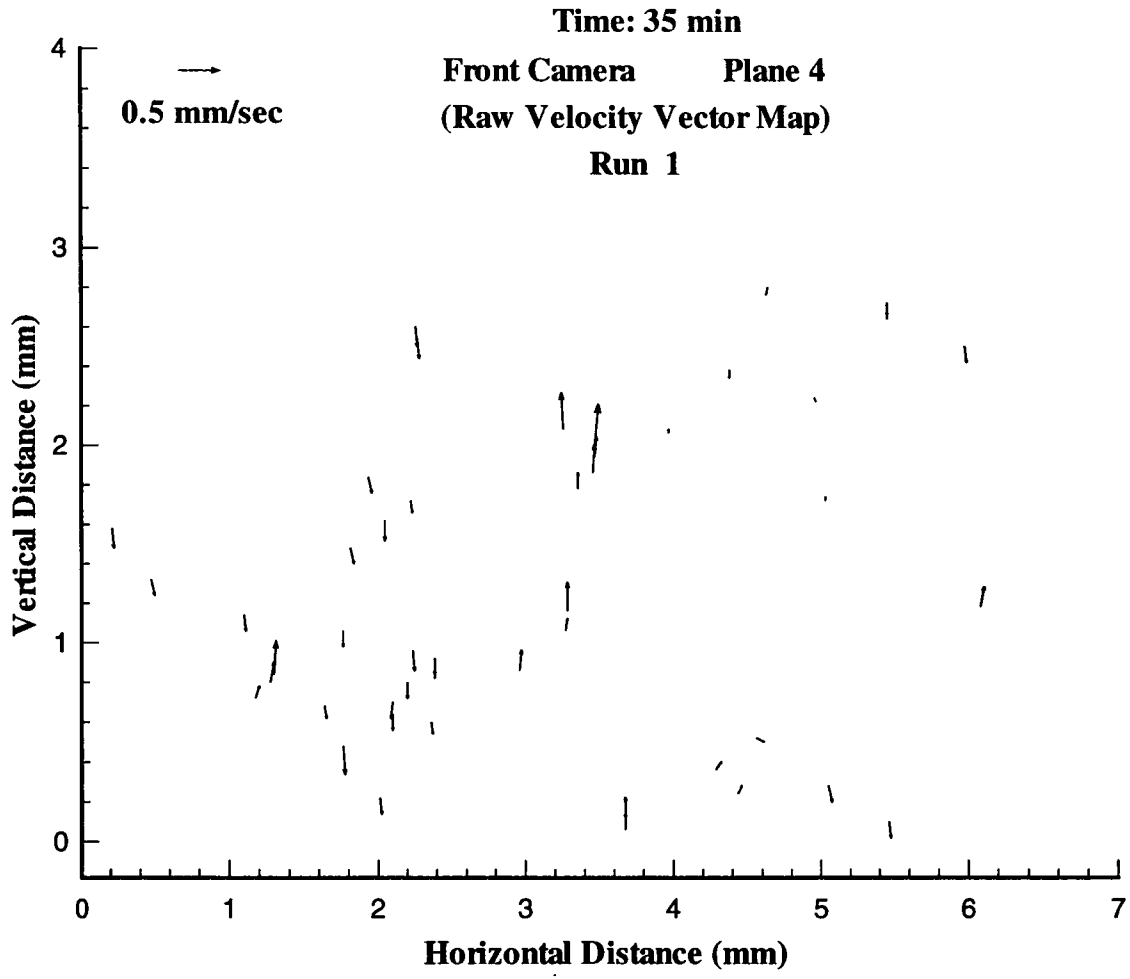


Figure 5.22 Raw velocity vector map, front Plane 4, t = 35 min, G = 15°C/cm, CR = 60°C/hr, Run 1

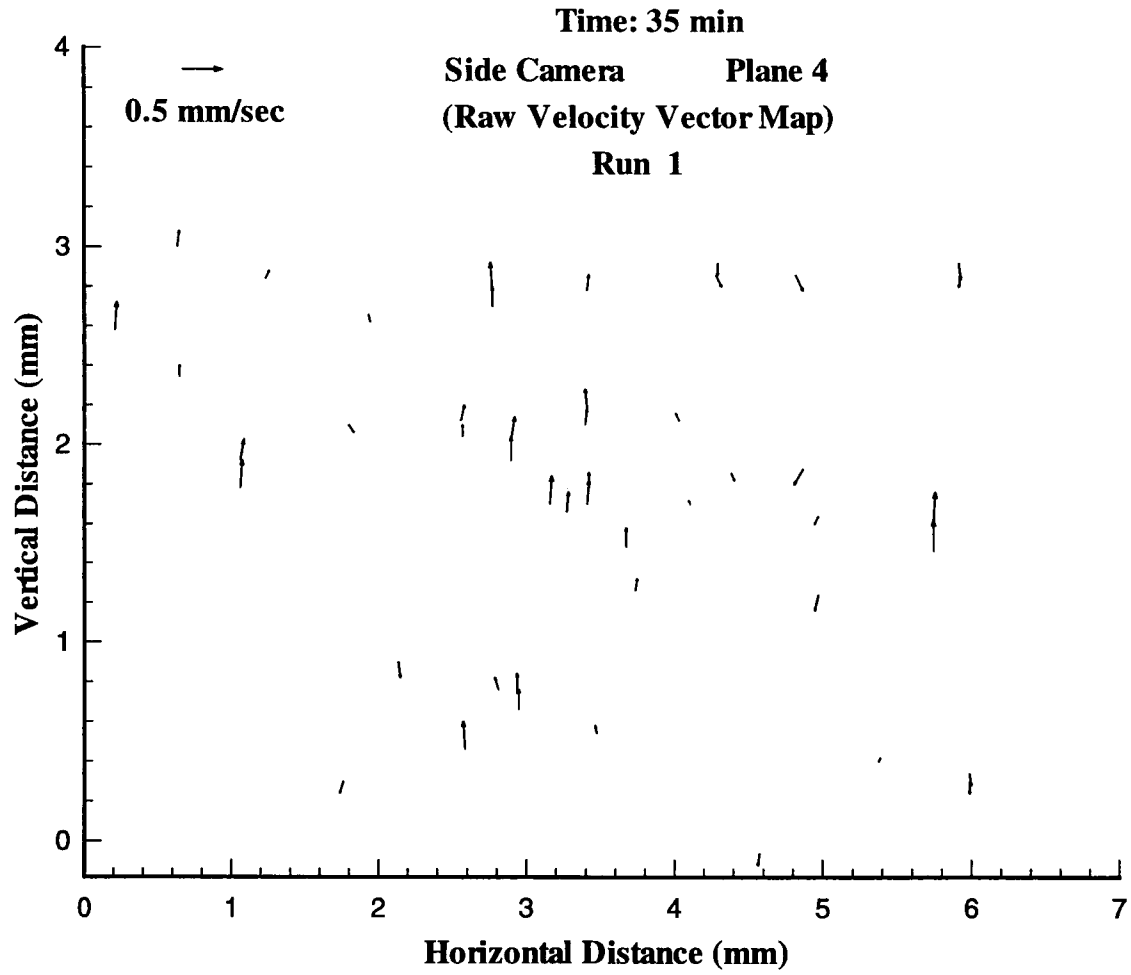


Figure 5.23 Raw velocity vector map, side Plane 4, t = 35 min, G = 15°C/cm, CR = 60°C/hr, Run 1

Consider Run 2. Figures 5.24 and 5.25 show the raw velocity vectors on the front and side center planes respectively. As mentioned in Section 5.2, two sets of frames, each at a different framing rate were used to arrive at the raw vectors in each plane. This identified both the faster velocity vectors within the jet and the slower vectors surrounding the jet. In addition, as in Run 1, an additional set of frames was analyzed and incorporated into the first set. This gave rise to an increased number of velocity vectors within the vector field. Next, the raw velocity vectors from each plane were used to perform 2-D interpolation within the respective planes. The interpolation procedure which was carried out within Tecplot does not retain the original vectors, but rather uses them to interpolate over the prescribed region. Essentially the original vectors are smoothed and an entirely new vector field is generated. Figure 5.26 shows the interpolated velocity vectors for the same plane as in Figure 5.25.

Fourteen such interpolated 2-D vector fields are then placed at the appropriate locations within the interrogation region, and a 3-D interpolation is performed within the region. The interpolated interrogation volume contains information at 25 X 25 X 25 points. Hence, in any given direction there are 25 planes with interpolated information contained within them. Figure 5.27 shows slices from the interrogation region parallel to the front face of the cuvette. The plots shown are contours of the vertical velocity, V_z. Since the flow is essentially traveling either up or down (along the Z-direction) and since little lateral movement (perpendicular to the Z-direction) is observed, the characteristics of the jet can be effectively observed by inspecting contours of V_z. The seven planes showed in the above mentioned figures are equidistant from each other and are plane numbers 1, 5, 9, 13, 17, 21, and 25. The direction of flow within the jet is upward, while the flow surrounding the jet is downward. The greatest velocity occurred at the center of the jet.

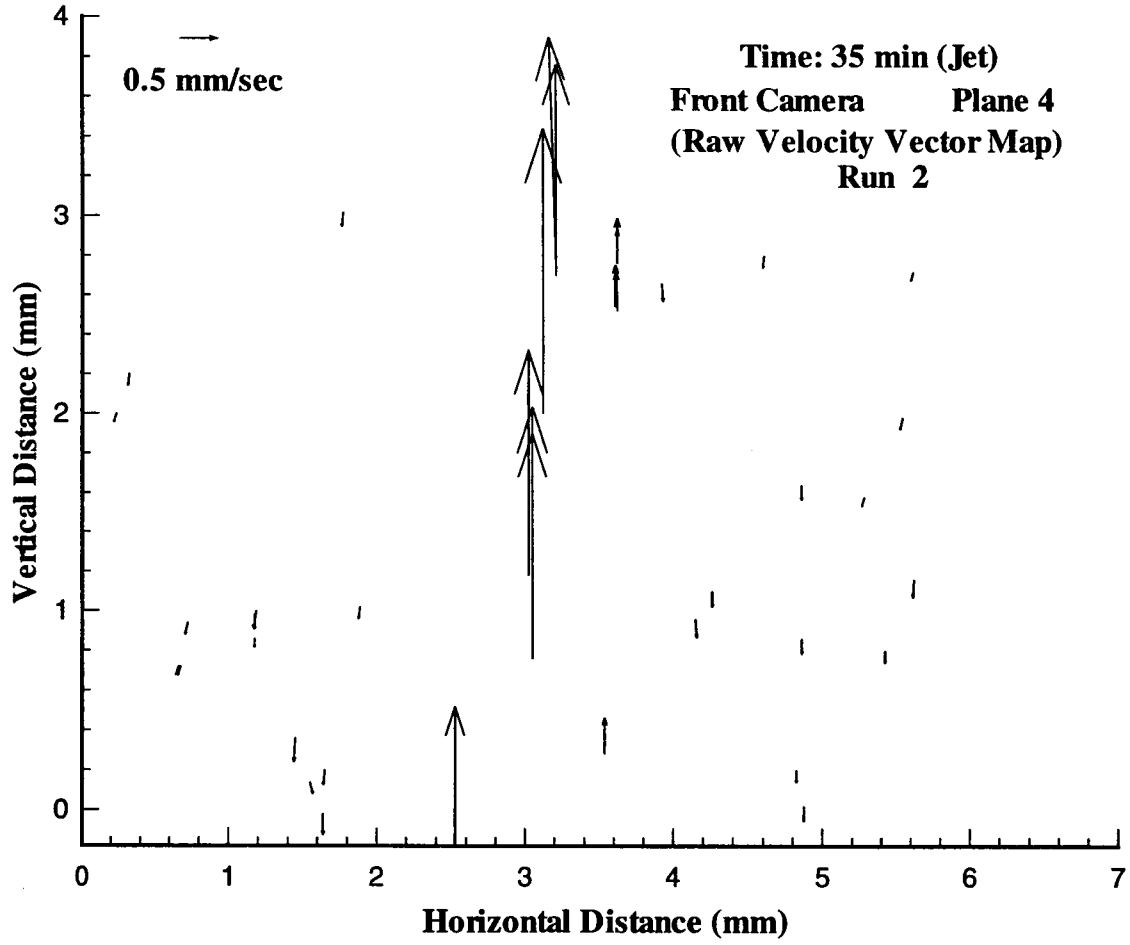


Figure 5.24 Raw velocity vector map, front Plane 4, t = 35 min (Jet), G = 15°C/cm, CR = 60°C/hr, Run 2

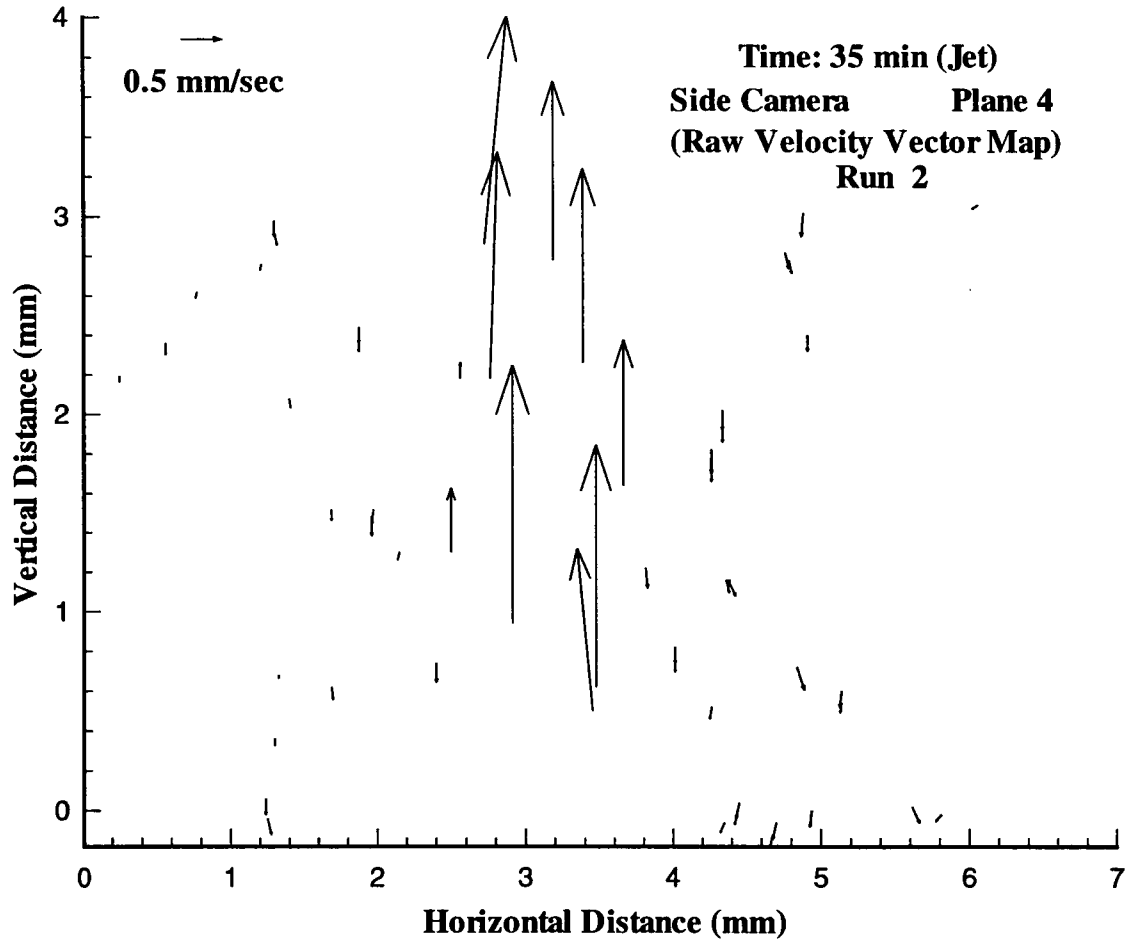


Figure 5.25 Raw velocity vector map, side Plane 4, t = 35 min (Jet), G = 15°C/cm, CR = 60°C/hr, Run 2

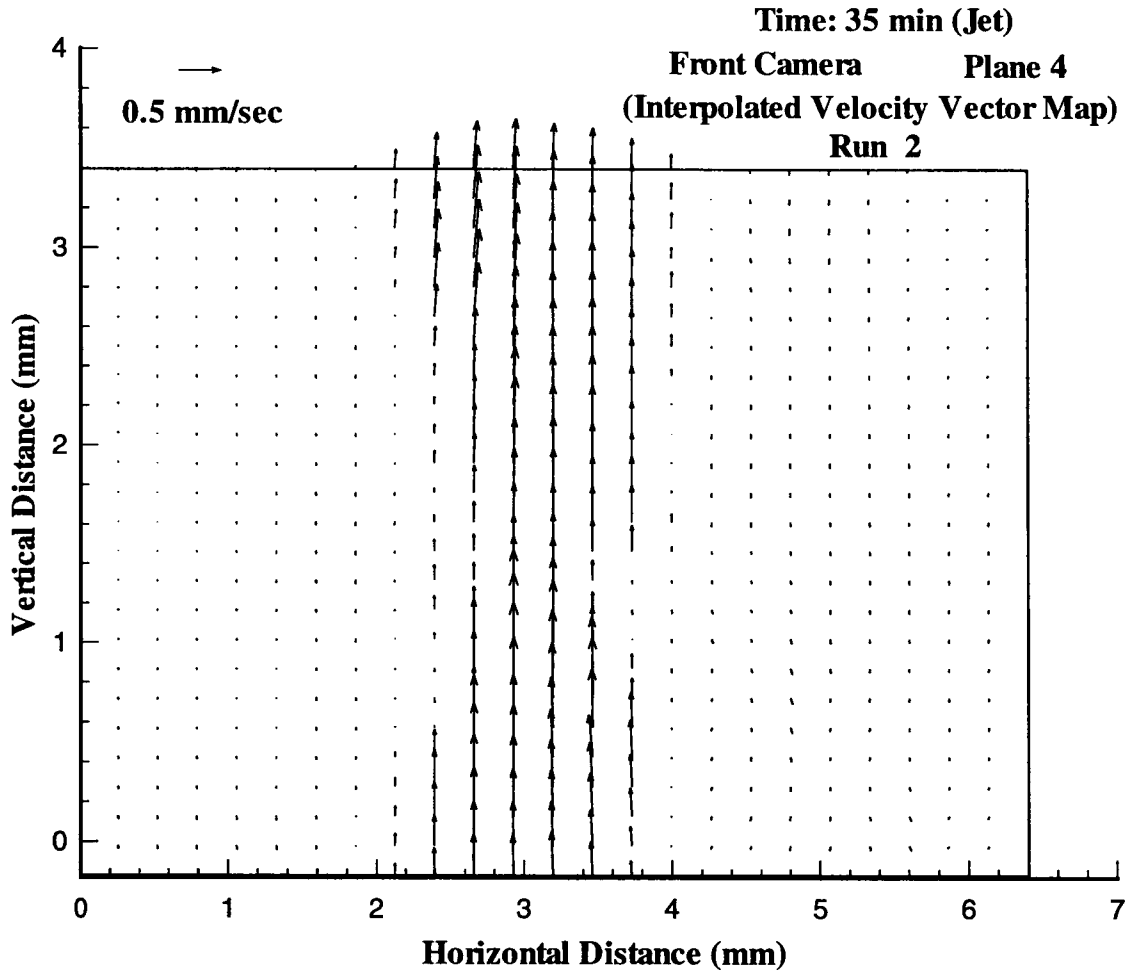


Figure 5.26 Interpolated velocity vector map, side Plane 4, t = 35 min (Jet), G = 15°C/cm, CR = 60°C/hr, Run 2

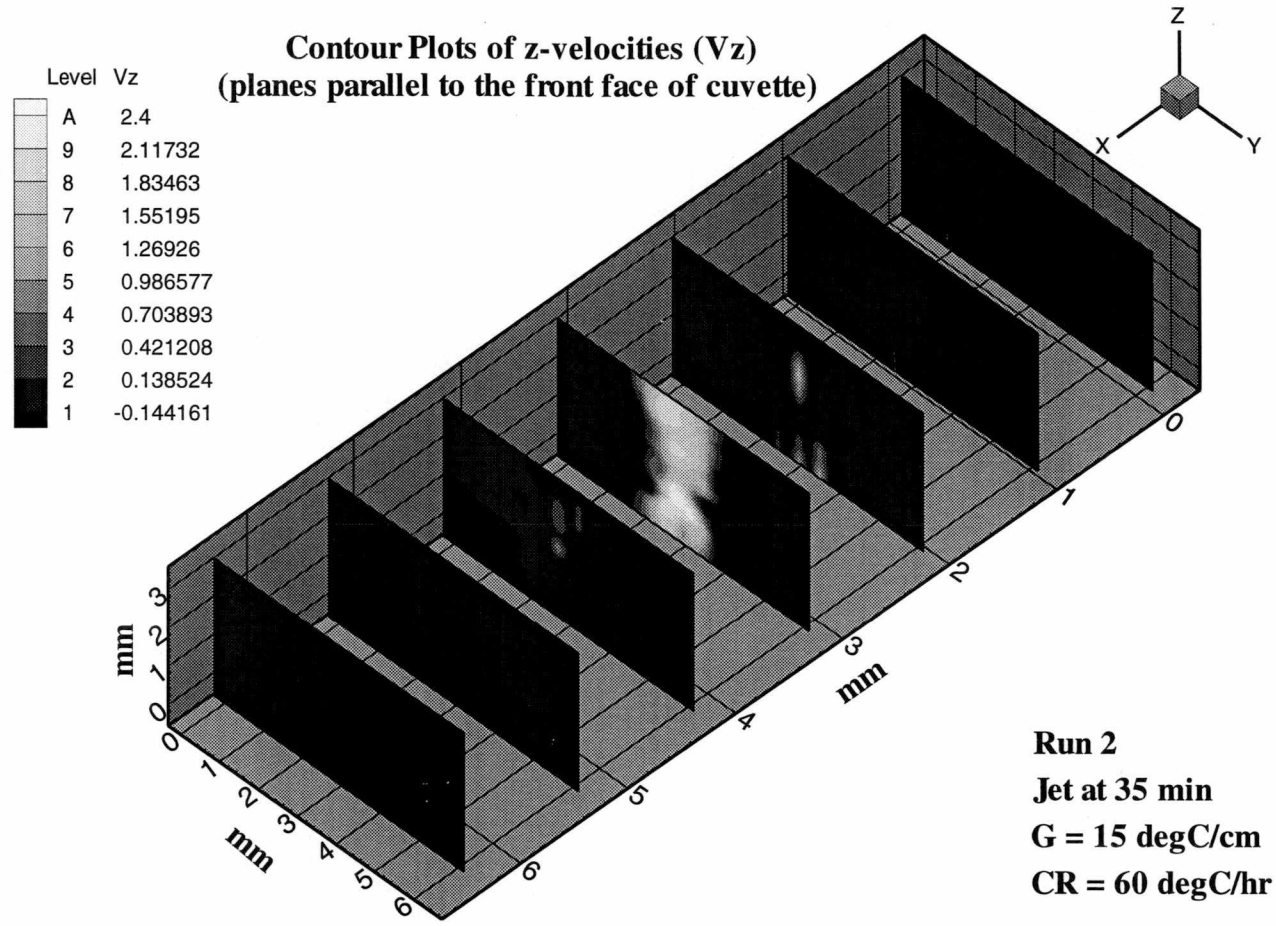


Figure 5.27 Contour plots of Vz at t = 35 min (Jet), G = 15°C/cm, CR = 60°C/hr, Run 2

The velocity within the jet radially diminished away from the core. The velocity within the jet was appreciably greater than the velocity surrounding the jet. The maximum velocity within the jet was +2.4 mm/sec, while the maximum velocity surrounding the jet was -0.2 mm/sec.

Figure 5.28 shows contour plots of V_z at two sides perpendicular to the z-axis, one at the bottom face of the interrogation volume, and the other of the top face. Figure 5.28 shows regions of positive (upward) and negative (downward) velocity in both the top and bottom faces. The darker shade in the plots represent downward velocity and the lighter the upward velocity. It can be seen that the positive velocity is concentrated in one area (where the jet is situated), while the surrounding liquid is almost everywhere negative. Also evident from the figure is that the locations of the region of positive velocity on both the top and bottom faces are essentially the same, indicating the straight columnar nature of the jet (see Figure 2.1).

Finally, the average level of 'activity' within the interrogation region was characterized. This is done by considering a normalized summation of the speed based on the raw velocity vectors identified at different times. The speed of each velocity vector in each of the fourteen planes, for a given time is calculated using Equation 5.1.

$$V = \sqrt{v_x^2 + v_y^2} \tag{5.1}$$

where, V_x and V_y are the y- and x-components of the raw velocity vector. For each time, all the speed calculations resulting from all the vectors in all fourteen planes are summed. Since different number of raw vectors are identified in different planes, a normalized summation is used as shown in Equation 5.2.

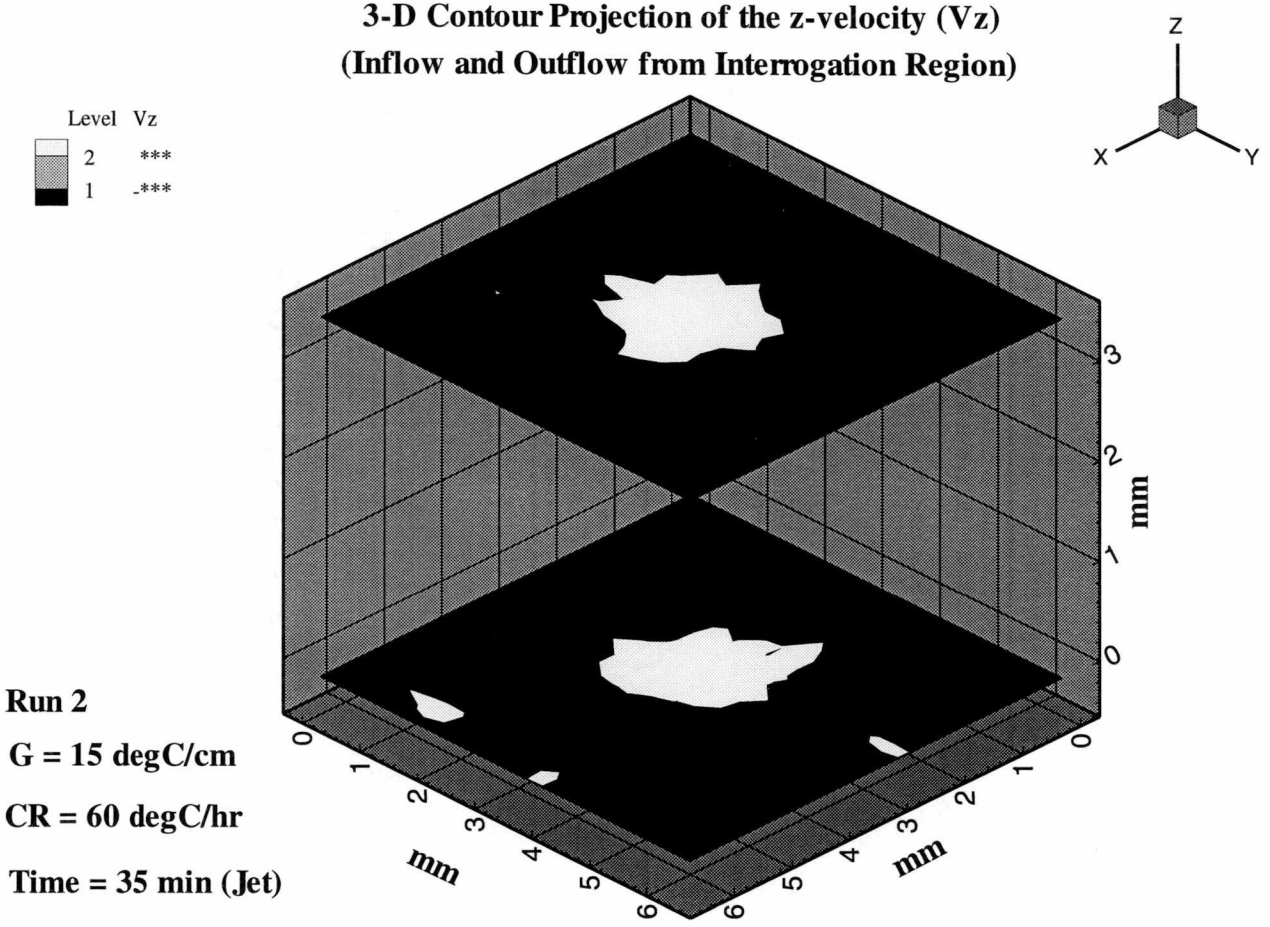


Figure 5.28 Contour plots of upward and downward velocities across the top and bottom faces of the interrogation region, t = 35 min (Jet), G = 15°C/cm, CR = 60°C/hr, Run 2

$$S = \sum_{j=1}^{k} \left\{ \frac{\sum_{i=1}^{n} V_i}{n} \right\} \qquad (5.2)$$

where, n is the total number of identified raw vectors per plane, V_i is the speed of individual raw vectors in a particular plane, and k is the total number of planes (k = 14, seven side and seven front).

Figure 5.29 shows a plot of the normalized summation of speed for different times during the entire duration of the experiments. Both non-jet results (Run 1) and the jet result (Run 2) are shown. The normalized flow activity is observed to dramatically increase from 1.3 mm/s at t = 5 min to 2.2 mm/s at t = 10 min. The activity continues to increase, at a slower rate, up until t = 20 min to 2.9 mm/s, after which it gradually decreases until the end of the run, t = 35 min to 2.2 mm/s. It is noted that although the activity decreases from t = 20 to t = 35 min, the level of activity at t = 35 min is still greater than the flow activity at t = 5 min. In the presence of the jet (at t = 35 min), the level of activity is observed to be appreciably greater than the level of activity in the absence of a jet. In addition, the level of activity with the jet at t = 35 min (S = 3.3 mm/s) is found to be higher than the greatest level of activity without the jet, that is, at t = 20 min (S = 2.9 mm/s).

5.4 Accuracy

In this section an attempt is made to estimate the error that arises in the velocity vectors identified using PDT, due to particle positioning error. The analysis carried out here is

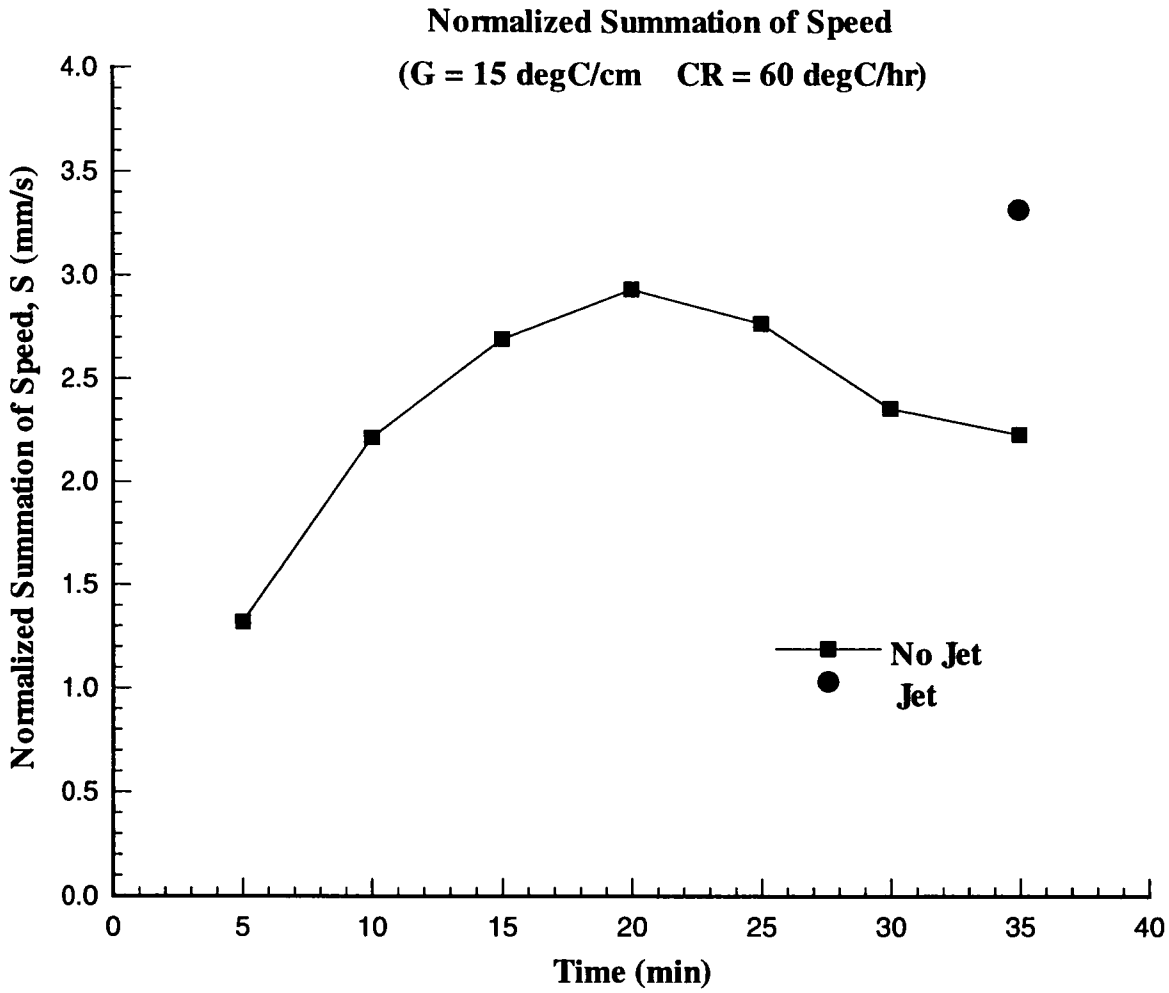


Figure 5.29 Flow activity levels at various times, G = 15°C/cm, CR = 60°C/hr, Run 1 and Run 2

based on the method used by Wernet (1990). Wernet defines a relative particle positioning error as follows:

$$\frac{\sigma_U}{U} = \frac{\sigma_X}{X} \tag{5.3}$$

where, U is the velocity, σ_U is the error in the velocity vector, X is the total displacement of a particle from the first frame to the fifth, and σ_X is the rms error in total particle displacement. For a ±1/2 pixel positioning error, the rms error, σ_X, is $1/\sqrt{2}$. Table 5.1 shows the *maximum* errors in velocity vectors due to positioning error for different times. Note in the case of the jet, maximum errors of vectors within and outside the jet have been computed.

Table 5.1 Maximum velocity vector errors due to particle positioning errors for various times, Run 1 and Run 2

Run	Time (min)	Maximum Displacement (pix)	% Velocity Vector Error
1	5	7	10.1%
	10	11	6.4%
	15	14	5.1%
	20	12	5.9%
	25	9	8.8%
	30	13	5.4%
	35	12	5.9%
2	35 (inside jet)	18	3.9%
	35 (outside jet)	8	8.8%

From Table 5.1, it can be seen that the smallest maximum error occurred for the velocity vectors within the jet (greater velocities), whereas the greatest maximum error occurred for velocity vectors at t = 5 min (smaller velocities). However, as evident from Equation 5.3, the total particle displacement is a governing parameter in the error estimate. Total particle displacement is a consequence of both particle velocity and framing rate. Hence to minimize positioning error, one needs to choose the optimum framing rate based on the apparent velocity.

VI. CONCLUSION

6.1 Conclusions

- The PDT technique has been successfully applied to characterize the flow field during directional solidification of a metal model, both quantitatively and qualitatively. Using 2-D information from various planes within the interrogation region, the 3-D nature of the flow field has been captured.

- Maximum velocity vector errors due to particle positioning error ranged from 3.9% for flow within a jet (at t =35 min) to 10.1% for flow at t = 5 min. The mean error for all times was 6.7%. Since the error is based on total particle displacement between the first and fifth frame, taking the optimum framing rate based on the velocity of the particle will minimize the error.

- Since interpolation carried out within Tecplot does not retain the original raw vectors, but rather smooths them out based on the neighboring vectors, the resulting interpolated structure of the flow field is slightly altered from the original structure displayed by the raw vectors. This is particularly evident from the interpolated data of the jet. Instead of displaying the expected near cylindrical profile, the interpolated jet profile shows the vertical velocity decreasing and then increasing with no apparent flow being transferred from within the jet to outside it or vice versa.

- Flow activity, indicated by the normalized sum of the magnitudes of the resultant velocity vectors at each of the fourteen planes indicates the following: The activity level rose appreciably from t = 5 min, to t = 10 min. The activity continued to rise at a lesser rate until approximately t = 20 min, and then gradually decreased until the end

of the run, t = 35 min. The activity at t = 15 min was greater than at t = 5 min. The activity at t = 35 min in the presence of the jet was greater than the flow activity in the absence of the jet. The flow activity during the jet was higher than the greatest flow activity without a jet (at t = 20 min).

6.2 Recommendations

- Cameras with faster framing rates incorporated in the PDT set-up will allow for better temporal resolution. The increase in temporal resolution would allow the PDT technique to capture parts of the fluid flows that display strong curvatures. This will result in more accurate representation of particle trajectory. Higher framing rate cameras can be incorporated in the current set-up.

- Since the method of interpolation within Tecplot smooths out the original raw vectors and produces flow structures slightly different from the actual flow structure, either the raw data only must be considered during analysis, or another interpolation method that retains the original raw vectors must be used.

- If only raw vectors are to be considered, analyzing several sets of five images separated by a small time interval at each plane at each time will result in a greater vector distribution throughout the field. However, this will consume a considerable amount of time and must be weighed against accuracy. Two sets of frames were analyzed for each case to generate more raw vectors so that flow structure can be correctly identified without interpolation. Although this action produced more vectors that were distributed fairly uniformly across the field, there still existed areas of void. Perhaps another interpolation technique that does not smooth out the original vectors may produce a more realistic interpolated flow structure.

- Further application of PDT might incorporate 2-D plane information separated at intervals less than 0.5 mm to capture the overall flow more accurately. However, cameras with shorter depths of focus may be required to consider planes that are located closer to each other, under the current set-up where illumination is provided by white light sources. An alternative would be to construct a set-up incorporating several lasers to produce laser light sheets of thickness in the order of 0.1 mm across several planes.

- The PDT technique should be applied to solidification jetting experiments at other conditions and compared with each other to establish a better correlation of flow characteristics. The condition reported herein should also be repeated to confirm repeatability of the results. The observation made in this study, that the flow activity rises and then gradually decreases until the occurrence of a jet may be unique to the particular conditions used in this study, or may be a global trend (for other conditions as well) at different levels. Further work is needed to confirm this.

- The PDT technique presented here is by no means restricted to the type of experiment reported herein. It can be applied to other casting and solidification related experiments where fluid flow quantification is a requirement, for example, the study of the nature of interdendritic fluid flow. The primary requirement is that flow should be of low velocity (< 6 mm/s).

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APPENDICES

Appendix A: IMGMOD.FOR

```
C234567
      PROGRAM DEINTERLACE
C     ================================================================
C     THIS PROGRAM READS IN AN IMAGE FILE FRAMEGRABBED BY THE DT-IRIS
C     FRAMGRABBER, AND REWRITES EITHER ONE NEW FILE, OR TWO NEW FILES, BASED
C     ON USER INPUT. IF ONE FILE IS REQUESTED, THE PROGRAM WRITES EVERY ODD
C     NUMBERED LINE TO THE NEW FILE. IF TWO FILES ARE REQUESTED, THE ODD
C     NUMBERED LINES ARE WRITTEN TO THE FIRST FILE, AND THE EVEN LINES TO
C     THE SECOND
C     ================================================================

      INTEGER I,J
      INTEGER*1 PIXEL
      CHARACTER*20 IMG1,IMG2,IMG3
      CHARACTER*1 ANSWER
      DIMENSION PIXEL(512,512)

C     ================================================================
C     ASK USER WHETHER TO REWRITE ONE OR TWO FILES. GET SOURCE AND
C     DESTINATION FILE NAMES. OPEN APPROPRIATE FILES.
C     ================================================================

      WRITE(*,*)'The two split segments could either be written as'
      WRITE(*,*)'one image (one on top of the other), or as two'
      WRITE(*,*)'different images (using only the top portion of each).'
5     CONTINUE
      WRITE(*,*)'Your preference: enter 1 for one image'
      WRITE(*,*)'                 enter 2 for two images'
      READ(*,15)ANSWER

      IF (ANSWER.EQ.'1') THEN

       WRITE(*,*)'Enter the initial file name (include extension):'
       READ(*,10)IMG1
       WRITE(*,*)'Enter the final file name (include extension):'
       READ(*,10)IMG2

       OPEN(1,FILE=IMG1,ACCESS='SEQUENTIAL',FORM='BINARY')
       OPEN(2,FILE=IMG2,FORM='BINARY')
       REWIND 1
       REWIND 2

      ELSEIF (ANSWER.EQ.'2') THEN

       WRITE(*,*)'Enter the initial file name (include extension):'
       READ(*,10)IMG1
       WRITE(*,*)'Enter the first final file name (include extension):'
       READ(*,10)IMG2
       WRITE(*,*)'Enter the second final file name (include extension):'
       READ(*,10)IMG3

       OPEN(1,FILE=IMG1,ACCESS='SEQUENTIAL',FORM='BINARY')
       OPEN(2,FILE=IMG2,FORM='BINARY')
       OPEN(3,FILE=IMG3,FORM='BINARY')
       REWIND 1
       REWIND 2
       REWIND 3

      ELSEIF (ANSWER.NE.'1'.AND.ANSWER.NE.'2') THEN
```

```
      GOTO 5

     ENDIF

 10  FORMAT(A20)
 15  FORMAT(A1)
 20  FORMAT(I3)

C    ================================================================
C    REWRITE ONE FILE USING ODDNUMBERED LINES
C    ================================================================

     IF(ANSWER.EQ.'1') THEN
      READ(1) (PIXEL(J,1),J=1,512)
      WRITE(2) (PIXEL(J,1),J=1,512)
      DO I=1,512
        DO J=1,512
          READ(1)PIXEL(I,J)
        END DO
      END DO

      DO I=1,511,2
        DO J=1,512
          WRITE(2)PIXEL(I,J)
        END DO
      END DO

      DO I=2,512,2
        DO J=1,512
          WRITE(2)PIXEL(I,J)
        END DO
      END DO
     END IF

C    ================================================================
C    REWRITE TWO FILES, THE FIRST ONE WITH ODD NUMBERED LINES, THE SECOND
C    WITH EVEN NUMBERED LINES
C    ================================================================

     IF(ANSWER.EQ.'2') THEN
      READ(1) (PIXEL(J,1),J=1,512)
      WRITE(2) (PIXEL(J,1),J=1,512)
      WRITE(3) (PIXEL(J,1),J=1,512)
      DO I=1,512
        DO J=1,512
          READ(1)PIXEL(I,J)
        END DO
      END DO

      DO I=1,511,2
        DO J=1,512
          WRITE(2)PIXEL(I,J)
        END DO
      END DO

      DO I=2,512,2
        DO J=1,512
          WRITE(3)PIXEL(I,J)
        END DO
      END DO

      DO I=256,512
        DO J=1,512
```

```
        PIXEL(I,J) = 0
        WRITE(2)PIXEL(I,J)
        WRITE(3)PIXEL(I,J)
      END DO
    END DO

    END IF

C   ================== PROCESS ANOTHER FILE ? ==================

    WRITE(*,*)'Do you want to process another file? (y/[n])'
    READ(*,15) ANSWER
    IF (ANSWER.EQ.'y'.OR.ANSWER.EQ.'Y') THEN
      GOTO 5
    ENDIF

    END
```

Appendix B: CENT.FOR

This program was written by Brent W. Blaha, Graduate Research Assistant, Center for Laser Applications, The University of Tennessee Space Institute. This program has been used in this study with permission from B. W. Blaha.

```
      PROGRAM CENTROID
C     ================================================================
C     THIS PROGRAM READS IN FIVE IMAGE FILES (P1.IMG --> P5.IMG)
C     MODIFIED USING IMGMOD, AND GENERATES FIVE OUTPUT FILES (PDT1.IMG
C     --> PDT5.IMG). THE PROGRAM ESSENTIALLY LOCATES EACH PARTICLE IN
C     EACH IMAGE AND COMPUTES THE GEOMETRIC CENTER OF EACH PARTICLE, AND
C     WRITES THE LOCATION AS A WHITE PIXEL UPON A BLACK BACKGROUND.
C
C     THE USER INPUTS A THRESHOLD VALUE UPON WHICH, EITHER ACCEPTANCE OR
C     REJECTION OF A PARTICULAR PARTICLE IS BASED ON.
C     ================================================================

      INTEGER*1 HEADER(512),G(512,512),F(512,512)
      INTEGER*1 S(512,512),0(512,512)
      INTEGER IROW,JCOL,N,JL,JG,IL,IG,XB,YB
      INTEGER GRAD,A(9),I,J,X,Y,THRESH,DONE
      CHARACTER*12,INFILE(5),OUTFILE(5)
      INFILE(1)="PP1.IMG"
      INFILE(2)="PP2.IMG"
      INFILE(3)="PP3.IMG"
      INFILE(4)="PP4.IMG"
      INFILE(5)="PP5.IMG"
      OUTFILE(1)="PDT1.IMG"
      OUTFILE(2)="PDT2.IMG"
      OUTFILE(3)="PDT3.IMG"
      OUTFILE(4)="PDT4.IMG"
      OUTFILE(5)="PDT5.IMG"

C     ================ ASK USER FOR THRESHOLD LEVEL ================

      WRITE (*,*) 'WHAT THRESHOLD LEVEL'
      READ (*,*) THRESH


     DO L = 1,5
      G = 0
      O = 0
      S = 0
      F = 0

C     ================== READ IN SOURCE FILES ==================

10    FORMAT (A12)
      OPEN (2,FILE=INFILE(L),FORM='BINARY')
C     READ IN HEADER
      READ (2) (HEADER(I),I=1,512)
      DO I=1,512
       READ (2) (F(I,J),J=1,512)
      END DO
      CLOSE (2)

C     ================================================================
C     CHECK TO SEE IF THE SUM OF THE GRADIENTS IS GREATER THAN
C     THE USER INPUTTED THRESOLD LEVEL, IF SO, LOCATE CENTROID
```

```
C     ================================================================

      DO J=2,511
       DO I=2,511
        N=1
        DO Y=-1,1
         DO X = -1,1
          IROW=Y+J
          JCOL=X+I
          A(N)=F(IROW,JCOL)
          IF (A(N).LT.0) A(N)=A(N)+256
          N = N+1
         END DO
        END DO
        GRAD = ABS(A(9)-A(1)) + ABS(A(7)-A(3)) + ABS(A(6)-A(4))
     +       + ABS(A(8)-A(2))
        IF (GRAD.GT.THRESH)  THEN

         DO Y=-2,2
          DO X=-2,2
           S(I+Y,J+X) = 0
          END DO
         END DO
         S(I,J)=-1
         G(I,J)=-1
        END IF
       END DO
      END DO
      DO J=1,512
       DO I=1,512
        IF (S(I,J).EQ.-1)  THEN
         IL = I - 1
         IG = I + 1
         JL = J - 1
         JG = J + 1
5        DONE=0
11       DO X = IL,IG
         Y = JL
         IF (G(X,Y).EQ.-1) THEN
          DONE = 1
          JL = JL - 1
          GOTO 11
         END IF
        END DO
20       DO Y = JL,JG
         X = IG
         IF (G(X,Y).EQ.-1) THEN
          DONE = 1
          IG = IG + 1
          GOTO 20
         END IF
        END DO
30       DO X = IL,IG
         Y = JG
         IF (G(X,Y).EQ.-1) THEN
          DONE = 1
          JG = JG + 1
          GOTO 30
         END IF
        END DO
40       DO Y = JL,JG
         X = IL
         IF (G(X,Y).EQ.-1) THEN
```

```
            DONE = 1
            IL = IL - 1
            GOTO 40
           END IF
          END DO
          IF (DONE.EQ.1) GOTO 5
          IF ((IG-IL.GE.15).OR.(JG-JL.GE.15)) GOTO 50
          XB = 0
          YB = 0
          N = 0
          DO Y = JL,JG
           DO X = IL,IG
            IF (G(X,Y).EQ.-1) THEN
             XB = XB + X
             YB = YB + Y
             N = N + 1
            END IF
           END DO
          END DO
          XB = NINT(1.0* XB / N)
          YB = NINT(1.0* YB / N)
          O(XB,YB) = -1
50        END IF
        END DO
      END DO

C     ================== WRITE OUTPUT FILES ==================

      OPEN (3,FILE=OUTFILE(L),FORM='BINARY')
      WRITE (3) (HEADER(I),I=1,512)
      DO J=1,512
       WRITE (3) (O(I,J),I=1,512)
      END DO
      CLOSE (3)
     END DO

     STOP
     END
```

Appendix C: FPART.FOR

This program is essentially the same as the program written by Mark P. Wernet, namely BOUND5.FOR, and is available through the NASA Lewis COSMIC program (Program Number LEW-14925). Modifications have been done to accommodate for the specific hardware used in this study. The program was used without permission from M. P. Wernet. The COSMIC package, however was purchased by CAST for usage.

```
      PROGRAM FINDPART
C=====================================================================
C
C     THIS PROGRAM INPUTS 5 FILES (PDT1,PDT2,PDT3,PDT4,PDT5) WHICH HAVE
C     ALREADY BEEN SAVED USING THE DT-IRIS FRAMEGRABBER, BEEN MODIFIED
C     USING THE PROGRAM IMGMOD, AND BEEN PROCESSED USING THE PROGRAM CENT.
C
C     THE PROGRAM THEN SEQUENTIALLY SEARCHES EACH FILE TO DETERMINE
C     CENTROID LOCATIONS OF ALL PARTICLES IN EACH FILE. THE CENTROIDS
C     ARE DETERMINED USING A BOUNDARY FOLLOWING ALGORITHM. THE
C     COORDINATES OF PARTICLE ARE WRITTEN TO A FILE, P1.OUT, FOR FURTHER
C     PROCESSING USING THE PROGRAM GVEL.
C
C     THIS BINARY FILE HAS THE PARTICLE IMAGES CODED BY THE
C     FRAME THEY WERE FOUND ON. THE FRAMES ARE DESIGNAED BY 2**I,
C     WHERE, I IS THE FRAME NUMBER OUT OF THE FIVE EXPOSURE SEQUENCE.
C
C     REVISED 08/25/94
C=====================================================================

      IMPLICIT INTEGER (A-Z)
      CHARACTER*1 IA(512)
      CHARACTER*20 BB(5),FNAME
      CHARACTER*64 A
      INTEGER*1 GG(512,512)
      INTEGER G(512,512),RIM(2,10000)
      INTEGER CX(5),GI(512),GJ(512),I1(4),I2(4),J1(4),J2(4)
      INTEGER N1,ZERO,IJK,DEN,GT,GTT,NFRAMES
      INTEGER IMN,JMN,IMIN,JMIN,IRUN,JRUN,IMAX,JMAX
      INTEGER IBOT,ITOP,JLEFT,JRIGHT
      REAL STORIJ(10,10000)
      EQUIVALENCE (A,IA(1))

      DATA IBOT/2/,ITOP/510/,JLEFT/2/,JRIGHT/510/
      DATA I1/0,-1,0,1/
      DATA I2/-1,0,1,0/
      DATA J1/1,0,-1,0/
      DATA J2/0,-1,0,1/
      DATA BB/'pdt1.img','pdt2.img','pdt3.img','pdt4.img','pdt5.img'/
      DATA FNAME/'p1.out'/

C=============================
C     INITIALIZE CONSTANTS
C=============================

      Z     = 0
      NFRAMES = 5
      NJ    = 512
      NI    = 512
      N1    = 10000
      KILL  = 0
```

```
      KILL2  = 1
      ZERO   = 0

C=====================================
C     INITIALIZE ARRAYS
C=====================================

      IFLAG = 0
      IFLAG = IFLAG+1

      DO I=1,10
        DO J=1,N1
          STORIJ(I,J) = 0.
        END DO
      END DO

      DO J=1,NJ
        GI(J) = 0
        GJ(J) = 0
      END DO

C=========================================
C     ASK USER FOR REGION OF INTEREST
C=========================================

      WRITE(*,*) ' Enter min and max particle perimeters '
      READ(*,*) NMIN,NMAX
      WRITE(6,*)' '
      WRITE(6,*)' Enter the coordinates of the pdt window'
      WRITE(6,*)' '
      WRITE(6,*)'          Upper left-hand corner '
      READ(5,*)ITOP,JLEFT
      WRITE(6,*)' '
      WRITE(6,*)'          Lower right-hand corner '
      READ(5,*)IBOT,JRIGHT
      WRITE(6,*)' enter threshold level (20) '
      READ(*,*) ITH

C=======================================
C            ==================
C     TOP OF LOOP ==============
C            ==================
C=======================================

      DO IJK=1,NFRAMES
        OPEN(1,FILE=BB(IJK),ACCESS='SEQUENTIAL',FORM='BINARY')
        REWIND(1)
        WRITE(*,10)BB(IJK)
10    FORMAT(' PROCESSING FILE ',A20)

C=============================================================
C     MOVE THE IMAGE FROM A BINARY FILE TO AN INTEGER ARRAY.
C     THE DATA ARE READ IN ONE LINE AT A TIME (1x512) TO A
C     1-BYTE INTEGER ARRAY, HENCE THE DATA STORAGE IS FROM
C     0 TO 128, AND -1 TO -127.  TO GET THE RAGE FROM 0 TO 255,
C     AN OFFSET OF 256 MUST BE ADDED TO VALUES BELOW ZERO.
C=============================================================

        READ(1) (gg(J,1),J=1,512)
        WRITE(*,*) ' header has been read, currently reading data '
        DO K=1,512
          DO J=1,512
              READ(1) GG(J,K)
```

```
                IF (GG(J,K).LT.0) THEN
                  G(J,K) = GG(J,K) + 256
                ELSE
                  G(J,K) = GG(J,K)
                END IF
              END DO
            END DO
            CLOSE(1)

            CX(IJK) = 0
            IND1   = ((IJK-1)*2)+1
            IND2   = IND1+1

C=============================================
C     FIND PARTICLE IMAGES.  SEARCH THE
C     BOUNDARIES IN A CLOCKWISE DIRECTION
C=============================================

            Z = Z + 1
            DO I=ITOP,IBOT
              DO J=JLEFT,JRIGHT
                    IF(G(I,J).LE.ITH) GOTO 100
                     JT  = J
                     IT  = I
                     NR  = 1
                     NC  = 0
                     GT  = 0
                     GTT = 0
                     DEN = 0
                     IMIN = 700
                     JMIN = 700
                     IMAX = 0
                     JMAX = 0

C=============================================================
C     FIND PARTICLE IMAGE BOUNDARY. IF THE DETECTED BOUNDARY IS
C     EITHER GREATER OR LESS THAN THE PRESCRIBED MAXIMUM OR MINIMUM
C     PERIMETER, RESPECTIVELY, DELETE THE ENCOMPASSED MASS.
C=============================================================

20          NC = NC + 1
                    IF(NC.GT.NMIN) KILL2=0

                    RIM(1,NC) = JT
                    RIM(2,NC) = IT
                    IF(RIM(1,NC).GT.JMAX) JMAX = RIM(1,NC)
                    IF(RIM(2,NC).GT.IMAX) IMAX = RIM(2,NC)
                    IF(RIM(1,NC).LT.JMIN) JMIN = RIM(1,NC)
                    IF(RIM(2,NC).LT.IMIN) IMIN = RIM(2,NC)
                    IF(NC.EQ.NMAX) KILL = 1
                    IF(NR.LT.4) GOTO 40
30          IF((RIM(1,1).EQ.RIM(1,NC)).AND.(RIM(2,1).EQ.
   +RIM(2,NC))) GOTO 80
40          IF(G(IT+I1(NR),JT+J1(NR)).LE.ITH) GOTO 50
                    JT= JT + J1(NR)
                    IT= IT + I1(NR)
                    IF(IT.LT.IBOT.OR.IT.GT.ITOP.OR.JT.LT.JLEFT.OR.
   + JT.GT.JRIGHT) GOTO 70
                    GOTO 20
50          IF(G(IT+I2(NR),JT+J2(NR)).le.ith) GOTO 60
                    JT = JT + J2(NR)
                    IT = IT + I2(NR)
                    GOTO 20
```

```
60          NR = NR + 1
                IF(NR.EQ.4) GOTO 30
                IF(NR.GT.4) GOTO 70
                GOTO 40

C=============================================================
C     IF THE SEARCH DOESN'T SEEM TO BE WORKING THEN SET INITIAL POINT
C     TO 0 AND GO TO THE NEXT POINT IN THE SEARCH. THIS AVOIDS HANGING
C     UP THE BOUNDARY SEARCH ON IRREGULAR SHAPES.
C=============================================================

70          DO IJ=1,NC
              G(RIM(2,IJ),RIM(1,IJ)) = ZERO
            END DO
            GOTO 100

C=============================================================
C     FIND PARTICLE IMAGE CENTER
C=============================================================

80          CONTINUE

            IF (KILL.EQ.1.OR.KILL2.EQ.1) GOTO 90
            KILL2 = 1
            IRUN  = IMAX-IMIN+1
            JRUN  = JMAX-JMIN+1
            IMN   = IMIN-1
            JMN   = JMIN-1

            DO K=1,IRUN
              DO L=1,JRUN
                IG    = K+IMN
                JG    = L+JMN
                GV    = G(IG,JG)
                GJ(K) = GJ(K)+GV
                GI(L) = GI(L)+GV
                G(IG,JG) = ZERO
              END DO
            END DO

            DO K=1,IRUN
              GT  = GT+GJ(K)*(K+IMN)
              DEN = DEN+GJ(K)
              GJ(K) = 0
            END DO

            DO L=1,JRUN
              GTT = GTT+GI(L)*(L+JMN)
              GI(L) = 0
            END DO

            IF(DEN.EQ.0) GOTO 100
            CX(IJK) = CX(IJK)+1
            IF(CX(IJK).EQ.N1) GOTO 120
            STORIJ(IND1,CX(IJK)) = FLOAT(GT)/DEN
            STORIJ(IND2,CX(IJK)) = FLOAT(GTT)/DEN
            GOTO 100
C=============================================================
C     FOUND AN IRREGULAR SHAPE, SO DELETE IT!!
C=============================================================
90          IRUN = IMAX-IMIN+1
            JRUN = JMAX-JMIN+1
```

```
                    DO IG=IMIN,IRUN
                      DO JG=JMIN,JRUN
                            G(IG,JG) = ZERO
                      END DO
                    END DO
                    WRITE(*,*) ' Deleting particle at ',IG,JG
                    KILL  = 0
                    KILL2 = 1
100             CONTINUE
                END DO
              END DO
              WRITE(*,110)CX(IJK)
110         FORMAT('  Found ',I6,' PARTICLES')
            END DO

C=============================================================
C     BOTTOM OF LOOP!!!!!
C
C     GENERATE THE OUTPUT FRAME BY USING THE STORED INDICES OF THE
C     DETECTED PARTICLE IMAGES IN THE MATRIX G(I,J).
C=============================================================
C
            DO I=1,NI
              DO J=1,NJ
                G(I,J) = 0
              END DO
            END DO
            DO I=1,5
              IND1 = ((I-1)*2)+1
              IND2 = IND1+1
              DO J=1,CX(I)
                G(NINT(STORIJ(IND1,J)),NINT(STORIJ(IND2,J))) = 2**I
              END DO
            END DO
C
C=============================================================
C     QUERY THE USER AS TO WHETHER THE DATA ARE TO BE WRITTEN TO A
C     BINARY FILE.  THE BINARY FILE WILL BE IN THE SAME FORMAT AS
C     THE IMAGE DATA.
C=============================================================
            WRITE(*,*) 'writing ',FNAME
            OPEN(8,FILE=FNAME,ACCESS='SEQUENTIAL',FORM='BINARY')
            DO K=1,512
              DO J=1,512
                IF (G(J,K).GT.128) THEN
                      GG(J,K) = G(J,K) - 256
                ELSE
                      GG(J,K) = G(J,K)
                END IF
                WRITE(8) GG(j,k)
              END DO
            END DO

            CLOSE(UNIT=8)

120     CONTINUE

            STOP
            END
```

Appendix D: GVEL.FOR

This program essentially follows the same logic as several programs written by Mark P. Wernet, for the purpose of PDT, and is available through the NASA Lewis COSMIC program (Program Number LEW-14925). Modifications have been done to accommodate for the specific hardware used in this study. The graphing routines from Wernet's program were discarded, and Tecplot was used for this purpose. Major additions to this program were the inclusion of user inputted threshold levels, minimum particle size, and displacement tolerance radius. Contents of the COSMIC package were used without permission from M. P. Wernet. The COSMIC package, however was purchased by CAST for usage.

```
      PROGRAM GETVEL

C=====================================================================
C
C     LOW VELOCITY PARTICLE DISPLACEMENT TRACKING
C
C     THIS PROGRAM SETS UP A WINDOW AROUND INITIAL PARTICLE POSITIONS
C     AND SEARCHES FOR 2nd EXPOSURE PARTICLES. THESE 2nd EXPOSURE
C     PARTICLES ARE USED TO ESTIMATE WHERE THE 3rd, 4th, AND 5th
C     PARTILCES ARE LOCATED, WITHIN A USER INPUTTED TOLERANCE.
C
C     THIS PROGRAM INPUTS 1 FILE WHICH HAS ALREADY BEEN PROCESSED BY
C     FPART, NAMELY P1.OUT. THE DATA IN P1.OUT ARE INTENSITY CODED
C     BASED ON THE FRAME FROM WHICH THEY ORIGINATED. THE OUTPUT,
C     WHICH CONTAINS THE VELOCITY INFORMATION IS WRITTEN TO THE FILE
C     V1.OUT.
C
C     REVISED 08/25/94
C
C=====================================================================

      CHARACTER*20 BB,FNAME
      INTEGER*1 GG(0:511,0:511)
      INTEGER B1,B2,B3,B4,B5,ZERO,G(0:511,0:511)
      INTEGER N1,CX,IX,XC(5),YC(5)
      INTEGER XX3(9),XX4(9),XX5(9),YY3(9),YY4(9),YY5(9)
      INTEGER SPX1,SPX2,SPX3,SPX4,SPY1,SPY2,SPY3,SPY4
      INTEGER XF2,XF3,XF4,XF5,YF2,YF3,YF4,YF5
      INTEGER DX2,DX3,DX4,DY2,DY3,DY4
      INTEGER IS(4000),JS(4000),IS2(4000),JS2(4000)
      INTEGER TLIM,BLIM,RLIM,LLIM,REGION,REGVEC
      REAL S(5,8000),H,H1

      DATA BB/'p1.out'/
      DATA FNAME/'v1.out'/

C=====================================================================
C     INITIALIZE CONSTANTS.
C=====================================================================

      NI  = 511
      NJ  = 511
      N1  = 8000
      NL  = 1
      ZERO = 0
      B1  = (2**1)
      B2  = (2**2)
```

```
        B3  = (2**3)
        B4  = (2**4)
        B5  = (2**5)

10    FORMAT(A1)
15    FORMAT(I4)
20    FORMAT(A20)
40    FORMAT(2I6)

C=====================================================================
C     ASK USER FOR SEARCH RADIUS AND DISPLACEMENT TOLLERANCE
C=====================================================================

        REGVEC = 10
        WRITE(*,45)REGVEC
45    FORMAT(' ENTER SEARCH RADIUS IN PIXELS [I3] <',I2,'>:',$)
        READ(*,40)IRG
        IF(IRG.NE.0) REGVEC = IRG

        WRITE(6,50)
50    FORMAT(' ENTER DISPLACEMENT-SEARCH TOLLERANCE (+/-PIXELS):',$)
        READ(6,*) PIX

        WRITE(6,55)
55    FORMAT(' EVERY WHAT FRAME (1ST, 3RD, ETC.) FROM OPTICAL DISC?'
     +,$)
        READ(6,*) H
        H1 = 1.0/H

C=====================================
C           ====================
C  TOP OF LOOP    ===================
C           ====================
C=====================================

        DO L=1,NL
          WRITE(*,60)BB
60      FORMAT(' PROCESSING FILE ',A20)
          DO I=1,4
            DO J=1,N1
                S(I,J) = 0.
            END DO
          END DO
          CX = 0

C=====================================================================
C     MOVE THE IMAGE FROM A BINARY FILE TO AN INTEGER ARRAY.
C     THE DATA ARE READ IN ONE LINE AT A TIME (1x512) TO A
C     1-BYTE INTEGER ARRAY, HENCE THE DATA STORAGE IS FROM
C     0 TO 128, AND -1 TO -127.  TO GET THE RAGE FROM 0 TO 255,
C     AN OFFSET OF 256 MUST BE ADDED TO VALUES BELOW ZERO.
C=====================================================================

          OPEN(1,FILE=BB,ACCESS='SEQUENTIAL',FORM='BINARY')
          DO K=0,511
            DO J=0,511
                READ(1) GG(J,K)
                IF (GG(J,K).LT.0) THEN
                  G(J,K) = GG(J,K)+256
                ELSE
                  G(J,K) = GG(J,K)
                END IF
            END DO
```

```
          END DO

          CLOSE(1)

C=============================================================
C     SEARCH FOR INITIAL PARTICLE POSITIONS (FROM FRAME 1)
C          RECORD DETECTED NUMBER OF PARTICLES
C=============================================================

          NP = 0
          DO I=NI-3,3,-1
            DO J=3,NJ-3
                IF (G(I,J).EQ.B1) THEN
                  NP = NP+1
                  JS(NP) = J
                  IS(NP) = I
                END IF
                IF (NP.EQ.4000) THEN
                  WRITE(*,*)'TOO MANY PARTICLES IN FIRST FRAME'
                  GOTO 180
                END IF
            END DO
          END DO

          WRITE(*,70)NP
70      FORMAT(' FOUND ',I4,' PARTICLES ON FRAME #1')

C=============================================================
C     SET-UP SEARCH REGION AROUND EACH FRAME-1 PARTICLE
C=============================================================

          REGION=REGVEC
          REGION2 = 2*REGION

          DO LL=1,NP
            XC(1) = IS(LL)
            YC(1) = JS(LL)
            RLIM  = YC(1)+REGION
            LLIM  = YC(1)-REGION
            TLIM  = XC(1)+REGION
            BLIM  = XC(1)-REGION
            IF(RLIM.GT.NJ-2) RLIM = NJ-2
            IF(LLIM.LT.2) LLIM = 2
            IF(TLIM.GT.NI-2) TLIM = NI-2
            IF(BLIM.LT.2) BLIM = 2
            NP2 = 0

C=============================================================
C     LOOK FOR 2nd FRAME PARTICLES WITHIN SEARCH REGIONS
C=============================================================

            DO IU=BLIM,TLIM
                DO JU=LLIM,RLIM
                  IF (G(IU,JU).EQ.B2) THEN
                    NP2 = NP2+1
                    JS2(NP2) = JU
                    IS2(NP2) = IU
                  END IF
                END DO
            END DO
            IF(NP2.EQ.0) GOTO 140
            WRITE(*,80) NP2,LL
80        FORMAT(I4,' POSSIBLE MATCHES FOUND FOR PARTICLE ',I4)
```

```
C=============================================================
C     DETERMINE DISTANCES BETWEEN FRAME-1 AND FRAME-2 PARTICLES
C=============================================================

            DO LA=1,NP2
                  SPX1  = IS2(LA)-XC(1)
                  SPY1  = JS2(LA)-YC(1)
                  RMAGS = SQRT(FLOAT(SPX1**2+SPY1**2))
                  IF(RMAGS.GT.REGION2) GOTO 130
                  XF2   = IS2(LA)
                  YF2   = JS2(LA)

C=============================================================
C     START THE SEARCH ON THIS VELOCITY VECTOR PATTERN
C=============================================================

                  IXMAX  = PIX + 1
                  IXMAX1 = (PIX*2) + 1

C=============================================================
C     PROJECT LOCATION OF FRAME-3 PARTICLE
C=============================================================

                  SPX2 = XF2+SPX1
                  SPY2 = YF2+SPY1

                  XC3  = SPX2
                  YC3  = SPY2

C=============================================================
C     SEARCH FOR FRAME-3 PARTICLE WITHIN GIVEN TOLLERANCE
C=============================================================

                  DO IX=1,IXMAX1
                    DO JX=1,IXMAX1
                      XX3(IX) = XC3+IX-IXMAX
                      YY3(JX) = YC3+JX-IXMAX
                      IF(XX3(IX).GT.NI.OR.XX3(IX).LT.1) GOTO 120
                      IF(YY3(JX).GT.NJ.OR.YY3(JX).LT.1) GOTO 120
                    END DO
                  END DO

                  DO IX=1,IXMAX1
                    DO JX=1,IXMAX1
                      IF (G(XX3(IX),YY3(JX)).EQ.B3) THEN
                            XF3 = XX3(IX)
                            YF3 = YY3(JX)
                            GOTO 90
                      END IF
                    END DO
                  END DO
                  GOTO 120
90          CONTINUE

C=============================================================
C     PROJECT LOCATION OF FRAME-4 PARTICLE
C=============================================================

                  SPX3 = XF3 + SPX1
                  SPY3 = YF3 + SPY1
                  XC4  = SPX3
                  YC4  = SPY3
```

```
C=============================================================
C     SEARCH FOR FRAME-4 PARTICLE WITHIN GIVEN TOLLERANCE
C=============================================================

                    DO IX=1,IXMAX1
                      DO JX=1,IXMAX1
                        XX4(IX) = XC4 + IX - IXMAX
                        YY4(JX) = YC4 + JX - IXMAX
                        IF(XX4(IX).GT.NI.OR.XX4(IX).LT.1) GOTO 120
                        IF(YY4(JX).GT.NJ.OR.YY4(JX).LT.1) GOTO 120
                      END DO
                    END DO

                    DO IX=1,IXMAX1
                      DO JX=1,IXMAX1
                        IF (G(XX4(IX),YY4(JX)).EQ.B4) THEN
                              XF4 = XX4(IX)
                              YF4 = YY4(JX)
                              GOTO 100
                        END IF
                      END DO
                     END DO
                     GOTO 120
100           CONTINUE

C=============================================
C     PROJECT LOCATION OF FRAME-5 PARTICLE
C=============================================

                    SPX4 = XF4 + SPX1
                    SPY4 = YF4 + SPY1

                    XC5  = SPX4
                    YC5  = SPY4

C=============================================================
C     SEARCH FOR FRAME-5 PARTICLE WITHIN GIVEN TOLLERANCE
C=============================================================

                    DO IX=1,IXMAX1
                      DO JX=1,IXMAX1
                        XX5(IX) = XC5 + IX - IXMAX
                        YY5(JX) = YC5 + JX - IXMAX
                        IF(XX5(IX).GT.NI.OR.XX5(IX).LT.1) GOTO 120
                        IF(YY5(JX).GT.NJ.OR.YY5(JX).LT.1) GOTO 120
                      END DO
                    END DO

                    DO IX=1,IXMAX1
                      DO JX=1,IXMAX1
                        IF (G(XX5(IX),YY5(JX)).EQ.B5) THEN
                              XF5 = XX5(IX)
                              YF5 = YY5(JX)
                        GOTO 110
                        END IF
                      END DO
                    END DO
                    GOTO 120
110           CONTINUE

C=============================================================
C     COMPUTE DISTACES BETWEEN PARTICLES FROM FRAME-1 THRU FRAME-5
```

```
C=============================================================

                CX = CX + 1

                DX2 = XF3 - XF2
                DY2 = YF3 - YF2
                DX3 = XF4 - XF3
                DY3 = YF4 - YF3
                DX4 = XF5 - XF4
                DY4 = YF5 - YF4

                SPXX = SPX1 + DX2 + DX3 + DX4
                SPYY = SPY1 + DY2 + DY3 + DY4

C=============================================================
C     DEFINE VELOCTY VECTOR MAGNITUDE AND POINT OF ORIGIN
C=============================================================

                S(3,CX) = SPXX*0.09375*H1
                S(4,CX) = SPYY*0.15*H1

                S(1,CX) = FLOAT(YC(1))
                S(2,CX) = FLOAT(XC(1))

                S(5,CX) = S(2,CX)/80.0

C=============================================
C     ZERO OUT THE DETECTED VELOCITY VECTOR
C=============================================

                G(XC(1),YC(1)) = ZERO
                G(XF2,YF2)     = ZERO
                G(XF3,YF3)     = ZERO
                G(XF4,YF4)     = ZERO
                G(XF5,YF5)     = ZERO
                GOTO 140

C=======================================
C     ZERO OUT OTHER VARIABLES
C=======================================

                SPX1 = 0
                SPY1 = 0
                XF2  = 0
                YF2  = 0
                SPX2 = 0
                SPY2 = 0
                XC3  = 0
                YC3  = 0
                XF3  = 0
                YF3  = 0
                SPX3 = 0
                SPY3 = 0
                XC4  = 0
                YC4  = 0
                XF4  = 0
                YF4  = 0
                SPX4 = 0
                SPY4 = 0
                XC5  = 0
                YC5  = 0
                XF5  = 0
                YF5  = 0
```

```
                DX2 = 0
                DX3 = 0
                DX4 = 0
                DY2 = 0
                DY3 = 0
                DY4 = 0
                XX3(IX) = 0
                XX4(IX) = 0
                XX5(IX) = 0
                XX3(JX) = 0
                XX4(JX) = 0
                XX5(JX) = 0

C=============================================
C           ==================
C  BOTTOM OF LOOP ==================
C           ==================
C=============================================

120          CONTINUE
130        END DO
140      END DO

           WRITE(*,150)CX
150      FORMAT(I6,' VELOCITY VECTORS FOUND ')

C=============================================================
C     WRITE OUTPUT (VELOCITY VECTOR COORDINATES AND MAGNITUDE),
C     BOTH TO THE SCREEN AND THE OUTPUT FILE V1.OUT (WRITTEN-
C     OUT IN A TECPLOT-COMPATTIBLE FORMAT)
C=============================================================

           OPEN(2,FILE=FNAME)
           WRITE(2,160)
160      FORMAT(1x,' TITLE = " PDT data " ')
           WRITE(2,*) 'Variables = " i","j "," Vx ","Vy" '
           WRITE(2,*) '  ZONE T="Zone-1",I=',
     +                  cx,',J=1,F=point '
           WRITE(*,*) '       x          y          Vx
     +     Vy '

C=============================================
C     COORDINATE TRANSFORMATION FOR TECPLOT
C=============================================

           DO I=1,CX

             DUM  = ((511-S(1,I))/50.0) - 7.0

             WRITE(*,*) S(2,I),S(1,I),S(3,I),-S(4,I)
             WRITE(2,170) S(5,I),DUM,S(3,I),-S(4,I)
170        FORMAT(4F12.4)

           END DO

           CLOSE(2)

         END DO

180    STOP
         END
```

VITA

Ram Sivakumaran was born in Colombo, Sri Lanka on July 30, 1967. After completing his secondary education in Sri Lanka, he came to the United States in 1985, to pursue his higher education.

He graduated with a Bachelor of Science degree in Aerospace Engineering in December 1988, from Parks College of Saint Louis University. He then joined the University of Tennessee Space Institute (UTSI) to begin his graduate study, while serving as a Graduate Research Assistant (GRA). In December 1991 he graduated with a Master of Science in Aerospace Engineering.

After a period of one year, he returned to UTSI as a Research Engineer to work on an experimental study on the nutation instability problem inherent in spinning solid rocket motors.

In June of 1993 he accepted a GRA to continue his graduate study in the area of solidification physics at the Center for Laser Applications (CLA). Ram graduated with a Master of Science in Engineering Science and Mechanics in December 1994.