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DEVELOPMENT AND APPLICATION OF A HIGH SPEED DIGITAL DATA ACQUISITION TECHNIQUE TO STUDY STEAM BUBBLE COLLAPSE USING PARTICLE IMAGE VELOCIMETRY

A Thesis

by

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Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

August 1992

Major Subject: Nuclear Engineering

FG02-88ER12813

ABSTRACT

Development and Application of a High Speed Digital Data Acquisition Technique to Study Steam Bubble Collapse using Particle Image Velocimetry. (August 1992)

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The use of a Particle Image Velocimetry (PIV) method, which uses digital cameras for data acquisition, for studying high speed fluid flows is usually limited by the digital camera's frame acquisition rate. The velocity of the fluid under study has to be limited to insure that the tracer seeds suspended in the fluid remain in the camera's focal plane for at least two consecutive images. However, the use of digital cameras for data acquisition is desirable to simplify and expedite the data analysis process.

A technique was developed which will measure fluid velocities with PIV techniques using two successive digital images and two different framing rates simultaneously. The first part of the method will measure changes which occur to the flow field at the relatively slow framing rate of 53.8 ms. The second part will measure changes to the same flow field at the relatively fast framing rate of 100 to 320 μs.

The effectiveness of this technique was tested by studying the collapse of steam bubbles in a subcooled tank of water, a relatively high speed phenomena. The tracer particles were recorded and velocity vectors for the fluid were obtained far from the steam bubble collapse.

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CHAPTER I

INTRODUCTION

I.1 Background

The study of two-phase flow patterns is important for the improvement of single-component systems (such as a pure liquid and vapor system like water and steam). Better information about the fluid dynamic and heat transfer processes occurring in these systems during convective boiling and condensation helps improve the design of water tube boilers and water-cooled nuclear reactors (Collier, 1972). Flow visualization is one of the experimental fluid mechanics tools available for gathering this data. It can make certain properties of a flow field directly accessible to visual perception (such as velocity and vorticity) (Merzkirch, 1974).

This study will use one method of flow visualization, Particle Image Velocimetry (PIV), to examine steam bubble collapse (one small part of the boiling process). The system which was assembled to capture the data is capable of acquiring digital images of an approximately 1.9 cm x 1.7 cm section of the flow plane with a 640 x 480 pixel resolution. The experimental setup to study steam bubble collapse is

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This thesis follows a style based on the ASME Transactions Journal of Heat Transfer.

shown in Figure 1. The setup for the data acquisition technique includes a high-energy Nd-YAG pulsed laser, two Panasonic CCD cameras, a beam splitter prism, and two Epix frame grabber boards. Additionally, an oscilloscope, a pulse generator, and a Wavetek signal generator are used.

The two CCD cameras are arranged to acquire the same view plane in the flow field of interest when a pulsed laser fires. To capture the fast flow field around a collapsing steam bubble, one camera is exposed to a double pulse of laser light, while, the second camera only captures the second pulse. The separation between the two exposures can be set from $100\mu s$ to $325\mu s$. The time between each double pulse set can be set to 53.8 ms or greater. So the cameras also capture the slow changes which occur in the longer time frame. This experimental setup can also be used to study other types of fairly fast phenomena.

I.2 Background for Pulsed Laser Velocimetry

Very few analytical solutions presently exist for multi-component and turbulent flows, and the solutions which are available are not very practical for general use. For example, the Navier-Stokes equations (an analytical solution) are extremely difficult to solve in their general form because they are nonlinear, partial differential equations. Simplifications, which restrict their universal use, are usually made to reduce their complexity so that they can be solved more easily.

One computational solution is for modern supercomputers to perform direct numerical simulation. However, the three-dimensional nature of turbulent flow makes

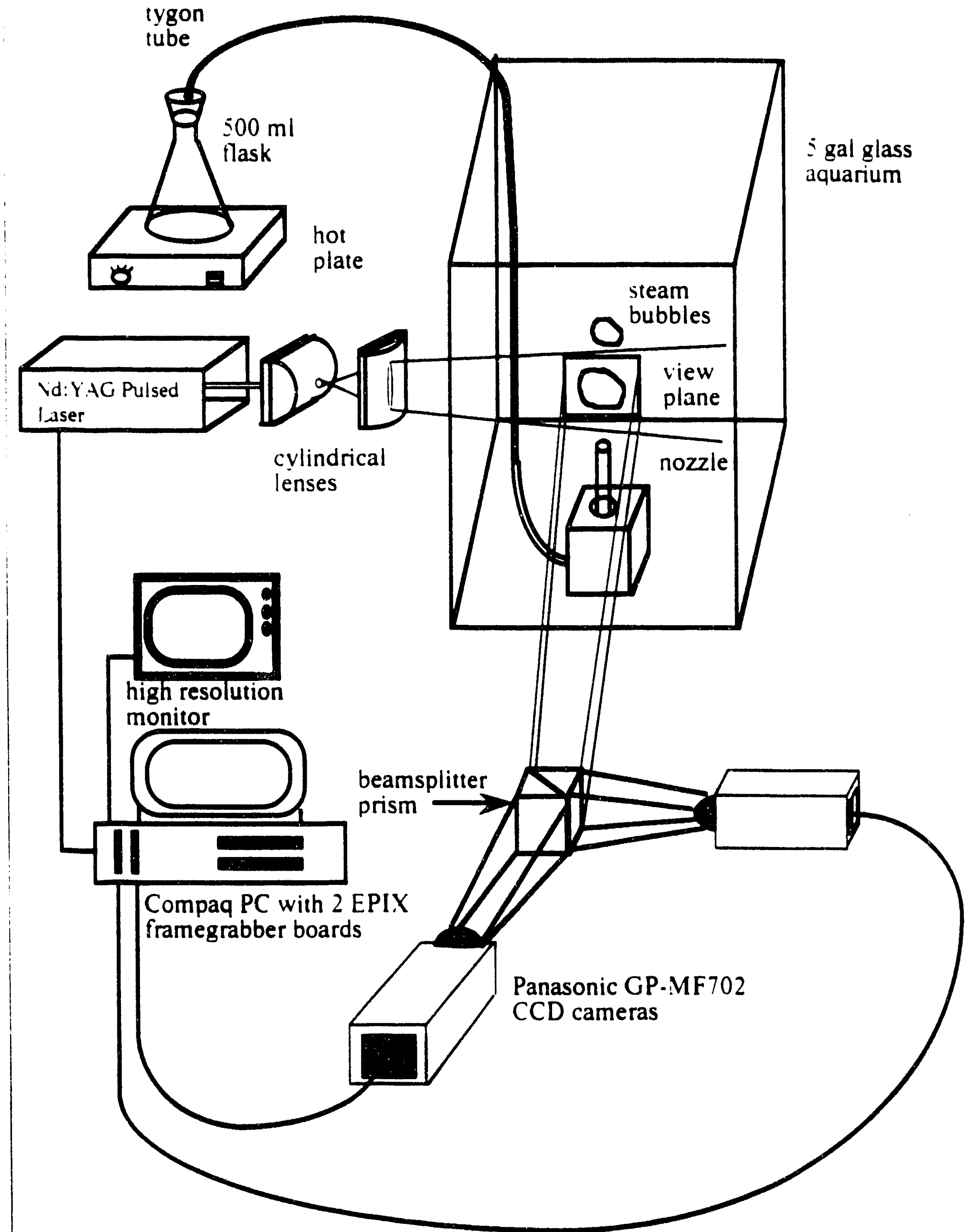

Figure 1. Experimental Setup

it difficult to obtain a solution for all but the lower numbers because of difficulties in resolving all the scales needed (Pruitt, 1991).

Presently, the most practical solution is to try to describe complex flow profiles by using an empirical formula derived from experimental data and numerical correlations (obtained from simplified forms of the conservation equations). This solution depends on accurate and reliable experimental data from similar flow patterns to accurately predict the behavior of a given flow.

A large assortment of experimental techniques have been developed to study two-phase or multi-component flow regimes and to provide accurate experimental data for the development of empirical correlations. The fundamental difficulty with obtaining accurate data from experimental measurement and analysis is that a large number of flow patterns and flow conditions can exist throughout a two-phase flow field, and the local condition at a point in the field is what is needed to determine the interaction between the phases present. So it is desirable to find an acquisition technique which can measure the local behavior at several points simultaneously and noninvasively.

The optical techniques have been the most successful at providing accurate experimental data. "Optical techniques are usually known for their largely nonintrusive properties as compared with methods like the Pitot tube or the hot-wire technique"(Lauterborn et al., 1984). Another disadvantage of intrusive techniques, like the hot-wire or Pitot tube, is that a probe, inserted in the field, can only measure what is occurring at one local point in the field. Therefore, it may see one phase continuously, or both phases intermittently. The value of this data is limited because it applies only to that point at a certain time. To obtain the general behavior for the whole two-phase flow field, the data is usually "space-averaged." However, this practice cannot identify the local condition for some particular point in the full flow field (which is required to determine the interaction between phases).

Optical flow-visualization techniques can be broadly divided into two categories : those that use variations in the refractive index and those that use light scattered from tracer seeds that follow the flow field. The first category includes: Spatial Filtering, Interferometry, and Holography. The second category includes the following techniques: Holography, Laser Doppler Anemometry (LDA), and Pulsed Laser Velocimetry (PLV) (Lauterborn et al., 1984). This study is concerned with using a technique from the second category.

Holography is a complicated experimental technique. It requires the precise alignment of a beamsplitter, mirrors, and lenses to form two laser beams which can be used to produce an image on a holographic plate. The analysis is performed by recreating the hologram with a continuous laser and taking two dimensional photographs of the hologram.

Laser Doppler Anemometry (LDA), more commonly referred to as Laser Doppler Velocimetry (LDV), is a standard method for obtaining fluid velocities with a high accuracy as a function of time. It is most commonly used to measure characteristics of single phase, one or two dimensional flows, however, it can be extended for use in three-dimensional flow studies. This capability to find three-dimensional velocity information is unique to LDA/LDV. Another advantage of LDA/LDV is its ability to provide turbulence data. However, it cannot detect small turbulence levels presently. "Very low turbulence levels, i.e. below 0.1%, are not obtained (on the contrary to hot wire anemometry) and the reasons still require some investigations"(Riethmuller, 1991). The limitation of LDA/LDV is it can only measure a single point in the fluid at any given time.

Hot wire anemometry is the other method for measuring turbulence. "One of the most common uses of the hot wire anemometer is to measure turbulence. In fact, before the development of the laser Doppler velocimeter, the hot wire anemometer was the only instrument capable of making high-frequency-response measurements of velocity"(Lomas, 1986).

There are two categories within PLV: Particle Image Velocimetry (PIV), and Laser Speckle Velocimetry (LSV). The difference between the two modes is the number of particles which are recorded in the images. If the density of the scatterers is small, PIV is used to measure the individual displacements of the particles. However, if the image density is high, the speckle patterns of the particles are recorded with LSV and the velocity found from their in-plane displacements (Adrian, 1986; Dudderar et al., 1977; Adrian, 1984).

PLV seems to be the best choice of the several optical techniques presently available. It gives a better and more complete picture of the flow field than LDA, and it is simpler to use than Holography. PIV is generally a better choice than LSV because "...the source densities encountered in many air and water flows of interest in research and practical applications will often not be high enough to produce speckle"(Adrian, 1984). The higher densities required for LSV can be achieved with some disadvantages. These include: accepting a limitation in the optical penetration by the imagers in larger systems because of the required seed concentrations, having to work with the more difficult and expensive volumes of seeding required for large scale or high speed flow systems, and having to use higher laser energies because of the higher seed concentration (Adrian, 1984). The higher laser power is required because the higher source density is normally attained (if the volume concentration of seeds to water is fixed) by using smaller seeds and "......with decreasing particle diameter the scattered light energy per particle decreases more rapidly than the number of particle increases" (Adrian, 1984). In general, it has been found that a lower source density limit offers the best trade-off for accuracy, ease of seeding, optical accessibility, and scattering effectiveness (Adrian, 1984).

One area where PLV still needs improvement is in high speed imaging. One method presently used for capturing fast flow fields with a PLV system is to double pulse the laser. However, in any double-pulsed PLV mode the magnitude of the displacement (component in the plane) is determined correctly, but its direction is ambiguous unless the first and second images of the tracer can be identified (Adrian, 1986). Several techniques have been developed to differentiate between the first and second images. These include using unequal light intensities when capturing the images, using different colors for each image, using a multiple-pulse sequence with coded spacing between frames, using fluorescent or phosphorescent particles whose images leave decaying streaks through an image, shifting the images as they are captured, and capturing a single pulse image separately. "These methods work for low image density PIV, but aside from the two-color [and image shifting] technique, they are not generally useful for high image density PIV or LSV"(Adrian, 1986).

Further work on the PIV technique may increase its capabilities. For example, PIV may be able to provide turbulence data eventually. Image processing is presently the major limitation. "Image processing is rather time consuming, and many instantaneous pictures must be taken and processed in order to have access to the turbulence."(Riethmuller, 1991) With further improvements in data acquisition and analysis, this technique may also provide three dimensional data.

Presently, the simplest solution for acquiring quantitative data for fast flow fields appears to be low image density PIV with a second camera capturing a single pulse image. This system has the advantage of using simple and inexpensive tracers and images which do not have to be shifted. Since a PIV technique is used, data for a full velocity field is obtained. PIV also has the potential for improvements which could enable turbulence and three dimensional data acquisition. A PIV system which uses digital cameras also has the potential for improvements in the image analysis time. This was the system developed in this study.

I.3 Methodology for Particle Image Velocimetry

In its present state of development, Particle Image Velocimetry is an extremely useful and powerful experimental data acquisition and analysis tool because it can be used to noninvasively obtain simultaneous velocity data throughout a two-dimensional flow field both quantitatively and qualitatively. It entails tracking neutral density seed particles suspended in the flow field under study. The resultant full-field flow visualization data is capable of providing both time-varying and/or instantaneous maps of several fluid flow parameters over a relatively large viewing area (compared to other flow visualization techniques). The flow parameters which may be obtained from the data include velocity, and vorticity.

This quantitative flow information is useful for verifying correlations previously formulated and for generating new ones. To obtain the same data that can be found in one PIV image, many simultaneous, individual, measurements with typical point flow probes would have to be performed. PIV's full-field nature of obtaining fluid flow parameter measurements provides a picture of a relatively large section of the flow field in one measurement.

All of the data acquisition techniques previously discussed require labor intensive analysis of experimental data to extract the desired flow information. ...though Particle Image Velocimetry has several advantages, presently it also requires labor intensive data analysis. However, it appears to have a significant potential for improvement in this area. If the data is taken with a digital data acquisition technique, one of the time–consuming steps (the conversion of the data to a digital format) in the analysis process can be eliminated.

I.4 Background for the Study of Steam Bubble Collapse

In order to test a high speed data acquisition system, a phenomena which is relatively fast had to be studied. A collapsing steam bubble is a fast phenomena that has been studied for a long time and for which a lot of qualitative data has been collected. "The uncertain origin, small size, and short life of the bubbles formed have provided a formidable challenge for experimenters studying the behavior of individual bubbles"(Blake and Gibson, 1987).

The interest in the dynamics of steam or cavitation bubble collapse in liquids, especially water, mainly stems from the destructive action they have on solid surfaces. "Cavitation damage is one of the major problems that may occur in hydraulic machinery, requiring the careful design of equipment to avoid its occurrence or at least allow it to exist in a controlled and hydraulically efficient form"(Blake et al., 1986). The "... cavitation damage may be responsible for the initiation of severe structural damage to ship propeller blades, turbomachinery, and hydraulic equipment"(Blake and Gibson, 1987). This damage is most likely to be caused by "a bubble collapsing near a solid boundary which develops a high speed liquid jet that moves towards the solid boundary. As the maximum jet velocity may exceed 100 m/s, the water hammer pressure produced by the jet impinging on the surface is regarded as a cause of cavitation erosion"(Vogel and Lauterborn, 1988).

Several methods have been developed to study an individual bubble's collapse. These include kinetic impulse, spark discharge, and pulsed-laser discharge (Blake and Gibson, 1987). These methods involve the use of additional equipment to generate the steam bubbles. A simpler method which has also been used by researchers, but does not generate a single bubble for study, is "low flow steam injection."

Information about the properties of steam-water interaction generated from "low flow steam injection"is useful because the injection of steam into a subcooled pool of water produces a high rate of heat transfer which is much more efficient than conventional heat exchangers. This type of system may be useful for storing the thermal energy in a solar plant or for quenching the blowdown from a boiling water type of reactor during a loss-of-coolant accident (Lee and Chan, 1980).

When steam bubbles are studied, both the repetition between measurements and the speed of each measurement are important. "The repetition rate of the measurement determining the temporal resolution is set by the lifetime of the bubble of only approximately 1 ms and should exceed 10,000 per second. The spatial resolution is set by the size of the collapsed bubble which usually is smaller than 0.1 mm and should reach several points of measurement per mm squared"(Vogel and Lauterborn, 1988).

Most of the data collected has been acquired at these faster framing rates. "Over the years rotating drum, mirror, and prism, cameras have been used with exposure rates varying from 1,000 to 1,000,000 frames/s, and more recently high-speed holography has been employed"(Blake and Gibson, 1987). However, most of this data was collected with purely photographic techniques.

These techniques provide qualitative information. Quantitative data is obtained by manually analyzing each of the photographic images. "It is now possible to calculate velocities and pressures anywhere in the flow domain, not just in a few isolated locations. Most experimental observations to date have been restricted to a sequential picture of the bubble shape leading to estimates of particle velocities on the surface"(Blake and Gibson, 1987). "Bubble motion was evaluated from the frames with the aid of a digital computer using a graphical input device"(Lauterborn et al., 1975). This test will attempt to acquire quantitative as well as qualitative data directly from the images without the aid of a "graphical input device."

1.5 Methodology for the High Speed Data Acquisition System

The use of digital cameras for high speed digital data acquisition could potentially expedite the whole data analysis process (from after obtaining the experimental data to the calculation of the flow field) for high speed fluid flow studies. "The trend of all modern flow–visualization techniques is clearly toward computerization and digital image processing"(Lauterborn et al., 1984).

The following steps were taken to advance present PLV techniques to allow for acquisition of high speed digital PLV measurements of two-phase flow field characteristics:

1) Literature searches for PLV and associated measurement techniques were performed to obtain information about previous work and elements which must be considered when taking and analyzing PLV data.

2) Literature searches for data on steam bubble experiments were performed to obtain information about techniques used to acquire data and the results obtained.

3) A computer program was developed to control and time a high-speed, full-field, flow data acquisition system which utilizes PIV techniques to acquire image data digitally.

4) **The new data acquisition system's timing was verified by testing various timing signals with an oscilloscope and photodiode.**

5) **An experimental setup was developed to allow investigation of the collapse of steam bubbles and to obtain experimental data for checking the feasibility of the data acquisition system.**

6) The experimental data which was obtained from the system was analyzed utilizing cross-correlation techniques developed by prior researchers. The analysis was conducted on the binary data obtained from the images.

7) The results from the analysis were further developed to allow interpolation of sparse vector data into full-field maps, and to extract flow parameters, such as streamline and vorticity using methods developed by prior researchers.

This study will demonstrate that the data acquisition and analysis process could potentially acquire data from a fast flow field (like steam bubble collapse) with digital cameras. If the analysis of the digital images for conversion to binary images and spot data could be automated, (possibly with a neural network code or a hard-wired gradient thresholding program) a real time imaging system might eventually be obtained.

I.6 Literature review

Pulsed Laser Velocimetry (PLV) is a noninvasive technique for quantitatively extracting information from complicated flows by tracking tracers suspended in the fluid flow. PLV flow visualization involves seeding the fluid under study with approximately neutral density particles (which follow the fluid's flow paths) and measuring the movement of the particles over known time intervals. The seeds follow the flow paths because they have a density close to the density of the fluid they are following (for this experiment in water, seeds with a specific gravity of 1.02 were used), and they have a small diameter (for this experiment, 6 micron seeds were used) and inertia (the time for the seeds to reach 80% of the speed of the fluid after a change was 4.1 μs). The time constant calculation is in Appendix J.

The measurements are performed by pulsing the fluid with a thin sheet of pulsed laser light, and capturing images of the particles following the flow with photographic film or digital cameras. After the data has been acquired, the tracer seeds have to be separated from the background and tracked through the frames.

The field of PLV is constantly being expanded and improved by new developments in algorithms and experimental techniques. One form of PLV is particle image velocimetry (PIV). Descriptions of recent work done in the PIV area of PLV field can be found in a number of papers (Adrian, 1986; Blanchat, 1991; Adrian, 1988; Vogel and Lauterborn, 1988). The accuracy of PIV research has advanced to a point where thousands of data points can be followed accurately in a flow field (Adrian and Yao, 1984; Blanchat, 1991). Studies of two-dimensional, two phase flow have been performed with new PIV techniques which are described in several recent works (Delahunte and Hassan, 1990; Blanchat, 1991; Hassan and Blanchat, 1991; Hassan and Canaan, 1991).

Accuracy in determining the tracers from background noise is one of the most important parameters required by PIV to insure that the quantitative results are valid. "The analysis of the recorded image is one of the most important steps in the entire process, as it couples with the image-acquisition process to determine the accuracy, reliability, and spatial resolution of the measurement : it is also the most time-consuming part of the process"(Adrian, 1991). There are several other factors which may also have a significant effect on PLV or PIV flow visualization results.

These include the accuracy and reliability of the tracking algorithm, the type of seed, the characteristics of the fluid flow under study, the characteristics of the laser light sheet, and the type of imaging system.

Two tracking algorithms were available for use. The first is the multiframe tracking (MFT) code and the second was the cross-correlation tracking code (CCT). The MFT code requires four frames of data and the CCT code only requires two frames. Both codes were tested for reliability and accuracy with synthetic data by prior researchers. They found "reliability and yield for both tracking techniques were greater than 70% for movements as large as 50 pixels between frames"(Blanchat, 1991). The accuracy and reliability of the results would be considerably lower for experimental data because of noisy images. The noise would be generated by seeds entering and leaving the view plane, and changes in the average gray level throughout the image (generated by changes in the light intensity and glare from large tracers).

The type of seed has an important effect on the outcome of the results because "at present pulsed laser techniques use particles that are somewhat larger than desirable from the viewpoint of following fluid motion. In water, [Adrian's] experience indicates that 10 μm plastic spheres are needed to give good photographs, with present equipment. These are optically equivalent to [(scatter as much light as)] TiO_2 particles about 2 μm in diameter"(Adrian, 1988). Tracers used for experiments run in air should be approximately 5 μm in diameter.

The concentration, or density, of the tracer seeds is also of concern. The concentration which can be used is dependent on the resolution of the equipment and the size of the seed available. The density must be small enough so that the recording instrumentation can record individual seeds, however, the concentration must be large enough to insure that data is available to accurately construct the full-field flow velocities.

Several fluid flow characteristics can have an adverse effect on the results if they are not considered prior to performing a PIV investigation. These include: the dimensionality of the flow, the type of fluid, and the speed of the flow. For example, turbulent flows are of interest to many investigators. However, turbulent flows are by their nature three dimensional. So care must be taken to produce a two dimensional flow for the study, unless data can be taken in all three dimensions. Two dimensional data may produce incorrect results because of particles moving in and out of the plane under study from the third dimension. This movement could result in the tracking algorithms finding incorrect seed matches between the frames (incorrect matches will produce incorrect vectors) (Sinha, 1988).

The index of refraction of the fluid medium should also be considered if the particles are away from the optical axis and a three dimensional flow is being studied. Light scattered from the seeds will be refracted to some extent in the fluid. This will lead to a slight displacement error in the position of the recorded image of the particle relative to the camera's internal image plane (Sinha, 1988). This error was not a factor for the two dimensional data from this experiment. Flow speed is another area of considerable concern and difficulty in tracking particles. If the fluid flow speed is too fast compared to the camera's ability to acquire the images, the camera will not capture seeds in successive frames. This will affect the tracking routine's results.

The thin sheet of light (approximately 1 mm thick) used to pulse the fluid is one of the keys to successful PLV research. The flash of light provides the ability to determine the instantaneous positions of the seeds in the flow. For a two dimensional study, the light should be shaped into a thin planar light sheet which runs parallel to the two-dimensional flow field (Vogel and Lauterborn, 1988; Sinha, 1988).

A pulsed laser is one means of producing the light sheet. Major considerations when selecting a laser for PLV research include: its peak power, the laser light's wavelength, the pulse frequency, and the pulse width. The peak power and laser wavelength are important because they affect how the light scatters from the seeds. Higher powers will scatter more light and permit smaller seeds to be used. However, too much power and light can overexpose photographic film, Vidicon camera tubes or CCD arrays, and possibly produce permanent damage.

The light wavelength is important because it may not work well with certain fluid media. For example, infrared wavelengths (1064 nm) will not penetrate water very well due to their large absorption coefficient in water. The laser's pulse rate determines the maximum possible flow speed which can be studied. It is often necessary to use a very high pulse rate to study turbulent flows. A small pulse width is desirable to obtain an instantaneous image of the flow.

The two major means of image recording presently used are photographic film and digital cameras. There are many film and exposure characteristics which should be considered that affect the images (Lourenco and Krothapalli, 1987; Lourenco and Krothapalli, 1988; Adrian, 1991). Both recording devices have a maximum frame acquisition speed (which is one of the determining factors when finding the system's maximum data acquisition rate). The maximum frame rate for high speed photography is 1,000,000 frames/s (Blake and Gibson, 1987). Digital cameras have a standard frame rate of 30 frames/second. This rate can be increased to 60 frames/second by decreasing the resolution. With special equipment, very high effective frame rates can be achieved from a single digital camera. The "selectable one to four port, very high speed 512 x 512 charge injection device" is one example. It can acquire 500 frames per second (Zarnowski et al., 1991). Higher effective rates may also be achieved by using more than one camera (by double pulsing the laser and capturing a double exposure, an effective rate of 6,666 frames/sec can be achieved).

Double pulsing experiments typically have a problem with directional ambiguity. Many methods have been suggested to overcome the ambiguity (Adrian, 1984; Adrian, 1986; Adrian, 1988; Dudderar et al., 1987; Delahunte and Hassan, 1990). Some of the methods include: marking the images with different light intensities, different colors, a multiple-pulse sequence with coded spacing, or fluorescent particles which leave decaying streaks (Adrian, 1986). Another solution is to shift the second image with respect to the first image (Adrian, 1986). Capturing a single pulse with a second camera is another possible solution (Delahunte and Hassan, 1990). This technique would require two cameras. It would double expose one camera's image and single expose the second camera's image. The single exposure would be used to resolve the directional ambiguity of the double exposure.

Another factor is the reliability and accuracy of the tracking algorithm. It must be checked for complicated flows. However, it is extremely difficult to produce a complicated flow and obtain data for which the results can be predicted to within several percent (Meynart, 1983). One possible solution is to perform the error analysis for the tracking routines with synthetic data (Blanchat, 1991).

After the imaging system has recorded the scattered light from the tracers, it is necessary to find individual seed or spot data in the images. Digital cameras record the scattered light in the form of gray levels in an array. Spot data can be determined through image processing using thresholding and edge detection techniques (Blanchat, 1991; Delahunte and Hassan, 1990; Hild, 1989). However, using a threshold can be a major source of error. If the threshold value is too high, many faint spots may be eliminated and the spots that remain may have misplaced centroids (because they appear smaller than they actually are). If the thresholding value is set too low, then background may be identified as part of identified spots or spots may be created. This can lead to errors when tracking the data, since the tracking routines require accurate pixel locations for determining spot correlation.

The use of a single threshold value is normally inappropriate for most images. Regional thresholds should be used if the laser sheet is not perfectly uniform, or there is unequal scattering (Canaan, 1990). This is normally the case because the laser produces a Gaussian or nonuniform beam (it is brighter in the middle), and the tracers scatter light differently (their size depends on how the seeds clump together). A regional threshold is a threshold which varies depending on the background gray level in a particular section of the image (so the threshold would be higher for the glare around a bubble and lower farther away from the bubble).

Although all of the above effects can adversely affect the results from PLV or PIV experiments, most can be minimized. The best seed for an experiment can be determined by trying several types to determine the best one. The best seed meets as many desirable characteristics as possible. The desirable characteristics include: density close to the fluid being tracked, small diameter, good light scattering properties, and low cost.

The characteristics of the fluid flow should be determined before the experiment, and the pulsed laser light sheet should be set up precisely before data is taken. The imaging system and the tracking routines should be checked for reliability and accuracy. The greatest source of error presently came from the difficulties in separating the seeds from background and noise. This problem may be minimized by taking good, clean data.

To take good data the cameras have to be focused on the view plane so that the seeds do not "balloon"(bloom, or expand) when the image is acquired. The laser power should be as low as possible so that the glare is minimized (however, it should be high enough so that the seeds are distinguishable from the background).

After the PIV analysis is performed, the local, fluid flow velocity is determined from the seed movement between two, sequential images. The flow velocity is assumed to be the seed velocity because the seed and fluid density are close (1.02 and 1.0 gm/cm^3 respectively), the seed diameter is small (6 micron), and the time for the seed velocity to reach the fluid velocity is small (4.12 μs to reach 80%).

The velocity is calculated by finding the distance the seed traveled between the two frames and dividing by the time between pulses (Adrian, 1986; Blanchat, 1991). The final objective of PLV is to quantitatively measure a large numbers of vectors over the full-field. This requires a fast, relatively error-free particle tracking algorithm.

1.7 Summary

The objective of this study was to improve techniques for high speed digital data acquisition and quantitative analysis of high speed fluid flows using the Particle Image Velocimetry (PIV) flow visualization method. The study also tries to partially duplicate the qualitative data collected about steam bubbles in previous studies with a totally digital system and to perform an analysis on the data obtained, both quantitatively and qualitatively.

To meet these objectives, a new PIV data acquisition technique was developed which performs particle tracking on two, sequential, images obtained with either a slow, single-pulsed mode of laser operations, or a high-speed, double-pulsed, mode of laser operation. The system was tested with data acquired from the study of steam bubbles to determine the method's reliability. The system's reliability for timing was checked with an oscilloscope. The experimental data was tracked with algorithms created and tested by prior researchers.

CHAPTER II

THE IMAGE ACQUISITION SYSTEM

II.1 Introduction

This section will discuss the main components of the Image Acquisition System. These consist of the two medium resolution digital CCD cameras which are used for acquiring the digital images and the two EPIX video frame grabber boards which are used for storing and processing the images. It will first briefly discuss the several possible configurations for the EPIX/Panasonic imaging system. It will then discuss in detail the final configuration. It will also briefly discuss the capabilities of the boards for timing an imaging system.

II.2 Description of the Medium Resolution CCD Camera Equipment

There are presently two GP-MF702 Panasonic Industrial MOS B/W cameras used for acquiring the high speed digital data. Their main components are a solid state charged coupled device (CCD) sensor with a 649 x 491 pixel array and a high resolution Transversal Signal Line (TSL) MOS chip (the pick-up device). The CCD array consists of a rectangular silicon sensor with discrete photosites arranged in rows and columns. Each pixel in the array is a 13.5 μm square.

The CCD camera collects images as electrical charges throughout the array. When light hits a photosite in the sensor it produces an electric charge directly proportional to the intensity of the light at that photosite by the photoelectric effect.

The CCD cameras transfer the image data in the form of a video signal which is generated with a "sample and hold" technique. The charge at each photosite, or pixel, is sampled and added to the output video signal. As each site is sampled, the voltage of the video signal is held constant at this value until the next site is sampled. So the output video signal looks like a step function (Henderson, 1991).

The form of the output video signal depends on which scanning mode is used to generate it. The two main scanning modes are: the 2:1 interlace mode (the RS170 standard) and the full line non-interlace mode (the sequential scan mode). When the interlace technique is used the video image or frame is divided into two fields which are transferred sequentially by the video signal to the frame grabber. The first field is generated by sensing the voltage from left to right across every other horizontal row (they may be the even rows) from top to bottom. Then the next field is generated by scanning across the set of rows (they may be the odd rows) which were skipped in the first pass.

The sequential scan technique senses the voltage at each site horizontally row by row sequentially. Since the scan does not skip any rows through each pass, the video signal contains each frame as one unit instead of two separate fields.

Both techniques take the same time to scan the whole array. The time required at the standard video frame rate of 30 frames/sec is 33 ms. The interlaced mode sends two fields at 60 fields/sec for a total of 30 frames/sec, while the sequential scan mode sends one complete field or frame at 30 frames/sec.

Figure 2 shows the timing for each video image. The top of the figure shows that each horizontal line takes approximately 63.55μs or 772 clocks (each "clock" is equivalent to the time it takes to scan 1 pixel) to be scanned. The total of 772 clocks is made up of the time to scan the 640 pixels in each line and the 132 clocks needed to synchronize the line (this synchronization time contains the horizontal drive signal which is used to "Genlock" the camera). "Genlocking" directly maps one row in the camera to one row in the frame grabber (to create an image of what the camera sees by starting a new line for each horizontal drive pulse and a new frame for each vertical drive pulse).

The bottom of the figure shows the vertical timing of the image. It takes 525 horizontal drives to make up one frame (for a total of 33.3 ms). The 525 drives consists of the 480 drives in the image, the 20 drives in the vertical blanking period (which contains the vertical drive signal used for "Genlocking"), and the remaining 25 drives which is used by the camera for synchronization and different resolutions.

Since the human eye can detect flickering (refreshes to the display) at 30 frames/sec, a sequential scan image must be displayed on a monitor that is designed to operate in a non-interlaced mode (otherwise the image will be flickering). This is not a problem for images displayed in the interlace mode since the images are refreshed at 60 frames/sec (which the human eye cannot detect).

The Panasonic camera also has several other modes of operation within these basic categories. Within the interlace category there are two modes. The camera can be operated in the frame accumulation mode (the previously discussed mode) or the field

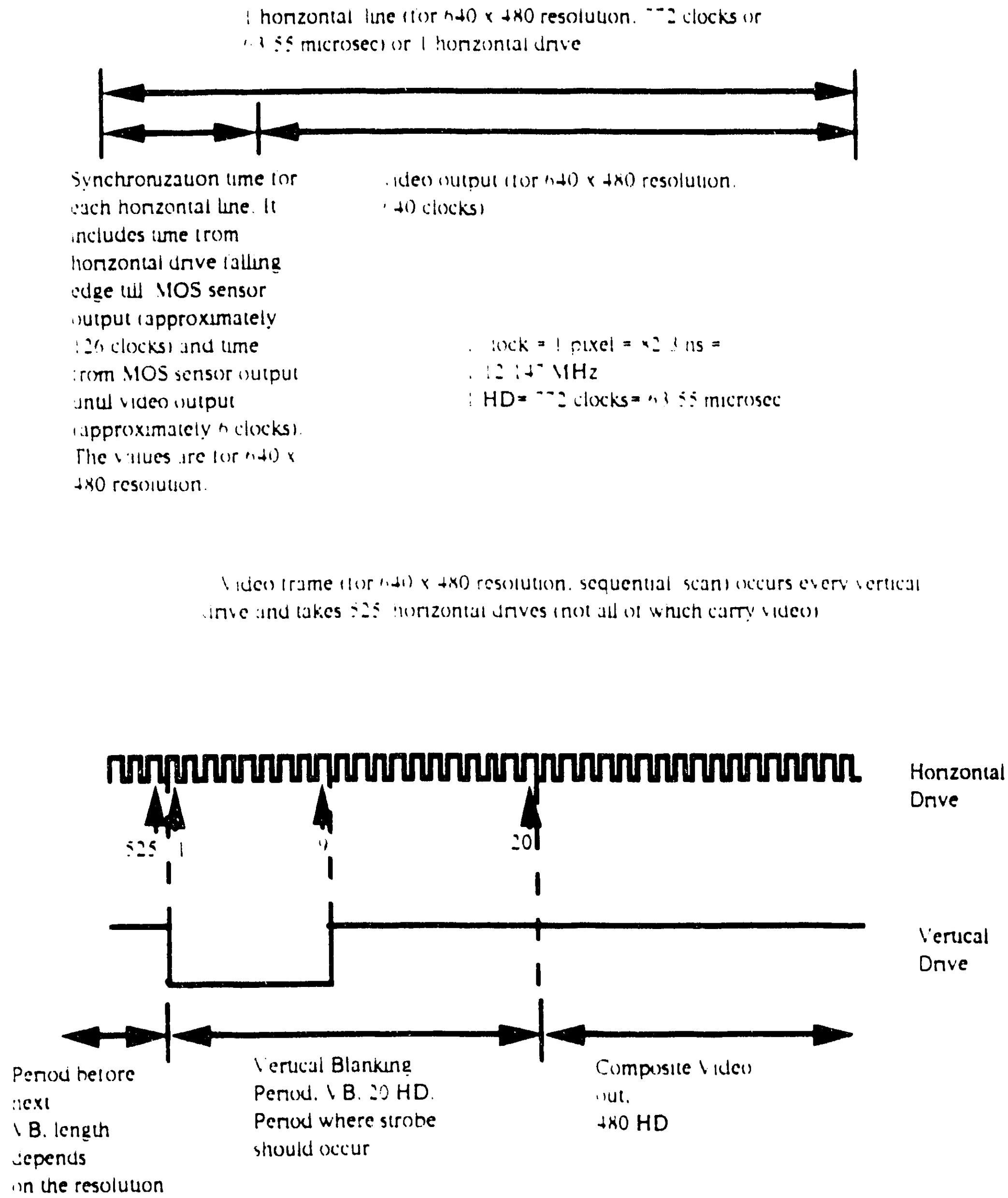

Figure 2. The Video Timing for each Image

accumulation mode. The frame accumulation mode generates an image every 1/30 second with a vertical resolution of 485 lines. The field accumulation mode generates a field every 1/60 sec. However, the vertical resolution is only 350 lines.

Within the non-interlace category there are three modes. These are the full line non–interlace (the previously discussed mode), the double speed full line non–interlace, and the non–interlace field accumulation mode. The full line non–interlace mode generates a frame with a vertical resolution of 490 lines every 1/30 sec. The double speed full non–interlace mode generates a frame every 1/60 sec with a vertical resolution of 490 lines. The non-interlace field accumulation mode also generates a frame every 1/60 sec, however, the vertical resolution is only 240 lines.

The cameras also have several other features of operation. These include their automatic charge reset modes : asynchronous VD reset or readout inhibit (R/I). These functions can be used to time the cameras with a specific event (like a laser firing). They require a trigger to reset the camera. Figure 3 shows the video timing for the readout inhibit mode. The figure shows that the readout inhibit signal must be raised (after it has been released) within the vertical blanking period. The image is output at the end of the vertical blanking period. The timing diagram in the figure shows the composite video out signal for the RS-170 mode of the camera. The Sequential Scan mode would output one continuous 33.3 ms composite video signal.

Figure 4 shows the video timing for the asynchronous reset mode. The top of the figure indicates that the trigger can occur at any time (the readout inhibit signal required that the trigger occur within the vertical blanking period). The next section

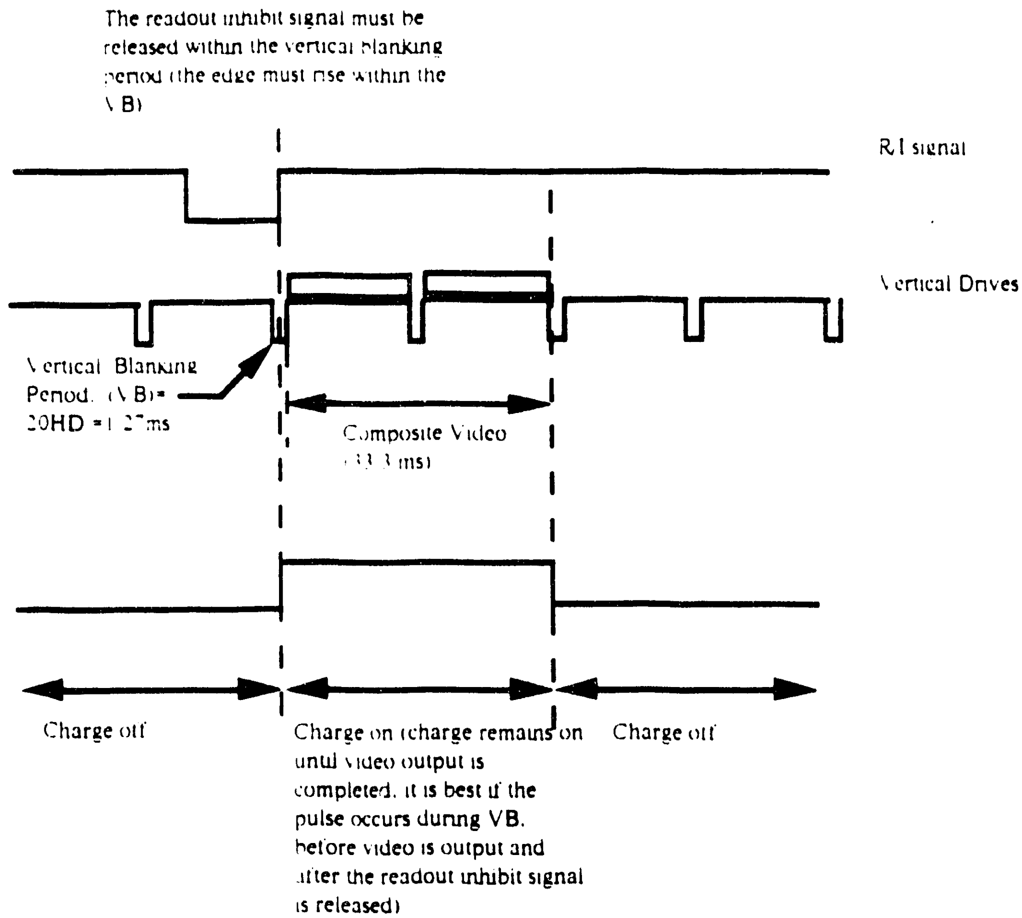

Figure 3. The Video Timing for the Readout Inhibit Mode

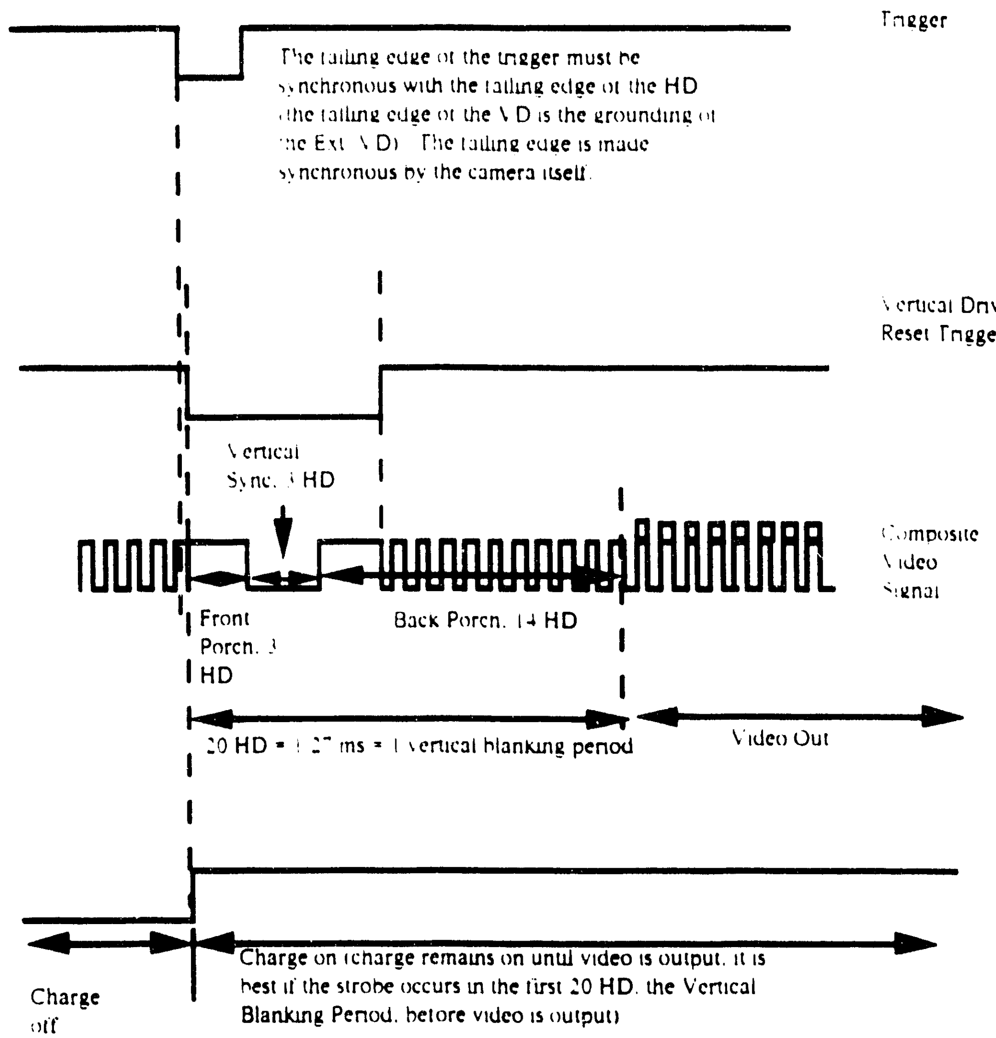

Figure 4. The Video Timing for the Asynchronous Reset Mode

in the diagram shows that the camera latches the trigger signal so that it is timed with the falling edge of a HD when it generates the "Vertical Drive Reset Trigger." The composite video is output 20 HD after the "latched" reset trigger is received. It is best if the strobe occurs within these first 20 HD because the photodiodes are accepting charge and the video data has not been output yet. The 20 HD vertical blanking period contains the "vertical sync" signal which is used for "Genlocking" the camera.

Once the analog video signal reaches the frame grabber, an A/D converter is used to reconvert the analog signal to a digital signal. The board's pixel clock rate should be the same as the camera's rate to sample the video signal properly and generate square pixels. If they are not the same, there will be some distortion.

The distortion results from over or under sampling the pixels from the video signal. So it is desirable to sample the video signal at the same rate the camera generates it. Since the cameras are synchronized to the frame grabber boards by "genlocking" the horizontal and vertical drive pulses of the cameras, this clock rate at which the image is sampled is important.

The cameras have the capability of operating in either a "pixel clock out" or "pixel clock in" mode. This can be used to generate more accurate images and eliminate the distortion caused by an over or undersampling of the pixels from the video signal. The period (time between successive horizontal synchronization pulses) for one line,or row of data, is 63.5μs. To generate this period the clock rate is based on the number of pixels in each row (so it varies slightly). The pixel clock rate for the Panasonic camera when it is operating with a resolution of 640 pixels per horizontal line is 12.147 MHz.

The cameras also have a feature which allows them to be synchronized together as well as to the boards (synchronize both cameras and both boards). If it is desired to synchronize both cameras together this can be done by making one camera the "master" camera and the other the "slave" camera. The master camera is set with the VD and HD signals output and the slave camera is set with these signals input (similar to a composite sync signal). The boards are synchronized to the cameras through their composite video out signal.

Each camera has a 12 pin connector cable which is used to connect them to other equipment. This can include a sync generator, a frame grabber, a power supply, and a host computer. The sync generator would be connected to the VD in/out and the HD in/out connections. This connection can be used to sync the components together. The cameras have internal switches which are used to select which mode the connector will be in (either signal in or signal out).

The frame grabber will normally be connected to the video out and possibly the pixel clock in/out. The power supply will be connected to the DC 12 V in connection and the ground connection. The host computer may be connected to the read-out inhibit line (for the charge reset mode readout-inhibit). The trigger signal generator for this connection may be the EPIX frame grabber boards or a circuit. If the asynchronous reset mode is used, the trigger signal should be connected to the VD connection (the internal switch should be set for VD out, however, it will reset when it receives the signal).

II.3 Description of the EPIX Frame Grabber Board Equipment

The frame grabber is the EPIX 4MEG Video Model 10 image acquisition and processing board. Presently there are two imaging boards located in a COMPAQ 386/20 Mhz. IBM compatible computer. Each board has an Analog Input Output connector attached. The connector extends out the back of the computer and is used to interface the board with the digital camera it controls.

Each camera is synchronized to the imaging board it sends its data to. Since each board is capable of holding 4 megabytes of data, they can hold 13, sequential, images;each having 640 x 480 (8-bit) resolution. The boards also serve as the timer for the whole system.

A total of 12 connections are available on the Analog Input Output connector. BNC cables can be used to extend the length of the connection from the EPIX connectors to the cameras, however, noise and loss of power should be considered when extending the length of the connection. The total number of cables necessary will vary with the setup.

With no pixel clock connection, two cables for each camera–board connection would be needed. One cable is used to couple the camera's video-out connector to the board's video-in connector. This connection carries the composite video signal from the camera to the frame grabbing board (the composite signal carries the horizontal and vertical drive timing signals which are used to synchronize the system as well as the video signal).

The other cable is used to carry the external out signal from the board to the camera's vertical drive connector. This connection carries a programmable 5-volt

TTL level output which can be used for timing (for example, to asynchronously reset the camera). The connection to the "master" camera also needs to be branched off for connection to the sweep generator to fire the laser.

If the Pixel clock is used there would be a third connector. It would carry the Pixel clock out signal from the camera to drive the boards.

The Epix system can be operated two ways. One is through the menu driven interface. The other method is through a "driver" or "object" code which the user can write in the "C" programming language. The user written code makes use of EPIX commands which are available in the "object" code library or the "image processing library." The object code library contains commands for taking data, while, the processing library contains commands for enhancing and manipulating pictures.

The EPIX menu driven software has the advantage of being very easy to use. Choices are made by using the mouse or keyboard and toggling choices on or off. Its disadvantage is that it lacks the flexibility necessary for some applications. This flexibility is provided by the "driver" code. Details on the "driver" code can be found in Appendix D and the code which was used for this setup can be found in Appendix F.

The EPIX system arrives equipped with a PIXEL Clock Generator Module (PCGM) with a frequency of 14.3 MHz. This frequency is also available from the computer bus itself. This frequency can be changed by switching the PCGM. Certain PCGMs are available at other common frequencies or a custom frequency can be made. The board can also be operated at other frequencies by using the PIXEL clock input connection.

It is designed to acquire and hold 4 megabytes of video data on the board. The data will stay there until new data is acquired or the power supply is cutoff (if the cameras acquired the image at 14.3 MHz) because the boards are using the computer's clock. So once the board is put in "display" mode (it is not digitizing and storing new data), the cameras can be turned off and the software exited and the data will remain until the power is cutoff. This is useful because the data can be acquired and examined to determine its value without having to go through the routine of saving the data. Another advantage is it helps improve the data acquisition process. Data can be taken and quickly stored on the hard drive until it is full and then one more set can be taken before data has to be transferred.

If the data is sampled from the cameras with a PCGM at a different frequency the images may be distorted when entering or exiting the EPIX software because of interference. This is because the format and Genlock is not set immediately when entering the EPIX software (it automatically starts up in a default format before the selected one is started so the image may develop dropouts).

If the data is acquired using the clock rate provided by the Pixel Clock from the camera the data will be lost if the cameras are turned off before the data is saved (dropouts will develop). The cameras must also be supplying the clock signal to the boards when the data is recalled.

II.4 Possible Epix–Panasonic Configurations

The EPIX boards and cameras are very flexible so they can be used in a variety of configurations. These include the following:

1) the Epix system can be operated with one camera per board (so it can be operated with one or two cameras)

2) it can be operated with the menu driven software or with a driver program

3) the boards can also be put into two possible video synchronizing modes (genlock configurations)

4) the cameras can also be operated in three possible charge reset modes. These are none, read-out inhibit, and asynchronous reset

5) it can be operated with the board operating at its own pixel clock speed and the camera operating at its own speed or with the board receiving the pixel clock signal from the camera (however, if the board operates at its own speed, the pixels will not be square because of the different sampling rates)

6) the cameras can also be operated in two possible video timing modes: interlaced or noninterlaced (sequential scan)

Since the double pulsed PIV experiment required some means of determining the direction of the velocity vectors from the double exposure, a second camera was used. It was timed to capture an image only during the second pulse of each double pulse set.

The option to write a driver program was used because it offered more flexibility for timing than the menu driven software. The menu driven software was used for image processing because it is easier to use.

Genlocking is how the imaging equipment is locked together. There are three components which have to be locked: the camera, the board, and the monitor. These components have to be locked for the two modes of operation of the system (digitizing and displaying). The monitor usually locks (genlocks) to either the board or camera. The connection between the camera and board is more flexible. The two possible modes are "genlock on" or "genlock off" (master mode). They can be set the same or differently. (It is preferred to keep both modes the same. If they are not the same there will be a slight jump when the boards switch from digitize to display).

For the cameras to lock to the board, there has to be a timing connection separate from the video connection to send the video timing information from the board to the cameras. The Panasonic cameras do not have this connection (although they do have the two separate connections for the horizontal and vertical drive). So the boards are usually genlocked to the cameras. One exception occurs when displaying data that has been previously acquired. If the board is genlocked to the camera while in display mode, then the camera has to be on to see the image because the board is expecting to use the cameras horizontal and vertical drive signals (from the composite video signal) for synchronizing or "genlocking". So to display the image when the camera is off, the board has to be in "master" mode and generating its own timing signal.

The camera's charge reset modes are used when the boards (or another device such as a circuit) is used for the timing. The normal operation of the camera can be used if the EPIX system is being timed to the camera.

To correct for the different pixel clock frequencies, a format can be created which puts the board into a "pixel clock-in" mode (it is expecting a pixel clock signal). This format requires the boards to be operated in the "genlock" mode. This mode requires the data to be displayed and stored at the same frequency it was acquired at (the cameras have to be on and sending the pixel clock signal).

The cameras can be operated in the interlaced or non-interlaced mode when digitizing, however, when the data is displayed the interlaced format is required because the monitor is not capable of displaying noninterlaced images. This is because of the speed at which the screen is refreshed. The interlaced format leaves one of the two fields on the screen as it refreshes the other every 1/60 sec. The noninterlaced format refreshes the whole screen every 1/30 sec (so the screen appears to flash or flicker).

So the flexibility of the system is with the charge reset mode, clock frequency, and digitizing mode selections. However, the following limitations were found with some of the possible configurations.

When the readout inhibit mode is used, the cameras operate in their normal digitizing mode of 30 frames/sec (33.3 ms between frames, 16.6 ms between fields) and are allowed to store charge when they receive a trigger. Because of the time required to fire the laser (about 3 ms) and transfer data this should take at least two frames (or 66.6 ms between frames). It was found that the time between frames drifted between 66.6 ms and 99.9 ms. It was also found that the cameras reset in the middle of a frame on some sets. So the asynchronous mode was chosen. It is capable of taking a frame every 53.8 ms. Some of the oscilloscope plots from this test are in Appendix H.

The asynchronous reset mode changes the timing between frames (or vertical drives) which the EPIX boards are not designed to compensate for. It was found that the option of using the pixel clock from the cameras did not work fully in this mode. The asynchronous resets resulted in diagonal dropouts across the images (an indication of a video timing problem) in virtually all the sets of data immediately after startup. After operating the system for about 10 minutes, about 80–90% of the sets were good. The dropouts decreased through each set of data (So the first image acquired was the worst and the thirteenth the best, with no dropouts). This decrease in dropouts probably occurs because the EPIX boards experience less resets for the later images.

It was also found that if the imaging board used its own onboard clock (it did not have to depend on the camera clock), the dropout problem was eliminated. Since the PCGM which came with the board operated at 14.3 MHz and the camera operated at 12.147 MHz, a new PCGM was obtained from EPIX which operated at 12 MHz (A PCGM which operated at 12.147 MHz would have to be custom made and cost twice as much). For a 14.3 MHz resample of a 12.147 MHz signal, the x to y ratio would be 1.17 to 1 (for a real 30x30 pixel section it would appear as a 35x30 section). For the 12 MHz resample of a 12.147 MHz, the x to y ratio is 0.9879 to 1 (for a real 30x30 section it would appear as a 29x30 section). So the 14.3 MHz sample rate shrinks the pixels on the x axis (by taking more samples than required), while the 12 MHz rate stretches them slightly. This results in the 14.3 MHz rate using up more storage space than actually required.

It was determined that when the cameras are operated in the interlace mode (RS-170) one field is lost (one of the interlaced fields) while digitizing. So the image appears to flash on the screen (as the image is refreshed with the lost field) when it is displayed. This loss of a field occurs when the external output signals are placed in the program (the field is not lost until the external out command line is inserted in the program).

So it may occur because of interference with the acquisition of the video signal. (The command has to be set with either the PXFNXT or PXFNOW command. The PXFNXT command occurs at the next video field while the PXFNOW command occurs as soon as possible. Since the RS-170 mode sends the frame as two fields this may interfere with the acquisition of the second field). So the cameras needed to be operated in sequential scan mode when acquiring or digitizing the data, otherwise one of the video fields is lost (Sequential scan sends the frame of data as one complete field or frame).

II.5 The Asynchronous Reset 29x30 Imaging Setup

The final system setup which should be used is the 29x30 asynchronous reset mode. Figure 5 shows how the cameras should be connected to the frame grabber boards to achieve this setup. Some of the timing diagrams for the camera and laser in this set up can be found in Appendix I.

For the setup, the two cameras are set up perpendicular to a beam splitter prism so they will look at the same focal plane. Each camera looks at a different face of the prism; one looks at the real image, and the other looks at a mirror image.

The cameras are reset asynchronously by an external out signal from the EPIX boards. The asynchronous mode provides the best control for the timing of the system because it allows the cameras to be turned on when desired. The cameras are automatically reset when the data has been removed from the CCD array. The cameras operate in sequential scan mode for digitizing and RS-170 for displaying. The boards use their own 12 MHz PCGM to generate their video timing.

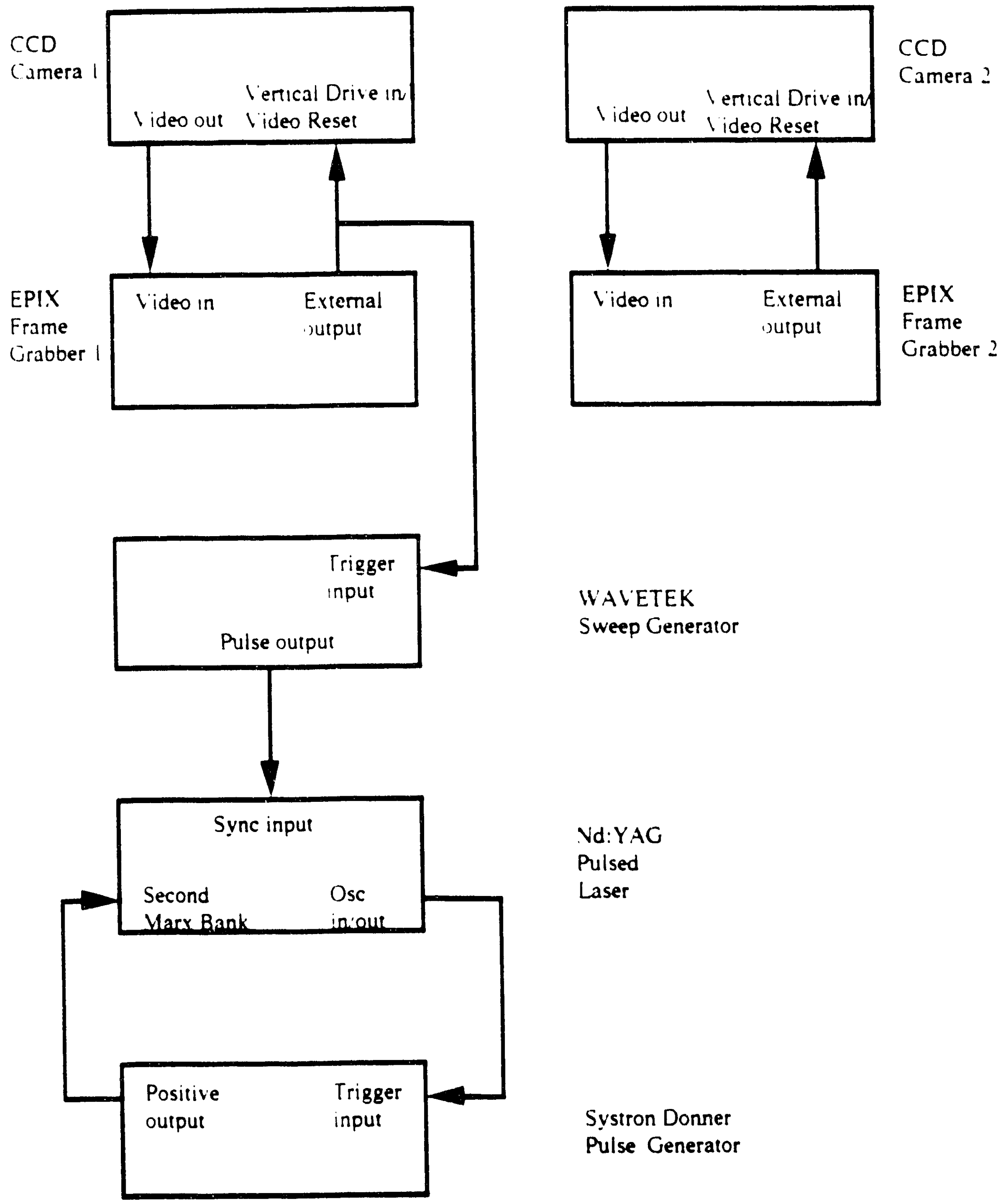

Figure 5. The EPIX/Panasonic Connection Diagram

Two cameras are required because their optimum framing rate is 33.3 ms and it is desired to capture a microsecond separation between pulses in the double pulse mode of the laser. An absolute maximum framing rate of 60 frames per second can be achieved (according to the camera specifications), however, at their maximum resolution, the maximum framing rate is 33 frames per second (unless double speed mode is used). The cameras are used at a 640 x 480 resolution.

The double pulse separation is captured by having one camera capture a double exposure because of the digital camera's relatively slow framing rate. The second camera is exposed only during the "second pulse." Figure 6 shows the camera operation and laser pulses. Details on timing the system can be found in Appendix C.

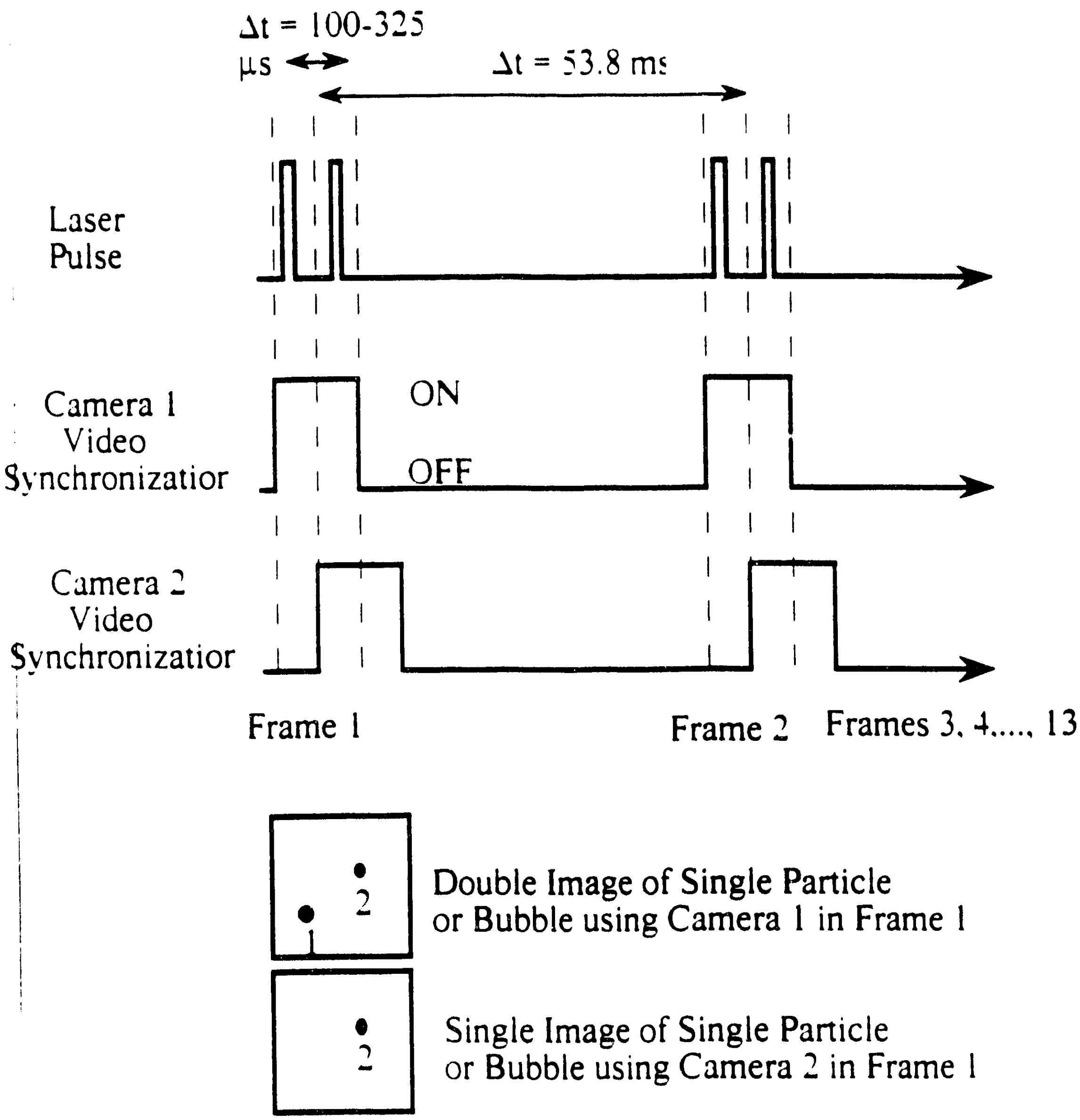

Figure 6. Double Pulse Camera Timing Diagram

CHAPTER III

THE DATA ACQUISITION SYSTEM SETUP

III.1 Introduction

This section will discuss how to connect and setup the high speed data acquisition system for acquiring data. It will discuss the connections between the EPIX imaging boards and the Panasonic cameras. It will also discuss the connections for the pulse generator, laser, and sweep generator.

III.2 Description of the Components

The experimental setup to study steam bubble collapse is shown in Figure 1. The setup for the data acquisition technique includes a high-energy Nd-YAG pulsed laser, two Panasonic CCD cameras, a beam splitter prism, and two Epix frame grabber boards. Additionally, an oscilloscope, a pulse generator, and a Wavetek signal generator are used.

The first step is to set up the two, medium resolution, Panasonic CCD cameras (GP-MF702 Industrial MOS B/W). Each has a 640 x 480 pixel resolution. One camera has to take a double exposure because of the relatively slow framing rate. The second camera is exposed only during the "second pulse" as explained later. The cameras should be put in the asynchronous reset mode by adjusting the external switches located on the back of the camera. This mode was necessary in order to control the video timing of the system. It allows the cameras to be turned on when desired. The cameras are automatically turned off after the data has been removed from the CCD array.

The two cameras are set up perpendicular to the beam splitter prism to look at the same view plane (each camera looks through a different side of the square prism). It is necessary to use a beam splitter prism to align and focus both cameras on the same view plane from the same distance. One camera views straight through the prism, while the other looks at a mirror image located inside the prism (The prism divides the light in half).

The next step is to set up the light source used in the experiment, a Spectra-Physics DCR-3G Nd-YAG high energy, pulsed laser. The light beam is positioned with high energy mirrors. Then the light is shaped from a circle into a plane sheet with a set of cylindrical lenses, and passed through the fluid under study. The lenses shrink the light from a 7 mm beam thickness into a 1 mm thick beam which is approximately 7 cm wide.

The near infrared laser light produced by the laser has an extremely high absorption cross-section in water. Since the experiments are done in water, a frequency doubling crystal is used to convert the 1064 nm (infrared) light to 532 nm (green) light. This results in a drop in the maximum energy output to 400 mJ. However, the extremely low absorption coefficient at this wavelength more than makes up for the loss in energy.

The laser is operated in the "double pulse" mode. The time between each pulse in the set of double pulses can be varied from 100 μs to 320 μs apart. The time between sets of double pulses is set to 53.8 ms (this time can be increased). Figure 7 shows the difference between the single and double pulse mode. Operating the laser in double pulse mode lowers the maximum output energy to approximately 150 mJ for each pulse. The laser Q-switch controls the amount of energy each pulse produces (by dividing the available energy from the flash lamps between pulses).

Then the cameras should be connected to the EPIX frame grabber boards. There are two boards located in a 386 20 MHz Compaq computer. Each camera has its own imaging board. The boards serve as the timer for the whole system. Each board is capable of sending out a 5 volt programmable TTL signal. This signal is used to reset the cameras. The signal is branched off from the first board and used to control the laser. A sweep generator (Wavetek Model 184 5-MHz) is used to invert the TTL signal from the frame grabber boards to fire the laser.

An oscilloscope and photodiode are used to set-up the initial timing; and to check the reliability of this tracking technique. The photodiode is connected to the oscilloscope and placed in the laser beam. The timing is set by firing the laser in the double pulse mode, and measuring the time between pulses with the oscilloscope. System reliability was checked by measuring the camera reset and video signals with the oscilloscope; and checking them against the laser pulses. A pulse generator (Systron Donner Model 100C) is used to control the time between pulses. It receives its input signal from the laser and sends a signal to the second Marx Bank, which fires the second pulse.

The dimensions between the components in the experimental setup are given in Figure 8.

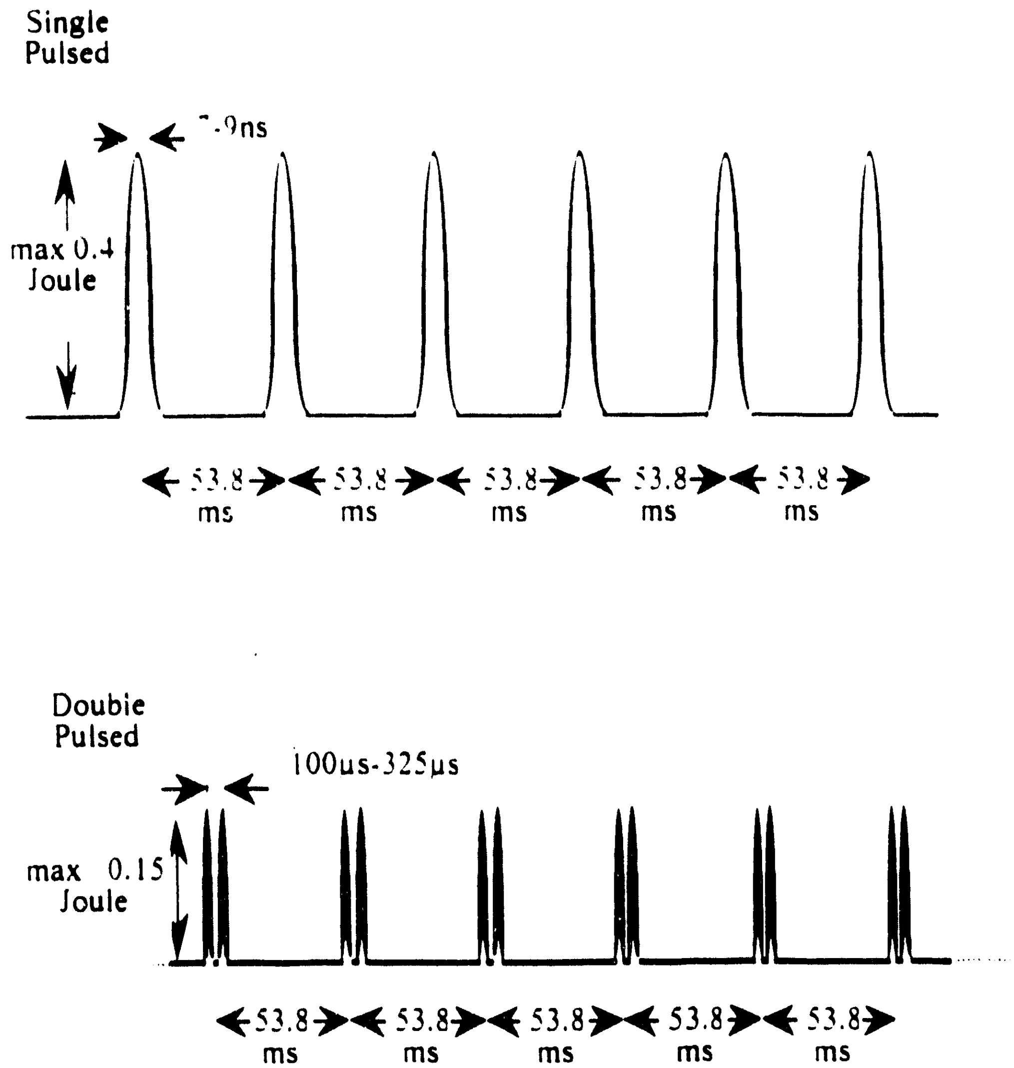

Figure 7. Single Pulse Mode and Double Pulse Mode

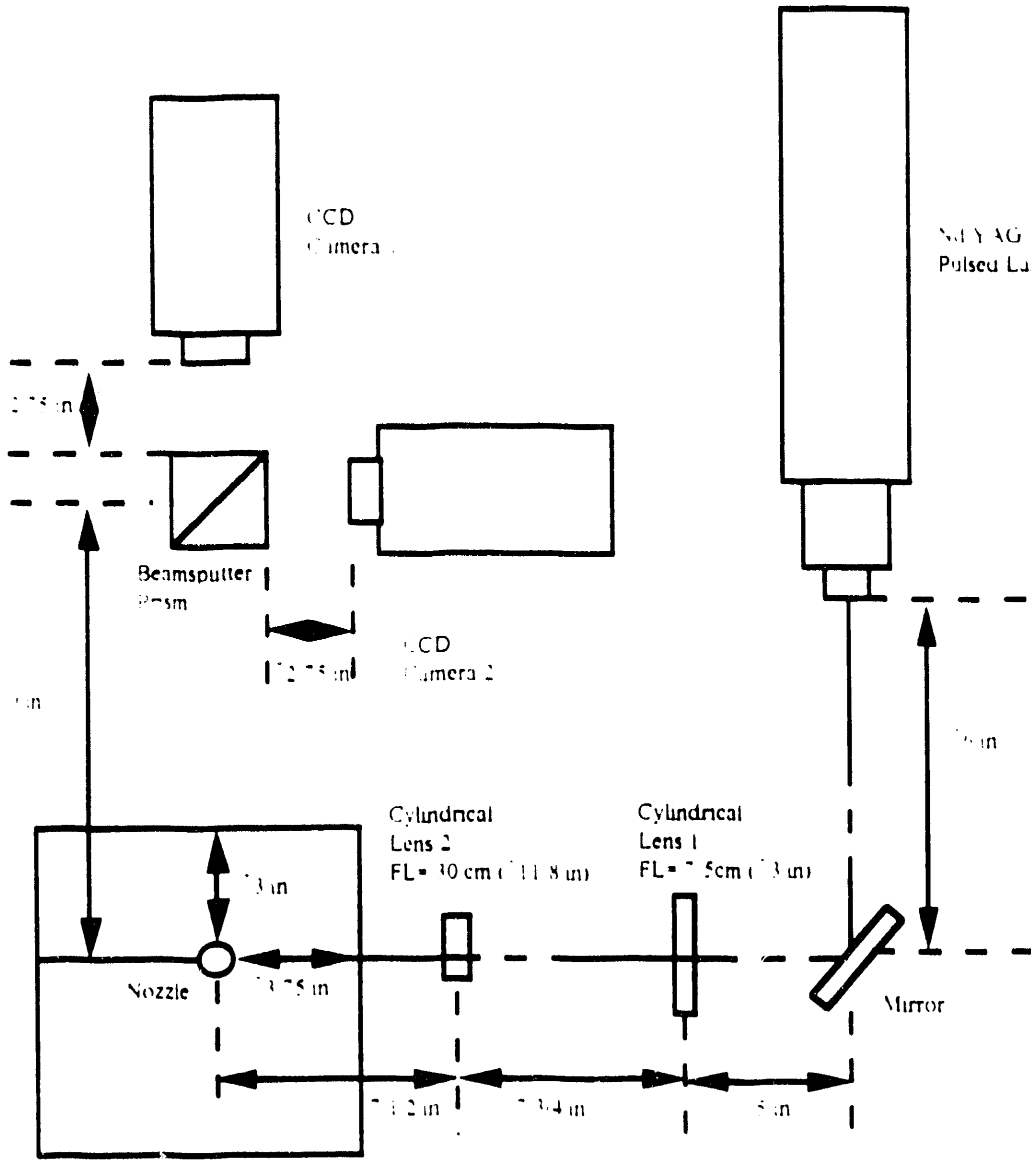

Figure 8. Dimensions for the Experimental Setup

CHAPTER IV

THE EXPERIMENTAL PROCEDURE

IV.1 Introduction

Once the high speed data acquisition system has been tested it can be used to investigate a relatively fast phenomena, like steam bubble collapse (approximately 1.8 m/s for the steam bubble edge and 0.02 m/s for the flow around the bubble). This section will discuss the experimental procedure after the data acquisition system has been setup. It will discuss the steps involved in acquiring the digital images and storing them for future analysis. It will also discuss some of the steps required for enhancing and processing the pictures. Finally, it will give recommendations for analyzing the data that has been acquired.

IV.2 Seed Selection

The first step in the experimental procedure is to chose an appropriate seed for the fluid that will be studied. Since this experiment involved studying the collapse of steam bubbles created by low flow steam injection into subcooled water, the velocity field for this fluid flow was determined by seeding the subcooled fluid with 6 micron diameter spherical seed which has a density of $1.02 gm/cm^3$ (approximately neutral density).

Since PIV "captures" particles in the flow field at one instant in time, one of the factors which affects the quality of the results obtained from an experiment is the seed choice. Several studies have been done on tracer seed suitability for PLV experiments and a variety of vendors produce different types of seeds. The main features which should be considered when selecting a seed are its density, size, capability to fluoresce, material make-up, and concentration in the fluid. These characteristics should be compared to the properties of the fluid medium that will be seeded.

The density and size will affect the seed's ability to follow the flow (the seed needs to have a neutral buoyancy in the fluid medium). The seed's ability to follow the flow is dependent upon its momentum. "Larger particles should be avoided, because small particles follow the flow better than large ones"(Vogel and Lauterborn, 1988). However, "scattering light from particles in liquids generally requires larger particles (than required in air) because water reduces the refractive-index ratio"(Adrian, 1984). The size of the seed should also be considered because very small seeds will scatter light according to Mie scattering theory, while larger seeds will follow Raleigh scattering (Adrian and Yao, 1985).

The color or fluorescence of the seeds may be useful for some experiments. "For example, fluorescent seeds can make discrimination (between seeds and bubbles) easy with the use of bandpass light filters"(Blanchat, 1991).

The composition of the seed is important because some materials scatter light better. For example, "Vestamid"particles "... have almost the same refractive index as latex spheres (n=1.53), but because of their polycrystalline structure, the scattering efficiency in the direction perpendicular to the light sheet is five times better"(Vogel and Lauterborn, 1988).

Concentration of seeds is important because it will determine what type of PLV experiment should be run and what type of data analysis performed. Higher concentrations of seeds should be studied with laser speckle velocimetry techniques (LSV) and lower concentrations with particle image velocimetry techniques (PIV) (However, the seed concentration should not be too low or there may not be enough data to obtain accurate full-field flow velocities).

The characteristics should be compared to the properties of the fluid medium because the seed's momentum or ability to follow the flow is also dependent upon fluid viscosity, as well its density and size.

The seeds which were used in this experiment had a specific gravity of 1.02 (close to water), and a 6 micron diameter. Fluorescent seeds were not required for this experiment. Latex spheres were used because the "Vestamid"seeds were not available at the time the experiment was performed.

IV.3 Experimental Apparatus

After the appropriate seeds have been chosen, the experimental apparatus should be prepared. For this experiment, a setup where low pressure saturated steam is injected into sub-cooled water was constructed. The system was constructed to allow full-field velocity measurements, with the high speed PIV technique, of the steam flowing into the tank. The main components required are the tank, laser, and cameras.

The steam bubble flow facility is illustrated in Figure 1. The enclosed, transparent, tank constructed with Plexiglas, is 16.5 cm x 16.5 cm x 27.5 cm. The tank was mounted on a jack which could be used to raise or lower it as required by the experiment.

A nozzle was needed to inject the steam into the tank. The top of a surgical needle was used. The needle was connected with a plastic insulated hose to a hole in a rubber stopper which was used to seal a Plexiglas flask. Deionized water was heated in the flask with a hot-plate to generate the saturated steam.

The deionized water in the aquarium was seeded with 6 μm diameter latex particle tracers (Expancel 551 DU, 1.02 specific gravity) prior to the experiment by pouring the seeds into the tank and mixing.

The circular light pulse from the Nd:YAG laser was shaped into an approximately 1 mm thick, 7 cm wide, sheet of light with a set of cylindrical lenses. The first lense was 2.5 in by 2 in with a 75 mm focal length. The second lense was 2 in x 2 in with a 300 mm focal length. Details on the operation of the laser can be found in Appendix A and details on the optical components can be found in Appendix B..

Two CCD digital cameras were used to record the images. The devices have a maximum frame acquisition speed, which determines the maximum pulse frequency (53.8 ms between sets of pulses).

IV.4 Experimental Setup

Once the equipment has been prepared the final preparations for the specific experiment should be made. The first step is to make sure the beam is thin (1 mm), perpendicular to the cameras, and covers the area of interest. The light beam was positioned using a mirror which reflected the beam 90 degrees. The beam could be

adjusted by moving the mirror slightly. After it was placed within the area of study, the cylindrical lenses were put into the path of the beam, to convert the circular beam into a planar sheet. The sheet is passed through one side of the Plexiglas tank (normal to its surface) into the fluid of interest coplanar to the two-dimensional flow pathlines above the tip of the nozzle at the camera's focal plane (This plane of light was set perpendicular, and just above, the tip of a nozzle).

The position of the sheet is fixed by first putting a plastic grid above the nozzle. The cameras are focused on this plane. Then the laser beam is positioned to hit the edge of the grid.

The production of a thin sheet of pulsed laser light is a key element in PLV research. The flash of light provides the ability to determine the instantaneous positions of the seeds in the flow. In a two dimensional study, the laser light should be shaped into a thin light sheet to minimize the effect of errors from out of plane motion.

The next step is to determine the camera view area. This is required to determine the scale of the data sets. This should be done by digitizing an image of the grid which was used to focus the cameras and position the sheet of laser light. The image should be stored on the hard drive (for possible future reference). The cameras were focused on the light sheet and the camera view plane size was calculated to be 1.89 x 1.65 cm).

IV.5 Taking data

After the high speed data system has been prepared, the double pulse timing is correct, the framing rate is correct, and the energy between the pulses is approximately

the same: data can be taken. The time between the single and double exposure was set to $254\mu s$. The time between each double pulse set was 53.8 ms.

Steam for the experiment was generated in a glass flask which was heated with a hot plate. The steam was run into the nozzle though an insulated plastic hose and the laser was fired in the double pulse mode.

The Epix frame grabbers were used to both trigger the laser and reset the cameras. The sequence of events consisted of :

1. The first Epix board sends a signal to the laser to fire it and a reset signal to the first camera (the "external out"signal is set low then high). The laser will take approximately 3 ms to actually fire after receiving this signal.

2. After a delay controlled by the computer (approximately 3 ms), the first board sends a second signal to the first camera and the laser (the "external out"signal is set low). This signal is ignored by the laser which has already received a signal to fire. However, the signal does reset the camera again.

3. The laser fires and the image is captured by the first camera.

4. The second board sends a signal to the second camera to reset it ("external out"signal is set low).

5. The Systron Donner pulse generator receives the sync input signal from the laser and after a set delay (controlled by the user) sends a signal which fires the second Marx bank of the laser.

6. The second camera captures the image. Because the photodiodes in the CCD camera cannot be "turned off"until the image has been transferred, the first camera also captures the image as a double exposure.

7. The data is transferred to the frame grabbers and stored in a buffer with the "display" command.

8. The "external out" signal is set high again (reset) for both boards.

9. Thirteen consecutive images were recorded at the 53.8 ms pulse interval.

10. Velocity calculations are then performed after determining particle positions, matching appropriate particles in the consecutive frames, and knowing the time increment between recordings.

IV.6 Flipping,Looking, and Appraising the Data

The EPIX boards have a feature which allows the data to be flipped (inverted similar to a mirror image) either horizontally, vertically or both. Since one of the cameras captured a mirror image, this feature was useful for flipping the data horizontally. By putting the command in the DRIVER program, the program can flip all 13 buffers automatically.

If a different format could be used for each camera (either by changing the format in the middle of the digitizing loop or using two different computers), one camera could automatically digitize its pictures flipped. This would not result in an error. The data would be stored on the frame grabber in reverse. However, it may increase the time between images.

It was also useful to put a routine in the DRIVER program which allowed the data to be examined within the program. This eliminated the need to exit to the menu driven software to examine the data before the next set of thirteen images was taken.

IV.7 Enhancing the Data

The EPIX software does have some routines which can be used to sharpen the images and threshold them. These may prove useful later. However, the Megavision software appears to offer more image processing features presently (Megavision is a 1024x1024 imaging or frame grabber system. It is different from the EPIX system).

The data can be sharpened with the Megavision software. Then the data can be brightened with a "Kmult" feature which multiplies every pixel by a constant up to 255 gray levels. Then the data can be thresholded with one of several options. "Median" presently appears the best. A "median" filter is used to reduce noise by replacing each gray-level with the median value of its neighbors (this does not affect pixels on the boundary) (Klaus, 1986). The Megavision "median" also converts the picture into a binary image.

Finally, the Megavision software has an object finding routine which can be used to identify spots or seeds. The software works on the binary image and an original image with gray levels. It uses the binary image and a "four-fold" or "eight-fold" (the number of adjacent pixels) connectivity routine to connect the black pixels into larger spots. It obtains gray level data from the original image.

IV.8 Data Analysis

The data can be analyzed with the imaging system hardware and a series of previously developed image processing and tracking analysis software developed for these types of flow experiments. The imaging system hardware available presently includes two systems. The data can be analyzed using either the EPIX menu driven software or the Megavision software. The Megavision software presently appears to be faster and have more features than the EPIX software.

After the imaging system has recorded the scattered light, it is necessary to find individual seed or spot data. Digital cameras record the scattered light in the form of gray levels. Spot data can be found through thresholding and edge detection techniques. The choice for the threshold setting can introduce a major source of error. There is a range of spot intensities because the laser produces a Gaussian beam (brighter in the center than on the edges), the seeds join together to form groups of different sizes (which scatter light differently), and the bubbles scatter light non-uniformly (which creates a large glare around the outside of the bubble). If the threshold value is too high, then many faint spots may not be identified, and the spots that are identified may have misplaced centroids. If the thresholding value is set too low, then background may be identified as being part of spots. This can lead to errors when using tracking algorithms, which depend on accurate pixel locations for determining spot correlation. The use of a single threshold value is incorrect for many images. Regional threshold values should be used if the laser sheet is not perfectly uniform, or when there is unequal scattering properties in the media (such as encountered with special two-phase flows like air bubbles or steam bubbles which create a bright corona around the outside of the bubble) (Canaan, 1990).

The following steps were used to analyze the data.

1 The "sharpen"command was used to enhance the contrast of the image. This command is a type of threshold which averages pixel values.

2 Then the "ksub" command was used to lower the gray level throughout the image linearly. This was done so the "kmult" command could be used to brighten the image without "washing" it out (making the image mostly white). A value of 20 was subtracted from each pixel's gray level value. Then each pixel's gray level was multiplied by a factor of 3.

3 Then the "not" command was used to create an inverse image, as required for the "median" command. Then the "median" threshold was used to create a binary image as previously discussed.

4 The "not" command was used again because a white spot on black background image is required for the "objects" routine. This routine connects and labels the spots in the image. The output from this routine is used for the tracking routine.

The local, flow velocity can be determined from the seed movement between two, sequential images. The flow velocity (assumed to be the seed velocity) is the distance the seed traveled between frames divided by the pulse time. Some tracking algorithms require several images taken in sequential time steps to determine velocity. Other algorithms require only two time steps. The algorithm which was used to analyze this data only required two time steps. Only two time steps are required because it tracks a pattern of seeds instead of an individual seed. It depends on the pattern remaining the same between the two frames. It was a PLV tracking algorithm, which was developed by previous researchers, which performs particle tracking on two, sequential, images.

The PLV algorithm which was used to track the seeds was tested with synthetic data to provide error estimates, and to demonstrate the method's reliability by prior researchers. It interpolates and removes erroneous vectors from the flow field, and extracts flow parameters such as streamline and vorticity.

Since the data from this experiment was very chaotic around the bubble, this section was removed from the data before it was analyzed between the long time frame (53.8 ms).

IV.9 Cross-correlation Tracking Algorithm

The PLV algorithm which was used to track the data is the Cross-correlation Tracking Algorithm. It is a dynamic, particle tracking method which can be quickly performed between two sequential, high resolution (640 x 480 x 8 bit) images, if the particle tracer information is first converted to binary data.

The data analysis steps include:

1 The 8-bit (0-255 gray level) particle tracer information is converted to 1-bit (value 0 or 1) information through the image processing techniques previously discussed (thresholding and connectivity algorithms on Megavision) and the tracers are labeled.

The following steps discuss how the correspondence between particles in the two sequential video frames is determined.

2 The centroid of a particle in frame 1 is selected.

3 A rectangular candidate region (the dimensions should be selected based on the maximum possible particle velocity expected and the values entered by the user) is centered on the centroid selected in step two in frame 2. All the particles in the candidate region are found.

4 The particles which are found in the candidate region in frame 2 are all candidates for the particle selected in step 2. To determine the best match a dynamic region is centered on each particle in frame 2. The dimensions of the region are expanded until at least 5 particles are in the region.

5 The dimensions for each dynamic region in frame 2 are used to create a dynamic region in frame 1 centered on the particle selected in step 2.

6 The two dynamic regions are compared and a cross correlation coefficient is calculated. The coefficient is calculated by finding the number of pixels which have a value of 1 in both images and dividing by the square root of the product of the total number of pixels which have a value of 1 in both images.

7 Then the matches are checked by finding the total distance that all the particles in the region moved.

8 Then a reliability check is made. This value is found by determining the number of particles which overlap (excluding the centroid particle from step 2 which will always overlap) and the number of pixels with a value of 1 which overlap. The index is the product of these two values.

9 The best match for the seed selected in step 2 is the pair which has the largest correlation coefficient, largest reliablility index, and smallest sum of distances between centroids.

10 Then steps 2 through 10 are repeated for each particle in frame 1. (Blanchat, 1991).

Factors which should be considered when using the algorithm are: the particle in the first image will always find a particle to correspond to in the second image and the algorithm depends on similar patterns between the two images. The first factor may be compensated for by the cleaning routine discussed later for removing incorrect vectors. The second factor does not have an effect providing there is little change in the local pattern of the distributed particles between the sequential video frames (the local pattern should be similar between the two frames if the frames are acquired with a very small time separation or the flow is slow). The second factor did not affect this experiment because the seeds close to the bubble were not tracked. However, if the time frame is not short enough (so the seeds do not move very much), it would have an adverse effect on the results in this region (if the seeds were tracked) because the flow has a very high speed and is turbulent. The flow farther away from the bubble could be tracked between the long time frame because it was slow.

IV.10 Interpolation and Cleaning of Sparse Vector Data

An automated method was used which eliminates tedious, undesirable, manual, operator assistance in removing erroneous vectors (Blanchat, 1991). The method required the operator to select a cross-correlation coefficient and reliability index value which left as many "good" vectors as possible. So the values were increased and vectors eliminated until only "good" vectors were left ("good" vectors are those which follow the general flow path that the majority of the vectors in that particular region follow).

Then an interpolation method was used on the remaining "good" vectors. The method used was developed based on the Hardy multiquadratic equations (Hardy,

1971) as discussed by (Narcowich and Ward, 1990). The method found coefficients based on the "good" vectors for the Hardy equations

The basic Hardy equations which were used are:

$$V_i = (u_i, v_i) \tag{1}$$

$$u_i(x_i, y_i) = \sum_{j=1}^{N} a_j \sqrt{1 - (x_i - x_j)^2 - (y_i - y_j)^2} \tag{2}$$

$$v_i(x_i, y_i) = \sum_{j=1}^{N} b_j \sqrt{1 - (x_i - x_j)^2 - (y_i - y_j)^2} \tag{3}$$

where V_i is the velocity vector at coordinates x_i, y_i; u_i is the x component of V_i, v_i is the y component of V_i, N is the number of vectors used in the interpolation (for example, 30–50 "good" vectors), V_j is the velocity vector at coordinates x_j, y_j of one of the "good" vectors; x_j is the x coordinate of V_j, y_j is the y coordinate of V_j, a_j is the x component constants, and b_j is the y component constants.

For each vector component (u_i and v_i), there are N (the number of "good" vectors) unknowns (the constant a_j for u_i and b_j for v_i). So there are N simultaneous equations to be solved. They can be solved by using one of a variety of matrix operation techniques. A Gaussian-elimination solver was used.

Once the values for a_j and b_j are found, the equations can be used with the associated x_j and y_j position coordinates (for a_j and b_j) to find the velocity at any given point in the field. The x and y coordinates for the point of interest are substituted for x_i and y_i. Vorticity and flow streamlines can then be derived using the full-field equation for the interpolated vector field

This method was an iterative process involving an interpolated field produced from the most reliable vectors, which allowed fast analysis and presentation of sets of PLV image data (Blanchat, 1991).

CHAPTER V

RESULTS

V.1 Introduction

Investigation of a fairly fast flow regime (approximately 1.8 m/s for the steam bubble edge and 0.02 m/s for the flow around the bubble) was performed to determine the effectiveness of the fast digital data acquisition system (approximately 254 μs between the single and double exposure and 53.8 ms between sets of pulses) which was developed for use with the PIV technique. The flow field around a collapsing steam bubble was captured using this system. The flow field was due to the relative motion between the fluid close to the tip of the nozzle (around the collapsing bubble) and the fluid farther away from the nozzle (being forced up by the jet of steam escaping from the nozzle). This flow field would be difficult to solve with analytical methods, but can be experimentally determined.

PIV "captures" particles in the flow at one instant in time. Multiple images of the flow field were acquired by pulsing the laser and storing the digitized images. Direct digitization of the fast flow regime was accomplished with an imaging system set to take medium resolution images (640 X 480 pixels X 8 bit CCD camera). Then the data was analyzed with imaging system hardware and a series of new image processing and tracking analysis software developed for these type of flow experiments by prior researchers. The tracking software was developed to match the particles from each of the consecutive image frames into tracks of particles through time.

The initial results obtained with the technique demonstrated that it has the potential for providing quantitative and qualitative data. However, the data which was obtained from this initial test is not fully reliable because insufficient vectors were obtained. This problem may have occurred because the seed concentration was too low.

V.2 Experimental Results

The digital data acquisition technique was tested on an experiment studying steam bubble collapse. The initial results obtained with this technique demonstrated that the technique has the potential for providing good quantitative and qualitative data, however, the data which was obtained from this initial test is not fully reliable because insufficient vectors were obtained. However, the results were run through the entire analysis process to evaluate the method's potential. The problem with these results may have occurred because of a low seed concentration. If the concentration was higher there would be more seeds available to generate vectors throughout the flow field.

The data was taken close to the tip of the nozzle, and a rough estimate of bubble collapse speed was found by estimating the change in the edge of the steam bubble, and dividing by the double pulse separation time (see Appendix J).

A velocity field plot directly above the nozzle within the path of the bubble could not be obtained with the long time frame tracking method because the flow field was very chaotic. The bubbles were collapsing every 10 ms (determined by using an oscilloscope, He-Ne laser, and photodiode) so the fragments of the collapsed bubbles in this area were changing more rapidly than the data could be acquired (every 53.8 ms). Therefore, results found using the cross-correlation algorithm between the long time frame in this area would not be accurate (the algorithm depends on the local pattern around a particle to only change slightly between sequential frames). However, the flow farther away from the nozzle was slower and could be tracked between the longer time frame. Figure 9 shows the set up which was used to find the interval between steam bubbles. The oscilloscope plot from this test of the bubble collapse speed can be found in Appendix G.

Changes to the flow directly around the bubble may be studied by tracking between the shorter time frame (100 to 320 μs). The results obtained did not appear to show much of a change in the position of the tracers between the single and double exposure. However, there was a considerable change in the bubble edge itself. Future studies should attempt to capture each pulse in a double pulse set separately (instead of one camera capturing a double exposure, each camera captures a single exposure).

The data was analyzed by tracking the seed centroid position with the cross-correlation tracking program between the long time frame. The tracking results give the sparse seed vectors in the water surrounding the steam bubbles along with the nozzle position.

The following results were obtained from the experiment. Figure 10 shows the water velocity vectors (obtained from two sequential images) surrounding the steam

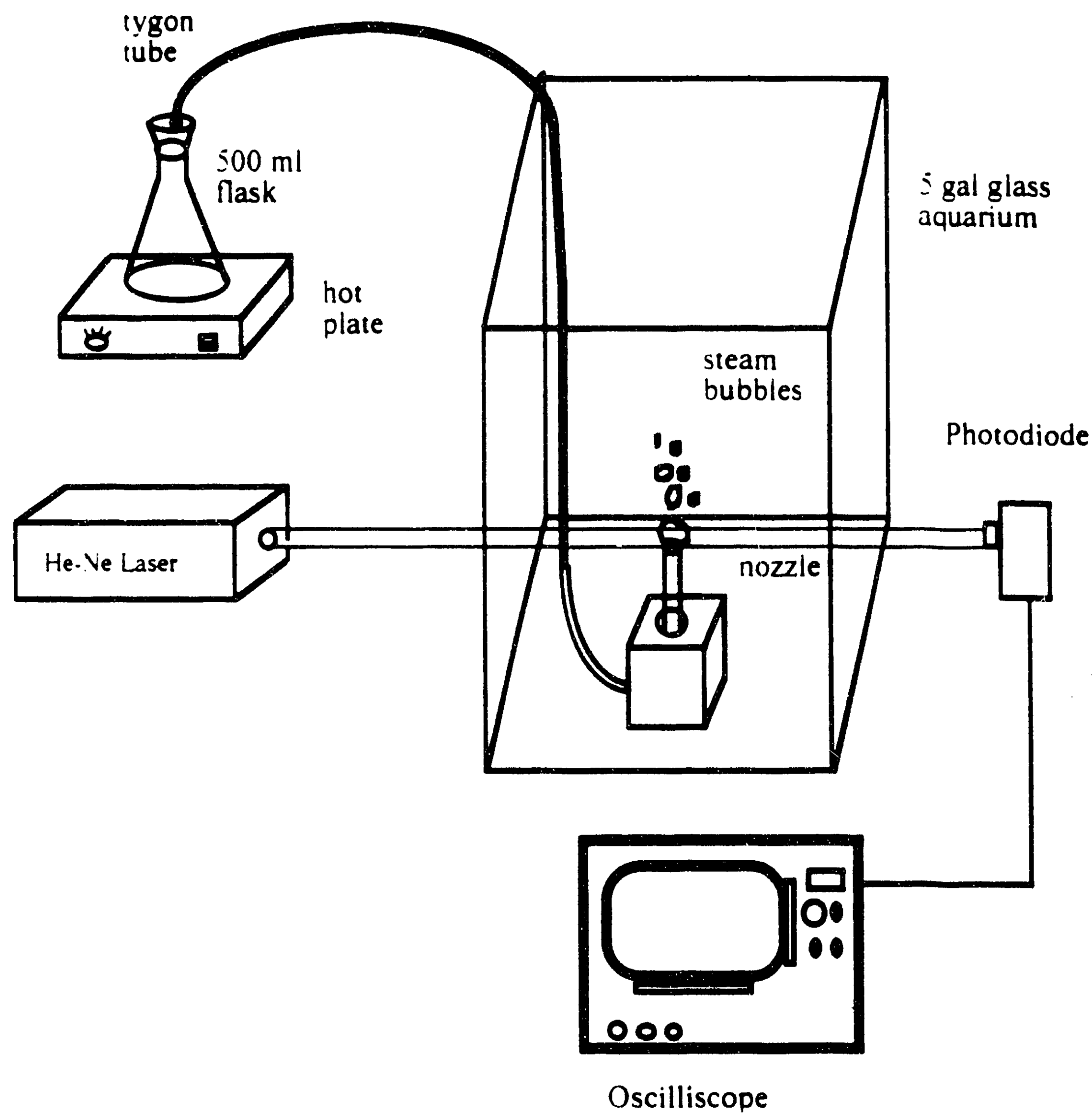

Figure 9. Arrangement to Find the Interval Between Steam Bubbles

bubble. This figure was processed separately from the rest of the set. The data for this figure was acquired with the 35 x 30 (35 x samples to 30 y samples) asynchronous imaging system. So the actual scale is 1.16 x 1 (the data is plotted on a square grid). The nozzle and a sample bubble have been drawn in to show scale. The rest of the figures from this data set are in Appendix E. All the figures were processed together using the same correlation coefficient.

The following figures show the results from the experiment between the single and double pulse. Figure 11 shows the edge collapse between the single and double pulse. Figure 12 shows an enhanced and enlarged image of the steam bubble from the camera which took the single pulse. Figure 13 shows an enhanced and enlarged image of the steam bubble from the camera which took the double pulse. Figure 14 shows an enhanced image of the steam bubble from the camera which took the single pulse. Figure 15 shows an enhanced image of the steam bubble from the camera which took the double pulse.

So a method has been presented which may eventually overcome the inherently slow frame acquisition rate of digital cameras, and allow the study of high speed phenomena (such as spray and steam bubble collapse) with Pulsed Laser Velocimetry flow visualization techniques. The method would be capable of measuring fast and slow fluid velocities simultaneously using successive digital images from two cameras. Standard PLV techniques can then be performed to quickly acquire flow information.

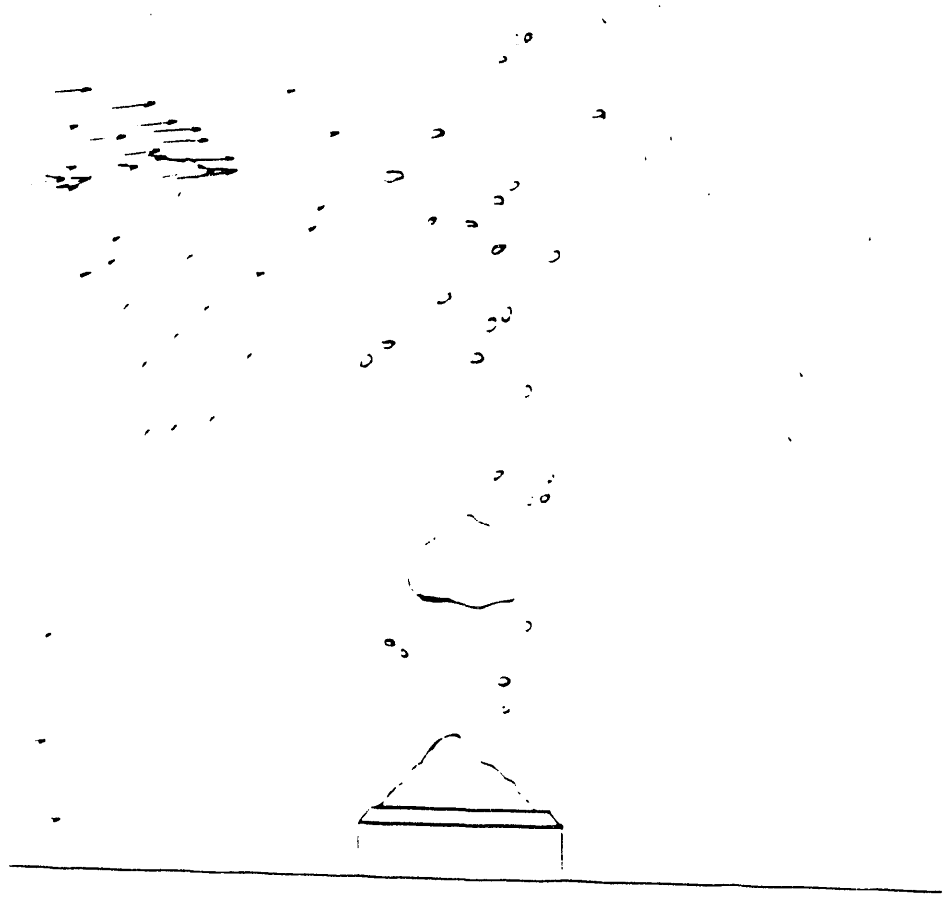

Figure 10. Water Velocity Vectors Surrounding a Steam Bubble

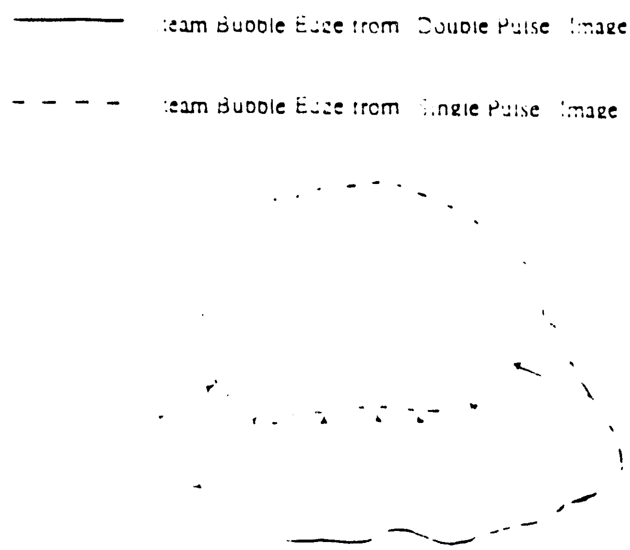

Figure 11. Steam Bubble Edge Collapse

Figure 12. Enhanced Steam Bubble Single Exposure Image (Enlarged by a Factor of 5)

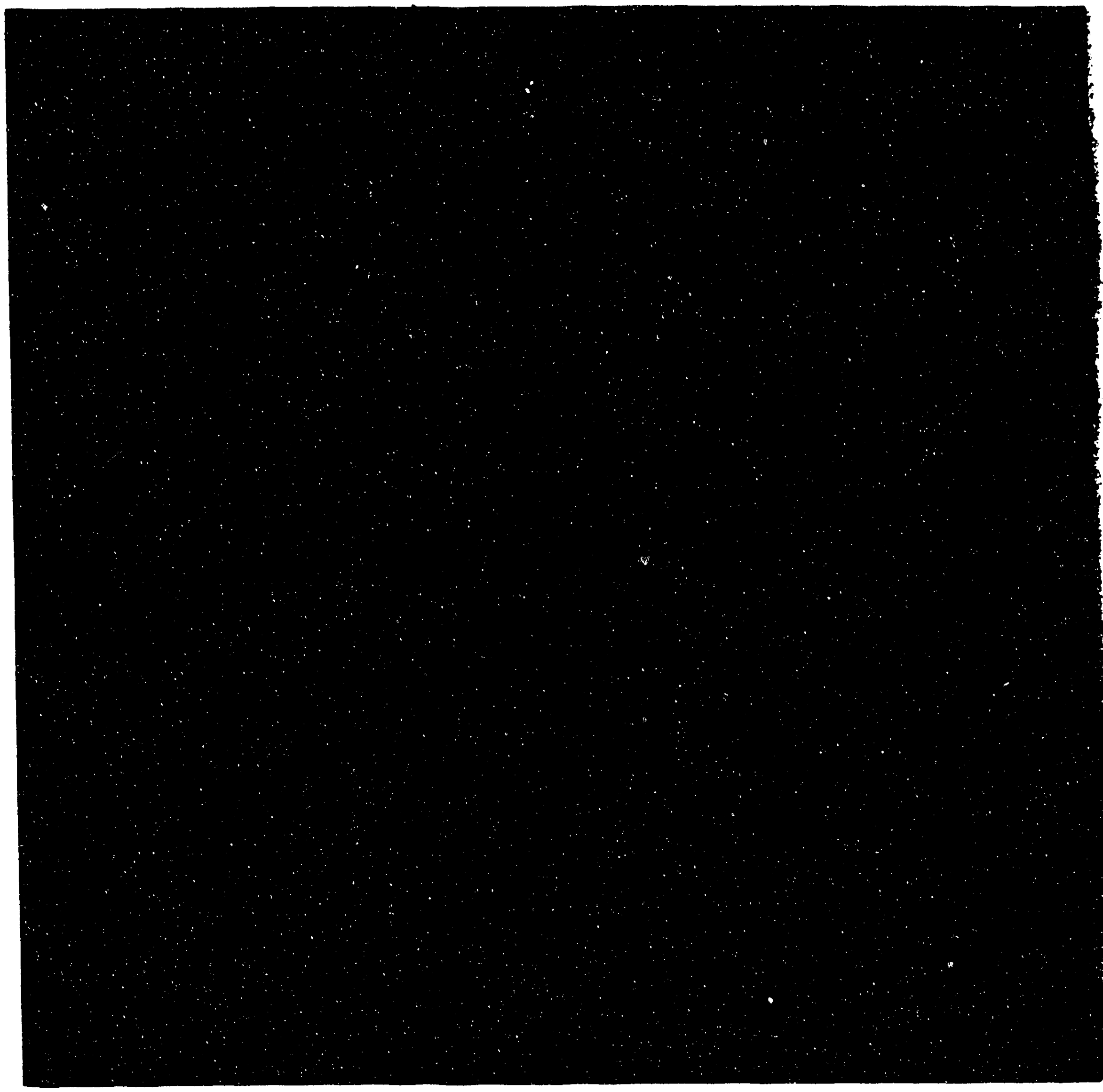

Figure 13. Enhanced Steam Bubble Double Exposure Image (Enlarged by a Factor of 5)

Figure 14. Single Exposure Image of a Steam Bubble

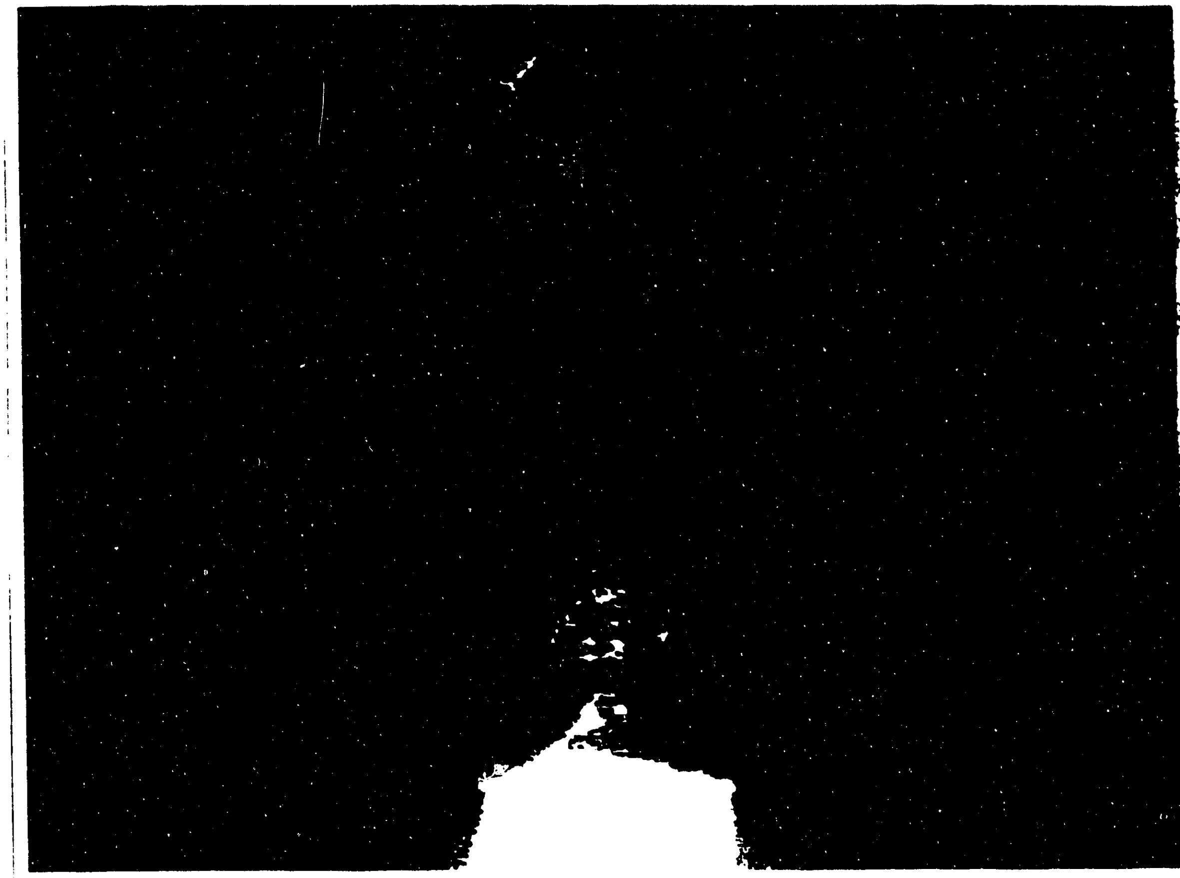

Figure 15. Double Exposure Image of a Steam Bubble

CHAPTER VI

CONCLUSIONS

A method has been developed which will track seed particles in a flow field, at two different framing rates, using digital cameras and the Particle Image Velocimetry (PIV) method, a type of Pulsed Laser Velocimetry (PLV) tracking technique. One part tracks particles through two or more frames at the relatively slow rate of 53.8 ms through a set of 13 frames. The other part tracks the particles at the relatively fast rate of 100 to 300 μs through only two frames.

An experimental setup consisting of a rectangular tank for holding the subcooled water, a heater for generating the steam, and a nozzle for injecting the saturated steam was used to conduct tests on a fairly fast flow, steam bubble collapse, to verify the technique. Flow visualization data was directly digitized, using two medium resolution cameras and PLV techniques, and analyzed with tracking software previously developed. Although the data from this initial test is unreliable because of the low number of vectors, future tests should yield more useful data.

The results from other researchers showed that the flow velocities around cavitation bubbles during their collapse near a solid boundary range from 2 m/s to 30 m/s. This study found a velocity of approximately 2 m/s.

VI.1 Recommendations for future work

Continue to develop techniques to analyze and present data quickly and accurately. One area where this improvement could be made is with thresholding. If an automated method could be developed, the time required for analysis would be greatly reduced.

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