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DEVELOPMENT OF ELECTRO-OPTICAL INSTRUMENTATION FOR REACTOR SAFETY STUDIES

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DEVELOPMENT OF ELECTRO-OPTICAL INSTRUMENTATION FOR REACTOR SAFETY STUDIES

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Abstract

The development of new electro-optical instrumentation for reactor safety studies is described. The system measures the thickness of the water film and droplet size and velocity distributions which would be encountered in the annular two-phase flow in a reactor cooling system. The water film thickness is measured by a specially designed capacitance system with a short time constant. Water droplet size and velocity are measured by a subsystem consisting of a continuously pulsed laser light source, a vidicon camera, a video recorder, and an automatic image analyzer. An endoscope system attached to the video camera is used to image the droplets. Each frame is strobed with two accurately spaced UV light pulses, from two sequentially fired nitrogen lasers. The images are stored in the video disk recorder. The modified automatic image analyzer is programmed to digitize the droplet size and velocity distributions. Many special optical, mechanical and electronic system components were designed and fabricated. They are described in detail, together with calibration charts and experimental results.

Introduction

The assessment of the safety of nuclear reactors is partially based on the application of complex computer thermal-hydraulic codes describing cooling behavior and heat transfer under various operating conditions. A quantitative knowledge of transient two-phase flow is important for the development of analytical predictive techniques for this safety assessment. In such flow, theoretical prediction of the flow parameters is not generally possible because the interaction between the phases is too complex. Consequently, it is particularly important to be able to perform realistic laboratory experiments which give accurate measurements of the flow parameters.

Annular two-phase flow is predicted to occur often in event of a light water reactor accident and in the shell of most pressurized water reactor steam generators during normal operation. The computer codes relating to the operation of these reactor facilities must make use of accurate experimental data to ensure adequate modeling. To obtain the required experimental data for reactor safety, it was necessary to develop an instrumentation system for observing and characterizing internal steam and liquid flow conditions. The system permits the observation of the configuration of the two-phase flow, the measurement of the size, velocity and distribution of water droplets, the thickness of the liquid film and entrainment thresholds. Also, to provide the adequate evaluation and calibration of this measuring system, it has been necessary to develop a new test apparatus which will permit the generation of either a co-current or counter-current annular water film flow with a flowing gas phase. Therefore, the objective of this program has been to develop an electro-optical instrumentation system suitable for the characterization of such a multiphase flow in an annular flow regime. The development of

necessary additional test apparatus will be the object of future efforts.

Some measurements of the two-phase flow parameters at various pressures and temperatures have been reported in the literature (1-7), but the described measuring systems generally have very limited value for generating the type of experimental data needed for the safety assessments mentioned above. A detailed critical review and evaluation of the applicability of the various measurement techniques are given in Ref. 8. As outlined in this reference, the state-of-the-art two-phase instrumentation does not have the capability of providing the detail and accuracy needed for nuclear safety assessment. The improvement of existing measuring systems and the development of new ones are therefore highly necessary if present and planned flow test programs are to yield results which will make possible analytical predictive techniques.

Over the past several years, attempts have been made to use light fluorescence (9) and scattering methods (10), laser Doppler anemometry (11-12), laser Raman scattering (13) and axial view photographic techniques (14) for two-phase flow analysis. Comprehensive reviews of these methods are to be found in Refs. 15-17. Most of the scattering and Doppler based methods run into difficulty when applied to contained two-phase flow systems because of the flow complexity. The main difficulty with high-speed film camera systems is long turn-around time between the actual experiment and the availability of the processed photographic record. As a consequence, real time or close to real time observations are not possible. Moreover, until the photographic record is seen, one cannot evaluate the adequacy of its quality. To our best knowledge, no electro-optical measuring system has been described with capabilities of measuring flow parameters over a wide dynamic range in real time or close to real time. Therefore, it has been necessary to develop a fast measuring technique appropriate for the typical operating conditions of a reactor safety research facility and to design a suitable fast measuring system.

Specifically, for measurement of the thickness of liquid film in a two-phase annular flow a fast measuring system using especially designed nonintrusive sensor electrodes and a capacitance meter was developed. The measuring system has a fast response time (cutoff frequency = 600 Hz) and it is sensitive enough to detect a capacitance change of 0.01 pF in 2 ms which represents a change of thickness of 3.4 μm . With this system it is possible to detect the fluctuations and fast wave motions of the water film passing over the sensor electrodes. The system is described in detail in Ref. 18. Further improvements of the system are described later in this report.

Based on previous work (19-26) a new technique for flow observation and measurement was developed using a pulsed laser subsystem and an automatic image analyzer (28,29). This technique makes use of our previous explorations (27) and experimental results. The laser-based system, using a continuously pulsed light source synchronized with a video recorder, is

capable of recording droplet and bubble flow in real time.

Short-duration flashes from a laser subsystem are used to illuminate the moving water droplets. Images are formed on the target of a vidicon camera. They are displayed in real time on a video monitor and simultaneously stored in a video recorder for instant replay in either a slow motion or stop action mode, frame by frame. The optical system is designed to have shallow field depth to limit the number of droplets in focus per frame. The stored image can be analyzed with an image analyzer. All droplets that are out of focus (indicated by different levels of grayness) are rejected by the logic circuitry in this automatic image analyzer. At 10 frames per second, the in-focus particle count rate is high enough to permit making a size distribution plot. The particle size can be determined visually using a reticule on the face of the monitor. Alternatively, the size distribution can be computed automatically, close to real time, by the image analyzer. At low counting rates this is accomplished by storing the images in the video recorder where they can be scanned by the automatic image analyzer with the accumulated counts subsequently being registered in the accumulator display. Velocity measurements are performed by double pulsing the laser subsystem. The double image displays the displacement of a droplet in known intervals of time. Light pulse separation can be easily varied over a range of a few microseconds to several milliseconds and, hence, velocities can be measured over a wide range, from very slow to several hundred meters per second. A description of the laser-based two-phase flow observation and characterization system is given in this paper.

Two-Phase Flow System Description

Flow Test System Description

The two-phase flow test apparatus is shown schematically in Fig. 1 and in the photograph, Fig. 2. A downwards flow mode was selected because it permitted the use of a comparatively short tube length and a small source of compressed air. An acrylic tube having an inner diameter of 1.25" is used. It is divided into five sections which are attached to each other by flanges and sealed with "O" rings. Since all the sections were originally cut from a single tube and were remounted in the same position, an unperturbed flow of the liquid phase along the tube wall is preserved.

The top section is 10" long with a coaxially mounted 25" long tube of small diameter passing through it. The water supply is attached to the top end of the small tube and an interchangeable spray nozzle (SN) is connected at the other. The next section consists of a 6.5" long porous jacket (PJ) which is also attached to the water supply. A steady diffusion of water through the porous wall of the jacket ensures a uniform downward film flow along the test tube wall. The water layer thickness is regulated by the valves V4 and V5.

The last section of the test tube (23" long) ensures a smooth flow of both phases into the waste-collecting vessel (WV). Purified water is used to minimize the chances of damaging some of the system components. Also, the electrical conductivity of the water must be controlled in order to ensure proper functioning of the capacitance meters.

In operation, the water first passes through water filters F1 and F2. The water flow rate is then measured accurately by two flow gauges; one, FG1, for low rates and the other, FG2, for higher rates. Combined, they cover a range of water flow rates from 0.1 to 25 GPM. Water can be supplied from either the nozzle or the porous jacket through the valves V1 to V5 in any desired combination.

As the water flows through each turbine gauge a periodic signal is produced proportional to the flow rate of the water. This signal is amplified and shaped in the flowmeter amplifiers (FA1 and FA2). Since the frequency is an inconvenient measure of the flow rate, two frequency-to-amplitude converters were built (FC1 and FC2) which convert the frequency of the signal into a proportional D.C. voltage level suitable for driving the data logger, (DL).

The container (WV) at the bottom of the flow tube collects the waste water. The level gauge (LG) controls a motor which drives the centrifugal water pump (PM and WP). The pump is turned on when the upper water level is reached. The tube end and the upper water level clearance are left large enough so the exit will not be blocked, since blockage would result in air pressure oscillations within the tube. The pump returns the waste to the water supply system. The check valve (V7) prevents flooding by inhibiting the return of the water from the external storage tank when the pump is not operating.

Gravity and the water pressure in the spray nozzle are usually sufficient to generate a composite downward two-phase flow. Additional velocity components can be added to the flow by introducing air from the air blower (AB) into the top section of the tube.

Most of the system components used for the control, monitoring and data logging are housed in a 6' rack. A standard CAMAC Minicrate (CM) provides housing and power for all the special electronics circuitry that was developed to provide proper interface between the various sections of the two-phase flow system. Moreover, the unused space in the crate allows for future system expansion. The CAMAC System can provide a convenient interface with an external computer, should the need for such interface arise later.

Film Thickness Measurement

The 8" section of the tube next to the porous jacket allows an equilibrium flow to be established prior to entering the next 4" long test section of the tube. This test section of the flow tube has a pair of electrodes, C1 and C2, at each end and two pairs of "point" electrodes, C01 and C02, placed diametrically opposite to one another midway down the section. The electrodes are made of conductive epoxy which fills grooves cut into the inside wall of the tube. The smooth face of each electrode is flush with the tube surface, thus offering no disturbance to the liquid phase flow along the wall. The electrodes serve as capacitive transducers for the thickness measurement of the liquid phase. The change of the capacitance measured between each set of electrodes is a function of the thickness of the water layer (29). Two identical capacitance meters (CM1 and CM2) are capable of measuring rapidly and very accurately small changes in capacitance.

The capacitance meters update their digital readout every second. Also, a fast analog signal proportional to the capacitance change is supplied by the meters which makes it possible to monitor rapid

changes in the liquid film thickness. The data from the two capacitance meters are recorded on paper tape by a Datel Systems Inc. Data Logger (DL). A Tektronix Model 5113 Dual Beam Storage Oscilloscope (SO) is used for visual monitoring and/or for photographic recording of the changes in the flow thickness.

Image Recording

Two holes in the test section (at the level of the point capacity electrodes, but 90° away from them) are provided to permit visual access to the central portion of the flow tube. The tip of a specially designed endoscope lens (EL), which is attached to the video camera (VS), can be introduced through a 0.125" diameter hole which permits observation of the water droplet flow generated by the spray nozzle. A quartz window (QW) is inserted into a 0.2" diameter hole in the flow tube opposite the endoscope. The window is movable and its position is adjusted to penetrate the water film. Ultraviolet light pulses from two Molelectron Model UV12 nitrogen lasers (NL1 and NL2) illuminate the interior of the tube through this port without suffering great attenuation.

The light pulses generated by the lasers are directed through the quartz window (QW) in the flow tube by four mirrors (M1 to M4), so adjusted to converge the beams onto a ground glass plate (GP) placed in front of the quartz window. By diffusing the light entering the flow tube, images free from diffraction bands are obtained. The background of each recorded frame is, consequently, more uniform.

In normal operation each laser is fired by trigger pulses which are generated by a specially designed control unit (CU). The trigger pulses are synchronized with either a Bausch & Lomb, Inc. Video Scanner (VS) or with an Arvin/Echo Science Co. Video Discassette Recorder (VR) for the storage and instant replay of images. The trigger pulse for the first laser is timed to occur at the beginning of the blank space between two selected video frames and fires a 10 ns wide, 337.1 nm light pulse (after a system time-delay of approximately 1 μ s). A second trigger pulse is then generated to fire the second laser after a very accurate time-delay which is digitally presettable in 4 decades of 0.1 μ s steps. The accuracy of the delay is controlled by a built-in 20 Mhz crystal. An accurate voltage, proportional to the preset digital time delay, is also generated in the control unit and assigned to one analog input channel of the data logger. The accurate time-delay between the two laser pulses is an important parameter for the calculation of the actual droplet velocities.

In operation, each laser requires a Busch Inc. R-5 Series Single Stage Vacuum Pump (VP1 and VP2) and a nitrogen source (NB). To prevent pump oil deposits on the optical surfaces of the laser and the endoscope lens the vacuum pump exhaust tube should terminate at a point external to the operating room. To ensure the most economical nitrogen flow at the given laser firing rate, the nitrogen bottle is equipped with a shut-off valve (V6), a pressure reductor (PR) with two gauges (G1 and G2) and a flowmeter (FM1).

Pressure Measurement

The pressure differential along the flow tube is measured by inserting a pressure sensor into the flow tube through any one of a row of holes along the tube length. The sensor is connected with hoses to the pressure gauge. The flowmeter supplies just enough air to keep the hollow tip of the pressure sensor clear of water. The pressure gauge generates a voltage

proportional to the pressure difference between the test point inside the tube and the return. The voltage is amplified by the pressure amplifier to a level suitable for driving the data logger.

Endoscope Lens and Video Scanner

Droplet diameters vary from 2 mm to 50 microns. The special endoscope lens built to permit the viewing inside the test tube has a circular field approximately 3 mm wide at any point between the wall and the center of the tube. The lens is attached to the video scanner by interchangeable cylinders which determine the image magnification. Droplet sizes less than 10 microns can be easily resolved. Beyond the tip of the lens a thin stainless steel tube protrudes. The 0.125" diameter of this tube is small enough not to introduce excessive disturbance to the droplet velocity distribution. A continuous, adjustable flow of air enters the lens head from the flowmeter (FM2) in order to keep the endoscope tube free of water and to prevent the lens from fogging. The endoscope single plano-convex lens is made of fused silica and produces minimal distortion and attenuation along the image-forming optical path.

A special, high-contrast video scanner with state-of-the-art resolution and linearity is used for imaging. The scanner is mounted on a precision X-Y slide. The radial position of the scanner in the test tube is monitored by a helipot attached to the slide gauge. A voltage proportional to the slide displacement is generated in the control unit and is supplied to the data logger.

Video Recorder

The scanner operates continuously at the standard rate of 30 frames/second (60 fields/second). Connected to the scanner is an Arvin/Echo Corp. video discassette recorder. A maximum of 200 images can be stored on each side of a disk. The maximum recording rate is 15 frames/second. Slower rates of 6, 3, and 1 frames/second, respectively, as well as manual (single-shot) operation can be selected. The recorder automatically locks in on the signal from the video scanner and generates appropriate synchro pulses for the control unit, which pulses in turn provide accurately timed trigger pulses for the two lasers.

Image Analyzer

The droplet size and velocity distributions are measured with a Bausch & Lomb optical image analyzer, (30-32). In the image analyzer, the video signal of the frame selected on the disk recorder is first electronically shaped to correct for background illumination level variations. The signal then passes through an adjustable level discriminator which converts the image intensity variations into a binary representation in which regions containing a feature are assigned a value of 1 and the surrounding regions are given a value of 0. This binary representation is then digitized for analysis by the computer.

A Nova 3/12 computer with dual floppy disks and a hard copy terminal is programmed, using software written in Fortran and assembly language, to analyze the digitized image. The first step in the analysis is to convert the digitized image into a series of line segments which represent features as seen on the television scan lines. The picture coordinates, which correspond to the beginning and end of each line segment, are then analyzed to compute the characteristics of every feature on the screen. The characteristics analyzed include the area (as determined by the total length of line segments enclosed by the feature)

and the horizontal and vertical diameters (as defined by the horizontal and vertical tangents at extreme points). In addition, the x and y coordinates of the center of each feature are computed.

The next step in the analysis is to determine if the measured features actually correspond to acceptable droplet formations. The criteria by which measured features are determined to correspond to acceptable droplet formations are the following: Minimum Area - any feature whose area is less than this value is rejected. Maximum Area - any feature whose area is greater than this value is rejected by the software. Aspect Ratio - any feature whose ratio of XSIZE to YSIZE is outside a specified range about unity is excluded. Circularity - features are excluded whose areas do not correspond to the formula for the area of a circle. The ratio evaluated is:

$$R = 4(\text{AREA})/\pi(\text{XSIZE})(\text{YSIZE}) \quad (1)$$

If R differs from unity by more than a specified amount, the feature is excluded. All areas and lengths measured by the program are in picture element units, or "pixels". Physical dimensions in real space are a function of the imaging optics. Calibration factors can be easily obtained, however, by recording and analyzing a calibration pattern of known dimensions. The above-mentioned feature selection criteria are controlled by the experimenter at the time of analysis by entering appropriate values on the computer keyboard.

After all the acceptable droplet formation features have been measured, they are divided into pairs in order to determine velocity. After a "pair" is identified as resulting from the double exposure of a single droplet, the degree of separation between the two pair members is calculated. The velocity can be determined from the known time between the laser firings.

The pair selection process can be divided into two parts. In the first part, pair candidates are excluded from consideration if the following cut-off criteria are exceeded: Pair Area Ratio - if the ratio of the areas of the two candidate members differs from unity by more than a certain amount, the pair is excluded. Pair Size Ratio - if the ratios of XSIZE or YSIZE for the candidate differs from unity by more than a certain amount, the pair is excluded. DX/DY Ratio Cut-off - any pair candidate is eliminated for which the displacement in the X dimension divided by the displacement in the Y dimension exceeds a given value. This ratio is the tangent of the angle of the droplets' trajectory with respect to the vertical. A small value would assume that most of the droplets were moving in a vertical direction. Finally, droplets whose Y separation exceeds half of the screen height are excluded.

Once obvious non-candidates are eliminated from consideration by the above-mentioned criteria selected by the operator, the remaining pair candidates are assigned probabilities based on their dimensional similarity. The probability function chosen is the reciprocal of the sum of the AREA, the XSIZE and YSIZE ratios. The computer then pairs up the features in a manner which maximizes this probability.

After selection of the features and pairs for a given image, the computer organizes them into a list which is stored on a floppy disk file named DATAFIL.TX by the program. The list's format is:

AREA1 X1 Y1 XSIZE1 YSIZE1

AREA2 X2 Y2 XSIZE2 YSIZE2 TRACK

The first 5 elements of the list represent the area, center and diameters of the first member of the pair, while the next 5 elements represent the same information for the second member of the pair. The last element indicates the track number of the recorded image. After analysis completion of an image the computer advances the video recorder to the next frame, and the analysis process is repeated.

When a sufficient number of frames has been analyzed and added to the data file, a separate program called FHIST is used to produce statistical summaries. According to the operator's input, statistical distributions can be obtained for the Y separation of the pairs (velocity distribution), for diameter distribution or for the area distribution.

Data file management is provided by a program called DLOG. Each time the main feature analysis program OVBRK is operated, the results are logged in the DATAFIL.TX file, thereby destroying the previous contents of that file. DLOG enables the data file to be preserved by renaming or appending it to another file.

DROPLET SIZE AND VELOCITY DISTRIBUTION ANALYSIS

Resolution of the Lens System

The accuracy and resolution of the droplet image analysis depend greatly on the quality of the lens system. An approximate expression for the angular radius θ of a blurred spot for the given endoscope lens is (33,34)

$$\theta = K(n)D^3f^{-3/2} + 1.22 \lambda/D \quad (2)$$

The size of the spot is the product of the image distance and $\tan \theta$. D is the inner diameter of the endoscope tube (2.4 mm) and $f = 15$ mm is the focal length of the lens; $\lambda = 337.1$ nm is the laser wavelength; $K(n)$ is a function of the refractive index n and the lens shape. For the plano-convex lens used, $n = 1.478$ at 337.1 nm and

$$K(n) = (n^2 - 2n + 2/n)/32(n - 1)^2 \quad (3)$$

From (1), where the first term defines the blur due to the lens aberration and the second one that is due to diffraction, an optimum f/D ratio can be derived for maximum resolution

$$(f/D)_{\text{opt}} = [3fK(n)/2.44\lambda]^{1/4} \quad (4)$$

By using (1) and (2), the calculated blur due to aberration is $2.44 \mu\text{m}$ and $2.57 \mu\text{m}$ due to diffraction. Experimental results confirm that the endoscope can resolve droplets smaller than $10 \mu\text{m}$.

Vidicon Image Formation Under Pulsed Light Conditions

An image projected onto a vidicon results in the electric charge being altered over the surface of the photoconductive target. The charge is restored by an electron beam that scans the target, line by line, 60 times per second. Each full scan is called a field. Due to the interlacing technique, two complete scans are required to read-out the entire target area. Thus, two fields (called the even and the odd fields) are

required to convert a single image, i.e. a frame, into a video signal.

If a still picture is projected continuously onto the target, the charge at any given spot will reach an equilibrium value determined by the combined effects of illumination and read-out and will produce a constant video signal. If, on the other hand, the image is produced by a single, short-light pulse, the illumination process will occur only once, but the read-out process will continue. The result will be a series of video fields of decreasing amplitude as the read-out scans restore the charge removed by the illumination flash (Fig. 3).

Were the source of light continuous the signal would be identical for both fields. The Bausch & Lomb Co. Image Analyzer utilizes both fields in normal image processing. It had to be modified to use only one field in the present, pulsed-light application. This, of course, results in a reduction by one half in the vertical resolution of the image analysis.

Several readout frames are required before the video signal is reduced to the level of the "dark current", i.e. to the signal generated without any external light entering the vidicon. The dark current can be compensated for by appropriate use of the "shading corrector" provided in the Bausch & Lomb Co. Image Analyzer.

Image Contrast Considerations

In order that the image analyzer produce accurate results, it is essential that optical images of good contrast be obtained between the dark circular outline of the water droplets and the white background surrounding them. The two major factors affecting this contrast are the uniformity of image field illumination and the photoelectric characteristics of the camera tube.

Typically, signal output characteristics for most types of camera tubes as a function of light intensity are quite non-linear. At low illumination levels the transfer curve is terminated by the camera "noise" which defines the minimum detectable light intensity. At high light levels the camera output saturates defining an upper limit for the range of detectable illumination. Thus, it is between these two levels of light intensity that the features must be detected.

In obtaining the picture of water droplets moving down the test tube shown in Fig. 5, the laser light pulses were diffused by a ground glass screen in order to secure uniform illumination. The droplets scatter the light so that their image appears black. A droplet in focus has a bright spot in its center owing to the direct passage of light through its center (Fig. 4). The out-of-focus droplets in the background attenuate the light so that each frame has a different (and non-uniform) "white" level. The non-uniformity of this background illumination is a major contributor to the reduction of image contrast.

In order to measure the velocity distribution of the water droplets, each frame is twice illuminated by firing two laser pulses accurately separated in time. The light pulse width is only 10 ns, which results in virtually "frozen" double images of the droplets at each shot (Fig. 5). Idealized conditions are illustrated in Fig. 8. A droplet's image is imagined to travel along a single scan line x-x' over the target face. Because the two images are separated, the composite illumination results in reduced contrast. The first droplet image is bleached by the second light pulse

and the second image is formed on an already illuminated area of the camera target by the first light pulse. If the intensity of the two pulses is equal and a linear illumination-to-signal transfer curve is assumed, only a 50% contrast can be achieved even under ideal circumstances. A non-linear transfer curve (dotted line in Fig. 8) is clearly undesirable and would lead to additional image contrast reduction. Finally, non-uniform background illumination would further reduce the margin of acceptable contrast.

Image Analyzer Calibration and Linearity Test

The complexity of the two-phase flow system requires an accurate testing and calibration method. For water droplet velocity measurements, it is especially important to know the system calibration factor, k, since

$$v_y = k_y \Delta y / \Delta T \quad \text{and} \quad v_x = k_x \Delta x / \Delta T \quad (5)$$

where v_y and v_x are axial and radial droplet velocity and ΔT is the time delay between the firing of the lasers. If the system is linear, the calibration factors k_y and k_x become equal. In order to test the linearity, a number of identical doughnut-shaped objects were arranged in a precisely defined pattern and photographically reduced 50 times. A slide of this photographic reduction was placed in front of the endoscope lens and the image was recorded in the video recorder by firing the laser. Fig. 9 shows the image as it appeared on the video monitor of the image analyzer. The joystick control on the image analyzer console was adjusted to frame the features to be analyzed.

Of the 16 recognized features, 12 were selected into 6 pairs by the computer program (Fig. 10). Had these features represented moving droplets, the pair separations would have been proportional to their velocity. The overall magnification of the image analysis system was adjusted to match the scale of Fig. 9 so that 1 mm equals 100 units of x_m and y_m in the computer print-out. The results show a remarkably small conversion error. A plot of differences $\Delta x_m = x_m - x_{om}$ and $\Delta y_m = y_m - y_{om}$ is shown in Fig. 11.

The slope of the Δx curve indicates that the x-axis calibration was off by about 0.6%. The integral conversion linearity is about $\pm 0.25\%$. The y-axis data show larger conversion non-linearities, as was expected, since only one video field of 256 lines is used in the analysis. The calibration is nearly correct; however, more data would be needed for more accurate statistics.

Droplet Velocity Measurement

The standard procedure for droplet image analysis is, first, to store a sufficient number of individual frames on disks in the video recorder and, then, to instruct the computer to begin the analysis. Any number of frames can be processed by typing in the initial and final number of the frames to be recalled one by one from the video disk by the software, whereupon the analysis proceeds automatically. Data is either stored on a floppy disk in the processor or typed out after the analysis of a frame is completed. The latter case illustrates how the analysis of a frame is accomplished. Fig. 5 is a photograph of a random frame taken from the video monitor. Four droplet pairs can be clearly seen on the picture. The frame was obtained by firing the two lasers at $\Delta T = 20.0 \mu s$ apart. The background shadows are the blurred images

of the out-of-focus droplets.

After proper adjustment of the discrimination threshold control on the image analyzer, the images to be analyzed are shown on the video monitor as "fill-in" areas (Fig. 6). The contrast of the first pair on the left was insufficient and caused the disappearance of some upper features. The print-out of the analysis (Fig. 7) shows that 8 features, F_1 to F_8 , met the size and circularity criteria.

The analyzer correctly selected 3 droplet pairs out of 8 available features. Fig. 7 shows the vertical separation between the centers ($\Delta y_m = y_m - y_n$) and the y-axis droplet velocities calculated from $v_y = k\Delta y_m/\Delta t$. The calibration factor, k , was found to be 2.634. For the time-delay of $\Delta t = 20 \mu s$, the velocities of the three droplets were calculated to be 45.5, 47.4 and 33.7 m/s.

Droplet Size and Velocity Distribution Measurement

Both sides of a video disk were filled with double-exposed frames similar to the one shown in Fig. 5. The image analyzer was operated in a semi-automatic mode, thus giving the experimenter an opportunity to inspect each frame before the analysis and so enabling better interpretation of the results. From the data print-out the two histograms shown in Fig. 12 giving the droplet size and velocity distribution were compiled.

LIQUID PHASE THICKNESS MEASUREMENT

Capacitance Gauge

The technique of water film thickness measurement by the capacitance method was described previously (18). A new capacitance gauge was developed, thereby proving the feasibility of dynamic measurements of the film thickness. Two types of electrodes are described: "point" electrodes, which measure the changes in the film thickness over a small area inside the test tube, and "ring" electrodes, which measure the average thickness of the water passing the test area.

Practical considerations require that there be unobstructed access to the two-phase flow test tube. The electrodes should be compact and suitable for use together with the video camera. Moreover, precise alignment of the electrode faces with the test tube surface is required to permit an unperturbed flow over the test area.

A new capacitance gauge was designed to include these features (Fig. 13). The electrodes are made of conductive epoxy resin injected into two pairs of grooves cut on the tube's inner wall. Each electrode has a terminal embedded in it for the purpose of connection to a capacitance meter.

In addition, two identical pairs of small rectangular "point" electrodes were constructed using the same technique. These pairs are located at the mid point of the test tube, in mutual opposition, and at 90° to the axis of the pair of windows for the endoscope and laser illuminator. Their small dimensions reflect local changes in film thickness. The separation of the point electrodes of 1 mm is intended for the measurement of film thickness to 1.5 mm. The four pairs of non-intrusive electrodes give the experimenter the possibility of studying the film flow both above and below the endoscope point as well as at the same level at which the droplets are observed. Access to the test tube is unimpeded since

relatively long cables can be used between the electrodes and the capacitance meters.

Calibration of the Capacitance Gauge

Electrodes permanently embedded in the circular test tube section can be directly calibrated with the help of a specially-made teflon plug. The plug can be moved like a piston along the inside of the tube. A 0.5" length of the piston fits snugly into the wall and leaves no gap when aligned against the electrode pair to be calibrated. The plug is tapered in a lathe to provide 25 discrete steps of 0.25" length each. In the first 10 steps the gap between the plug and tube wall is successively increased by 0.1 mm. In the next 5 steps, the gap is increased by 0.2 mm each and in the last 10 steps by 0.4 mm.

As the plug, step by step, is withdrawn, it leaves a precisely circular gap of known thickness. The capacitance between the electrodes is measured at each step, with the gaps filled first by air, and then with water. Low-conductivity water was used in this measurement. The thickness of the water layer over each set of electrodes as a function of measured capacitance is shown in Fig. 14.

Two Model 72BD Boonton Electronics capacitance meters were used. 1 MHz signals generated by these instruments are supplied to the capacitance under test and measured by a phase-locked current detector. The meter generates a signal proportional to the measured capacitance for oscilloscope monitoring and remote data logging. A digital display on the meter provides a visual read-out two times per second. The film thickness fluctuation can thus be directly observed on a oscilloscope.

Although the meters are accurate even for quite lossy capacitors, the high conductivity of the water, especially above room temperature, must be taken into account. This problem is alleviated by adding a fixed, good quality capacitor, C_p , in parallel with the measured one. The "loss angle" of the composite capacitor thus becomes smaller:

$$\tan \delta = 1/\omega(C + C_s + C_p)R \quad (6)$$

where $\omega = 2\pi f$ ($f = 1 \text{ MHz}$), C is the measured capacitance and C_s the stray capacitance of the connecting cables. C_s and C_p are constant through the measurement and are subtracted as the measurement proceeds step by step.

The change of capacitance as a function of flow rate was measured. One capacitance meter was connected to a pair of ring electrodes, and the other capacitance meter to a pair of point electrodes so that the data could be simultaneously taken. In addition, the curve $r(d)$ was plotted by using the capacitance gauge calibration curves C_1 and C_0 shown in Fig. 5-7. The relation of the falling water film thickness to the water flow rate was thus determined.

CONCLUSIONS

A new electro-optical instrumentation system was developed to observe and characterize two-phase flow parameters in model systems appropriate to reactor safety studies. The parameters measured included particle size, velocities of the moving droplet phase and liquid film thickness.

In this effort our goal was to utilize commercially designed components and subsystems wherever

feasible, modifying them as necessary for this application. Additional electronic and optical components were constructed to provide interface and control capabilities. A description of each component, together with operating instructions and calibration procedures, has been given, thereby enabling the reader to use or to reproduce this instrumentation.

A Bausch & Lomb Image Analyzer was used to digitize water droplet sizes from the images recorded on a video disk. A special software package to provide velocity measurement capabilities was developed by the manufacturer and modified by the authors.

In particular, the spatial linearity and accuracy of the droplet images analysis was found to be remarkably good. As shown in Fig. 11, the scatter in measurement points (for a precisely generated test pattern) indicates a linear precision of a fraction of a percent (of full scale) in the horizontal direction, with a somewhat larger uncertainty in the vertical. This difference in measurement accuracy is due to the requirement (resulting from the use of flash illumination) that only one field of the TV scan format could be used in analysis. Because the droplet motion in these experiments is predominantly vertical, it would be advantageous to rotate the camera 90°, thereby placing it on its side, in order to exploit the increased resolution available.

The processing speed of the image analyzer is somewhat slower than anticipated, especially for a large number of features per frame. With the present software, processing and storage of analysis results from a typical video frame requires approximately 10 seconds. Streamlining and other improvements in the software, it is believed, would substantially reduce image processing time.

Images with good contrast are essential for analysis, especially in the fully automatic mode of operation. The key factors are the video camera characteristics, image field illumination and video signal processing. It was shown that non-linear illumination vs. signal response of the vidicon camera tube furnished with the image analyzer results in signal contrast compression. An optional camera tube called a Chalnicon, however, has a close-to-linear response. A camera incorporating this tube was used briefly in the system and yielded a far superior signal contrast.

A large number of random frames must be processed in order to obtain good statistics. Since each side of the video disk has storage capacity for a maximum of 200 frames, and since many randomly shot frames do not contain features worth analyzing, some kind of "preview" in the recording procedure seems desirable and should lead to a considerable saving of analysis time. The simplest method is to edit manually each recorded frame. A frame is simply re-recorded when a satisfactory image is seen on the instant playback video monitor. A provision was made so that the lasers do not fire when the even-odd parity of the two fields in the frame is not correct. This correct parity must be preserved if the automatic mode of image analysis is selected.

In the future, a video tape recorder can be used for the storage of a large number of frames. Group by group of 200 frames can be transferred from the tape and stored in the video disk recorder. The re-recording "on the fly" would eliminate image distortions which are typical for image tape recorders operating in the single frame mode.

An improved capacitance gauge for water film thickness measurement was described and the results presented. The improved gauge does not disturb the water flow at all and thereby offers superior performance and accuracy, especially for very thin films approaching the dry-up point. The small size of the electrodes and easy connection to the capacitance meter enables such probes to be placed very close to the point in the test tube where the droplet images are taken.

A single teflon calibration rod was constructed for accurate in situ calibration of the capacitance gauges. Although the data logger and oscilloscope provide adequate means for the recording of the average thickness, for the observation of transients and waves in the film flow, a more elaborate recording system is recommended. Moreover, a faster analog-to-digital converter can be used to strobe and digitize the changes in the film thickness at higher rates than is now possible. Synchronous strobing of two identical "ring" gauges, separated by a few inches, can give information on the nature and magnitude of water film waves travelling along the tube.

Although we have been unable, to date, to perform extensive testing of the experimental equipment, the results obtained thus far have been very gratifying. Measurements of water film thickness, both instantaneous and averaged, have met the resolution requirements and the "double image" droplet velocity measuring system has performed well. When further development will have been implemented, the electro-optical system will be a very effective tool for reactor safety research.

ACKNOWLEDGEMENTS

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NBL 8010-12529

Fig. 1 General block diagram of the laser-based two-phase flow measuring system.

XBB 805-5501A

Fig. 2 View of the two-phase flow measuring system.

XBB 8010-11672

Fig. 3 Vidicon camera output for featureless images at 7.5 frames/sec. laser firing rates (scale: 20 ms/div.)

XBB 8010-11505

Fig. 4 A scan line passing across center of the circular image in Fig. 5 (scale: 10 μ s/div.)

XBB 8010-11808

Fig. 5 Typical video monitor display of a recorded frame obtained by firing two lasers 20 μ s apart.

XBB 8010-11809

Fig. 6 In "fill-in" mode only features selected for analysis by setting level control are shown.

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OVRBK
0 FOR DISK 1 FOR TTY ?1
0 FOR EVEN 1 FOR ODD ?0
PAIR AREA RATIO=1.5
PAIR X SIZE RATIO=1.3
PAIR DY/DX CUT=.5
MIN AREA =200
MAX AREA =10000
ASPECT RATIO=.4
CIRCULARITY=.4
START TRACK=10
STOP TRACK=10
2310 676 288 58 61 10 F1
1001 446 388 36 52 10 F2
6496 815 376 85 100 10 F3
3012 288 405 62 65 10 F4
3006 671 468 64 61 10 F5
1443 444 516 43 45 10 F6
7078 811 549 89 100 10 F7
1235 1125 707 58 42 10 F8
6496 815 376 85 100 7078 811 549 89 100 10 F1; F7 4 173 45.5
2310 676 288 58 51 3006 671 468 64 61 10 F1; F6 5 180 47.4
1001 446 388 36 52 1443 444 516 43 45 10 F2; F6 2 128 33.7
0 MORE TRACKS, 1 NEW PARAMS, ELSE QUIT?
Am xm ym dxm dym An xn yn dxn dyn Feature x0 y0 vy
XBL 805-9599A

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Fig. 7 Analysis results of Fig. 4. Out of 8 features found within the parameter range, 3 pairs of droplets were correctly selected.

Fig. 8 Illustration of vidicon image formation by double-pulsed illumination and expected signal contrast as a function of linearity of vidicon transfer characteristics.

Fig. 9 Video monitor displaying a record of the test pattern reticule as "seen" by the video camera.

```

1
0 FOR EVEN 1 FOR ODD ?0
PAIR AREA RATIO=1.3
PAIR X SIZE RATIO=1.3PAIR DY/DX CUT=.25
MIN AREA =1000
MAX AREA =5000
ASPECT RATIO=.4
CIRCULARITY=.4
START TRACK=1
STOP TRACK=1
0 MORE TRACKS, 1 NEW PARAMS, ELSE QUIT?0
START TRACK=1
STOP TRACK=1
2720 357 180 59 68 1 F1 360 180
2492 509 186 56 71 1 F2 510 180
2323 810 237 54 71 1 F3 810 230
2661 1113 235 58 68 1 F4 1110 230
2509 407 281 57 68 1 F5 410 280
2161 711 286 52 68 1 F6 710 280
2509 1012 267 57 68 1 F7 1010 280
2343 911 338 55 68 1 F8 910 330
2616 1062 388 58 68 1 F9 1060 380
2564 358 435 58 68 1 F10 360 430
2317 560 435 55 68 1 F11 560 430
2297 760 487 54 68 1 F12 760 480
2447 460 533 56 68 1 F13 460 530
2333 662 536 54 68 1 F14 660 530
2538 962 541 55 71 1 F15 960 530
2720 357 180 59 68 2564 358 435 58 68 1 F1; F11
2492 509 186 56 71 2317 560 435 55 68 1 F2; F10
2323 810 237 54 71 2297 760 487 54 68 1 F3; F12
2509 407 281 57 68 2447 460 533 56 68 1 F5; F14
2161 711 286 52 68 2333 662 536 54 68 1 F6; F13
2509 1012 267 57 68 2538 962 541 55 71 1 F7; F15
0 MORE TRACKS, 1 NEW PARAMS, ELSE QUIT?
Am xm ym dxm dym An xn yn dxn dyn Feature x0 y0
XBL 805-9597A

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Fig. 10 Image analysis print-out of Fig. 9 test pattern. Actual coordinates x₀ and y₀ (as measured by a microscope) are added for comparison.

Fig. 11 X and Y linearity of image analysis calculated from test pattern data in Fig. 10.

Fig. 13 Test section of two-phase flow tube with two pairs each of ring and point electrodes.

Fig. 12. Droplet velocity and diameter distribution compiled from analysis print-out of 200 images (such as those in Fig. 5) stored on video disk.

Fig. 14 Calibration curves of capacitance gauges in Fig. 13. Curve $r(d)$ shows falling film thickness as function of water rate.