Holographic and Photographic Studies of High-Quality Steam-Water Critical Flow

High-quality (95%) steam-water critical flow through a straight pipe was studied using high-speed photographic and holographic techniques. The results indicate that most of the water exists as a discontinuous or continuous thin film which flows along the wall with a speed much slower than that of the steam. This results in slip ratios higher than those reported before. Although a separated flow model would seem to describe the actual flow situation more closely than other models, the assumption of thermal equilibrium between phases and the fact that the flow is not separated except close to the exit plane are probably explanations for differences in slip ratios obtained in this study from those predicted.

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SCOPE

Interest in vapor-liquid critical flow phenomena has increased enormously in recent decades. The use of water as a coolant in nuclear reactor power plants has stimulated much research effort aimed at understanding hypothetical pipe breaks in coolant loops of nuclear reactors which will experience critical flow of steam-water mixtures. Accurate prediction of critical flow phenomena is important to the safe design of nuclear reactors. It is a well-known fact that critical flow rates predicted by homogeneous models are much smaller than those measured. The existence of metastability and slip between phases are believed to be the two main reasons for this departure from the theoretical predictions.

Several models have been developed by various investigators (Fauske, 1962; Cruver, 1963; Moody, 1963; Levy, 1965) which predict critical flow rates more accurately than the homogeneous model. Because of complexities of the phenomena and the lack of accurate experimental data, however, those models have assumed that the deviation from ideality is caused either by slip or metastability alone. Critical flow rates can be predicted with a fair degree of accuracy in certain ranges of quality with most of these models. Until a generalized system of equations describing two-phase flow is developed, however, it appears that the flow process must be subclassified according to flow patterns. Each flow pattern would be expected to exhibit different transfer mechanisms and would require a different system of equations to characterize the flow analytically. A recent example of such an approach is the work of Chang (1973). Therefore, it is believed that the acquisition of information on phase distribution and slip between phases will be very helpful for the development of new models that can provide better descriptions of critical flow.

Many investigators have attempted with limited success to determine the size and velocity distribution of particles being transported by a gas stream in various kinds of geometry. Sampling and probing techniques have the disadvantage of locally disturbing the flow field. Photographic techniques have been successfully applied for determing both size and velocity of drops without disturbing the flow fluid, but the high magnification required results in small areas of observation and a narrow depth of field. Parrent et al. (1963) first successfully obtained size distribution by using holograms. The velocity of particles can be measured by the use of double-exposure holograms.

In this study, techniques involving the use of a pulsed laser were applied for holographic and photographic studies of moving droplets in a high quality steam-water critical flow jet. The goal was to obtain information on phase distribution and slip between phases for high quality steam-water critical flow.

CONCLUSIONS AND SIGNIFICANCE

In-line holographic techniques were successfully applied to the study of droplet distribution and vapor-liquid slip ratio in high-quality (95%) steam-water critical flow through 0.63-cm lines ranging in length from 12.7 to 48.3 cm. For the longest test section the vapor-liquid flow at the exit appeared to be completely separated. For the shorter test sections, the results showed a few droplets in the central region of the jet plume, but separated flow predominated. Widely used separate flow models do not give the correct values of slip ratio at this quality because of changes in the flow pattern from homogeneous to separated flow. No single pattern would be sufficient to truly represent the flow distribution.

Results of the study indicate the possibility of using the same techniques for studying low-quality steam-water critical flow. As far as the optics are concerned, there is no difference in principle between the detection of water droplets in steam (high quality) and steam bubbles in water (low quality).

PREVIOUS WORK

Two reasons are most commonly cited to explain the discrepancies between critical flow rates predicted from the homogeneous model and those measured experimentally. First, the departure from thermodynamic equilibrium, called metastability. Due to the fast flashing process, steam-water mixtures will not have enough time to reach an equilibrium state and will become superheated or subcooled depending on their initial quality. The net effect of this metastability is to reduce the effective compressibility of the mixture and hence to increase the critical flow rate. Secondly,

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the slip between phases. Since the vapor has a much lower density than the liquid, vapor will be accelerated at a much higher rate and will have a higher velocity than the liquid. The net effect of the slip phenomenon is to reduce the total kinetic energy for a fixed driving force. In other words, the existence of slip provides more available space for the flow, hence a higher flow rate.

Attempts to determine the magnitude of metastability have not been successful (Cruver, 1963; Klingebiel, 1965; Rosenfeld, 1969). Various factors are responsible for difficulties in experimentally measuring this phenomena. For example, local static pressure might be in error due to the tap geometry or the local evaporation of droplets; the measured temperature might be in error due to aerodynamic heating, droplet evaporation, and well conduction. These effects make the available information on metastability difficult to evaluate. The combination of slip and metastability make the situation formidable. If one can accurately measure slip and evaluate its effect, then the effect of metastability can be estimated from that information together with flow data.

Measurement of the size and the velocity of particles in two-phase flow is important in explaining heat, mass and momentum transfer during the flow process. Experimental data on slip ratios are scarce, especially for local slip ratios. Vance (1962) studied the slip ratio of steam-water subcritical flows by use of a momentum cage. He could not obtain a slip ratio at choking conditions because he was unable to determine the exit pressure. Klingebiel (1965) measured slip ratios by using an impulse plate similar to that used by Vance. Sampling and probing techniques have been tried, but they have the undesirable effect of locally disturbing the flow field. Most investigators have concluded that distribution of particle size and velocity for high velocity flow can probably be best obtained by photographic and holographic techniques.

Nguyen and Segel (1977a and 1977b) developed a theory for two-phase, gas-liquid flow. This theoretical treatment was successfully applied to experimental data for air-water mixtures. The flow field was divided into three regions, two of these were single phase regions and the third was a mixture of two phases.

Wallis and Richter (1978) presented a new model for flashing two-phase vapor-liquid flow. This is based on an idealized situation with no irreversible processes. Lynch and Segal (1977) have made direct measurements of void fractions by nuclear magnetic resonance techniques. They have explored the complete range of void fractions (0 to 1.0) and found this method to be highly satisfactory.

Matkin (1968) used holographic techniques to study fast moving drops in steam-water critical flow without much success due to condensation nuclei. Later, Lee (1973) found that Matkin's failure might come from the small aperture size he used which caused poor resolution. A description of the in-line holographic technique with a large aperture was given by Lee (1973). This paper presents the study of phase distribution and the velocity of the liquid phase for high quality steam-water critical flows by using high speed photographic and holographic techniques.

EXPERIMENTAL EQUIPMENT AND METHODS

Critical Flow Equipment

The experimental apparatus for generating and making measurements of critical flow is shown schematically in Figure 1. It was designed to provide high-quality, steam-water mixtures undergoing critical discharge through a test section and air gap to an atmospheric pressure collector. Upstream pressure as measured at the pressure regulator of Figure 1 could be varied up to a maximum of 827 kPa, the steam supply pressure. Three test sections were used; all had a common diameter but were of different length. The apparatus included steam and water supply lines with instrumentation for measuring flow rate, temperature and pressure; a mixing section; the test section; and the atmospheric collector. A 5.08 cm open space between the test section exit plane and the collector inlet was the location at which holographic and photographic measurements of the critical steam-water jet were made.

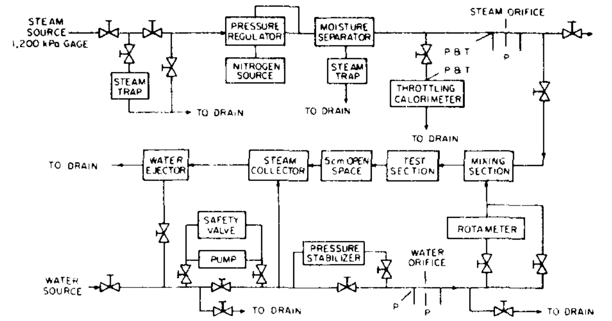


Figure 1. Schematic diagram of critical flow equipment.

The mixing section was used to supply a high quality, homogeneous mixture of steam and water for discharge through the test section. A BETE fog nozzle (Model PT-5) was used to generate a fine mist of small water droplets with a low water flow rate of approximately 0.5 g/s. This nozzle produces the finest fog of any direct pressure type nozzle, actual drop size measurements showing a larger fraction of drops with diameters less than 50 and a lower average drop size than any other type of nozzle known.

The test sections were fabricated from type 304 stainless steel. The outside diameter was nominally 9.52 mm and the i.d. was 6.35 $\pm$ 0.05 mm. Variation in inside diameter over the entire length was less than 0.05 mm with a finish of $\pm$101.6 μm RMS. Holes were drilled for pressure taps in the test section and copper tubes were silver soldered in place. Most of the experiments were conducted with a test section 48.3 cm long, but experiments were also conducted with 25.4 and 12.7 cm long test sections to examine the influence of test section length on water droplet distribution at the downstream gap.

The steam-water collector consisted of a receiver with a built-in water nozzle which sprayed water evenly throughout the receiver and condensed the steam (up to 20 g/s) so effectively that no pressure buildup in the receiver was observed and hence no backflow occurred.

Additional details concerning the design and specifications of the apparatus may be found elsewhere (Lee, 1973).

Holographic and Photographic Methods Used

In photography the intensity of light reflected or transmitted by an object to the film is recorded. In holography the interference pattern of coherent laser light caused by the object is recorded and a three-dimensional hologram of the object may be reconstructed. Holographic principles and techniques for recording and reconstructing holograms may be found elsewhere (Matkin, 1968).

The main objective of these experiments was to measure the spatial and axial velocity distribution of water droplets moving at high speeds in a two-phase flow field. Extremely short duration light pulses were necessary therefore to meet the criterion that the observed particle not move more than one-tenth its diameter during the recording (Dotson, 1941). The light source used in these studies was a Q-switched, pulsed ruby laser which had a duration of approximately 50 ns, which allowed a 40 μ particle to move with a maximum speed of 80 m/s. The laser could be used either in a single pulse mode for examining drop size and distribution, or in a double pulse mode with a separation of 5 μs between pulses for obtaining velocity distribution.

Figure 2 shows schematically the arrangement use for recording holograms. The distance between the central object plane and the film was 5.08 cm, which according to Lee (1973) provided optimal resolution. Figure 3 is a schematic diagram showing the arrangement used for reconstructing holograms. A He-Ne Spectra-Physics Model 120 laser was used as a reconstruction light source and had a maximum power output of 5 mW. A concave lens or pinhole was used as a generating source of spherical wavefronts and the holograms were held by a Uni-slide to provide two dimensional

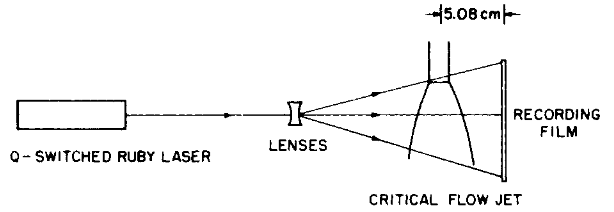


Figure 2. Arrangement for the recording of holograms.

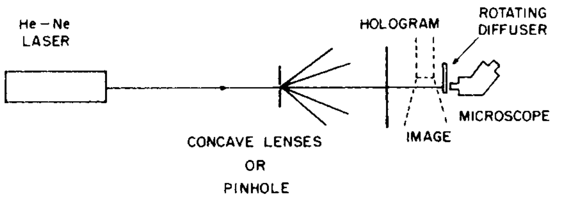


Figure 3. Arrangement for reconstructing hologram.

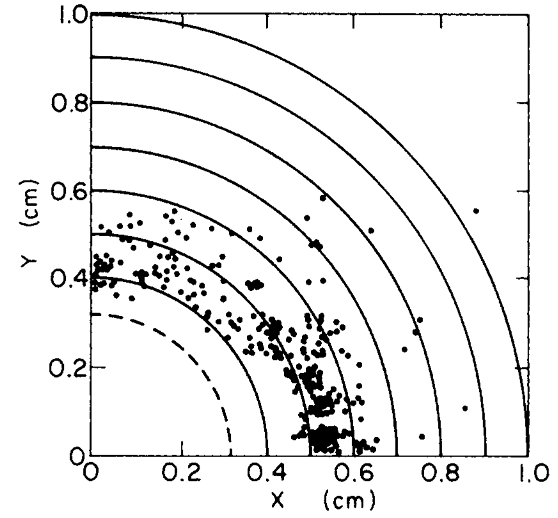


Figure 4. Droplet distribution in ¼ of observation plane distance from exit of test section 0.37 cm.

movement of the reconstructed images. The third spatial dimension could be obtained by traversing with the microscope. Reconstructed real images were formed on the rotating diffuser and viewed through the disc with a Bausch & Lomb Dynazoom Microscope (Model PB 425) whose magnification could be varied from 30× to 800×. The rotating diffuser consisted of a carefully ground (#305 emery) glass disc spinning at a speed of approximately 20 rpm. The diffuser served to limit the depth of field and to eliminate the speckle pattern resulting from coherence patterns of background light.

A calibrated micrometer disc scale was inserted into an eyepiece of the microscope for use in measuring the droplet size in the reconstructed image, while a dial indicator was attached to the microscope to indicate the transverse movement of the microscope perpendicular to the plane of the image. Images were recorded using a Polaroid camera attached to the microscope.

In some experiments where only spatial distribution was sought the pulsed laser, operated in the single pulse mode, was used simply as a short, intense light source and the image was photographed through the microscope. Photographic images obtained in this fashion were not useful for determining precise droplet size, but the existence of water droplets could be determined because of their unique interference pattern. This method was used in all experiments with the 25.4 and 12.7 cm test sections. It should be used cautiously because damage to the optics of the microscope may result.

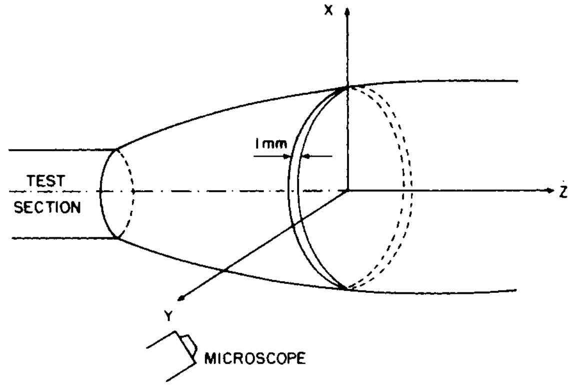


Figure 5. Typical volume of reconstruction image studied.

EXPERIMENTAL RESULTS

Droplet Space Distribution

Using the 48.3 cm test section, single pulse holograms were recorded at several different distances from the exit plane. Reconstructed holograms were examined visually, droplet size and position determined, and the results tabulated. The size and position of a single droplet could be found by using the known relation between object and reconstruction image established by Matkin (1968). A typical droplet distribution in space is shown in Figure 4 where each dot represents a droplet of water observed within a 90° segment of a 1 mm cross-sectional slice of the jet located 0.37 cm downstream from the exit of the test section. Figure 5 illustrates the segment that was sampled. In these studies it was observed that for a given operating pressure, most droplets at a particular location had approximately the same size and therefore the size distribution was not determined.

Figure 6 shows the distribution of droplets under the same flow conditions as in Figure 4, but at a distance 3.23 cm downstream from the exit plane. A comparison of the two figures shows substantial divergence of the jet and some indication of asymmetry.

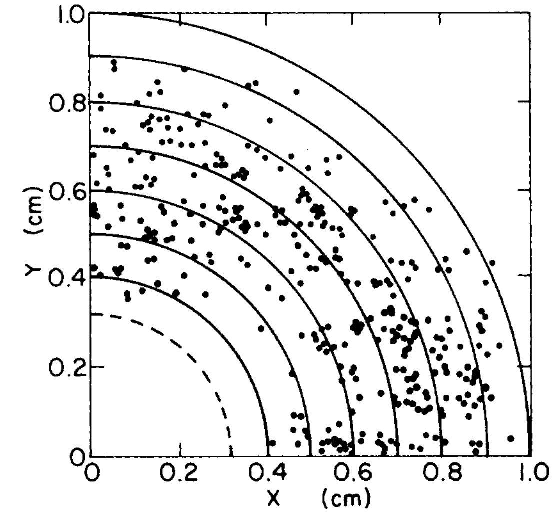
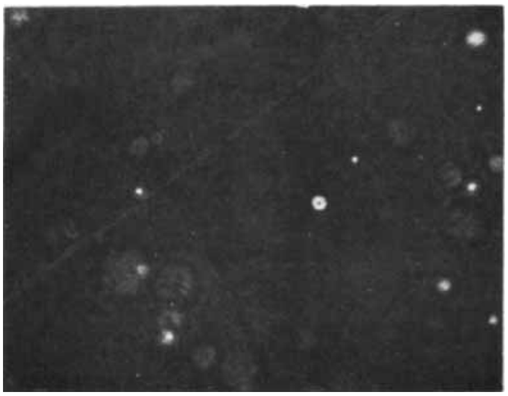


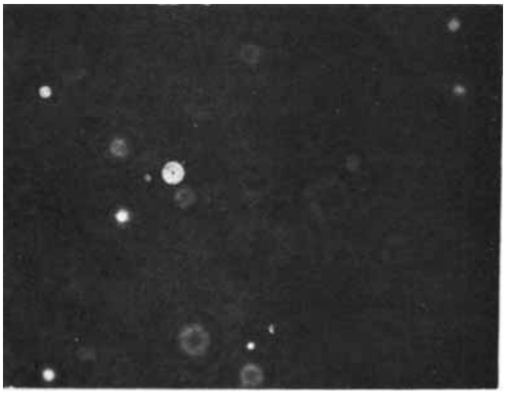
Figure 6. Droplet distribution in ¼ of observation plane distance from exit of test section 3.23 cm.

The dashed line in each figure indicates the inner radius of the test section itself. No droplets were found within that radius in any of the experiments using the 48.3 cm test section.

While the droplet distribution at the exit plane would be of principal interest, the complete distribution could not be obtained using these methods since multiple interference caused by the



(a)



(b)

Figure 7. Image of droplets in critical flow jet with X_H = 91.4%.

(a) High Concentration Region

(b) Low Concentration Region

higher droplet density close to the exit resulted in poorer resolution as one attempted to locate droplets close to the exit plane. Moreover, the test section itself blocked a significant portion of the reference light and contributed to the deterioration of the reconstruction image. Figure 7 shows photographs taken of the reconstructed critical flow jet where the effect of droplet concentration on image quality is clear. Images of droplets in less densely populated regions have better quality and can be resolved with much greater precision.

Figures 4 and 6 show that all of the droplets are located at positions outside the inner radius of the test section with the spatial distribution spreading as the drops move downstream. Because the lower limit of pulse duration of the laser used in the study was 50 ns, there was a possibility that drops existed in the central position, but were moving with such a high speed that the recorded interference pattern was incoherent and that information about such droplets was lost. Since shortening the pulse duration below 50 ns required substantial modification of the equipment, an alternative method was used to check for the existence of droplets in the central region of the flow. This was to use the laser in a single pulse mode as a light source. If droplets existed in the center of the jet, their presence should be detectable by taking conventional photographs through a microscope using the laser pulse as a combined light source and shutter.

Photographs taken in this way are different from conventional photographs because spherical interference patterns are present due to imperfections in optical equipment and contamination from dust and other particles. Droplets, however, give rise to unique and different patterns, and even if they are moving at a velocity as high

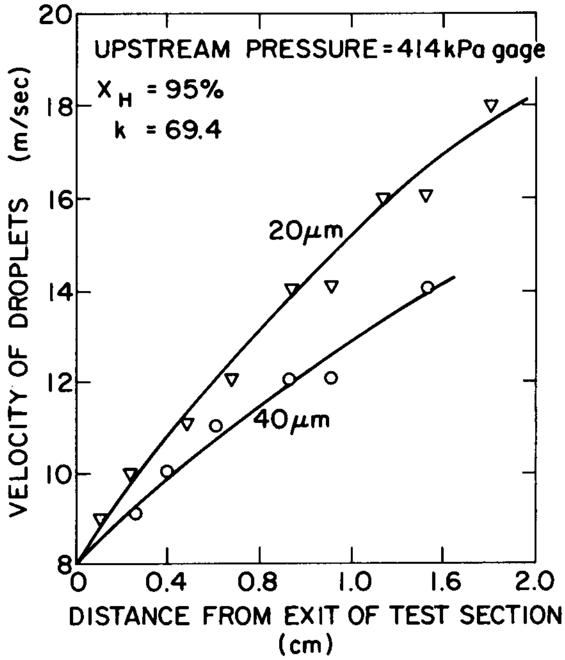


Figure 8. Velocity of droplets in critical flow jet, P_o = 414 kPa gage.

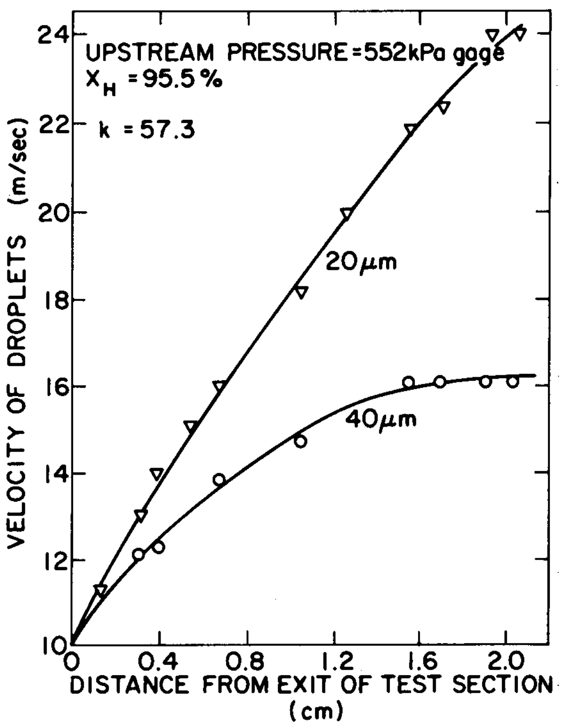


Figure 9. Velocity of droplets in critical flow jet, P_o = 552 kPa gage.

as 200 m/s will show up as a streak on the film.

Such photographs were taken at different pressures for the 48.3 cm test section and no drops were observed in the portion of the jet within the inner test section radius. It was thus concluded that for this length test section and for high quality steam-water choked flow the flow pattern changed from a homogeneous mixture at the mixing section to a separated flow at the exit plane.

Photographs were taken under similar conditions using the two shorter test sections. The results showed that with the intermediate-length (25.4 cm) test section there were not droplets in the central portion of the jet core with an upstream pressure of 690 kPa, but there were a few at 414 kPa and lower pressures. Results with the shortest test section, 12.7 cm long, showed that droplets were present in the central core even at the highest pressure (690

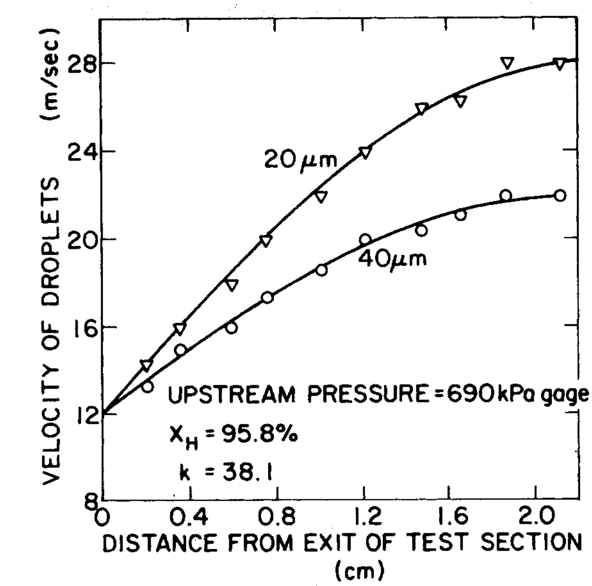


Figure 10. Velocity of droplets in critical flow jet, P_o = 690 kPa gage.

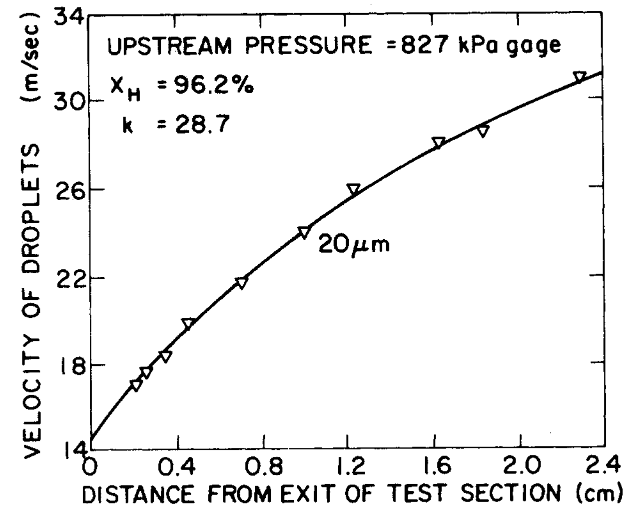


Figure 11. Velocity of droplets in critical flow jet, P_o = 827 kPa gage.

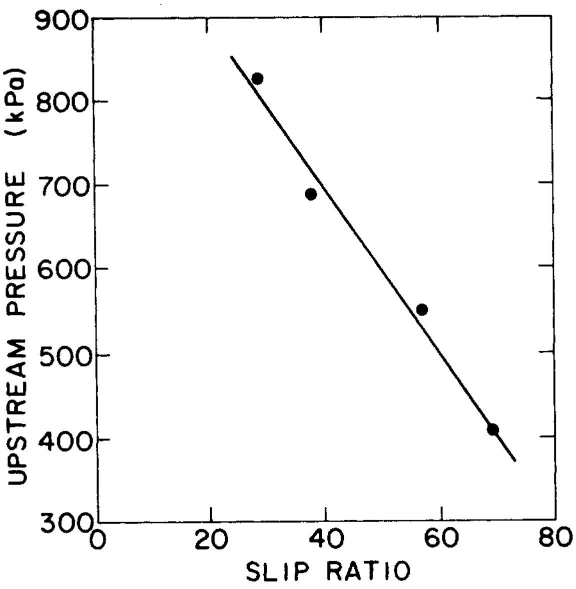


Figure 12. Relation between slip ratio and upstream pressure at X_H = 95.0%.

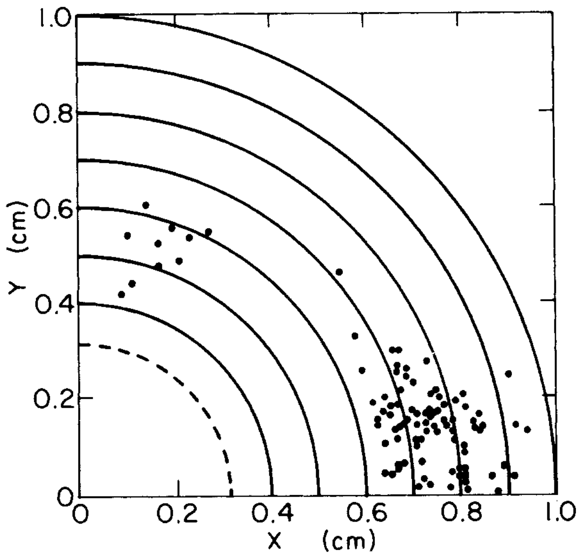


Figure 13. Unsymmetrical distribution of droplets in critical flow jet.

kPa) at which experiments were conducted. The quality of the photographs is not good enough for useful reproduction nor can the photographs be used to determine accurately the droplet size or number distribution, but the evidence of the existence of droplets was conclusive and repeatable.

Droplet Velocity and Calculated Slip Ratio

Using the longest, 48.3 cm, test section, double exposure holograms were recorded using double laser pulses with a separation of 5 μs between pulses. Images of an individual droplet at the two instants in time were used to determine the distance travelled by the droplet during the separation interval. Although there is a distribution of velocities at any given location downstream from the exit plane of the test section, the variation is not large and samples of at least twenty droplets were used at each location to determine an average droplet axial velocity. The radial component of velocity was small and was neglected in these calculations. Average axial velocities as a function of distance from the test section exist are shown in Figure 8. Results indicate that rapid acceleration occurs after the droplets leave the test section exit and that drop size has a significant effect on the acceleration.

The droplet velocity at the exit plane (actually the film velocity) was estimated by extrapolating upstream to the exit plane the measured velocity distribution. These extrapolations appear to converge to a common velocity for all drop sizes, giving credence to the hypothesis that droplets are being formed at the exit plane by the breakup of a continuous water film on the inside surface of the test section.

The slip ratio, defined as the ratio of the vapor phase speed to the liquid phase speed, was obtained by using the extrapolated value of droplet speed at the exit plane for the liquid phase speed, and calculating the speed of the vapor (steam) phase from the known steam mass velocity, pipe diameter, and exit plane pressure, and assuming saturated steam properties. Figures 8 through 11 indicate the calculated slip ratios, given as k on the figures for upstream pressures ranging from 414 to 827 kPa. Figure 12 shows that the calculated slip ratio is a strongly decreasing function of increasing pressure. The exit plane quality was essentially constant, although actually it varied from 95.0% to 96.2%.

DISCUSSION

Results from studies of single exposure holograms show that at the exit of the 48.3 cm test section separated flow prevailed, with

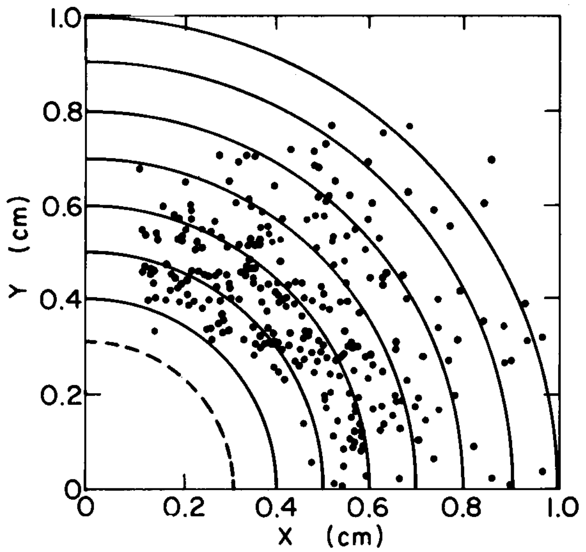


Figure 14. Typical droplet distribution in air-water critical flow jet (Lee, 1973).

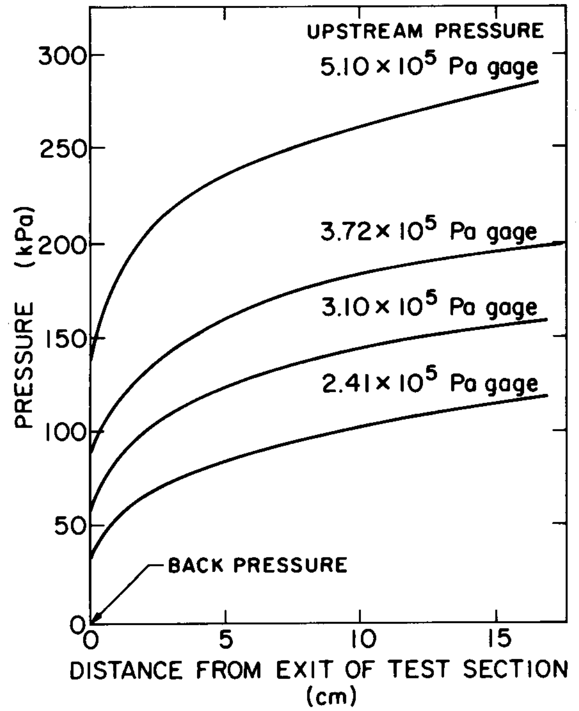


Figure 15. Test section pressure profiles.

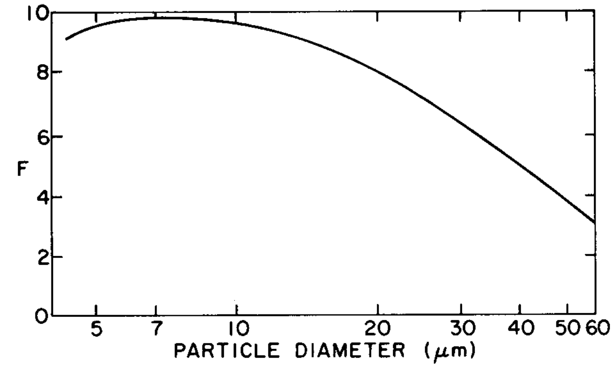
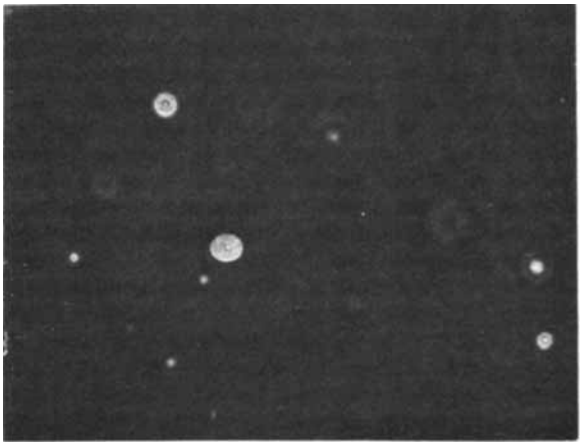


Figure 16. Estimated fraction of particles entering pipe which will deposit on wall under flow conditions of this study.



DROP SIZE 100μ

Figure 17. Reconstructed image of a deformed droplet.

water existing as a thin film flowing along the wall of the test section and with steam in the central core. Occasionally the film may have been discontinuous, resulting in an asymmetric droplet distribution, similar to that shown in Figure 13. Droplet distributions in air-water critical flow have shown similar patterns Figure 14. With shorter test sections the separation was not complete, some droplets being observed within the cross-sectional area corresponding to the internal area of the test section. Since the flow from the mixing section to the test section exit changed from homogeneous to separated, it is apparent that there was deposition of droplets along the wall of the test section. Calculations based on the model developed by Hutchinson, et al. (1973) showed that almost all drops less 15 μ in diameter will deposit on the wall. This is shown in Figure 16. For droplets with diameters greater than 40 μ, however, less than half would be expected to be deposited.

Due to the extremely steep pressure gradient at the test section exit, however, it is likely that relaminarization will occur (Sternberg, 1960; Sergienko and Grestov, 1959). Radial migration of droplets in laminar flow has been well established (Segre and Silberberg, 1962; Jeffrey and Pearson, 1965), and may account for the disappearance of large drops from the center of the critical flow jet. Qualitative calculations show that migration of large drops toward the wall is rapid enough to account for their deposition if relaminarization occurs towards the end of the test section. Inertial effects and droplet deformation are the most commonly cited reasons for droplet migration in laminar flow. Figure 17 shows clearly that large drops are readily deformed in critical flow.

Critical flow is characterized by a very steep pressure gradient near the exit as shown in the typical pressure profiles of Figure 15. In every case there is some uncertainty about the calculated steam velocity at the exit plane. These uncertainties, however, do not alter the conclusion that the slip ratios obtained in this study are substantially higher than those reported earlier. Lee (1973), using an almost identical system for studying air-water critical flow, found slip ratios that lay between those predicted using the models of Fauske (1962) and of Cruver (1963) and Moody (1963). The experimental value of k reported by Lee is probably in error, however, because it was obtained using only the in-line holographic measurements downstream from the exit of the test section instead of using extrapolated measurements to determine k at the exit plane. The rapid acceleration of droplets after leaving the test section would result in a substantially lower value of the slip ratio downstream from the exit plane compared with the value at the exit itself. The theoretical prediction of either $(V_g/V_l)^{1/2}$ as given by Fauske or $(V_g/V_l)^{1/3}$ as developed by Cruver and Moody will not give correct results because the flow pattern changes continuously during the flow process instead of remaining the same throughout the test section as postulated in most models. Table 1 compares slip ratios obtained in this study with those calculated

TABLE 1. COMPARISON OF CALCULATED AND EXPERIMENTAL VALUES OF SLIP RATIO

Exit Plane Pressure, kPa \ Slip Ratio, k	$(V_g/V_l)^{1/3}$	$(V_g/V_l)^{1/2}$	Experimental Values, This Study
221	9.08	27.37	69.4
276	8.46	24.6	57.3
345	7.94	22.4	38.1
414	7.46	20.4	28.7

using the two different theoretical models. This shows that the experimental values of slip ratio obtained in this study are considerably (two to seven times) higher than the calculated values.

Since the experimental results were obtained at very high qualities, with the mass fraction of liquid approximately five percent (and the volume fraction much less), it is not surprising that the slip ratio is very high. Once deposited on the inner surface of the wall, the liquid will form a very thin film and wall friction will play a strong role. One would expect that as quality decreases and film thickness increases, the average liquid velocity would increase and a smaller slip ratio would result. In addition, a thicker liquid film may lead to more entrainment of droplets in the vapor stream. Both of these effects would tend toward a decreasing slip ratio with decreasing quality. Unfortunately, this could not be confirmed in this study because the quality of reconstructed hologram images became very poor as the quality decreased below 95%. It appears that holography may be successful, however, at very low qualities where the population of vapor bubbles is relatively small in a continuous liquid phase. Such experiments would require substantial modification of the existing equipment, but would be very interesting.

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