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VISUAL OBSERVATION OF AN AIR-WATER MIXTURE FLOWING THROUGH A TUBE SUPPORT PLATE WITH CIRCULAR-HOLE AND TREFOIL-HOLE DESIGNS

BY

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RESEARCH REPORT

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ABSTRACT

The flow patterns of an air-water mixture at atmospheric pressure were visually observed through a simulated vertical steam generator tube support plate of circular hole and trefoil designs. Flow oscillations with a period on the order of 0.4 seconds were observed in both support plates at similar mass flow rate combinations. The oscillation consisted of a period of rapid surging followed by a low flow or stagnation period on the order of 0.1 seconds. Reverse (downward) flow was also observed for part of the oscillation cycle in the trefoil support plate. The flow oscillations that exist in one tube support plate are coupled to the oscillation phase that exists in the preceding tube support plate. The operation of a steam generator in a region where this flow oscillation occurs could result in reduced steam generator life due to increased corrosion.

ACKNOWLEDGEMENTS

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INTRODUCTION

Current nuclear steam generator design requires the prediction of conventional engineering quantities for performance and material integrity evaluation. Historically little attention has been given to corrosion and the location of where it may occur in the steam generator. Recently this trend has been reversed due to corrosion causing potentially catastrophic steam generator failures which has resulted in costly repairs and decontamination. It is well documented that the flow patterns which result from the local geometry determine the pressure drops and heat transfer characteristics but these flow patterns also dictate the location and, to a certain extent, the type of corrosion that occurs.

In most commercial pressurized water reactor steam generators, the heat flux is less than the critical heat flux required to cause dryout or vapor blanketing (Smith and Armstrong 1983). Vapor blanketing may still occur, however, as a result of internal structural components such as tube support plates, antivibration bars, and shroud supports causing vapor retention or prevention of rewetting of the tube surface. The mechanism or type of corrosion that occurs in the vapor blanketed area depends on the chemistry control system employed. There are two general chemistry control systems in use.

The first involves the addition of a weak base or the salt of a weak acid which produces a basic pH environment. (The passivity of most metals is enhanced if the environment is basic provided it does not become excessively caustic.) In areas of vapor blanketing the pH agent concentrates and deposits on the tube surface resulting a very high pH and subsequent caustic stress corrosion (Smith and Armstrong 1983). Depending on the metal and ehcmicals involved, the high concentration of the salt or base may cause a direct attack on the metal oxide. The second chemistry control system involves the use of a volatile chemical which is carried off with the vapor. This results in essentially no pH control near the vapor blanketed metal surface and will cause noticeable corrosion increases in less passive metals within the steam generator (usually structural components). It is only in the regions where vapor blanketing continually occurs that the corrosion effects are of significance, neamely at some internal structural supports and possibly sludge deposits on heater surfaces (Smith and Armstrong 1983).

The purpose of this study was to visually observe the flow patterns that exist through a trefoil (broached) shaped hole and a circular hole tube support plate. The fluid is an air-water mixture at atmospheric temperature and pressure with no heat addition. The experimental apparatus is the same used by Yarizadeh (1982), for which he developed an empirical pressure drop correlation across the circular tube support plate.

EXPERIMENTAL APPARATUS

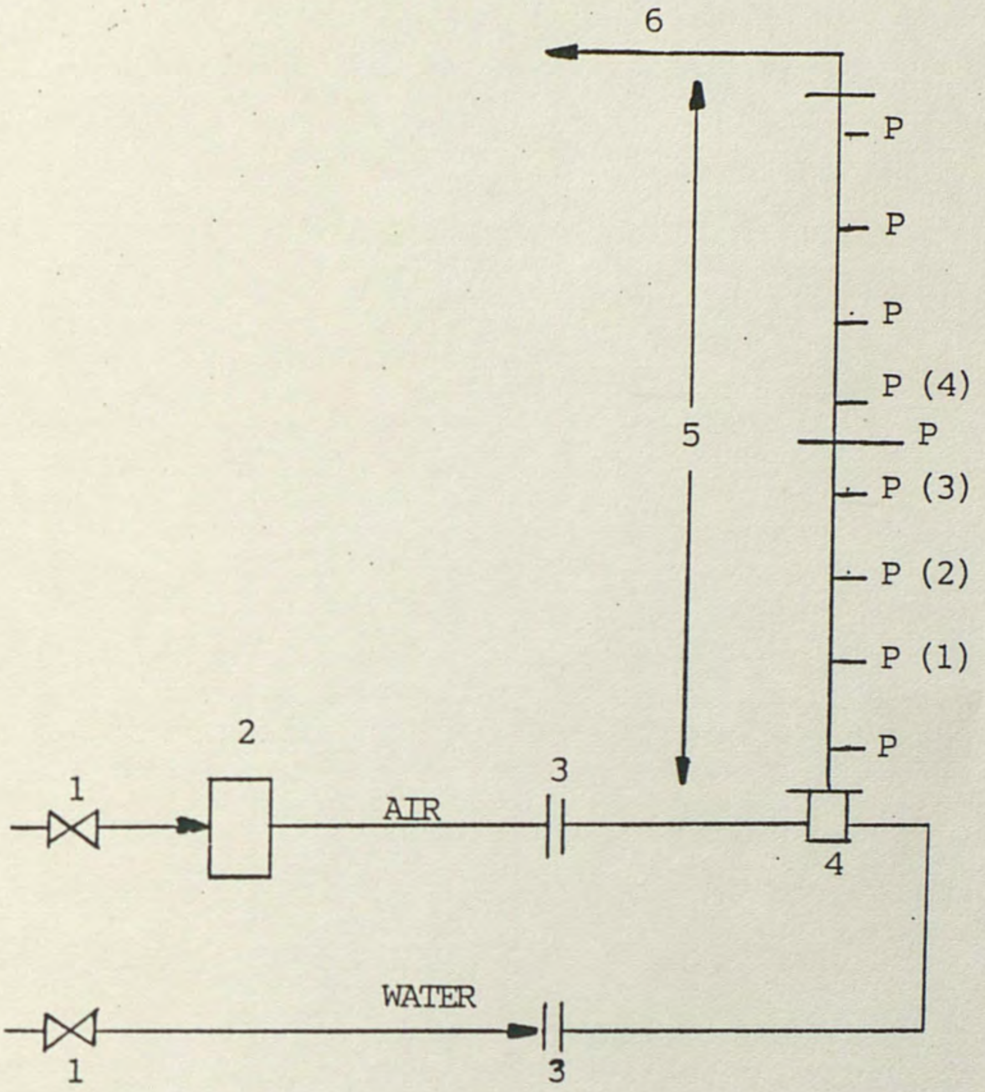
Description of Flow Loop

The flow loop consists of a large transparent vertical Plexiglass tube with seven internal solid vertical Plexiglass rods simulating the steam generator shell and tubes respectively. The tubes are held in place by Plexiglass support plates that contain either the trefoil or circular hole orifices. Air and water enter the inlet mixing plenum at the bottom of the large Plexiglass tube after being throttled and metered. The loop is shown schematically in Figure 1.

Design of the Flow Loop

> Two cast Plexiglass tubes, with an inner diameter of 2.25 inches and a wall thickness of 0.25 inches, were used to form the housing for the testing area (Figure 2). Each tube is 17.625 inches long and has flanges at the upper and lower edges. These flanges are 0.75 inches thick and were fabricated from a 7.0 inch diameter. Plexiglass circle with a 2.75 inch diameter hole bored through it. Four equally spaced holes were drilled in the flanges to match the bolt circle of a standard 2½ inch pipe flange so that the tube support plate, mixing and exit chambers could be attached to the test section. The flanges were glued to the tubes (Yarizadeh 1982).

The support of interest was installed as the center tube support plate and was secured to the flanges by bolts and nuts. This support plate was fabricated from a 7.0 inch diameter, 0.75 inch Plexiglass circle with seven equally spaced holes drilled in a triangular pattern. The circular hole support plate holes were 0.530 inches in diameter (Figure 3). The trefoil holes were formed by drilling seven 0.510



1. Valves
2. Air Filter
3. Flow Meter
4. Mixing Plenum
5. Test Section
6. Exit Chamber

P Pressure Tap

Figure 1. Schematic diagram of the flow loop (Yarizadeh 1982).

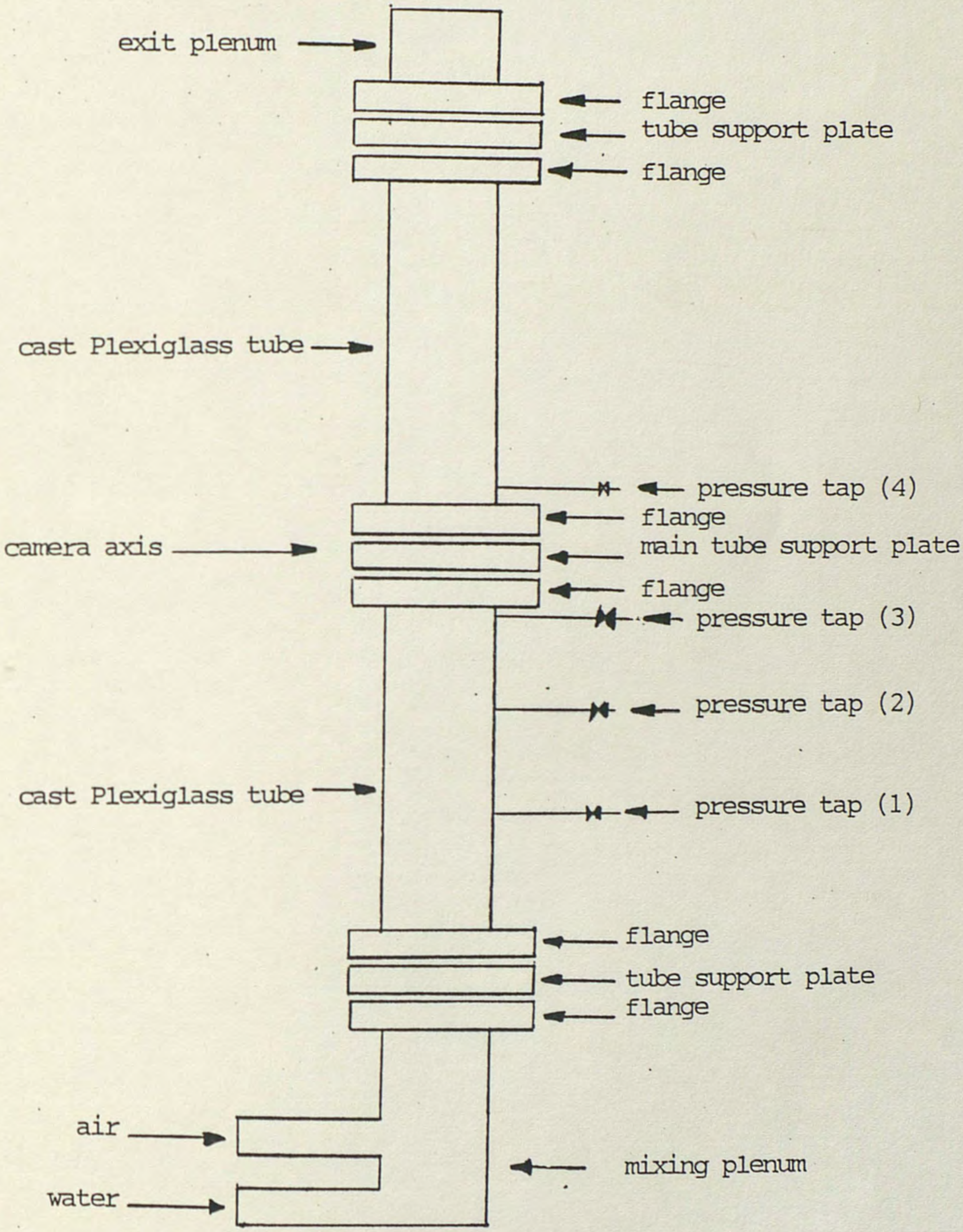


Figure 2. Test section.

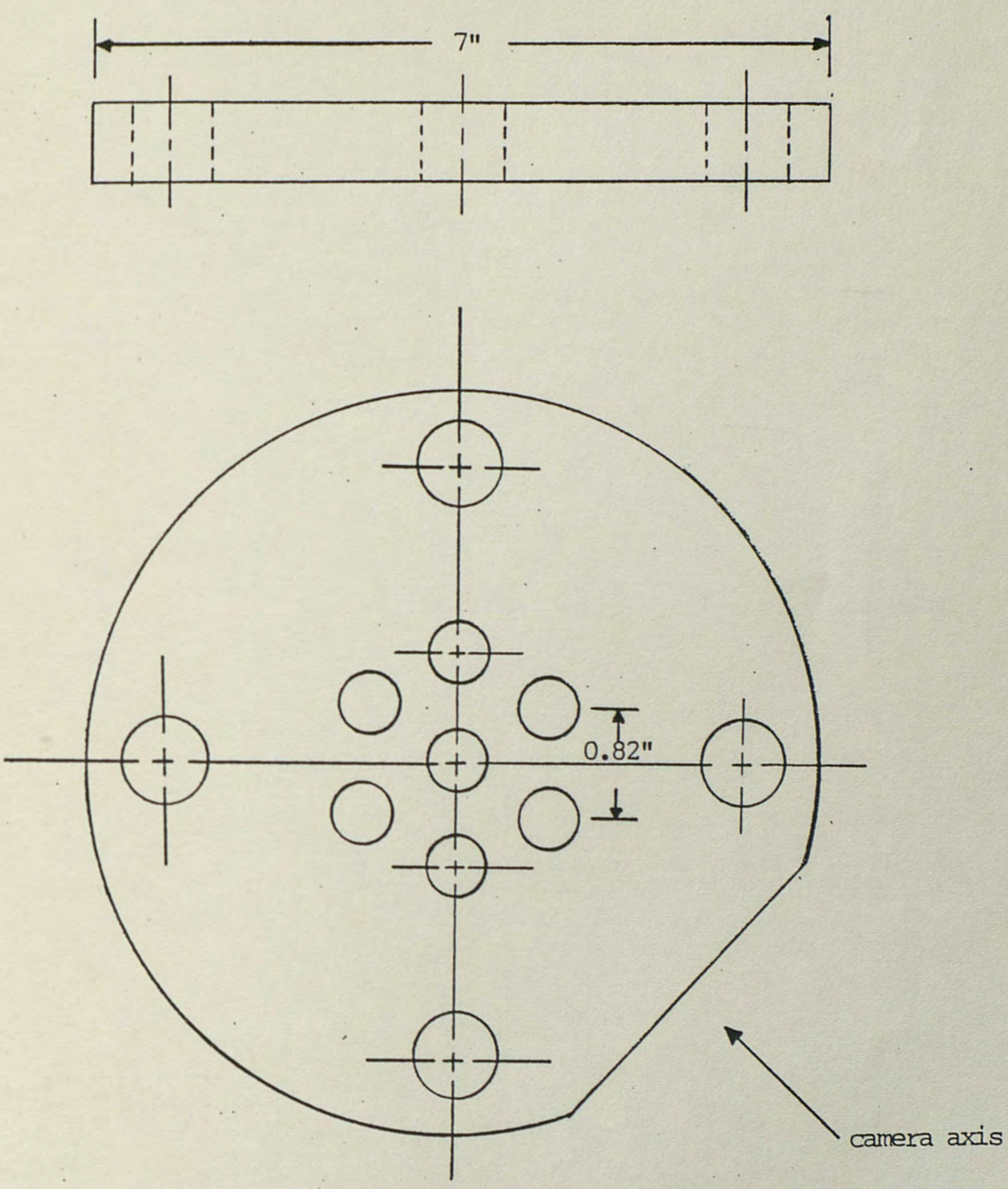


Figure 3. Top and front view of the circular-hole tube support plate.

inch diameter holes and broaching each hole in three areas 120 degrees apart (Figure 4). The total flow area for the circular hole support plate is 1.180 x $10^{-3}ft^{2}$ with an individual hydraulic diameter of 0.0025 feet. The trefoil support plate has a total flow area of 3.923 x $10^{-3}ft^{2}$ with an individual hydraulic diameter of 0.0076 feet. Area calculations appear in Bashar (1983). A flat surface was machined on the vertical edge of the support plates to provide a normal surface.

The tube bundle consisted of seven solid Plexiglass rods, each 0.50 inches in diameter which extended into the inlet plenum and exit chamber.

Eight pressure taps were installed in the test section at a distance of 2 inches, 6 inches, 10 inches and 14 inches from the centerline of the center support plate (Figure 5). The pressure taps sampled the static pressure at the main test tube inner wall surface only. Each tap was individually valved. The taps also served as access parts for dye injection.

The flat vertical surface of the test support plate and internal holes were polished by hand to optical clarity using a powder toothpaste and water mixture. Small vertical and horizontal grooves which occurred in the holes from the fabrication process and were not removed. The grooves provided a surface irregularity but did not appear to affect the vapor bubbles.

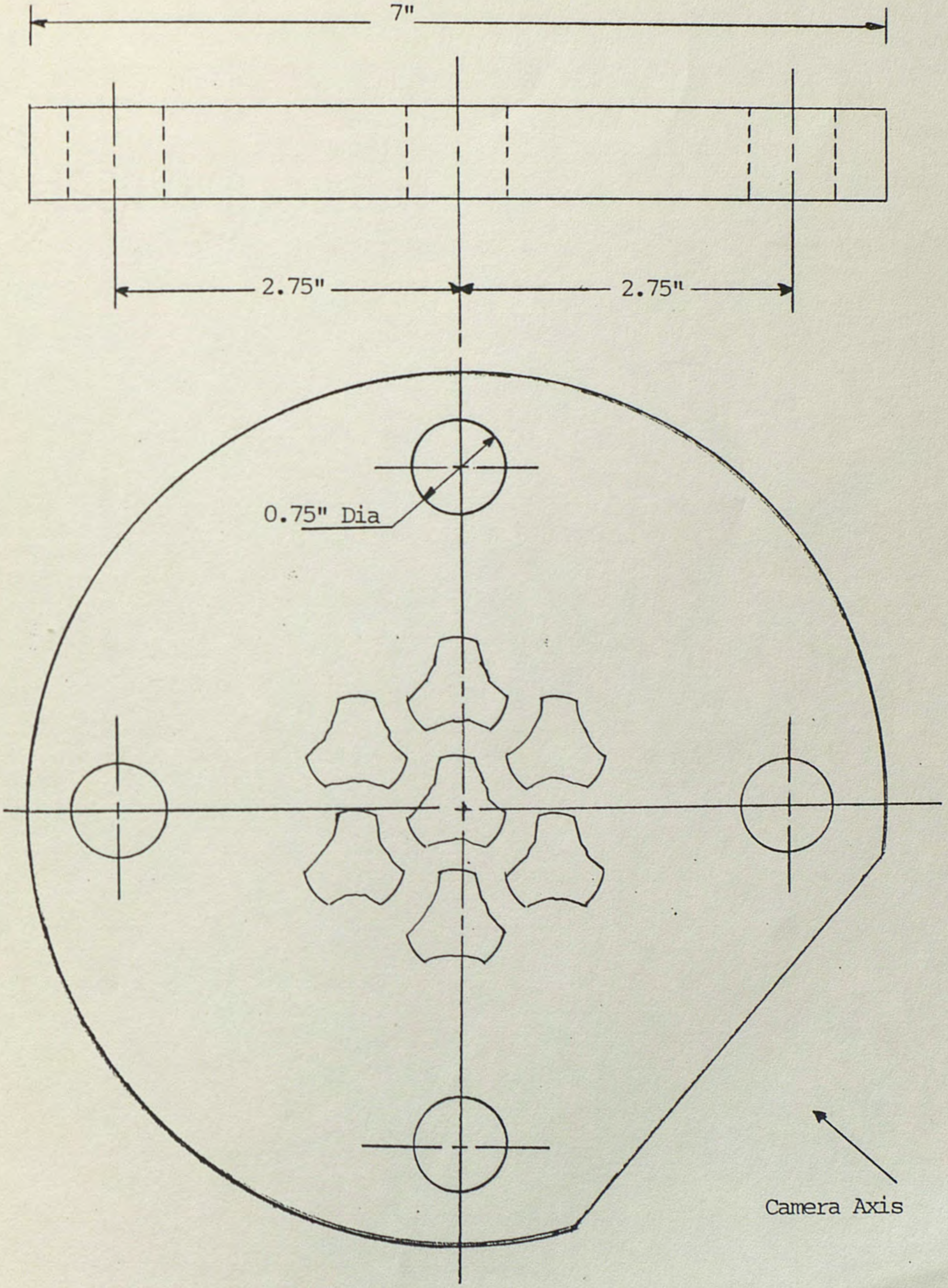


Figure 4. Side and top views of the support plate (Bashar 1983).

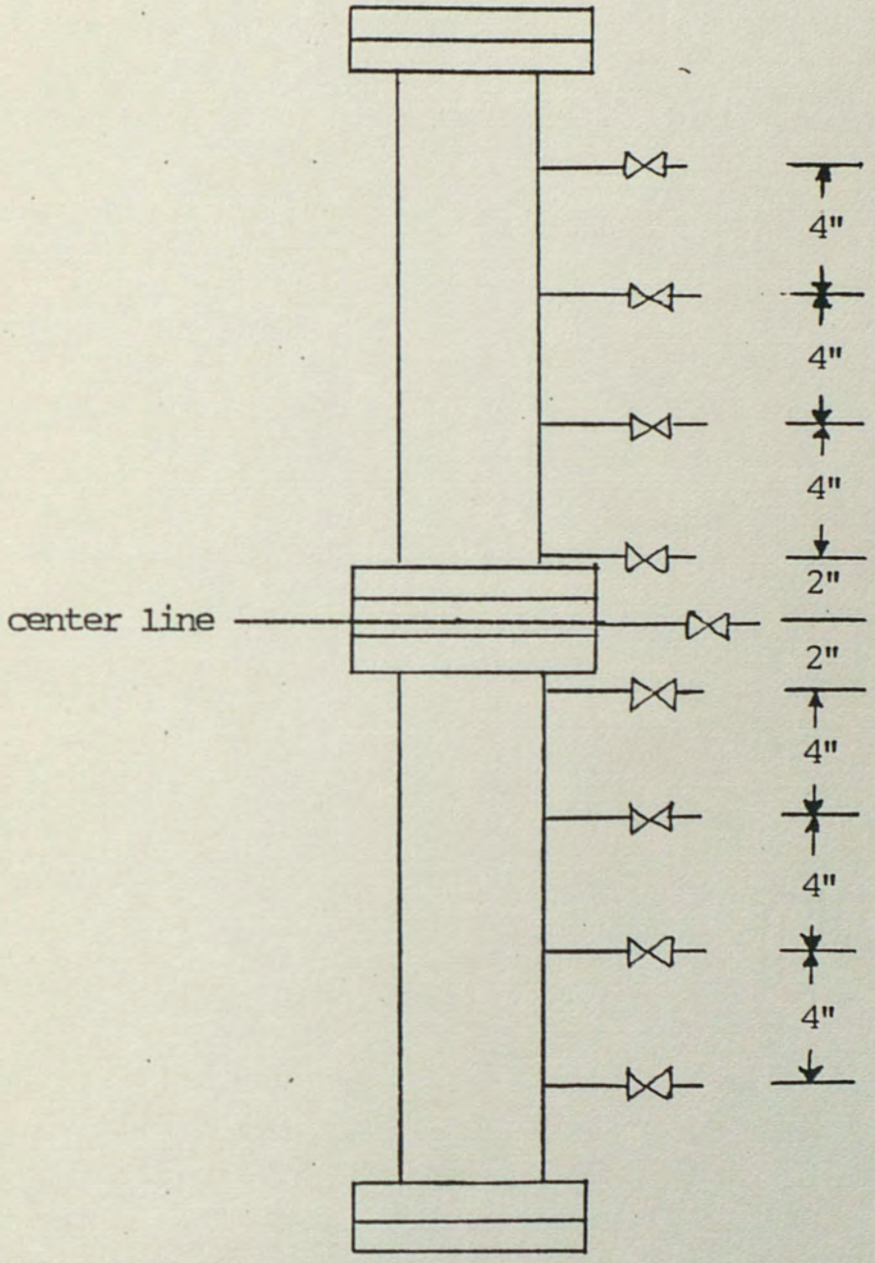


Figure 5. Location of pressure taps on the test section (Yarizadeh 1982).

EXPERIMENTAL PROCEDURE

Moisture-free air and water at atmospheric pressure and ambient temperature were introduced into the inlet plenum of the flow tube where mixing occurred. Test runs were at the following flow combinations:

Water (GPM)	Air (SCFH)
2	20 100 200
3	20 100 200
5	20 100 200

The mass quality varied between 0.0006 and 0.015 with a void fraction variation of 0.33 to 0.93 (assuming slip ration = 1.0). The flow tube exhausted to the laboratory drain system.

High speed motion pictures were taken perpendicular to the flow tube axis with the lens axis at the center of the support plate. The field of view included the entire support plate and approximately 1½ inches above and below the support plate. The framing rate was 1000 frames per second.

The water flow rates were stable within ± 5%. The air flow rates were stable within ± 5% for the 20 and the 100 SCFH flow and within ± 10% for the 200 SCFH flow rate.

FLOW PATTERN DESCRIPTIONS

The flow patterns were divided into two categories which are characterized by the presence or absence of oscillations in the main flow direction. The oscillations occurred at approximately the same mass flow rate combinations for the trefoil and circular hole support plate. There are no significant differences in the flow pattern between the trefoil and circular hole support plate prior to the occurrence of the oscillations. The primary difference in the oscillations is that reverse flow occurs as part of the oscillation cycle in the trefoil support plate. This reverse flow was not observed in the circular hole support plate.

The nonoscillatory flow patterns is characterized as bubbly flow (Figure 6). The bubbles are spherical and relatively uniform in size below the support plate. Bullet-shaped bubbles are interspersed at the low flow rate combination. The bubble velocity is approximately uniform and predominately upward. Some of the bubbles become smaller at the support plate due to collision with the support plate and other bubbles. As the bubble enters the support plate it becomes stretched and pancaked. The bullet-shaped bubbles become more circular as the pancaking occurs. The stretching effect is greater in the circular hole support plate resulting in the bubble covering a larger area. The velocity of the bubble through the plate was relatively uniform except near the top of the support plate where rapid acceleration occurred. Once the bubble exits the support plate,

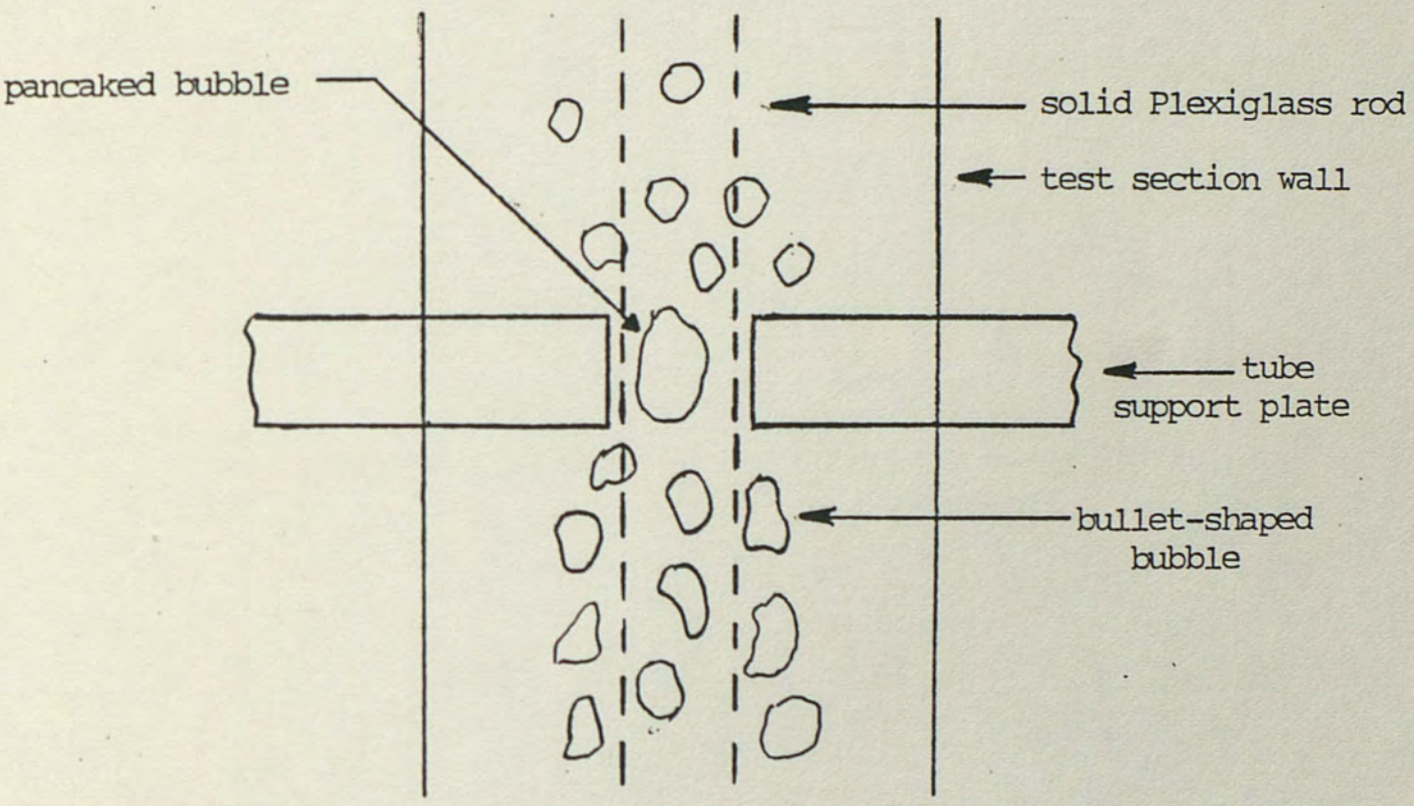


Figure 6. Bubbly flow.

it was broken up by the chaotic flow. Above the support plate there was upward vertical flow along the tubes with slight downward flow as the radical distance from the tube increased. At the immediate top of the support plate, random horizontal flow was also observed.

The flow oscillations can be characterized as a surging effect. There exist two distinct flow patterns in the circular hole support plate. The first is a very rapid, violent upward flow of both water and air, called jetting. The second is an almost stagnant condition where the water velocity is assumed to be in the same direction and approximate magnitude as the bubble velocity. In the trefoil support plate, a third distinct pattern of reverse (downward) flow occurs immediately after stagnation.

In the circular hole support plate, the duration of the stagnation and jetting periods and the violence of the jetting is a function of the mass flow rate combination. In the 20SCFH/2GPM air-water combination, the jetting is not excessively rapid and lasts approximately 0.2 seconds. The fluid velocity then quickly decreases to a very small upward velocity (not complete stagnation). The duration of the low flow period is approximately 0.1 seconds. This periodicity appears to be constant within the accuracy of visual observation.

The surging propagates in a step-like fashion through each support plate in the flow tube. The surge of bubbles from the lower plate impacts the center support plate which initiates the jetting through that support plate. The flow decelerates very rapidly to the stagnant condition when there is a substantial decrease in the bubble population. The bubble population below the plate starts to increase and slow upward flow begins. This slow upward flow continues until the surge from the lower plate impacts the center support plate causing a large increase in the bubble population below the plate and jetting occurs.

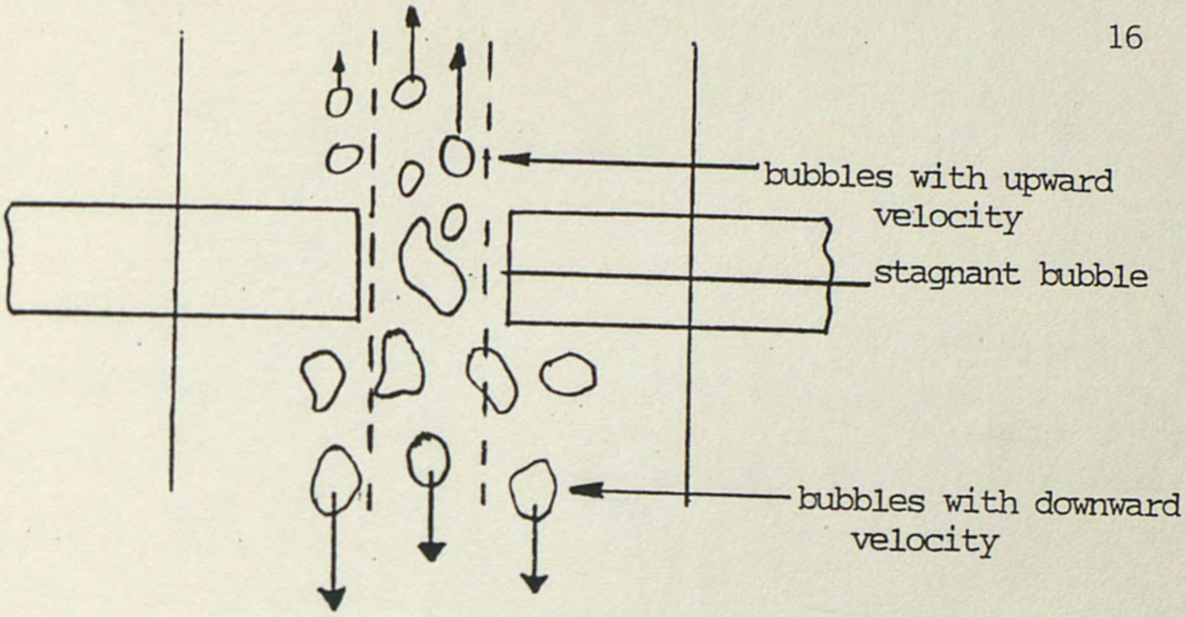
During the jetting phase, there is an increase in turbulence above and below the support plate. The bubbles above the support plate are very small and spherical in shape. The flow velocity is too rapid through the support plate to distinguish any individual bubbles.

The duration of the low flow or stagnation period was approximately 0.1 to 0.2 seconds. The jetting lasted about 0.3 seconds. As the air flow rate is increased (same water flow rate), the duration of the stagnant period decreases and the velocity, turbulence and duration of the jetting increases. In addition, the average bubble size decreases. As the water flow rate increases, the duration of the stagnant period is decreased and a higher air flow rate is required to obtain the same velocity of jetting that was observed under low water flow rates. In addition, the bubbles are slightly larger (for same air flow rates). For higher water flow rates, the sympathic effect of the surge from the bottom support plate is not as pronounced and there is not the large accumulation of bubbles below the plate prior to jetting. The absence of bubbles above and below the support plate following the jetting still occurs.

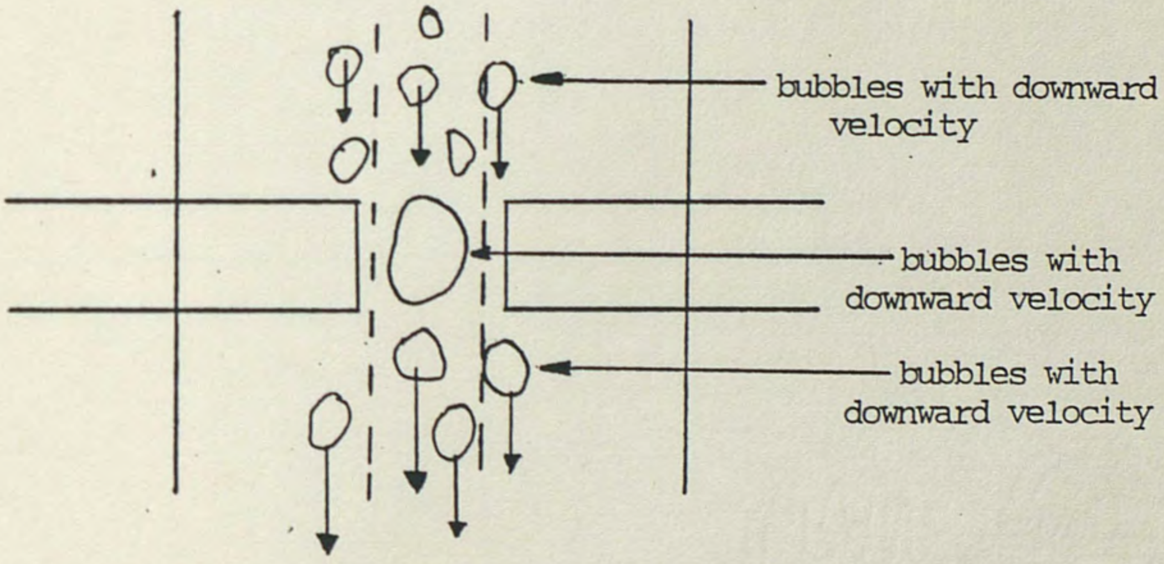
In the trefoil support plate, the oscillations are similar to those in the circular hole support plate with two additional phenomena: 1) there are velocity oscillations during the jetting flow period that were not present in circular hole jetting period; and 2) during the stagnation period of the oscillation there is reverse flow present.

The velocity oscillations during the jetting were random and the actual magnitudes were not measurable. They appeared to occur with greater frequency at the higher mass flow rates.

The reverse flow is initiated from below the support plate. Initially upward flow is still occurring in and above the support plate and downward flow below the support plate. Then a true stagnation of flow occurs where the bubble velocity and, presumably, water velocity are zero. The downward or reverse flow that is occurring below the support plate then causes reverse flow ot occur in the support plate which subsequently initiates reverse flow above the plate. The reverse flow in the support plate stops when the surge from the lower support plate impacts the bottom of the center support plate (Figure 7). The bubble surge was observed leaving the lower support plate and traveling upward as a group of bubbles. The group impacted the reverse flowing bubbles which were swept upward eventually through the center support plate (jetting). The concentration of bubbles above and below the group was markedly smaller.



Reverse flow initiates from below support plate.



Reverse flow fully established.

Figure 7. Initiation of reverse flow.

The degree of backflow depends primarily on the water flow rate. At 2 GPM water flow rate, the backflow lasts 0.1 to 0.2 seconds. As the water flow rate is increased to 5 GPM, the backflow lasts less than 0.1 seconds. During the stagnation and reverse flow phases, the bubble population above and below the support plate is very small.

In both support plate designs, the flow patterns and oscillations occurred uniformly across the flow tube. The randomness of the oscillations increased at higher mass flow rates.

Single-phase (water) observations were made using dye injected through pressure taps 1, 2, 3, 4 (Figure 1). The water flow rates were 2, 5, and 7 GPM. No surging or reverse flow was observed. Two-phase observations show increased mixing as expected and extensive reverse flow along the tube walls (taps 1, 2). Reduced reverse flow at taps 3 and 4 was also observed. No dye was observed to travel from above to below the support plate (dye injected at tap 4).

DISCUSSION

The test section simulates the tube support plate area that exists in many commercial steam generators. It is not intended to simulate the entire steam generator since many of the complex feedback relations that exist in the steam generator, such as recirculation, do not exist in the loop. The mass qualities and void fractions are similar to commercial steam generators. The mass flow rate of 360 pounds mass per hour per tube (100SCFH/5GPM) is comparable to commercial steam generators during normal operation.

Current research on two-phase flow oscillations can generally be divided into two categories. The first deals with oscillations in heated tubes where fully developed flow is allowed to occur. The second deals with general flow observations in the steam generator where many complex oscillation modes and feedback reactions occur. The overriding concensus is that actual system oscillations are usually complex combinations of fundamental oscillations (Bergles et. al. 1981). Additional research is required to close the gap between the two categories.

Since no heat is added to the flow loop, the oscillations attributed to density and enthalpy changes can be eliminated. The density wave instability which has been observed in operating steam generators is also not applicable to the flow loop.

One possible explanation of the oscillations is a mechanism similar to the fundamental relaxation instability. This instability is a result of the transition from bubbly flow with an associated large pressure drop to annular flow with a relatively smaller pressure drop. As the flow rate is not sufficient to maintain the annular flow pattern and it reverts back to bubbly flow. This flow instability assumes a fully developed flow pattern. Bergles, Lopina, and Fiori (1967) showed that the fundamental relaxation instability occurs in a quality range of 0.0 to 0.002 for an air-water mixture flowing in a tube at low pressures (less than 100psia). They proposed that increased agitation caused by an increased heat flux or restrictions would slightly reduce the transition quality. Annular flow was not detected and the fundamental relaxation instability offered no explanation of the stagnant or reverse flow phases but a flow pattern transition during jetting remains a possibility.

Wallis and Heasley (1961) describe how a travelling vapor plug can cause a decrease in system outlet pressure which initiates a surge. The surge is stopped when the exit quality is reduced and exit pressure increases. This surge effect, although derived for a natural circulation system, may offer a partial explanation to the reverse flow portion of the observed oscillation. Immediately after a jetting phase has occurred in the center support plate, there is a local quality increase near the bottom support plate. This may result in a temporary lower pressure at the bottom support plate causing reverse flow.

Dryout or vapor blanketing may occur during the periods of stagnation and reverse flow. The dryout would have serious corrosion consequences since it would be continually occurring in the same location, namely the support plate.

Smith and Armstong's analysis (1983) shows that the land area of a broached (trefoil or quatrafoil) support plate could become vapor blanketed over its entire width (analysis assumes constant flow with heat addition). In addition, the circular hole support plate was demonstrated to have extensive vapor blanketing. Several methods of eliminating the degree of vapor blanketing were pointed out:

1. Limit the contact region between support plate and tubes.
2. Cause abrupt contour changes using flat lands versus curved lands in the broached design.
3. Use hourglass-shaped lands.
4. Vary the gap width in flow direction.

This analysis demonstrates inherent vapor blanketing caused by the hole design and when coupled to the reverse flow and stagnation periods, corrosion could be substantially increased.

Yarizadeh (1982) states that the air-water mixture has a higher pressure drop than a similar quality steam-water mixture. This suggests the oscillations may occur at higher mss flow rates than the air-water mixture if the oscillations are related to the pressure drop. If the oscillations are related only to the mass flow combination, the steam-water oscillations should occur at approximately the same flow rates as the air-water combination. As heat is added along the tube length, the quality increases vertically which should result in increased oscillations. Due to the higher temperatures of an operating steam generator, the corrosion effects will be significantly accelerated implying less vapor blanketing required for damage to occur.

Conclusions and Recommendations

In summary, the observed oscillations do not appear to be described entirely by any of the single classical flow oscillation mechanisms. They are related to the void fraction and are present in both tube support plate geometrics. This investigation has raised many questions concerning these oscillations that need to be addressed in future research:

1. How the water velocity corresponds to the bubble velocity.
2. Real time pressure measurements during the oscillation.
3. Heat addition effects on the oscillations.
4. Are the oscillations present in steam-water mixtures, and what is the pressure-temperature dependence?
5. Oscillation depends on hole size/hydraulic diameter.

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