TECHNICAL REPORT NO. 13

LIQUID AND GAS DISTRIBUTIONS IN A TWO-PHASE BOILING ANALOGY

BY

GRAHAM B. WALLIS and PETER GRIFFITH

FOR

THE OFFICE OF NAVAL RESEARCH

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ABSTRACT

This report contains a description of the design and operation of an experimental apparatus for the analysis of two-phase flows similar to those occurring in boiler tubes at low pressures. Velocity and density profiles of air-water mixtures are determined across a passage in which boiling conditions are simulated by pumping air through porous walls into a water stream. Photographs of the flow patterns are also presented as a qualitative check on the quantitative data.

The results obtained are:

1) Velocity and concentration profiles of the two phases for various values of the flow rates of each.

2) A classification of the flow into several patterns or regimes with quantitative data describing each regime.

The data is suitable for use in comparing the physical phenomena with mathematical models and for developing a more accurate theoretical treatment of the flow of boiling fluids in heated channels.
**NOMENCLATURE**

<table>
<thead>
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<th>Variable</th>
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<tr>
<td>$D$</td>
<td>channel width</td>
</tr>
<tr>
<td>$f(x)$</td>
<td>flow fraction intercepted by knife at $x$</td>
</tr>
<tr>
<td>$G(x)$</td>
<td>rate of flow at $x$</td>
</tr>
<tr>
<td>$h$</td>
<td>enthalpy</td>
</tr>
<tr>
<td>$P$</td>
<td>knife position, micrometer reading, thousandths of an inch</td>
</tr>
<tr>
<td>$p$</td>
<td>pressure</td>
</tr>
<tr>
<td>$\Delta p$</td>
<td>pressure drop</td>
</tr>
<tr>
<td>$q/A$</td>
<td>heat flux</td>
</tr>
<tr>
<td>$q_s$</td>
<td>steam dryness</td>
</tr>
<tr>
<td>$Q$</td>
<td>total flow, c.f.m.</td>
</tr>
<tr>
<td>$v$</td>
<td>specific volume</td>
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<tr>
<td>$V$</td>
<td>volume</td>
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<tr>
<td>$W$</td>
<td>total mass flow</td>
</tr>
<tr>
<td>$X$</td>
<td>water concentration</td>
</tr>
<tr>
<td>$x$</td>
<td>distance from channel wall</td>
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**Subscripts**

<table>
<thead>
<tr>
<th>Subscript</th>
<th>Description</th>
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<tbody>
<tr>
<td>$a$</td>
<td>air</td>
</tr>
<tr>
<td>$L$</td>
<td>left-hand side</td>
</tr>
<tr>
<td>$R$</td>
<td>right-hand side</td>
</tr>
<tr>
<td>$T$</td>
<td>total channel</td>
</tr>
<tr>
<td>$w$</td>
<td>water</td>
</tr>
<tr>
<td>$x$</td>
<td>value of properties at $x$</td>
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INTRODUCTION

The study of two-phase flow with boiling is of particular interest to heat transfer engineers in many fields. Nuclear reactors and rocket motors are obvious examples.

A number of theories, correlations and theoretical analyses are available in the literature on the various aspects of two-phase flows with heat addition. All of them suffer from the same disadvantage, a lack of experimental information concerning the physical processes occurring. It is all very well to postulate a flow pattern; quite another thing to show that it actually corresponds to reality. The objective of these experiments was to observe the flow patterns and liquid and gas distributions in a channel in which heat addition was simulated. This information will be of assistance in framing analytical models which are appropriate for pressure drop, liquid distribution and burnout calculations.

In this report we describe a method for measuring the distribution of concentrations and velocities of the two phases across a simple channel. Boiling is simulated by pumping air through the porous bronze walls of the channel. The flow is analyzed over a cross-section at the exit. Flash photographs are also made of the flow itself to check results and to show the patterns present along the length of the stream.

Every experiment performed is described. Because these methods have not been used before, to the author's knowledge, it was considered worthwhile to give all details of the development of techniques and the various problems encountered and to try to show the capabilities and limitations of this kind of apparatus.
The apparatus and experiments are reviewed critically throughout the report. Certain definite conclusions are drawn about the nature of two-phase flow patterns and the velocity and density distributions in the passage. Parallels are drawn between the flow of air-water mixtures with air addition through porous walls and the corresponding problem of the flow of boiling fluids in heated pipes such as boiler tubes, reactor coolant channels, etc.

Suggestions are made as to further similar experiments which could be performed.

Hopes are entertained that an analysis of two-phase flows on these lines will lead to a fuller understanding of the phenomena and the eventual development of an effective mathematical theory to predict pressure drops, burnout points, heat transfer coefficients, and other important engineering data.
The basic feature of the flow of a boiling fluid in a heated tube is the continuous creation of the vapor phase at the walls. The phase may be created in the form of bubbles, small or large compared with the channel dimensions, or conceivably in the form of a sheet or film of vapor.

It has been observed that several possible flow regimes exist for two-phase boiling mixtures, "Bubbly", "annular", "slug", "dropwise", and combinations of these, are well known adjectives used to describe patterns and there is no need to dwell on the subject. We shall proceed with the description of the analogy.

The vapor which is created on the walls of a boiler tube is represented in this analogy by air. To obtain conditions of surface nucleation similar to those prevailing under boiling conditions, a superfine grade bronze filter material is used through which the air is pumped into the water stream. Each pore becomes a bubble nucleation point and under normal conditions the bubbles will grow at these points and be swept away into the main stream. It is claimed that a distinct parallel exists between the flow regions observed under these conditions and those prevailing in a boiler tube of similar geometry.

Further, it has been suggested that the burnout heat flux is determined entirely by hydrodynamic considerations. In this case it seems reasonable to expect that the analogy will throw light on this phenomenon as well.
Simulated Boiling Test Section

The test section is modelled after one previously built by Marlen D. Miller and operated by R. di Menza (ref.1) in the Heat Transfer Laboratory at the Massachusetts Institute of Technology. The idea is to simulate the generation of bubbles at a boiling surface by pumping air through a porous bronze filter material into a stream of water.

Numerous geometries are, of course, possible. In this apparatus we have chosen one of the simplest, a rectangular passage. Two walls of the passage are the "boiling" surfaces consisting of 1/2-inch wide bronze strips. These are clamped 1/4-inch apart between two sheets of plexiglas transparent plastic so that the flow may be viewed and photographed. The whole assembly is shown in Fig. 5. Four air lines feed the plenum chambers behind the bronze. Two others feed a mixing chamber before inlet to the passage so that any desired inlet quality may be obtained. Each air line has its own needle valve.

Water enters by the central tube at the top and flows via the mixing chamber to the simulated boiling section.

The frame is cut from 1/2" brass to which the bronze strips are soldered. The plexiglas sides are clamped firmly by the bolts and nuts shown. The cross-pieces are stainless steel spring strips which are needed to ensure that the plexiglas, which is slightly flexible, grips the bronze firmly. Gaskets between the plexiglas, bronze and brass are of cork cut from a single sheet. This material was found to provide the best solution after experiments with various kinds of rubber and fabric gaskets. Air and water lines are firmly brazed in the brass frame.
The whole assembly is glued to the plexiglas base plate which is designed to slide on the top surface of the air-water separating chambers described later.

**Flow Sampling Technique**

We desire to measure the air and water velocity distribution across the outlet from this passage. Any kind of sampling device or pitot tube is of questionable value in a flow consisting of bubbles and drops, since entry and surface tension effects are of predominant importance. To be of any value such a device would have to be about the size of the channel itself. Since we should like a resolution to a few thousandths of an inch, such an arrangement is obviously impracticable.

The solution to this problem is to cut the exit flow into two parts by passing it over a sharp straight knife-edge and to measure the air and water flows on each side of the blade. The edge represents a negligible barrier to the flow. To obtain mass flow distributions all that is necessary is to differentiate the readings as the knife is moved across the channel. The differentiating process is a source of inaccuracy but this may be compensated for by increasing the accuracy of the flow measurements since the only limit to this is the external instrumentation.

In the actual set-up the knife-edge is stationary and the boiling analogy assembly slides over it. The position of the slide is recorded by a micrometer head. Details of the fitting of the slide over the knife and the seal obtained both against leakage to the atmosphere and across the knife, are shown in Fig. 8. Further details are given later.
Measurements of Flow Rates of the Two Phases

The two-phase mixtures issuing from the passage on the two sides of the knife pass directly into large chambers where the phases are separated. A system of baffles and stainless steel wool dissipates the considerable energy of the stream. Air collects in the upper part of the chamber and is sucked through an orifice plate flowmeter to be exhausted to the atmosphere. The air exhaust system comprises a vacuum cleaner which maintains a suction in a plenum cylinder.

Valves in the ducting to the exhaust system enable the pressures in the chambers to be adjusted to atmospheric before readings are taken. In this way leakage either between the chambers or to and from the atmosphere is prevented. The chambers are air-tight and all joints are carefully fitted with gaskets, nevertheless the method of equalising pressures is an added precaution helping to give one more measure of confidence in the results. Leakage between the chambers can only occur through the small clearance between the knife and the exit end of the passage. This clearance is adjusted to a few thousandths of an inch by a method described later. Since there is no pressure difference between the chambers anyway this leakage may be neglected. It only introduces a very slight statistical fluctuation which is not biased in favor of either chamber. The maximum pressure difference allowed between chambers was one millimeter of water.

Air flow is measured by orifices of various sizes chosen to fit the particular requirements. The orifices are of standard design and the calibration curves are known. Comparison between air flows measured in the main air supply line and at these orifices showed excellent agreement.
Pressure difference across the chamber metering orifices is measured by a 100 centimeter vertical water manometer reading to one millimeter. Chamber pressure is adjusted to atmospheric by bringing the reading of a differential water manometer to zero.

A mass balance on the air flow is obtained by comparing readings from the main supply line with those from the two chamber orifices. The air line pressure is measured by a 300cm mercury manometer and pressure difference across the main orifice by a 300cm water manometer.

Water flow is measured by stainless steel V-notches and hook-gauges (Figs. 2 and 3). For very small flows a weighing technique is used; this is the reason for the spouts placed below the notches. The water surface is sufficiently smoothed by the baffles and stainless steel wool so that hook gauges can be read to one thousandth of an inch under normal conditions.

Since the plexiglas may sag or distort with time under stress or as it absorbs water, the notch and hook gauge assembly is a separate construction of channel steel which maintains its shape in any event. As a precaution, periodic checks of hook gauge calibration were carried out throughout the series of experiments. No significant change was detected. In fact, the hook can be read more accurately than is warranted by the weigh-bucket method of calibration, slight flow changes due to surface tension changes with temperature, etc.

Hook gauges are shown in detail in Fig. 3. The brass hook is screwed into a 3/8-inch diameter steel rod which slides in holes in the frame. Readings are given by the micrometer head. The micrometer tip is soldered into a precision bearing which is the fixed point of the
metering system. Adjustment is made by means of the 3 screws shown until motion is quite free in all parts of the travel. Thermal expansion effects in the rod are negligible. The performance of these gauges was excellent throughout all experiments.

The notches were made by hand and sharpened as accurately as possible with fine files. They are occasionally smeared with a film of oil to help prevent any adherence of the jet to the surface. A notch performing under low head is shown in Fig. 2. Calibration curves for the notches are shown in Figs. 11 and 12.

In practice, because of some inevitable fluctuations in the flow rates and the large number of adjustments necessary before equilibrium was attained, it proved better to concentrate one series on water metering only and to do the corresponding air series separately.

A photograph of the whole apparatus is shown in Fig. 1, a view from above with the slide assembly removed in Fig. 4, and a schematic diagram in Fig. 7.

It was a definite advantage to make the whole apparatus of plexiglas since visual checks could easily be made on the functioning of any part. The nature of the flow past the knife could also be seen.

Adjustment of Knife-Edge Clearance

The rectangular test section assembly fits in a slot both in its baseplate and in the frame. Before finally fixing the test section to the baseplate the whole assembly of chambers and knife was built-up. Two thicknesses of suitable paper were then placed on the blade edge and the test section lowered through the two slots until it rested on the paper.
Vertically and alignment were checked and the gluing of the test section to its baseplate performed in situ with plastic cement. When the cement dried and the paper was removed, the test section slid with its proper clearance over the knife-edge.

A crude, but effective, rack and pinion mechanism is used to traverse the slide. The micrometer head is for measurement purposes only and is not used to help move the slide at any time. In this way the integrity of its readings is maintained.

Air Seal Between Slide and Chamber Assembly

Details of the seal between the slide and the chamber assembly are shown in Fig. 8. The horizontal sliding surfaces of plexiglas may be kept wet or smeared with grease in order to provide a perfect seal against air penetration, but this is a luxury.

The side of the slot in the plexiglas roof of the main assembly is finished flat and serves as a guide for the slide. The other side is sealed by a strip of gasket material as shown in the drawing. The gasket is stuck to the slide with glue.

It is easily seen that the only place where significant leakage could conceivably occur is in the clearance between the knife and the sliding piece and we have already stated that this is negligible.

As for perturbations in the main stream due to a possible slight pressure difference between chambers, they are not biased in favor of either side and can be expected to average out. In fact, the results show no evidence of any such effect.
Knife and Scoop

In Fig. 6 is shown the knife and the "scoop". The scoop was a later refinement used to sample the middle section of the passage and eliminate the effect of water which runs down the plexiglas sidewalls and in the corners. The scoop results are nearer those which would be obtained using a two-dimensional model with the bronze walls infinite in extent in the direction perpendicular to the direction of flow.

Weaknesses and Limitations of the Apparatus

1) The soldering technique used to fit the bronze to the brass results in some solder being absorbed by the bronze at the ends of the passage. Thus the air does not enter uniformly over the last 1/2" of the channel. Large scale flow patterns will not be changed much by this fault, but there is some uncertainty in the interpretation of results close to the wall.

2) Erosion of bronze and gasket material near the exit. There is a certain amount of flow down between the bronze and the wall at the exit due to erosion of a few hundredths of an inch of the gasket. There are also two or three channels worn in the bronze some 10 or 15 thousandths of an inch deep and a little wider. These should not carry an appreciable flow but may account for thin jets of water seen passing the knife edge when it had already passed what was theoretically the end of its traverse.
3) Blocking of porous bronze pores by dirt in the air. A filter was installed in the air line but all the same some particles of dirt can be seen to have come into the plenum chambers and have stuck to the gasket material. Some attempts were made to wash out dirt in the bronze by pumping high pressure water in a reverse direction to the normal air flow.

4) A "choke" effect at high flow rates which results in a large pressure drop near the exit of the passage. This means that much more air enters at the lower end than in the entrance region. In fact there comes a point (Fig. 96) where almost no air gets in the first part of the channel at all. Under these conditions it is impossible to specify a bubble generation rate indicative of the actual physical situation.

5) Flexiglas eventually distorts under the influence of stresses, water, and internal stress-relieving as a result of storing and cutting. Eventually the baseplate of the slide does not fit flat on its base. This is only a slight disadvantage for most purposes as it turns out but it is nevertheless a weakness.

6) Too many gauges which have to be adjusted simultaneously, and at low flows a long time constant before steady conditions are obtained. Also, some fluctuations in water and air pressure which could not be entirely damped out. Tricks to get around these problems were developed as familiarity with the apparatus increased.

7) Assymetry in the apparatus. Unfortunately, the physical layout at present gives rise to assymetries in the flow pattern. This can be corrected by adjusting the air valves on each side, but is then only good at one particular set of flow conditions. Since there is no guarantee that in practice a boiler tube will be heated uniformly the assymetry in this apparatus is not so serious as might be supposed. However, theoretical analyses are more easily performed when dealing with symmetrical flows.
8) A passage consisting of two "boiling" walls and two "insulated" walls is not the best model for practical purposes. The flow observed is a kind of hybrid between what we should have for air addition on all faces and for air addition at entry to the passage alone. Nevertheless, we observe phenomena which are initiated solely by the "boiling" faces and by using the scoop rather than the knife, we try to minimise the effects of the plexiglas.

The weaknesses described above in 1) through 7) can be corrected by improved design of the apparatus. The last fault is inherent in any attempt to simulate a two-dimensional flow in a finite apparatus.
Preliminaries and Investigation of Apparatus Capabilities

The first series of experiments (Figs. 13-20) was performed to investigate the capabilities of the apparatus and to get some idea of the kind of results to be expected.

Figs. 13 and 14 show water measurements for traverses across the exit plane of the passage. All the air is fed into the inlet chamber before the passage since we know what kind of flow to expect for these conditions, it is in fact an annular flow with an air core. The upper curves show variations in total flow during the experiment. It is seen that the points define a smooth curve and that fewer points are necessary except near regions of special interest.

Fig. 15 shows an improvement to the above by plotting the fraction of total flow rather than the absolute magnitude. In this way all graphs are normalized to the same scale and the variations in the total flow become less significant.

Figs. 16 and 17 show two air traverses, normalized, for the same outlet conditions but in one case with all the air put in the mixing chamber and in the other case, all the air pumped in through the bronze. These graphs tend to underestimate the accuracy with which air measurements can be made since at that time experience in running the apparatus was small.

We can do several things with these graphs. Fig. 18 shows the results of differentiating a pair of normalized graphs for air and water flows. The result is a time-average rate of flow (volumetric or gravimetric) distribution curve.
If we assume no slip between the phases, we can divide the water mass rate of flow by the total volume flow obtained by summing the air and water curves, multiplied by suitable weighting factors, and obtain an estimate of the water concentration profile. The scales of these graphs are all proportional to the quantities stated above and may be converted to absolute magnitudes if desired.

It should be stressed that since the flow is very turbulent the local velocities and concentrations change with time and we only measure the time-average values here. A mathematical analysis is given in Appendix B.

In Fig. 18 we also show the result of calculating $X$ from $G_w$ and $G_a$ curves. The concentration of water at the wall is very noticeable.

In the set of graphs Fig. 18 the technique for obtaining the best curve was to measure the four slopes of the $X$ curves at points equidistant from the center and to calculate a mean. This way some of the error in curve drawing is reduced. This is all very well if the flow is substantially symmetrical and is all right for the particular case here. In the general case, of course, only slopes at the particular "$x" are to be measured.

Fig. 19 shows the comparison of the results of differentiating the graphs in Figs. 16 and 17. The difference in air velocity profiles under the two conditions is clearly shown.

Fig. 20 is a comparison of water flow semi-profiles obtained by differentiating Fig. 15.

With practice in reading the graphs it is easily possible to deduce the general character of air and water velocity direct from $F$ graphs.
Conclusion to Preliminary Tests

Experimental results are encouraging and show that the method has promise. Accuracy obtainable is very satisfactory and can be improved considerably if desired.

A Series of Traverses with Simulated Boiling

The series of graphs Figs. 21-34 show further air and water integrated flows $F_A$, $F_W$. They are again of an exploratory nature and describe the effect (on the air speed profile) of a steady increase in the water flow.

Air traverses were taken first. These are shown in Figs. 21-30 and clearly show for all cases a uniform velocity in the center of the stream with a "boundary layer" with thickness a fraction of the air-water flow rates.

The results are shown differentiated and presented as velocity profiles in Fig. 31. It is to be noted that the velocity becomes steadily more uniform, the boundary layer decreasing in size as the water fraction in the stream is increased. Accuracy near the walls is bad because of the low flow rates there.

These results are particularly impressive in showing the large core in which the air speed is constant. Almost without exception the curves show a clearly defined linear portion with experimental points falling dead on the line.

In some figures only a portion of the graph is shown because of experimental limitations to the air flow distributions which could be handled by the vacuum cleaner system.

Water traverses (Figs. 32-34) show again a linear portion in the center of the channel with curvature opposite to that of the $F_A$ curves towards the sides of the passage.
Figs. 35-43 show further air and water traverses for which the air flow rate is near the maximum obtainable with the present apparatus. It was hoped that these experiments would shed some light on the conditions approaching burnout. No noticeable or dramatic effects were observed, however, except that the water appears to be concentrated more towards the sides of the channel.

Conclusions

Air traverses, though they provide valuable information about the overall velocity profiles, are not suitable for highlighting the various flow regimes. Furthermore, a greater accuracy is needed in order to probe the most interesting region, that near the channel walls.

Flow Near the Walls

At this point we became particularly interested in the flow near the bronze walls. Since it appears that a uniform velocity and water concentration area exists in the middle of the passage the changes in flow patterns will probably be most marked in the regions near the walls. If we know the profiles in these boundary areas we can simply join them up to each other with a straight line apparently. We are also keen to find some clue as to the nature of the burnout process which is almost certainly accompanied by a decrease in liquid concentration at the wall.

To this end traverses were taken close to the wall for flows at particularly low qualities. Results are shown in Figs. 44-46. The concentration of liquid at the wall is particularly pronounced. It is especially noticeable in Fig. 44 where the results for single phase flow of water are also plotted. Fig. 46 suggests the possibility of some new effect just at the wall, such as for example a sub-layer or in water, which could indicate the onset of flow conditions leading to burnout.
Conclusions

The water flow distribution near the wall is of particular interest and can be measured accurately.

See the next section for a more critical assessment of these results.
DESCRIPTION OF EXPERIMENTS WITH THE SCOOP

Reasons for Changing to the Scoop

It was now realised that the relevance of the analogy (in its form at that time) to the model it was supposed to represent should be re-examined.

Nobody ever makes a rectangular boiling tube with pure insulation on two sides. This is what we have in the present analogy. We should prefer to eliminate (or at least minimise) the effect of the plexiglas walls.

A visual observation of the flow leaving the passage shows that a noticeable fraction of the water runs down the plexiglas and in the corner between bronze and plexiglas. In fact, the flow we want to measure, that in the channel center, is obscured in our measurements so far by the effect of the superposed flow down the walls. From our measurements we can only say that the layer on the plexiglas is thin since it will be of the same order of magnitude thickness as the layer on the other walls presumably.

**N.B.** The air velocity profile is not obscured in any important way by this effect so that the knife in its present form is good enough for air traverses.

To get over this problem the scoop shown in Fig. 6 was designed for use in place of the knife. It performs the same function essentially as did the straight edge but it now samples only the middle 0.400 inches of the stream and avoids the layers on the walls. It is not good for measuring air flows since the seal between the chambers was designed for
the straight knife and clearances are not so close now. Pressures are still balanced between chambers so that negligible forces act to divert the water phase, which has considerable momentum anyway.

A few experiments showed that results for water flows with the scoop were far more realistic than those taken using the straight knife. A traverse (Fig. 49) under conditions of fully-developed annular flow shows an almost zero water concentration in the channel center (shown as zero slope on the graph). By successfully subtracting the obscuring effects of the plexiglas we have succeeded in highlighting the main stream conditions and approaching the ideal which would be a measure of flow distribution in a channel of infinite width, the effect of the plexiglas faces having been reduced to zero by pushing them far away.

A traverse in the scoop case is slightly longer than in the case of the straight edge since the scoop edge is not truly parallel to the bronze faces. Since we are differentiating to get results this effect is of minor importance. We are simply measuring the average flow over some 0.010 inches centered at "x" instead of the flow itself at "x" and the only significant error is caused at the walls or close to them where the scoop is at its least effective as an accurate sampling device anyway.

**Experimental Results**

With the development of the scoop it was felt that a fuller and more systematic exploration of the range of flow obtainable was timely. The series shown in Figs. 51-59 is typical of what happens when the air flow is increased in steps, keeping the water flow rate constant. The graphs are shown differentiated in Fig. 60.
The dotted line across the graphs shows the fraction of the total water flow which is captured by the scoop. There is some correlation between this and the flow patterns, as will be seen.

The general sequence of flow regimes is as follows:

With no air flow the water has the usual parabolic velocity distribution.

As air flow is increased the water flow down the center of the passage increases at the expense of the walls. This effect is particularly clear in the next series Figs. 61-68. This is thought to be partially due to the increased viscosity of the bubbly layer at the wall.

On further increase of the air flow the distribution becomes parabolic again and soon the linear center portion becomes more noticeable.

A transition point is reached where the concentration at one wall suddenly increases considerably. This is accompanied by a more violent noise at exit to the passage, something like a roar, compared with the soft sound of bursting bubbles in a frothy liquid which was observed previously.

After passing through the transition region the flow adjusts to a double-humped distribution which strongly suggests the annular flow found before. As in the case of Fig. 18, the curve of actual water concentration is far more vivid in showing this effect and it should be borne in mind that the height of the peak at the wall will be many times the level in the passage center if we plot such a curve. Rather than increase the already large number of graphs presented, this re-presentation is left to the reader.
As air flow is further increased the profile tends to become more uniform again. Noise level increases steadily as more air is introduced.

Further traverses (Figs. 61-66) were taken in an effort to map the area of the first transition region. This region is not very well defined except at low water flow rates since its determination depends on our being able to classify a particular flow as being of one kind or another. In fact at high rates of water flow the transition, annular and uniform flow regions become more and more indistinguishable.

The general area of the transition region is shown in Fig. 90 which summarizes the classification of flows in this series.

**Conclusions**

This experiment was the most satisfactory one of the series.

We have succeeded in mapping three distinct flow regimes which will later be identified as "bubbly", "transition", and "annular".

Further quantitative results for the magnitude of the changes in flow patterns may be obtained by the methods indicated.

**Simulated Burnout Experiment**

With the burnout problem still in mind it was decided to investigate flows at the maximum air capacity of the system. The Griffith correlation (ref.2) gives an estimate for the water flow rates of Figures 87 thru 89, of around 11 cubic feet per minute of air at atmospheric pressure supplied uniformly down the passage to bring about an approach to burnout conditions.
At such low pressures this figure of 110cfm may be inaccurate by a factor of 2 or so, so there is no guarantee of success, especially in a channel of unusual cross-section. About the maximum air flow obtainable with this apparatus is 13cfm. Results of traverses are shown in Figs. 87-89.

Water flows can be measured as accurately as desired, and as patience permits, by waiting for equilibrium and weighing the flow over long periods. The evaporation of water into the air is not significant here since once the water becomes vapor it behaves as the gas phase in the channel and we are only interested in the distribution of water which remains in the liquid phase.

The uniform distribution of flow rate is very marked over the greater part of the channel. Fig. 89 is a particularly good example. There is still a film at the wall which is conceivably maintained by drops sticking to the wall.

In some cases, a strange effect occurs at the left hand wall. In Fig. 88 several points on the abscissa "P = 600", show multiple values of the readings which may indicate an instability akin to "burnout". In Fig. 87 the whole linear shape is lost, there appears to be a shortage of water on the left hand side which could be interpreted as a case of "burnout". (This run was made at the absolute maximum of air compressor capability, pressure line bursting point, etc. and was not repeated.)

The model for such a case is presumably that the velocity of air away from the wall is sufficient to blow the drops, which have turbulent velocities in the stream core, away from the wall with sufficient force to prevent them getting through to the wall itself. Such a model seems reasonable for the burnout phenomenon in the high-quality, low pressure range. More detailed and accurate experiments are needed to confirm or disprove this.
We thus add the final regime to the set; drop-wise flow of water in a stream of air.

**Conclusions on the Simulated Burnout Experiments**

A reasonable model for the approach to burnout at high qualities seems to have been found, it is this:

At high boiling rates the turbulent motion of the water drops in the main stream is insufficient to support the water film which runs down the wall and is being continually depleted by evaporation and by being "blown off" the wall. Burnout conditions result.

Note that at all flow rates the burnout region seems to be preceded by a flow regime in which both phases are uniformly distributed across the channel.

**Checking the Scoop Method**

These experiments are not complete without a demonstration that the scoop is not influencing the flow distribution in the exit plane and making the readings unreliable. To this end the scoop was turned and three flow distributions checked with the reversed scoop.

These are shown in Figs. 81A, 82A, and 83A, which check with Figs. 81, 82, and 83, respectively. Of course, the readings have to be reflected before plotting.

The water-rich layer on the right hand wall of Fig. 83 is checked by Fig. 83A. The rest of the curve is not very good because of large changes in the water flow rate, however the main point has been checked sufficiently.
PHOTOGRAPHS OF FLOW PATTERNS

A further technique possible with this apparatus is to photograph the flow using a high-speed flash. The various flow patterns are well defined and provide a very useful check on the previous experiments. A few photographs of a similar type have been taken by Di Menza (ref.1).

Procedure

The photographs provide essentially a measure of the attenuation of light rays in passing through the flowing mixture. In the experimental set-up the flash, ground glass screen, test section, and camera are arranged in a straight line. The flash gives an intense pulse of light lasting 2 microseconds and this is sufficient to obtain instantaneous pictures of the flow. In spite of the parabolic reflector behind the flash and the ground glass screen in front of it, the illumination of the test-section is not quite uniform. All the pictures turn out to be brighter in the center, but all the same the general flow characteristics are usually clearly visible for the whole length of the passage.

Photographs were taken with camera settings from f8 to f32; the aperture value being chosen to give optimum detail on the negatives. f8 represents the upper limit since for this value the depth of focus becomes insufficient to view the whole flow clearly. There is also the distortion of the image by the plexiglas to be considered at the ends of the section. This is the same as the well-known effect whereby the bottom of a swimming-pool appears to rise away from the side of the pool until it finally hits the water surface.
A pair of photographs was taken at each setting to obtain an estimate of how steady the flow patterns were with time.

It should be stressed that the brightness of successive photographs is not a measure of the relative attenuation of the light rays since both the camera aperture and the printing exposure time are chosen for each picture separately to emphasize the local contrast as well as possible.

Results

Samples of photographs are shown in Figs. 91-97. The trend from "bubbly" to "annular" and finally to a more uniform "streaky" flow at high qualities is clear.

Description of Flow Patterns

"Bubbly" Flow

This flow pattern (or flow regime) consists of air bubbles of all sizes with the interstices filled with water. A close inspection of the pictures shows that many more bubbles near the walls and in some cases these appear attached to a point on the wall, presumably a "nucleation point". The distribution of the two phases looks fairly uniform across the channel. A special enlargement of the bubbly flow regime is shown in Fig.97.

"Transition" Flow

This regime is just what might be expected from a transition from bubbly to annular flow. It is a hybrid of the two forms.
"Annular" Flow

Essentially this regime consists of a core of air, which may contain some water in the form of drops, surrounded by bubbly layers on the bronze walls. The pattern is not at all steady and in places there are bridges of bubbles which appear to span the channel, although these may be only one or two layers thick on the side wall. The bubbly layer on the bronze walls experiences heavy shear stresses from the high speed air stream in the core and is excited to form surface waves, some of which develop into crests and appear to be being torn off to form droplets which are then carried along in the core.

"Drop-wise" Flow

As air flow rates, and hence flowing speeds, are increased the annular flow gives way to a new regime. The photographs show a rather unintelligible mist of varying opacity which it is thought might be due to a flow pattern in which the water in the stream is in the form of drops swirling around with extremely turbulent velocities. There may be some bubbles present but they will be very small since any large ones are torn apart by the intense shear stresses. This model would account for the tendency to uniform water flow rate across the channel at high flowing velocities observed in previous traverse experiments.

"Streaky" Flow

At very high air flow rates the pattern is further obscured by shear stresses acting on the liquid layer on the plexiglas. An enlargement of this kind of flow is shown in Fig. 97.
"Choking" Effects

For high rates of water flow a "choking" effect, similar to that observed for flashing flow of hot liquids, gives rise to high pressure gradients near the exit so that only a small proportion of the air can get in at the beginning of the passage (see Fig. 96).

Comments on Results

One might expect the local flow regime to be a function mainly of the flow rates of the two phases. This would mean that we should have the same series of flow patterns mounting up the passage as we increase the air flow rates from the sidewalls. For example, we should have the same flowing rates of air and water and presumably the same flow regime about 1/2 the way up picture C of Fig. 91 as at the exit of picture B.

Unfortunately, such a correlation does not succeed at all. Picture C appears nearly all annular whereas picture B is certainly bubbly. The flow regime seems in general to be determined more by the rate of bubble formation at the wall (i.e. the simulated boiling rate) than by either the flowing quality or the length along the passage in which the flow has had time to develop.

It should be borne in mind that a photograph does not show all features of the three-dimensional flow. For example, an annular core will not be visible if it is behind a row of bubbles on the plexiglas wall.

An attempt to classify the pictures representing bubbly, transition, and annular flows resulted in transition lines at higher qualities than those shown in Fig. 90. This is partly due to the fact that the photograph does not extend to the full length of the channel (one and one-half inches or so short) and partly due to the shielding effect described above.
The photographs show one thing that the previous traverses cannot hope to show; the variation of flow patterns along the length of the passage.

**Supplementary Photographic Experiments**

A further series of photographs was taken with all the air being introduced at the top end of the passage. The results are not particularly relevant to the present report but the pictures are available at M.I.T. should interest in this type of flow arise.

**Conclusions**

1) Changes in the distribution of the liquid and vapor across the channel correspond to changes in the flow configuration such as from bubbly to annular or drop-flow.

2) The distribution of liquid and vapor across the channel and the flow regime is markedly altered if the vapor is generated at the walls instead of passing with liquid down the channel for the same apparent flowing conditions.

3) No slug flow regime develops when the vapor enters at the walls at a sufficiently high rate.

4) No striking change in flow regime is detected in passing through a simulated burnout.

5) At large rates of vapor formation at the walls, the flow regime appears to be more dependent on the rate of vapor formation than either flowing quality or local velocity.
Mathematical Description of the Analogy

The mathematical description used here is extremely simple.

For a boiler tube we have the approximate relation (which is accurate if the pressure drop in the tube is small):

\[
\text{Volume addition to flow per unit length} = \frac{q_{\text{v}}}{A h_{\text{v}}}
\]

For the analogy:

\[
\text{Volume addition to flow per unit length} = V.
\]

For simple comparisons we equate the above quantities and write:

\[
V = \frac{q_{\text{v}}}{A h_{\text{v}}}
\]

since steam and air properties are comparable at atmospheric pressure.

The main flow characteristics are a result of the interaction of the light gas with the heavy liquid and are determined primarily by the immense density difference. Thus we do not expect significant errors by replacing steam by air.

The analogy does not take account of the loss of water mass when steam is formed. At low pressures this effect is negligible.

Of course a more complete analysis is possible. Dimensionless parameters may be introduced which take account of the difference in properties of steam and air, of the bronze and a boiling surface. Such a development is considered premature in this report which is more a description of techniques and of the kind of results obtainable than an exhaustive investigation.
APPENDIX B

Mathematics of the Differentiation Process

In mathematical symbols we have:

\[ \frac{F_w}{100} = f_w(x) = \text{water flow fraction up to distance } x \]

\[ \frac{F_a}{100} = f_a(x) = \text{air flow fraction up to distance } x \]

\[ Q_w = \text{total water flow cu.ft.per min.} \]

\[ Q_a = \text{total air flow cu.ft.per min.} \]

\[ D = \text{width of passage.} \]

Whence the results:

\[ f_w(D) = f_a(D) = 1 \]

\[ G_w = Q_w \frac{df_w}{dx} = \text{rate of water flow at } x \]

\[ G_a = Q_a \frac{df_a}{dx} = \text{rate of air flow at } x \]

\[ G = Q_w \frac{df_w}{dx} + Q_a \frac{df_a}{dx} = \text{total volume rate of flow at } x. \]

For no slip:

\[ \text{Water concentration } X = \frac{G_w}{G} = \frac{Q_w \frac{df_w}{dx}}{Q_w \frac{df_w}{dx} + Q_a \frac{df_a}{dx}} \]

In most cases \( G_w \ll G_a \) and the stream velocity profile may be taken as the same as the air flow profile, except close to the wall where there is usually a layer rich in water.
APPENDIX C

Simulated Burnout Analysis

Fig. (1) of a report by P. Griffith, "The Correlation of Nucleate Boiling Burnout Data" (ref. 2) shows burnout points plotted on a graph

\[ \frac{P'}{P_c} \text{ vs.} \ \frac{41.5 \left( \frac{h}{h_0} \right)}{(h_g - h_f) / \left( \frac{1}{\rho_g} \left( \frac{k_g}{k_f} \right)^{1/3} \right)} \]

where \( \frac{P'}{P_c} \) is the ratio of stream pressure to the critical pressure.

For the analogy we estimated \( \frac{P'}{P_c} = 0.005 \) giving an ordinate of around 5000.

\( (h_g - h_f) \) is replaced by \( h_g \left( 1 - \frac{2}{3} \right) \)

\( \frac{\dot{Q}}{\dot{Q}_{crit}} \) is given by Appendix A.

The rest of the variables are taken as the corresponding values for air and water where appropriate.

The result is:

for burnout \( Q_c \approx 10.7 \left( 1 - \frac{2}{3} \right) \text{ cu.ft/min.} \)
APPENDIX D

Specification of Materials and Apparatus Details

Test Section

Length 10\textsuperscript{th}, bronze walls 0.50\textsuperscript{in} wide, 0.020\textsuperscript{in} gaskets, section at exit 0.542\textsuperscript{in} x 0.250\textsuperscript{in}.

Porous bronze 1/4\textsuperscript{th} thick, grade 2000 superfine, manufactured by Chrysler Corporation, Detroit, Michigan. Size range of particles filtered 5-12 microns. Pressure drop across bronze 100 inches of water at flow rates of 2 c.f.m./sq.in.

Transparent plastic: 3/8\textsuperscript{th} thick. "Plexiglas".

Scoop

Width 0.40\textsuperscript{in}, sampling center of channel.

Ratio of scoop area to full channel area, 0.74.

Photographic Data

ILLUSTRATIONS

Description of Apparatus

Figs. 1-8 Photographs and diagrams.

Figs. 11-12 Hook gauge calibration curves.

Preliminary Tests of Apparatus Capability

Figs. 13-14 Water traverses, all air added in mixing chamber before flow passage, water flow rate as ordinate.

Fig. 15 Series of water traverses as in 13,14. Fractional flow rate as ordinate.

Fig. 16 Air traverse. Air added in mixing chamber.

Fig. 17 As 16. Air added through bronze walls to simulate boiling.

Fig. 18 Water and air flow rate profiles for Figs. 15,16.

Fig. 19 Comparison of air flow semi-profiles for Figs. 16,17.

Fig. 20 Water flow semi-profiles for Fig. 15.

Simulated Boiling Experiments Using Knife Edge

Figs. 21-30 Air traverses

Fig. 31 Air flow profiles for Figs. 21-30.

Figs. 32-34 Water traverses corresponding to Figs. 24,25,30.

Figs. 35-40 Air traverses for high air flow rates.

Figs. 41-43 Water traverses for high air flow rates.

Figs. 44-48 Detailed water traverses close to wall for high air flow rates.
Simulated Boiling Experiments Using Scoop

Figs. 49-50  Preliminary Tests. Air added in mixing chamber.
Figs. 51-59  Water traverses with simulated boiling. Water flow constant, air flow varied.
Fig. 60  Water flow profiles for Figs. 51-59.
Figs. 61-66  Water traverses.
Figs. 87-89  Simulated burnout experiments. Water traverses.
Figs. 90  Flow regimes deduced from Figs. 49-89.
Figs. 91-97  Photographs of flow patterns. Flow downwards from top of page in all cases. Air added through bronze.
Acknowledgements

This work has been entirely supported by the Office of Naval Research and has been performed in the Heat Transfer Laboratory of the Massachusetts Institute of Technology, which is under the supervision of Professor W. M. Rohsenow.

References

1) "Flow Regimes in a Two-Phase Boiling Analogy",  
   R. G. Di Menza  
   M.I.T.  

2) "The Correlation of Nucleate Boiling Burnout Data",  
   P. Griffith  
200 psi Air

Filter

Orifice Plate \( \Delta p_o, p_o \)

Air to top

Air to sides

Position P of T/S Measured by Micrometer head

City Water Supply

Test Section

Knife Edge

Water - rator

Air - water Separator \( p_R \)

Orifice Plate \( \Delta p_R \)

Vacuum Cleaner

Suction Chamber

Exhaust

Weir and Hook Gauge \( h_R \)

Sink

Left hand half of system not shown on drawing. It is identical with the right hand half.

FIG. 7 SCHEMATIC SYSTEM DIAGRAM
SECTIONAL VIEWS OF KNIFE ARRANGEMENT
AIR SEAL
SCALE: FULL SIZE

FIGURE 8
No bolts, nuts or screws shown.
PAGES (S) MISSING FROM ORIGINAL

Figure 9 ?
PAGES (S) MISSING FROM ORIGINAL

Figure 10 ?
$Q_0 = 0.88$
$Q_w = 0.29$

$Q_0 = 2.16$
$Q_w = 0.29$

FIG. 13

FIG. 14
FIG. 15

\[ Q_a = 0.40 \quad Q_w = 0.29 \]
\[ Q_a = 0.88 \quad Q_w = 0.29 \]
\[ Q_a = 2.16 \quad Q_w = 0.29 \]
\[ Q_a = 3.08 \quad Q_w = 0.29 \]
\[ Q_a = 5.00 \quad Q_w = 0.29 \]

FIG. 16

\[ Q_a = 3.08 \]
\[ Q_w = 0.29 \]
FIG. 17

Air in Sides Only

FIG. 18

$Q_a = 3.08$
$Q_w = 0.29$
$Q_a = 3.08$
$Q_w = 0.29$

Air in top only

Air in sides only

$G_a$

$P$

FIG. 19

$Q_a = 0.40$ $Q_w = 0.29$
$Q_a = 0.88$ $Q_w = 0.29$
$Q_a = 2.16$ $Q_w = 0.29$
$Q_a = 3.08$ $Q_w = 0.29$
$Q_a = 5.00$ $Q_w = 0.29$

$G_w$

$P$

FIG. 20
FIG. 21

$Q_a = 3.7$
$Q_w = 0.032$

FIG. 22

$Q_a = 4$
$Q_w = 0.066$

FIG. 23

$Q_a = 4$
$Q_w = 0.184$

FIG. 24

$Q_a = 3.7$
$Q_w = 0.182$
FIG. 25

\[ Q_a = 3.7 \]
\[ Q_w = 0.288 \]

FIG. 26

\[ Q_a = 3.7 \]
\[ Q_w = 0.40 \]

FIG. 27

\[ Q_a = 3.8 \]
\[ Q_w = 0.80 \]

FIG. 28

\[ Q_a = 3.6 \]
\[ Q_w = 1.12 \]
\[ Q_a = 5.2 \]
\[ Q_w = 1.12 \]

\[ Q_a = 6.5 \]
\[ Q_w = 0.80 \]
FIG. 44

- $Q_a = 11.6 \quad Q_w = 0.347$
- $Q_a = 0 \quad Q_w = 0.393$
\begin{figure}[h]
\centering
\includegraphics[width=0.7\textwidth]{fig45.png}
\caption{FIG. 45}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=0.7\textwidth]{fig46.png}
\caption{FIG. 46}
\end{figure}
$$Q_a = 3.90$$
$$Q_w = 0.234$$

FIG. 56

$$Q_a = 5.4$$
$$Q_w = 0.233$$

FIG. 57

$$Q_a = 9.2$$
$$Q_w = 0.234$$

FIG. 58

$$Q_a = 14.0$$
$$Q_w = 0.237$$

FIG. 59
FIG. 69

\( Q_e = 2.5 \)
\( Q_w = 0.357 \)

FIG. 70

\( Q_e = 3.3 \)
\( Q_w = 0.360 \)

FIG. 71

\( Q_e = 4.0 \)
\( Q_w = 0.357 \)

FIG. 72

\( Q_e = 4.06 \)
\( Q_w = 0.400 \)
\[ Q_a = 3.18 \]
\[ Q_w = 0.091 \]

\[ Q_a = 5.55 \]
\[ Q_w = 0.088 \]

\[ Q_a = 1.93 \]
\[ Q_w = 0.122 \]

\[ Q_a = 2.12 \]
\[ Q_w = 0.154 \]
FIG. 81
SCOOP REVERSED

Q_a = 2.42
Q_w = 0.141

FIG. 82
SCOOP REVERSED

Q_a = 2.81
Q_w = 0.125

FIG. 81A

Q_a = 2.40
Q_w = 0.120

FIG. 82 A

Q_a = 2.92
Q_w = 0.104
FIG. 90

- ● Bubbly flow
- ○ Transition region
- □ Annular flow
- △ Simulated burnout points (dropwise flow)
FIGURE 91
PHOTOGRAPHS OF FLOW PATTERNS.
FIGURE 92

A

\( Q_{(cfa)} \) 0.075
\( Q \ (cfa) \) 0.72

B

0.074
1.45

C

0.074
3.6

D

0.070
6.8

E

0.067
12.1
FIGURE 95

A

\[ Q_w (\text{cfm}) \] 0.304
\[ Q_a (\text{cfm}) \] 1.84

B

0.293
5.3

C

0.280
11.1
FIG. 97 TYPICAL FLOW REGIMES

BUBBLY

ANNULAR

STREAKY