SEMI-ANNUAL STATUS REPORT ON BOILING FLOW INSTABILITY

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By A. H. Stenning and T. N. Veziroglu

The boiling flow instability studies carried out during the fourth six-monthly period of the project can, in general, be divided into four groups; viz., (a) the classification and explanation of different types of instabilities, (b) inlet pressure drop versus overall density ratio relationships at the stability boundary for the density-wave type oscillations, (c) subcooling versus mass flow rate relationships at the stability boundary for the density-wave type oscillations, and (d) pressure drop versus mass flow rate relationships for the pressure-drop type oscillations.

The results of the experiments leading to the classification of the boiling flow instabilities and their explanations have been presented as a separate report [1] early in the period in January 1965.

As a continuation of the program started during the last six-monthly period, to investigate inlet pressure drop versus overall density ratio relationships at onset of density-wave type instabilities, a new series of experiments were carried with a different system geometry. The results, in agreement with the earlier experiments [2], again indicate that a one-component two-phase flow system is more stable than a two-component two-phase flow system.

Two series of experiments - with and without exit restrictions - were carried out to investigate the subcooling versus mass flow rate relationships at the stability boundary of density-wave type oscillations. For the range studied, the curves at constant power input have S shapes with rather sharp (acute angled) bends. This feature of the curves for Freon-11 is in contrast with rather smoothly inverted C shaped curves obtained for water by Gouse and Andrysiak [3].

Some experiments have been carried out to gain an insight into the mechanism causing the pressure-drop type oscillations. These indicate that during the oscillations the heat flux to the fluid changes considerably although the heat generated in the heater (tube wall) is nearly constant.

FREON-11 APPARATUS

All the experiments were carried out using the Freon-11 apparatus described in an earlier report [2]. However, since then some changes have been incorporated in the apparatus. Figure 1 shows the Freon-11 apparatus including the new changes. A differential pressure transducer, Sanborn Model 270, has been installed at the upstream side of the heater to record the instantaneous flow rate and also the flow oscillations. The clear lucite walled surge tank, which failed due to fatigue, has been replaced by a stainless steel surge tank of 4 in. dia. x 9 in. height, with a sight glass. In addition to tubing downstream of the heater, the upstream tubing between the heater inlet and the Freon-11 container and the surge tank have all been insulated using glass wool and asbestos tape. This helped to minimize the temperature decrease between the Freon-11 container exit and the heater inlet by reducing the heat losses during the subcooling experiments.

During the second series of experiments carried out to study the effect of subcooling on density-wave type oscillations, the exit valve was removed from the system and replaced by a 3/16 inch O.D. nichrome tube. In all the other experiments, the exit valve was installed and used with various pre-settings.

EXPERIMENTAL PROCEDURE

In experiments for studying the inlet pressure drop versus overall density ratio relationship at the onset of density-wave type oscillations, first, liquid Freon-11 was run through the system with the inlet valve partly closed and the exit valve fully open, after pressurizing the Freon-11 in the container up to 50 to 60 p.s.i.g. by means of pressurized Nitrogen gas. Then the heater was started at a relatively low power level of about 100 watts.

The heater power input was then increased to a predetermined test level by 50 watt increments. In order to prevent unwanted transient instabilities, about 5 to 10 minutes was allowed to elapse after each change in power level. During the heater power level increases, the Freon-11 flow rate was increased as required by further opening the control valve so that the system was always operating within the stable region at steady state. After the test power level was reached, the exit valve was set so as to provide a predetermined exit pressure drop and the control valve was set to provide a predetermined flow rate. Then the inlet valve was slowly opened till the onset of the density-wave type oscillations was noticed. At the stability boundary the room temperature, barometric pressure, Freon-11 mass flow rate, heater voltage and current, and pressure and temperature (thermocouple) readings at various stations along the test system were recorded. After taking the readings, the flow rate was slightly reduced by closing down on the control valve. This caused the system to operate in the unstable zone. At this stage, the heater exit pressure oscillations and the oscillations in the differential pressure across the venturi-meter (i.e. Freon-11 flow rate) were recorded on the Sanborn recorder. Figure 2 shows a sample of such recordings. The above mentioned procedure was repeated for various flow rates, exit valve settings and heater power levels.

In the experiments carried out to study the effect of subcooling on the stability boundary for density-wave type oscillations, the pressurized (50 to 60 p.s.i.g.) Freon-11 in the container was heated to a predetermined temperature level between the room temperature and the saturation temperature for the heater inlet conditions, using the immersion heater in the Freon-11 container and its thermostat controls. The inlet valve was kept completely open and the exit valve was partially opened, and this setting of the exit valve was kept the same throughout the first series of the subcooling experiments. Then the heated Freon-11 (liquid) was run through the system by opening the control valve and the "main" heater was started at a relatively low power. The heater power was then increased by small increments up to a predetermined level by making sure that at all times the system was operating within the stable zone as described in the paragraph above. After the test power level was reached, the control valve was slowly closed thereby reducing the mass flow rate till the onset of density-wave type oscillations was noticed. At this stage all the readings, as in the case of above mentioned experiments, were taken. The procedure was repeated for various inlet temperatures by changing the Freon-11 container thermostat setting, and also for various heater power levels. A second series of subcooling experiments were run with the exit valve removed, in order to study the effect of exit restriction.

In experiments on the pressure-drop type of two-phase flow oscillations, steady state pressure drop versus mass flow rate curves for various heater power levels were obtained for the region covering these oscillations. In these steady state experiments, the exit valve was set to a predetermined opening, and the system was started and the heater power level was brought up to a predetermined level as explained for the density-wave experiments in the first paragraph above. Then, by further opening the control valve and the inlet valve, the mass flow rate was brought up to a maximum. At this stage all the pressure, temperature, flow and power readings were taken. The procedure was then repeated by reducing the mass flow rate, by means of the control valve, at predetermined steps. Whenever required, the heater inlet pressure drop was increased, by partially closing the inlet valve, to make sure that the system operation was stable. In some of the experiments, an X-Y Recorder was employed to obtain a direct plot of the heater inlet to system exit pressure drop versus mass flow rate. Using the same recorder, also some pressure-drop oscillation limit cycles were plotted with the inlet valve open.

To check the efficiency of the vacuum jacket around the "main" heater, a few tests were run. The heat input into the Freon-11 calculated from the mass flow rate and the enthalpy increase was within 3 per cent of that found from electrical measurements, indicating an efficient thermal insulation.

EXPERIMENTAL RESULTS

In studying the overall density ratio versus the inlet pressure drop relationships for onset of density-wave type oscillations, it was not possible to keep all but two of the parameters - affecting the stability boudary - constant and investigate their relationship. Under the circumstances, in order to reduce the number of variables, first overall density ratios ($1/r_{exit}$) were plotted against the heat fractions expended in removing subcooling (c) for all the experiments falling into this group (Fig. 3). As seen from the figure, points corresponding to constant heater power levels fall on smooth curves which are in fact operating curves for the system. Then the points corresponding to a constant c have been selected from Figure 3, and the inlet pressure drop fraction (y) and the overall density ratio ($1/r_{exit}$) have been determined for each such point. In order to keep c constant, some of the points have been found by interpolation between the two nearest onset points. The results have been plotted for various values of c in Figure 4. The region above each curve is stable from the point of view of density-wave type oscillations, and below unstable. From Figure 4, it can be seen that for density-wave type instability, (a) increase in overall density ratio decreases stability, (b) increase in the inlet pressure drop fraction increases stability, and (c) increase in subcooling decreases stability for the range of the parameters investigated. All these observations were also made in the case of similar experiments carried out during the third six-monthly period [2], for a different system geometry. In the earlier experiments there was no surge tank which resulted in a relatively long inlet tubing with an inlet tubing length to heater length ratio of 3.32, while in the present experiments with the surge tank the length ratio was only 0.91. Comparing the results of the earlier experiments (Fig. 4 of the report [2]) with the results of the present experiments (Fig. 4), it can be observed that (a) for zero inlet pressure drop fraction the boundary curves for a given value of the subcooling parameter c tend to intersect the overall density ratio axis at the same point (or at the same overall density ratio) irrespective of the inlet tubing length, and (b) as the inlet pressure drop fraction increases, the system with the shorter inlet tubing becomes more stable. All of the above experiments were carried out with inlet temperatures below 80°F.

Figures 5 and 6 show subcooling (the difference between the temperature at the start of boiling and the inlet temperature) versus mass flow rate relationships at the stability boundary of density-wave type oscillations, with and without exit valve respectively. The variation in subcooling was obtained by increasing the Freon-11 inlet temperatures from room temperatures up using the tank immersion heater. It was found that the inlet temperatures could not be raised up to saturation temperatures without having some cavitation visible in the glass tube at the heater inlet. In order to keep the number of variables down to a minimum, cavitation of Freon-11 before entry into the heater was avoided by limiting the inlet temperature to the heater. As can be seen from Figures 5 and 6, the minimum subcooling allowable (without cavitation before the heater) ranged from 7^{o}F. at a heat flux of 8500 BTU/hr.ft.^{2}(corresponding to a heater input of 300 watts) to 20^{o}F. at a heat flux of 22650 BTU/hr.ft.^{2} (corresponding to a heater input of 800 watts). From a study of Figures 5 and 6 it can generally be observed that for the density-wave type oscillations (a) increase in heater heat flux (or increase in heater input) decreases stability, (b) removal of the exit restriction has a slight beneficial effect on stability. The shapes of the curves, more clearly shown in Figure 6, are interesting. They have, for the region investigated, S shapes with rather sharp bends, indicating a sudden increase in stability as the subcooling is increased above a certain value (which increases with the heater input). The curves show that for a given mass flow rate there may exist three different subcooling values at the stability boundary. Probably there would be at least one more subcooling value at the boundary, a value greater than any of the three indicated in the diagrams, since the upper branches of the curves must turn back towards the subcooling axis as the subcooling is increased above the range investigated. Another interesting feature of the results is the tendency of the upper branches of the curves to form into one envelope. Gouse and Andrysiak [3] have reported similar experiments using water. Their results, plotted as subcooling versus mass flow rate at the stability boundary, do not show S shaped curves, but inverted C shapes. However, they indicate that the nature of closure at the bend is not quite clear.

Figures 7 and 8 show the results of the experiments carried out for a better understanding of the pressure-drop type oscillations. Figure 7 shows mass flow rate versus heater inlet to system exit pressure drop for three different heater power inputs, covering the region of pressure-drop type instability. As explained in the last report [1], the pressure-drop type oscillations occur in the negative slope region of the curves provided that the inlet pressure drop fraction is low enough. One interesting feature of the curves is that they each appear to have two maxima with a small dip in between. This feature is more prominent in the curves B and C corresponding to heat inputs of 355 and 390 watts. Figure 8 shows X-Y Recorder plots of mass flow rate versus heater inlet to system exit pressure drop for steady state corresponding to a heater input of 350 watts, and also for two different pressure-drop oscillation limit cycles for the same heater input. The limit cycle A corresponds to pure pressure-drop oscillations, and the limit cycle B corresponds to pressure-drop oscillations with a few super-imposed density-wave oscillations. During the pressure-drop oscillations the heater wall temperatures were observed to oscillate with amplitudes of about $2^{\circ}F$. This fact, and a study of the figures 7 and 8 show that during the pressure-drop oscillations there must be large changes in heat flux into the Freon-11 although the heat generation in the heater is steady. Instead of moving along a single pressure-drop curve (as would be the case if the heat input to the fluid stayed constant during the oscillation), the system follows a closed loop which covers a range of power levels.

OUTLINE OF THIRD YEAR'S PROGRAM

The third year's program will mainly consist of the work outlined below:

1. Run stability boundary and other experiments for density-wave oscillations in the superheat region using Freon-11 apparatus.
2. Run stability boundary and other experiments for pressure-drop oscillations, using Freon-11 apparatus.
3. Run experiments to study slip in two-component two-phase flow using Air-Water apparatus.
4. Make a digital computer study of pressure-drop oscillations.
5. Time permitting, make a more detailed computer study of density-wave oscillations with a closer representation of pressure drop, heat transfer and slip effects.
6. Study oscillations in boiling water, using the Freon-11 apparatus, to determine whether results for different fluids can be scaled using similarity laws.

University of Miami
Coral Gables, Florida
May 1965

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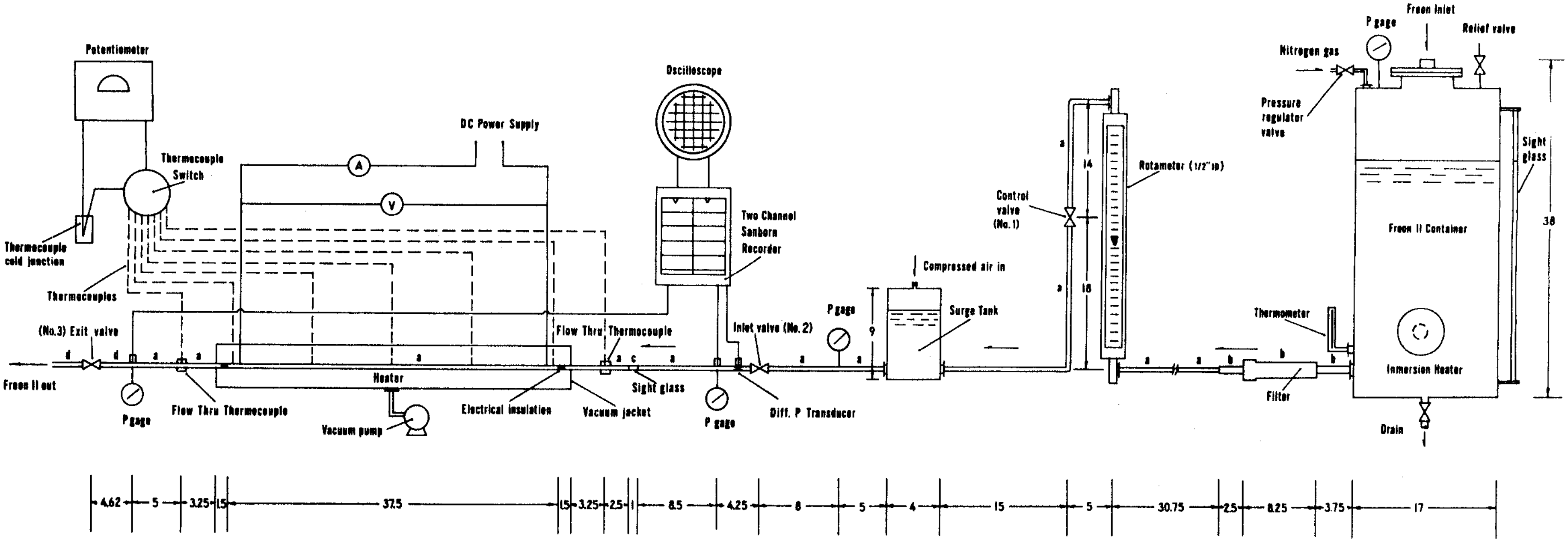
2. Stenning, A. H. and Veziroglu, T. N.: "Semi-Annual Status Report on Boiling Flow Instability", NASA Grant NsG-424, Report No. 5, November 1964.

3. Gouse, S. W. and Andrysiak, C. D.: "Flow Oscillations in a Closed Loop with Transparent, Parallel, Vertical Heated Channels", M.I.T. NSF Grants G11355 and G19771 Report No. 8973-2, June 1963.

LIST OF FIGURES



Inside Tube Dia	
a	0.1475
b	0.5
c	0.155
d	0.185

__Note__: All dimensions in inches.

FIG. 1.— SCHEMATIC DIAGRAM OF EXPERIMENTAL SET-UP FOR ONE-COMPONENT TWO-PHASE FLOW INSTABILITY [FREON-11 APPARATUS]

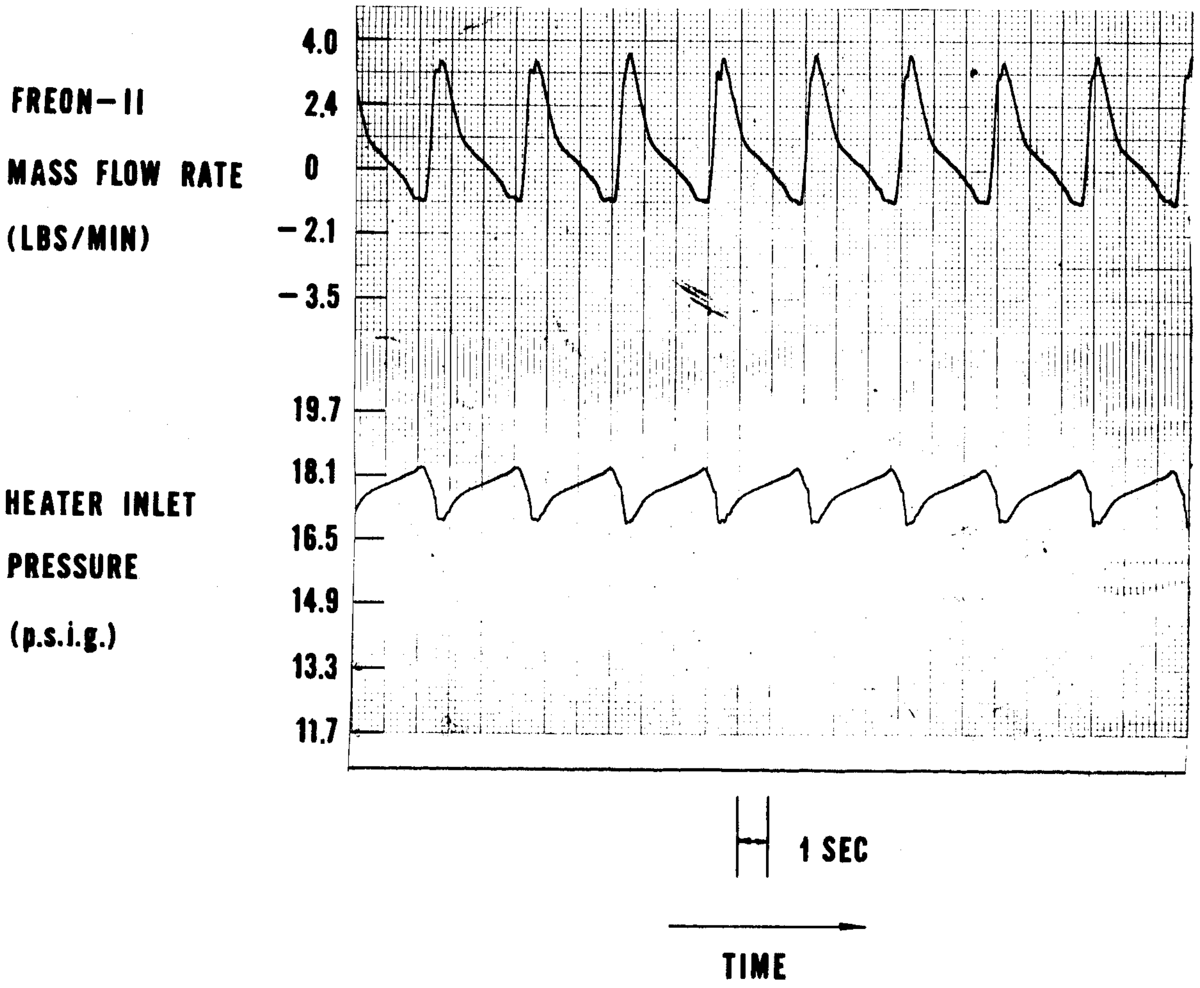


FIG. 2.– MASS FLOW RATE AND PRESSURE RECORDING OF DENSITY–WAVE TYPE OSCILLATIONS

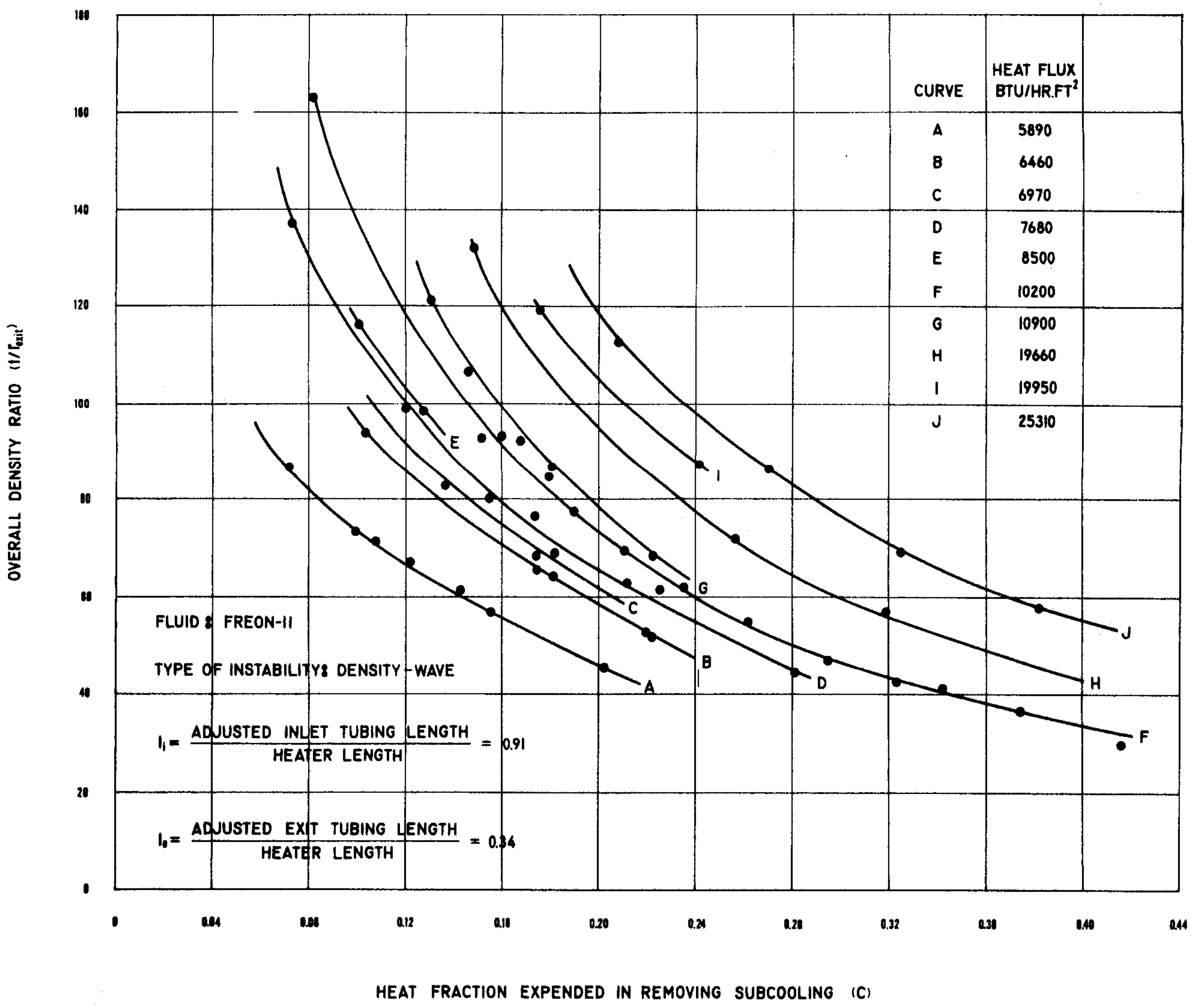


FIG. 3.- OVERALL DENSITY RATIO VS HEAT FRACTION EXPENDED IN REMOVING SUBCOOLING

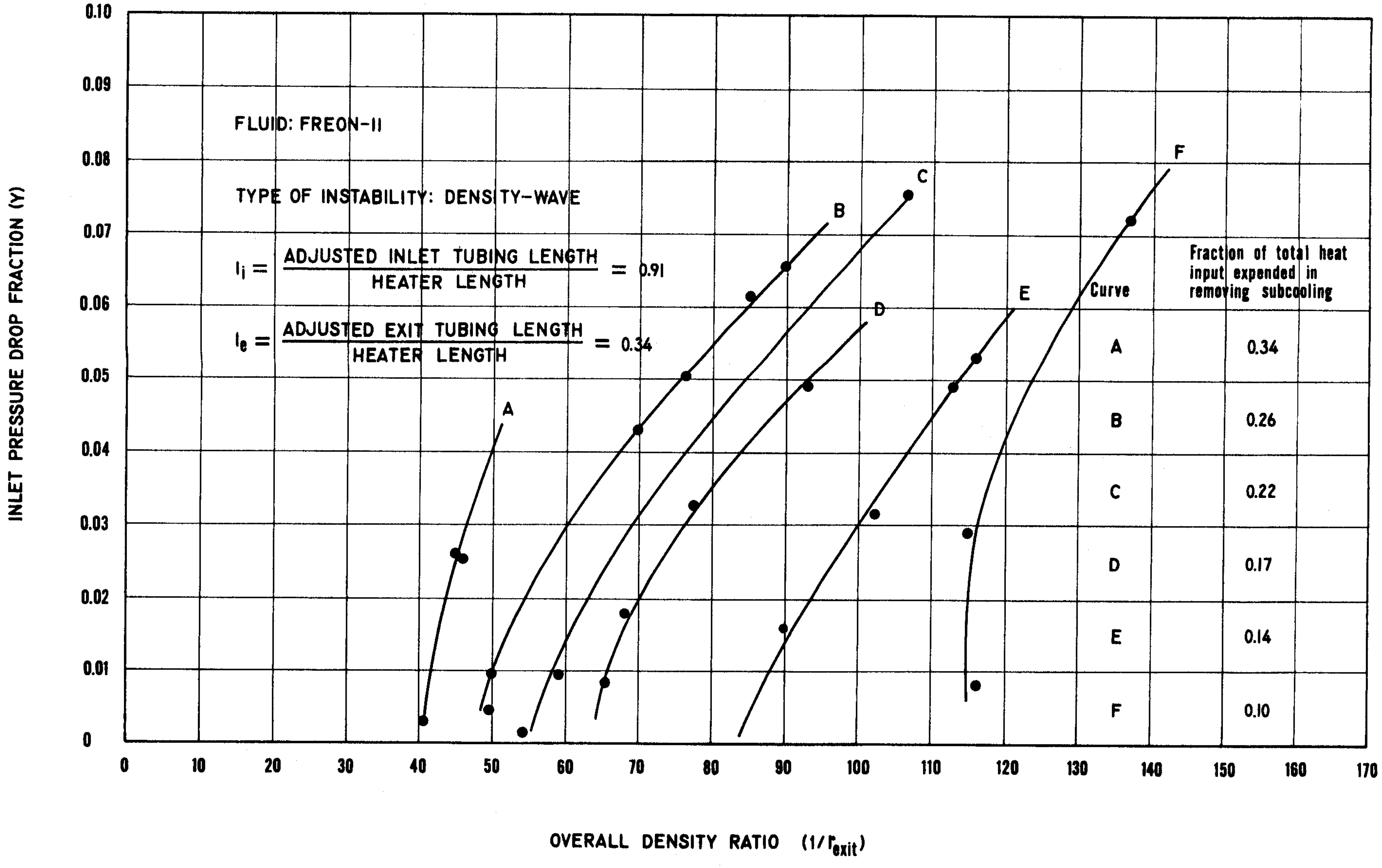


FIG. 4.- INLET PRESSURE DROP FRACTION VS OVERALL DENSITY RATIO AT STABILITY BOUNDARY

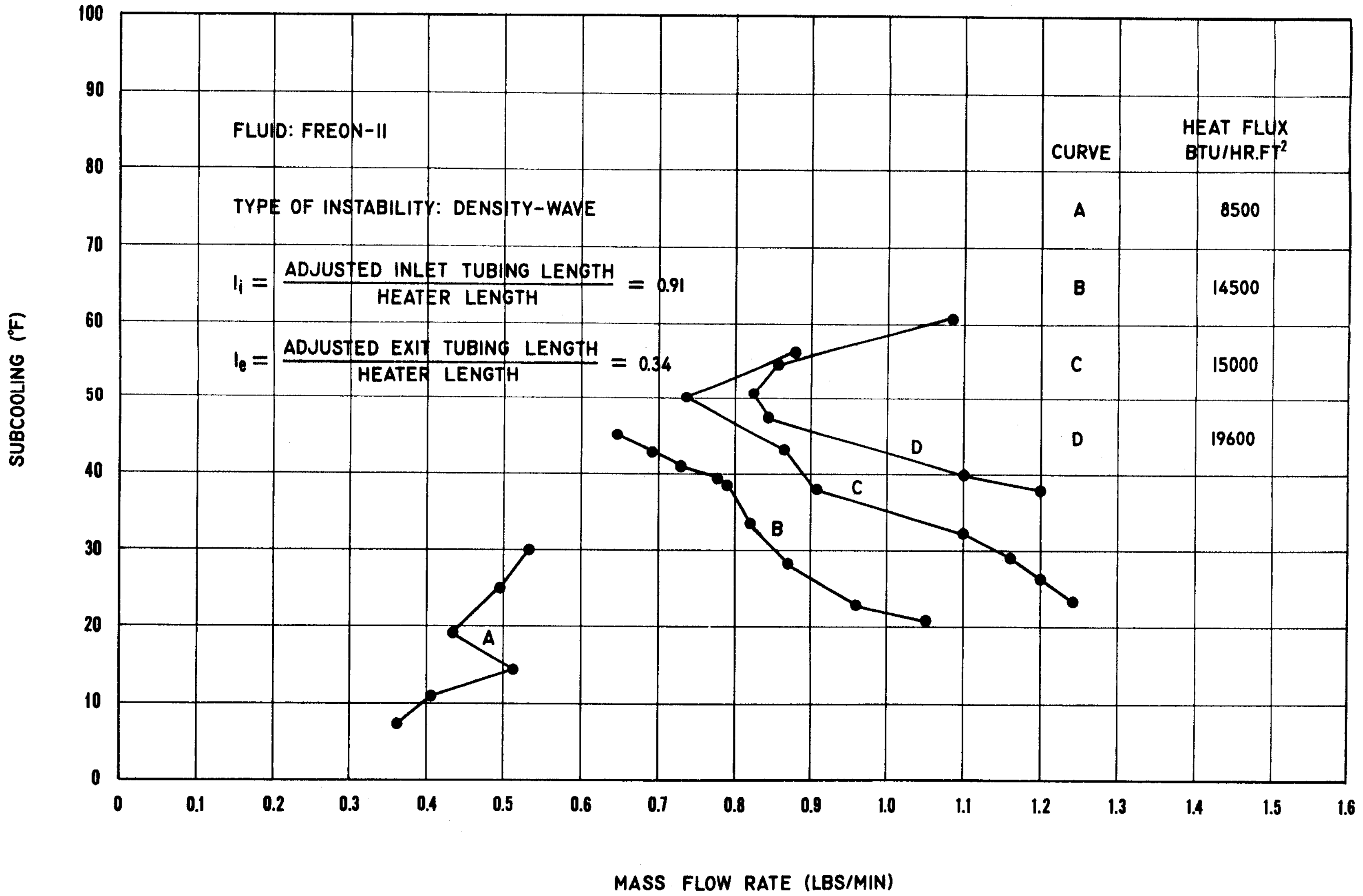


FIG. 5.- SUBCOOLING VS MASS FLOW RATE AT STABILITY BOUNDARY FOR FIXED GEOMETRY (EXIT VALVE PARTLY CLOSED)