Int. J. Multiphase Flow Vol. 5, pp. 463–478
Pergamon/Elsevier, 1979. Printed in Great Britain
AECL–6743

EXPERIMENTAL STUDY OF CHF IN VERTICAL AND HORIZONTAL TUBES COOLED BY FREON-12

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(*Received* 1 *April* 1979; *in revised form* 27 *September* 1979)

Abstract—The influence of test section orientation and diameter on flow boiling crisis occurring in tubes has been studied experimentally using Freon-12 as a coolant. At low mass flux the critical heat flux (CHF) was lower in horizontal flow than in vertical. As either the liquid or vapour velocity, or both, were increased the vertical and horizontal CHF results converged. Above a mass flux of $4\,Mg \cdot m^{-2} \cdot s^{-1}$ the results were essentially identical.

The effect of tube diameter on boiling crisis in general depends crucially on the parameters which are maintained constant when the comparison is made.

1. INTRODUCTION

The magnitude of heat transfer rates which can be achieved in two-phase flow boiling systems is limited by the boiling crisis phenomenon. This situation can occur when, due to local hydrodynamic conditions, a dry region appears on a heater surface, causing a precipitous drop in the local heat transfer coefficient. If heat input to the surface persists, large and potentially hazardous temperature excursions can result. The ability to predict the critical heat flux (CHF) at which boiling crisis occurs is therefore essential for such components as boiler tubes and nuclear reactor fuel channels.

Considerable work has been performed to date on this phenomenon under conditions of vertical upflow, however, data for horizontal flow systems are limited. This situation may be caused partly by the results of several early experiments by Schmidt (1960), Waters *et al.* (1964) and Hesson *et al.* (1964) which indicated very little difference in CHF between vertical and horizontal flow. The reasons for these results can be found in the flow conditions under which the measurements were taken.

Differences between horizontal and vertical two-phase flow and heat transfer are caused by the transverse gravity force which is present in horizontal flow. This force, if unopposed, gives rise to a stratification of different density fluids with the lighter phase migrating towards the top of the flow channel and the heavier phase to the bottom. Opposing this separation of phases is the turbulent mixing phenomenon which tends to homogenize the phase distribution across the cross section. The behavior of a two-phase flow in a horizontal channel is therefore affected strongly by the ratio of buoyancy to mixing forces.

Schmidt (1960) conducted boiling crisis experiments in tubes of small diameter in a pressure range of 17–21 MPa, and found essentially no difference between vertical and horizontal flow. At these high pressures, however, the density ratios (liquid density/vapor density) were in the range of 2–4.6, resulting in small buoyancy forces compared to those which occur at lower pressures.

Waters *et al.* (1964) performed all their CHF measurements in a pressure range of 6.9–10 MPa at and above a mass flux of $6.8\,Mg \cdot m^{-2} \cdot s^{-1}$. Under these conditions, as discussed by Merilo (1977), bouyancy induced phase stratification is effectively thwarted by the turbulent mixing, and flow direction no longer affects the boiling crisis.

Hesson *et al.* (1974) compared the critical heat flux in a vertically and horizontally oriented 19-rod bundle and found very little difference for mass fluxes as low as $1.4\,Mg \cdot m^{-2} \cdot s^{-1}$ at a pressure of 8.27 MPa. When the mass flux was reduced to $0.68\,Mg \cdot m^{-2} \cdot s^{-1}$, however, the

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horizontal CHF declined by as much as 30 per cent when compared to the vertical. The reason that the mass flux could be reduced to $1.4\,\mathrm{Mg \cdot m^{-2} \cdot s^{-1}}$ in horizontal flow without any adverse effect on CHF, is probably that the bundles were wire wrapped, greatly enhancing the turbulent mixing over that which would otherwise exist.

More recent experiments by Becker (1971), Robertson (1973) and Merilo (1977), have shown that the orientation of the test section can exert considerable influence on CHF. In particular, the concentration of the void near the top of the test section in horizontal flow, makes this area susceptible to premature boiling crisis when compared to vertical flow.

Becker (1971) conducted horizontal flow CHF experiments in tubes with bores of 9.95 and 12.6 mm, and a heated length of 96 cm. The pressures ranged from 1 to 3 MPa. The results were compared with a correlation for vertical flow. He found that for a mass flux greater than $0.5\,\mathrm{Mg \cdot m^{-2} \cdot s^{-1}}$ the horizontal results and vertical calculations were substantially in agreement. At lower mass flux upstream boiling crisis was observed and the critical quality decreased abruptly. The effect of increasing the tube diameter was to increase the mass flux at which upstream boiling crisis first appeared.

Robertson (1973) compared Becker's unpublished horizontal CHF data in a tube with a 12.6-mm bore with vertical data in an identical tube obtained by Bennett *et al.* (1965) under otherwise identical conditions. This comparison showed a significant degradation of CHF in horizontal flow. He further speculated that the reduction in CHF for a horizontal tube over that for a vertical tube increases as the tube diameter increases, but no directly applicable experimental evidence to support this contention was presented.

In an earlier study Merilo (1977) compared the vertical and horizontal CHF obtained in a 12.6-mm tube using both water and Freon-12 as coolant. It was found that vertical and horizontal boiling crisis were the same at high liquid velocity (high mass flux, low quality range) and at high vapor velocity (high quality). Otherwise, however, the critical heat flux in horizontal flow was less than that in vertical flow. This is consistent with the role of turbulent mixing in opposing the buoyancy induced stratification. It was further found that modeling parameters for fluid-to-fluid modeling of boiling crisis in vertical flow are not applicable to horizontal flow.

It is the purpose of the present set of experiments to elucidate the effects of diameter on CHF in horizontal flow, and to provide data suitable for the determination of corresponding fluid to fluid modeling parameters. To achieve this goal, tests were performed with Freon-12 as coolant in tubes with a bore of 5.3 and 12.6 mm, under otherwise identical conditions. Experiments were also conducted in a 12.6-mm tube with water as a coolant.

The test results for the 12.6-mm tube are discussed in detail by Merilo (1977), however, the actual data for both tubes are given by Merilo & Ahmad (1979). This data, in conjunction with that reported by Robertson (1973) was used by Merilo (1979) to determine fluid-to-fluid modeling parameters applicable to CHF in horizontal flow. The present report concentrates on the experiments with the 5.3-mm tube and provides a comparison with the larger diameter tube results where appropriate.

2. APPARATUS AND PROCEDURE

The test section consists of a Monel tube with a bore of 5.3 mm. The heated length can be changed to any desired value less than 3.05 m by moving the upstream power clamp. A schematic diagram of the test section showing the clamp and thermocouple locations is presented in figure 1. The test section is directly heated with a 55-kW d.c. power supply.

A simplified schematic diagram of the MR-3 Freon-12 loop is shown in figure 2. Subcooled Freon-12 coming from the pump is split into a test section flow and a bypass flow. The test section flow rate is controlled by a throttling valve while the temperature at the inlet of the test section is regulated with a preheater just downstream of this valve. The test section outlet pressure is adjusted by controlling the pressure in the jet condenser with a pressure controller which operates a three-way valve in the bypass.

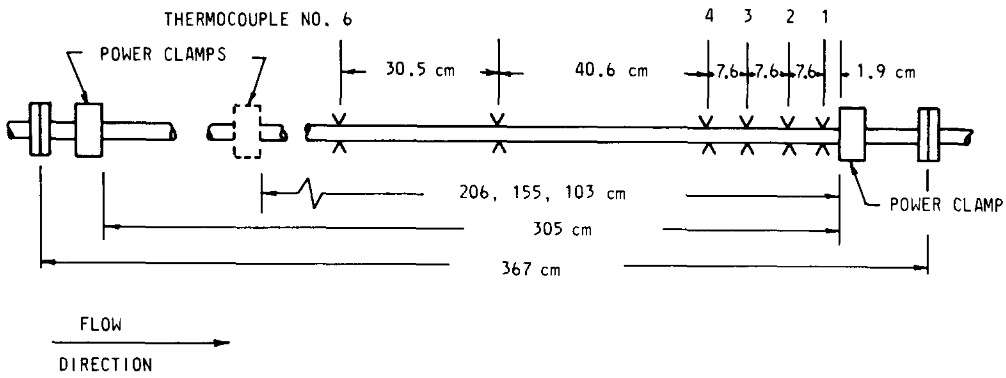

Figure 1. Schematic diagram of the test section.

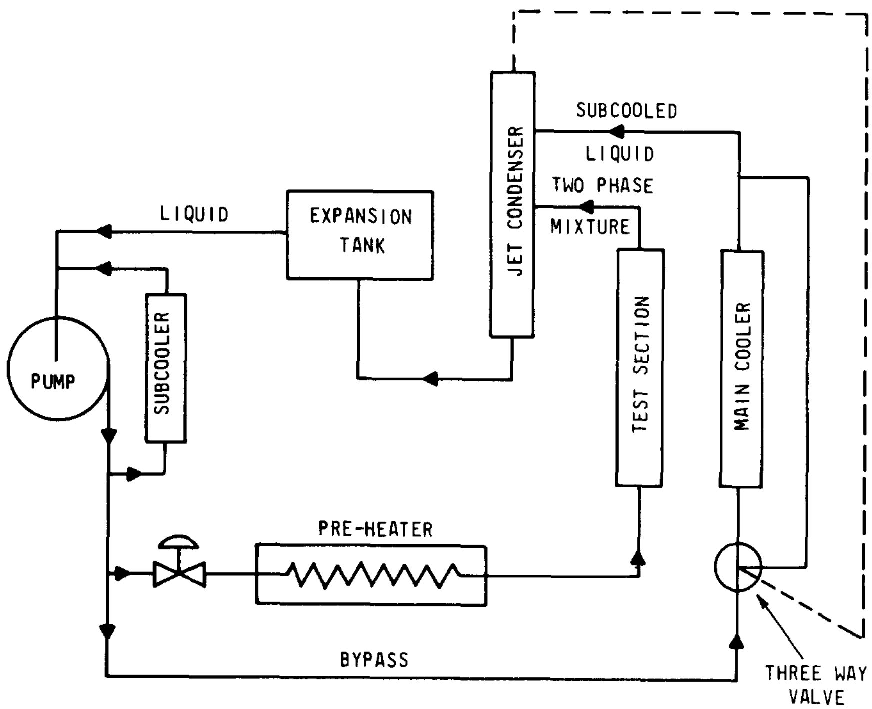

Figure 2. Schematic diagram of the Freon loop.

Power to the test section is determined by measuring the voltage drop across the test section and across an on-line calibrated resistor. The outlet pressure is measured with a Heise Bourdon type pressure gauge while the test section and bypass flow rates are monitored with turbine flow meters. The thermocouple outputs are recorded on Brush 8-channel recorders.

The measurements were performed by maintaining the test section outlet pressure, inlet temperature and flow, constant while the test section power was slowly increased. CHF was detected by observing the response of the thermocouples to small increases in test section power. A sudden increase in the heater temperature was taken as an indication of the breakdown in the heat transfer mechanism characterizing boiling crisis. At this point the power was decreased until the thermocouple location had rewet.

The test conditions were then readjusted, if necessary, and the power was raised slowly until boiling crisis was again observed. At this point computer scans of all the instrument signals were taken and recorded. The range of conditions tested is given in table 1.

Table 1. Range of variables

Outlet pressure	1.05 and 1.52 MPa
Density ratio	20 and 13
Mass flux	1.6–8.1 $Mg \cdot m^{-2} \cdot s^{-1}$
Inlet quality	−35–0 per cent
Heated length	1.03–3.05 m
Length/diameter	193–571

The outlet pressure and the L/D ratios were chosen to be the same as the tests for the 12.6-mm tube so that proper comparisons of the data could be made. To elucidate the mechanism of distributed boiling crisis at high mass flux, a copper clamp was attached to the test section in the region over which distributed boiling crisis was previously observed. This clamp, by providing a low resistance path for the current, produced an unheated section, or cold patch over this region.

3. EXPERIMENTAL RESULTS AND DISCUSSION

3.1 *Basic results*

In vertical flow, boiling crisis was always detected first at the downstream end of the heated length. Occasionally, however, at high mass flux, the exit as well as a considerable portion upstream would experience boiling crisis simultaneously. This is consistent with the observations which were made by Merilo (1977) on the 12.6-mm-dia. tube.

The situation where boiling crisis is distributed over an area of the tube including the end of the heated length is referred to as a "distributed boiling crisis". This is in contrast to an "upstream boiling crisis" which has the implication that portions of the heater surface downstream of the critical location still remain wet.

In horizontal flow, boiling crisis was most often detected at the top of the test section exit, though occasionally a distributed boiling crisis along the top of the tube was also observed. No upstream boiling crisis was noticed, however, in contrast to the results obtained from the 12.6-mm tube. In part, this result may be due to the measurement technique. Only thermocouples were used in the present experiments and consequently boiling crisis could only be detected at those locations where thermocouples were installed. For the measurements with the larger diameter tube, however, a temperature sensitive encapsulated liquid crystal film was used and boiling crisis could be detected at any location.

The results for vertical upflow are shown on a local condition basis in figures 3 and 4 for exit pressures of 1.05 and 1.52 MPa. At both pressures an inverse mass flux effect on critical heat flux (CHF) at constant critical quality is apparent up to a mass flux of 4.1 $Mg \cdot m^{-2} \cdot s^{-1}$. At higher mass fluxes the mass flux effect is direct. These results are also consistent with the local conditions hypothesis in that curves for different heated lengths appear to coincide; implying that the CHF is independent of the heated length. For uniform axial heating this is a common result, however experiments with non-uniform heat flux profiles have shown that this hypothesis is not true in general.

3.2 *Distributed boiling crisis*

At a mass flux of 8.1 $Mg \cdot m^{-2} \cdot s^{-1}$, with a heated length of 3.05 m, a distributed boiling crisis occurred over at least the last 65 cm of the test section. This corresponds to a critical quality range of from 12 to 20 per cent, which is the same range over which distributed boiling crisis was observed in the 12.6-mm tube.

To study this phenomenon more closely, an 8-cm long split copper sleeve was clamped to the tube, butting against the upstream side of thermocouple 3 (figure 1). Thermocouple 4 was moved to a location approx. 3 cm upstream of the sleeve. Since the tube was directly heated, the sleeve provided a low resistance path for the electric current, thereby introducing a cold

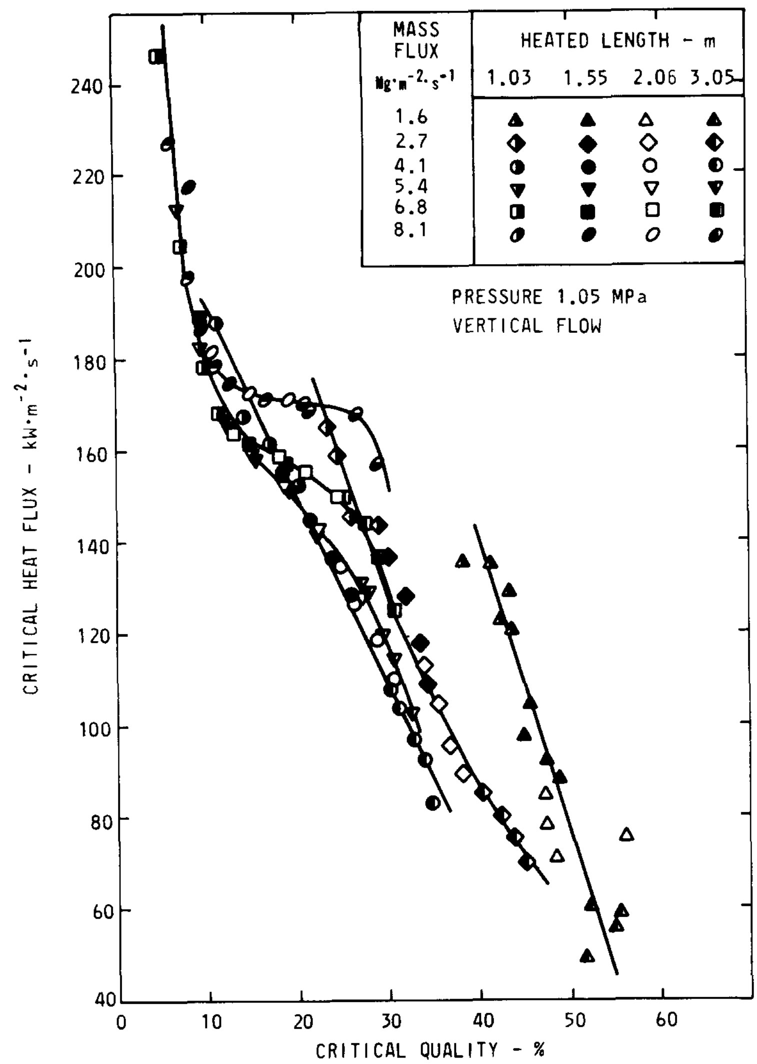

Figure 3. Vertical CHF as a function of quality at a pressure of 1.05 MPa.

patch into the heated length. The cold patch location was chosen to be wholly within the region of distributed boiling crisis for a mass flux of 8.1 Mg · m^{-2} · s^{-1}. When a previous experiment, for which thermocouples 1-5 had all indicated simultaneous boiling crisis, was repeated, thermocouples 1, 2, 4 and 5 again exhibited simultaneous boiling crisis. Thermocouple 3, however, indicated that at the location of the sleeve the tube was still wetted.

This result strongly suggests that a distributed boiling crisis is not the result of either a thermally or hydrodynamically induced propagation of a vapor–liquid interface, which should be hindered, if not stopped, at the cold patch. Instead, it appears that distributed boiling crisis arises essentially simultaneously over a susceptible region where the local, near wall conditions are similar.

3.3 *Comparison of horizontal and vertical flow*

The critical heat flux results for horizontal flow are shown as a function of quality in figures 5 and 6. As in vertical flow the local conditions hypothesis provides a good representation of the data for various heated lengths. Whether it will continue to do so for non-uniform heating is questionable.

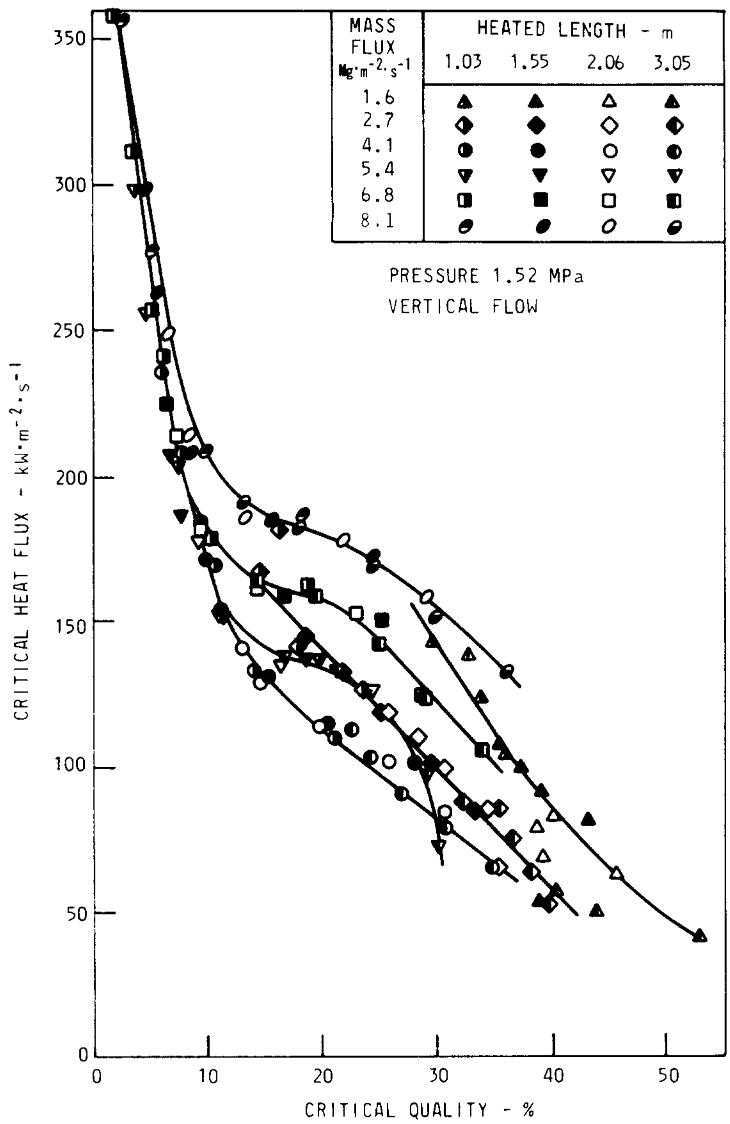

Figure 4. Vertical CHF as a function of quality at a pressure of 1.52 MPa.

Distributed boiling crisis was observed for mass fluxes of 6.9 Mg · m^{-2} · s^{-1} and up, over the region where the CHF vs critical quality curves flatten out. For clarity, these points are not identified on the plots, however, they can be obtained from the data reported by Merilo & Ahmad (1979).

It is interesting to note that for a mass flux of 2.7 Mg · m^{-2} · s^{-1} a portion of the CHF vs critical quality curve is either vertical or has a slight positive slope. The reason for this behavior is not clear, though it could be associated with a flow regime transition from slug to annular flow.

The vertical and horizontal CHF results from figures 3 to 6 are compared on a local conditions basis in figures 7 and 8. At a mass flux of 4.1 Mg · m^{-2} · s^{-1}, and above, the vertical and horizontal results coincide, however, at lower mass flux the vertical CHF is generally higher than the horizontal, the difference increasing as the mass flux is decreased. At a mass flux of 1.6 Mg · m^{-2} · s^{-1} the vertical and horizontal results tend to converge with increasing quality, and hence, increasing vapor velocity.

These results show that the differences between vertical and horizontal CHF tend to decrease as either the liquid or vapor velocity, or both, increase. The reason for this behavior is

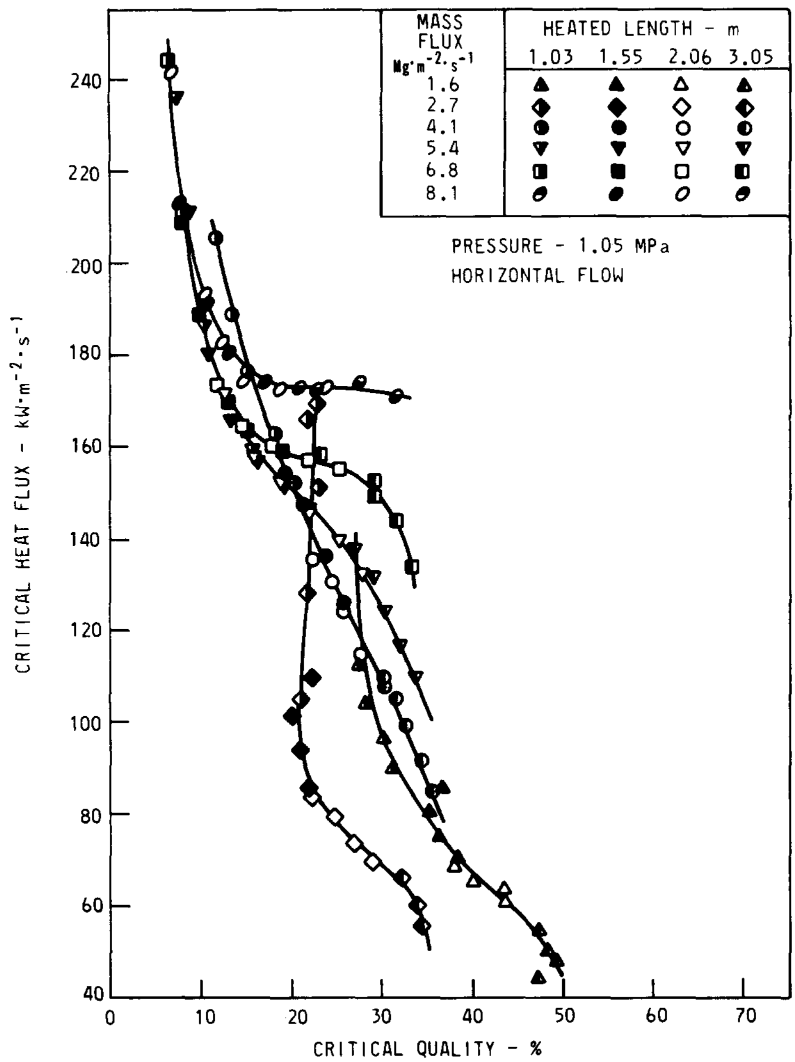

Figure 5. Horizontal CHF as a function of quality at a pressure of 1.05 MPa.

that an increase in velocity promotes turbulent mixing which in turn counteract the gravity induced phase separation. At high enough velocity the mixing would be expected to dominate the effects of buoyancy causing the vertical and horizontal results to become similar.

3.4 *Effects of tube diameter*

The subsequent figures (9–13) provide comparisons of the effects of tube diameter on CHF. There are a number of ways in which these comparisons can be made, and the conclusions which are drawn can be quite contradictory unless the basis of the comparison is clearly stated. In particular it is necessary to specify which parameters are being held constant.

The problems which can arise are well illustrated in figure 9 for both vertical and horizontal flow. Here the effects of diameter on CHF are indicated on a typical system parameters type of plot, showing CHF as a function of inlet subcooling, or inlet quality. The results for the 12.6-mm diameter tube serve as a reference. For both vertical and horizontal flow a decrease in the tube diameter to 5.3 mm *decreases* the CHF when the heated length is held constant, and *increases* it when the length to diameter ratio is held constant.

A similar comparison is shown on a local conditions basis in figure 10. For both vertical and horizontal flow an increase in tube diameter leads to a decrease in CHF for a constant critical

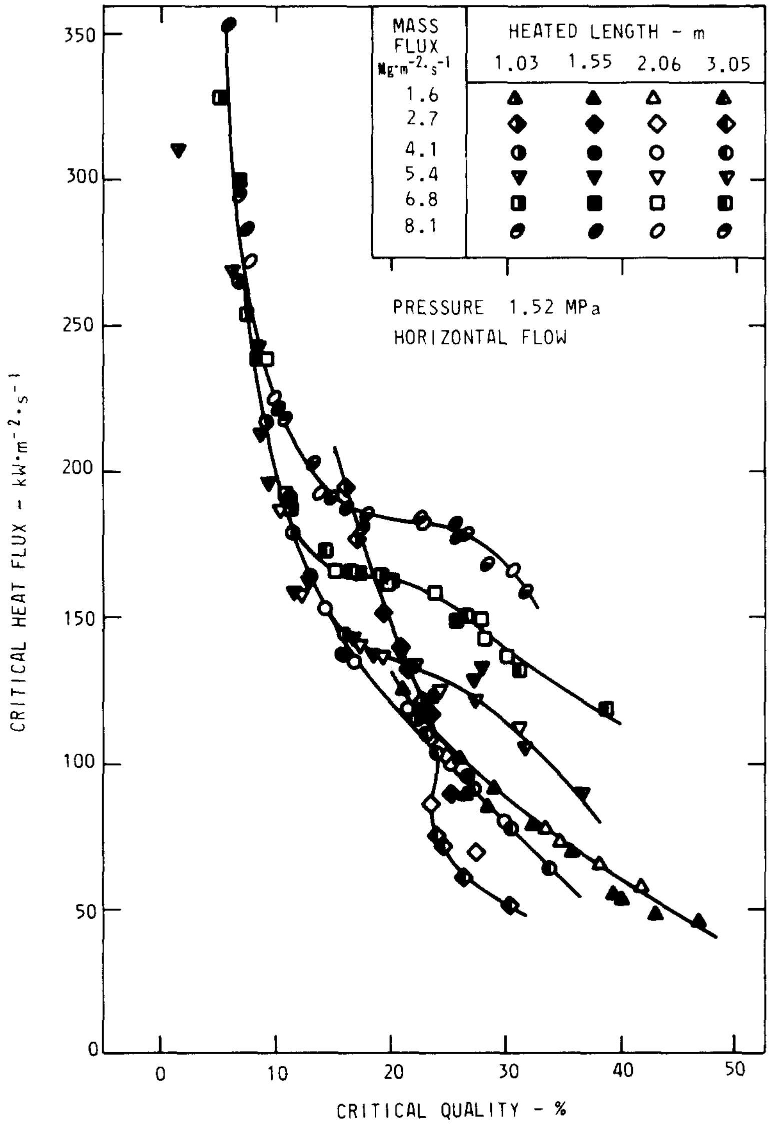

Figure 6. Horizontal CHF as a function of quality at a pressure of 1.52 MPa.

quality. The heated length and inlet subcooling are not considered in this method of comparison because the local conditions hypothesis implies that they have no effect on CHF.

Figures 11 and 12 show the effects of mass flux on CHF for tubes of different diameter at pressures of 1.05 and 1.52 MPa respectively. The inlet subcooling at each pressure is held constant and the heated length is identical. Under these circumstances an increase in tube diameter leads to an increase in CHF.

It is interesting to note that, as Merilo (1977) previously observed for water in a 12.6-mm tube, the vertical and horizontal results for Freon-12 become essentially identical at a mass flux of approx. $4\,Mg \cdot m^{-2} \cdot s^{-1}$ for both tube diameters and at both pressures. If this effect is the result of a flow pattern transition from intermittent to dispersed bubble flow, then the transition appears to be a function of the mass flux alone and is independent of the tube diameter in this range.

The difference in CHF between vertical and horizontal flow can be seen from figures 7 and 8 to decrease with increasing pressure, as would be expected from elementary considerations of the density ratios and the buoyancy forces.

CHF as a function of mass flux at constant critical quality is shown in figure 13. Here a

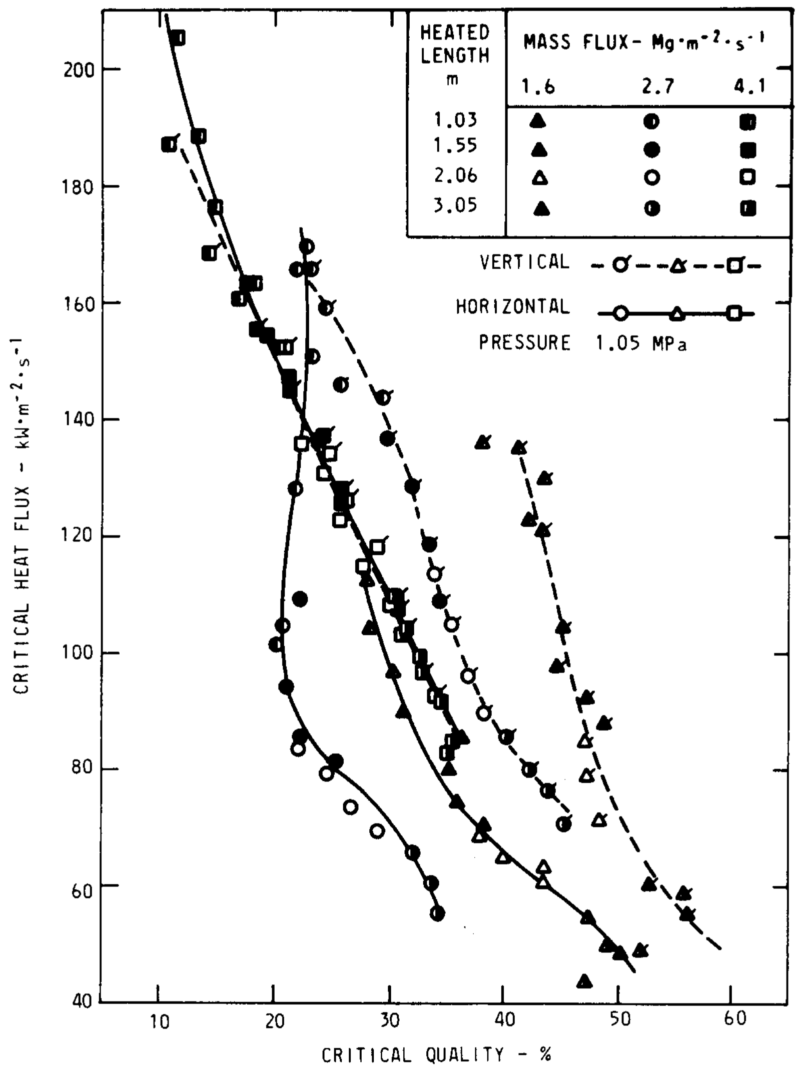

Figure 7. Comparison of CHF in vertical and horizontal flow at a pressure of 1.05 MPa.

decrease in tube diameter leads to an increase in CHF. An inverse mass flux effect is apparent for both vertical and horizontal flow below mass fluxes of 4 and 2.8 $Mg \cdot m^{-2} \cdot s^{-1}$ respectively, except for the 12.6-mm tube in horizontal flow. Again, the vertical and horizontal results become similar at mass fluxes of 4 $Mg \cdot m^{-2} \cdot s^{-1}$ and above.

A summary of the effects of diameter on CHF in both vertical and horizontal flow is shown in table 2.

4. CONCLUSIONS

(1) The gravity force transverse to the flow direction causes a deterioration of CHF in horizontal flow over that which is obtained in vertical flow. As either the liquid or vapor velocity, or both, are increased the horizontal and vertical CHF results tend to converge.

(2) Over the range of conditions tested, the vertical and horizontal CHF results become identical at and above a mass flux of approx. 4 $Mg \cdot m^{-2} \cdot s^{-1}$.

(3) The effect of tube diameter on CHF in both vertical and horizontal flow depends crucially on the parameters which are being maintained constant when the comparison is made.

(4) The spread of distributed boiling crisis in vertical flow does not appear to be the result of a propagating vapor liquid interface. Rather, it arises essentially simultaneously over the affected area.

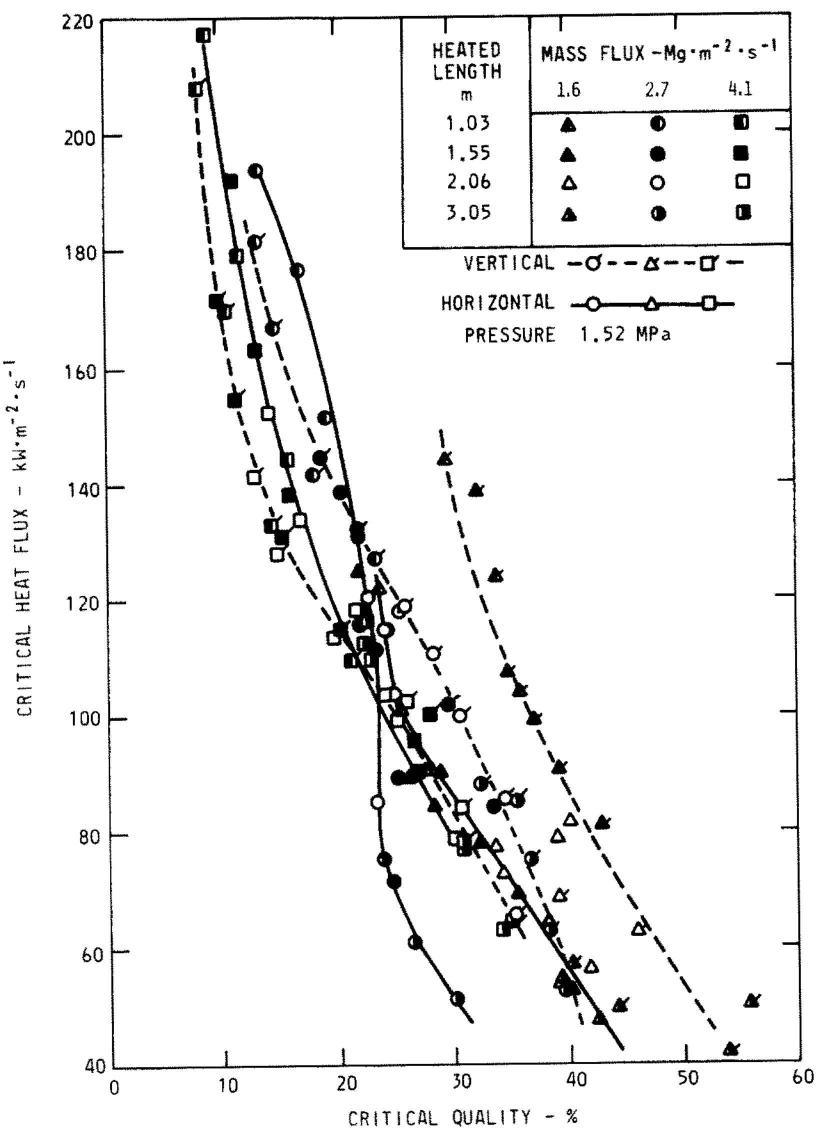

Figure 8. A comparison of CHF in vertical and horizontal flow at a pressure of 1.52 MPa.

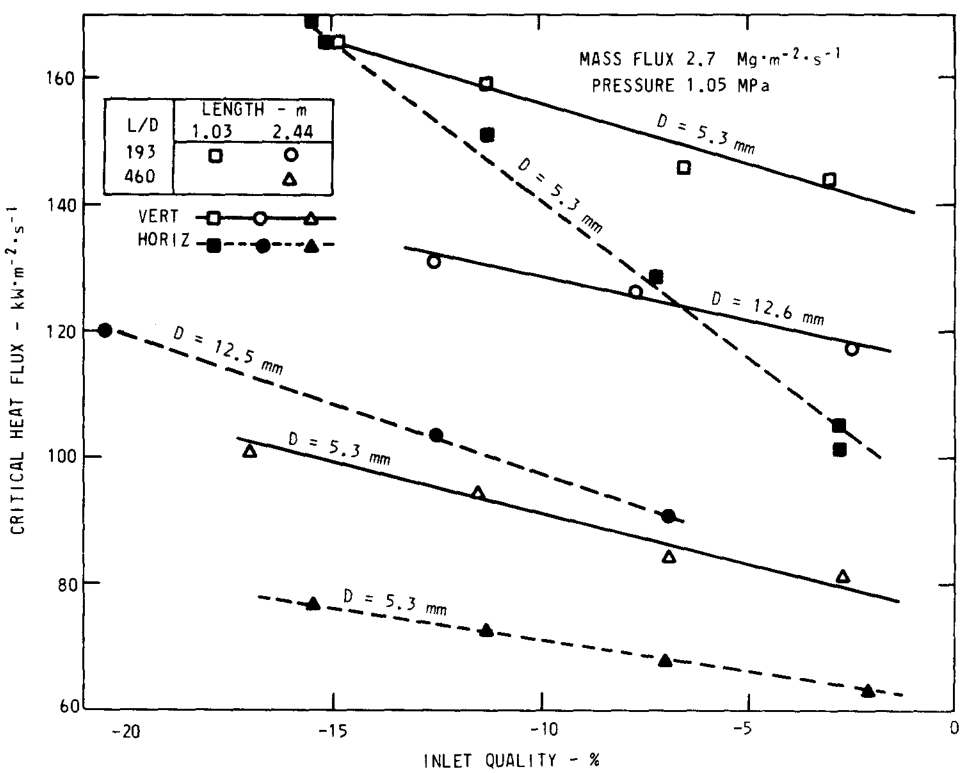

Figure 9. The effect of diameter on CHF in vertical and horizontal flow on a system parameter basis.

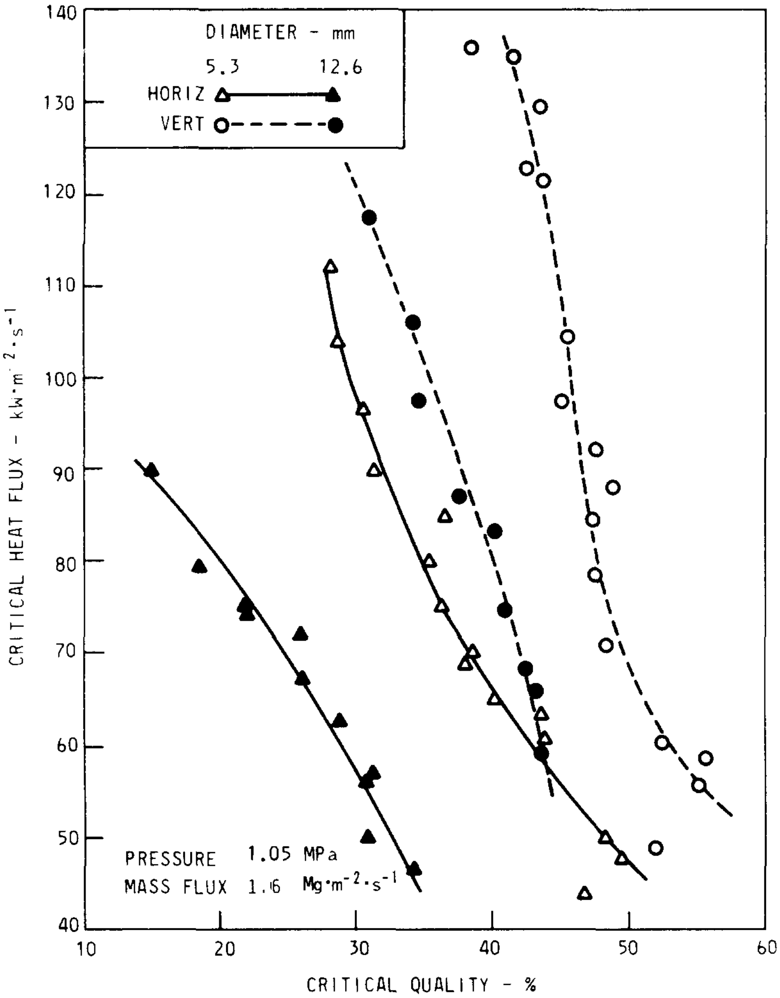

Figure 10. The effect of diameter on CHF in vertical and horizontal flow on a local conditions basis

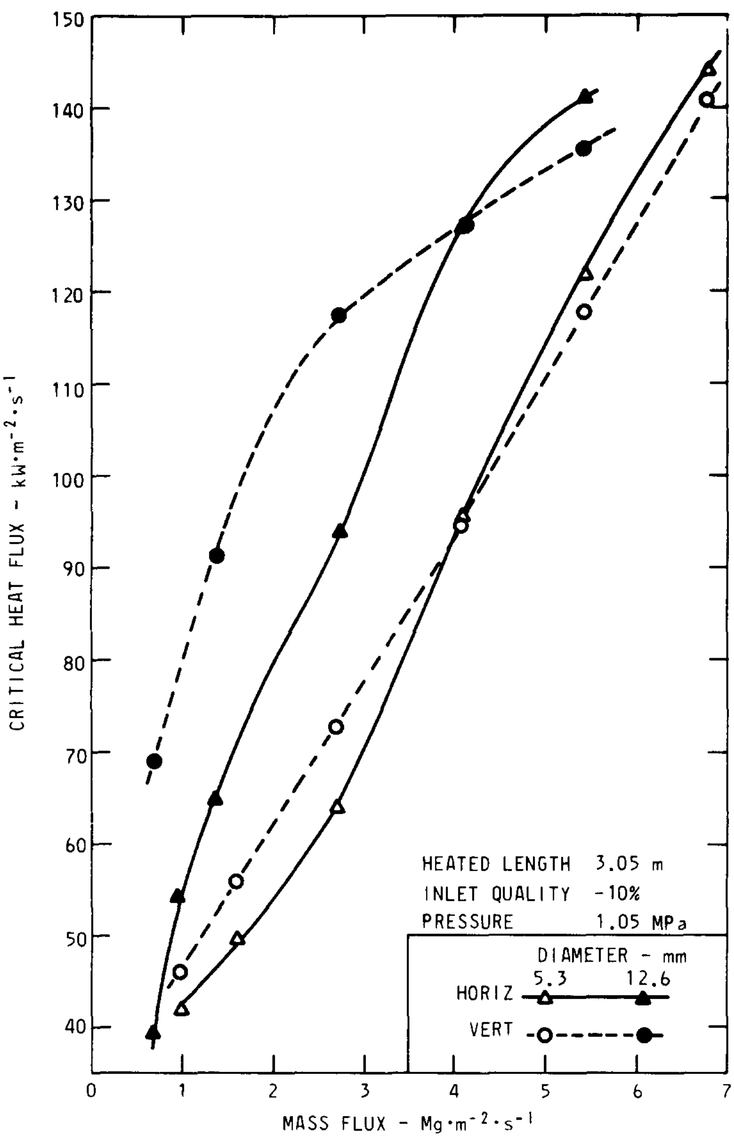

Figure 11. The effect of mass flux on CHF in vertical and horizontal flow at constant inlet quality and a pressure of 1.05 MPa.

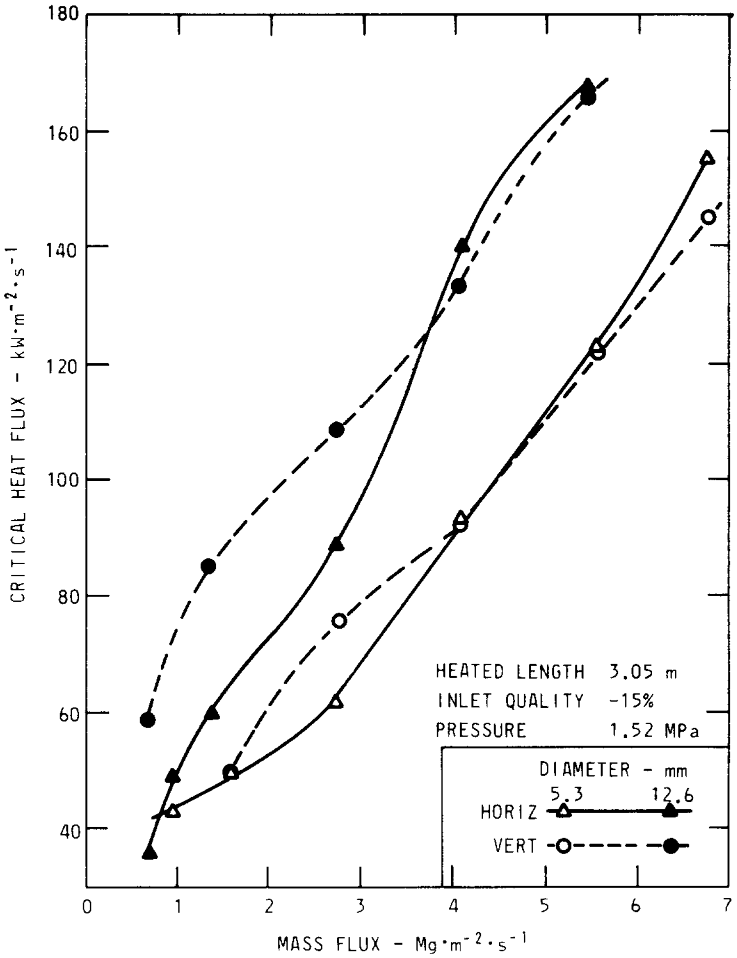

Figure 12. The effect of mass flux on CHF in vertical and horizontal flow at constant inlet quality and a pressure of 1.52 MPa.

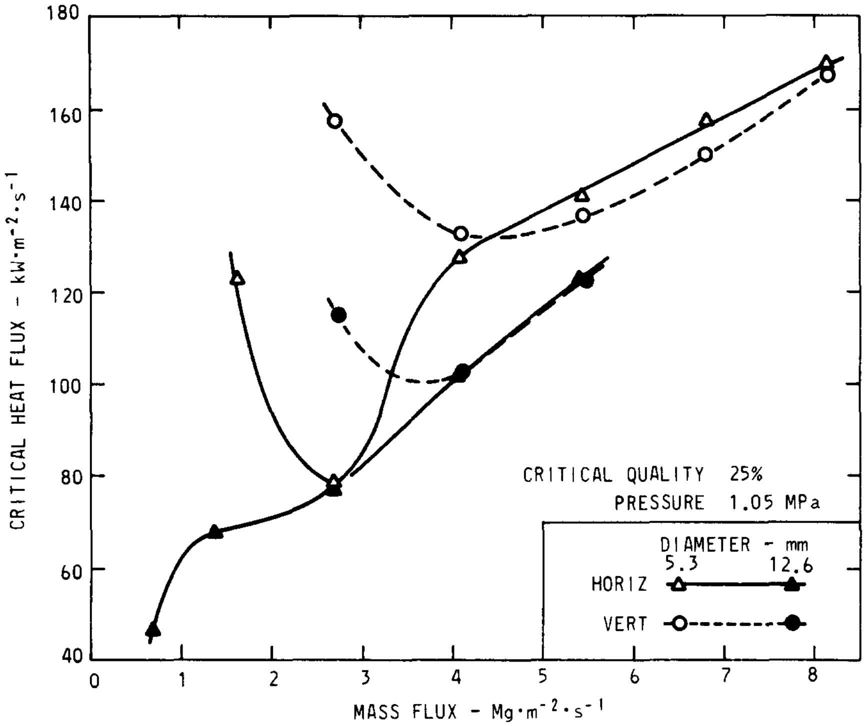

Figure 13. The effect of mass flux on CHF in vertical and horizontal flow at constant critical quality.

Table 2. Variation of CHF with diameter in vertical and horizontal flow for constant mass flux and pressure

Constant	Diameter	CHF
Inlet quality Heated length/diameter	Increases	Decreases
Inlet quality Heated length	Increases	Increases
Critical quality	Increases	Decreases

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