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On the superposition of injection induced swirl during enhancement of subcooled critical heat flux

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Abstract—Enhancement of subcooled critical heat flux with the use of single and multiple tangential injectors placed on a 1.73 cm i.d. tube is investigated in this work. In the experiments Freon-113 was used as the coolant and the heated length of the tube was varied from 8.8 to 37.1 cm. The superposition of swirl was studied by using single and double injectors at one axial location and by varying the distance between injection locations. The results of the experiments show an enhancement of up to 80% in the critical heat flux. It is found that injection superimposed on already swirling two-phase flow is less effective in enhancing CHF than injection into a non-swirling flow.

INTRODUCTION

In the last three decades, numerous studies of critical heat flux during forced flow boiling in tubes have appeared in the literature. Most of these studies have lead to correlations of maximum heat fluxes under a variety of thermal, hydraulic and geometrical conditions of the flow channels. Though much is to be gained by increasing the now well-accepted upper limit of the heat removal rate by boiling, only a few studies have been made in the past to push this limit upwards without paying excessive penalty in terms of the pumping power. This paper deals with superposition aspects of the staged swirl flow concept proposed earlier in ref. [1] for enhancing the maximum heat flux.

A review of most of the existing studies on critical heat flux under forced flow conditions in tubes was performed by Boyd [2, 3]. Similar reviews have earlier been performed among others by Hewitt [4]. From these reviews it can be concluded that though we have learned a lot about the dependence of the maximum heat flux on various flow parameters, as yet no mechanistic model exists for the occurrence of the maximum heat flux. Katto [5] has correlated a large number of existing CHF data for axial flow through tubes. Recognizing that saturated and subcooled CHF occur under very different hydrodynamic conditions, he provides different correlations for the various CHF regimes.

The earliest study on enhancing critical heat flux by inducing swirl in the flow was made by Gambill and Greene [6]. In their experiments water was used as the test liquid and swirl in the flow was generated by either a helical ramp or a tangential slot vortex generator placed at the test section entrance. The study was limited to very short (0.1 cm i.d. and 5 cm long tubes) test sections. In another study Gambill *et al.* [7], inserted a twisted tape in the tube to induce swirl. Both of those studies showed up to two-fold enhancement in the subcooled critical heat flux. The enhancement decreased with decreasing mass flow rate and was insensitive to the liquid subcooling.

Swirling flow can also be created by tangentially injecting part of the fluid along the axis of the tube. In an early paper, Kreith and Margolis [8] suggested the use of tangential fluid injection to enhance single-phase heat transfer. The first study using this concept to enhance CHF in subcooled flow was made by Weede and Dhir [1]. In that work experiments were conducted with Freon-113 flowing through resistively heated tubes of 1.73 cm i.d. Tangential injectors, of 0.25 and 0.38 cm i.d., were placed at three, evenly spaced locations along the test section. Heated lengths of up to 35 cm were used, and fluid injection took place with injected mass flow to total mass flow ratios of up to 0.8. Several important observations made in that work are listed below.

(a) A more appropriate parameter for correlating the enhancement in CHF is the ratio of tangential to total momentum flux rather than the ratio of injected to total mass flow rate.

(b) With tangential injection of sufficient strength downstream of the tube entrance, the location of occurrence of CHF could be shifted from the test section exit to a location just upstream of the point of tangential injection.

(c) Swirl flow induced enhancement in CHF decays nearly exponentially with distance from the point of injection.

(d) Tangential injection of equal flow rates at three locations with injected to total mass flow rate ratio of 0.8 resulted in a CHF enhancement of 67% in a 35 cm long tube.

(e) Swirl enhances CHF by inducing a centripetal force which pushes the vapor from the wall towards the center of the tube.

NOMENCLATURE

- a flow cross-sectional area of the test section
- a_j flow cross-sectional area of an injector
- CHF critical heat flux
- CHF_a critical heat flux in pure axial flow
- CHF_s critical heat flux with swirl
- c_{pl} specific heat of liquid at constant pressure
- d internal diameter of the test section
- d_j internal diameter of an injector
- G_j injected mass flux at location j based on test section cross-sectional area
- G_T total mass flux at test section exit based on test section cross-sectional area
- G_0 total mass flux at test section entrance based on test section cross-sectional area
- h_{fg} latent heat of vaporization
- I 'excess vapor' integral
- $I_{m,n}$ 'excess vapor' integral between injection locations m and n
- L_{htd} heated length
- L_j distance of injection location j from test section exit
- M_j momentum flux at injection location j, $(G_j a)^2/\rho_l a_j N$
- M_T total momentum flux through the test section, $G_T^2 a/\rho_l$
- N number of injectors operational at one location
- P_j injection effectiveness at location j
- T_i liquid temperature at test section inlet
- T_{sat} saturation temperature of the liquid
- x_i inlet subcooling parameter, $c_{pl}(T_i - T_{sat})/h_{fg}$.

Greek symbols

- Φ CHF enhancement based on total mass flux
- Φ_j CHF enhancement based on total mass flux at test section exit due to injection at location j
- $\Phi_{m,n}$ CHF enhancement based on total mass flux, at location n due to injection at location m
- $\Phi_{m+n,k}$ CHF enhancement based on total mass flux, at location k due to injection at locations m and n
- ρ_l density of liquid
- ρ_v density of vapor
- σ surface tension.

The purpose of the present work is to determine as to how swirl introduced simultaneously at several locations along the tube axis superimposes. Also, to compare the enhancement in CHF resulting from injection at one circumferential location with that at two locations. The data are to be taken by varying the heated length, inlet subcooling, and momentum of injected flow.

EXPERIMENTAL APPARATUS AND PROCEDURE

The experimental apparatus used in this study was essentially the same as that employed in ref. [1]. The Freon-113 loop consists of a heat exchanger, a reservoir, a centrifugal pump, 20 μm filters and a turbine flowmeter. The piping of the flow loop is schedule 40 PVC. The reservoir and heat exchanger tanks are made of polypropylene. The valves and fittings are made of brass or stainless steel. The choice of materials was based on the ease in fabrication and control and compatibility with Freon-113. Figure 1 shows a schematic diagram of the flow loop.

The test section was resistively heated with current from a Plasmadyne P.S. 62 d.c. power supply rated at 50 kW. The output of the power supply was controlled with a 115 V saturable reactor on the primary side of the transformer. The two test sections used in this work are shown in Fig. 2. The only difference between the two is the number and spacing of the injection locations. The tube material was Inconel 600 alloy, cold drawn–annealed–redrawn. The tube had a 1.727 cm i.d. and a 0.089 cm wall thickness. A brass electrical terminal was silver soldered to the tube at the exit and another movable brass terminal was located upstream. A hydrodynamic entrance region of at least 25 diameters was always allowed upstream of the movable terminal.

Pressure and temperature taps were installed in the fixed exit electrode and in the tube fitting at the entrance. Also, a glass sight section was located just downstream of the exit to allow viewing of exit flow conditions. Only the unheated portion of the test section was insulated, as insulation over the heated length would have interfered with the visual detection of CHF. Calculations on similar test sections [9] showed that the heat loss to the atmosphere from the heated length was less than 1% of the total power input.

Details of the injector design are also shown in Fig. 2. Brass rings, of 2.5 cm o.d. and 1.0 cm width, were silver soldered to the tube at the desired locations. A 0.48 cm hole was then milled tangentially through the ring and the tube wall at a 70° angle to the tube axis. The injector tubes 0.38 cm i.d. and 2.54 cm long and made of stainless steel were silver soldered to the brass ring. The ring was deemed necessary to shunt electrical current past the area of injector attachment and to thereby render this small area unheated.

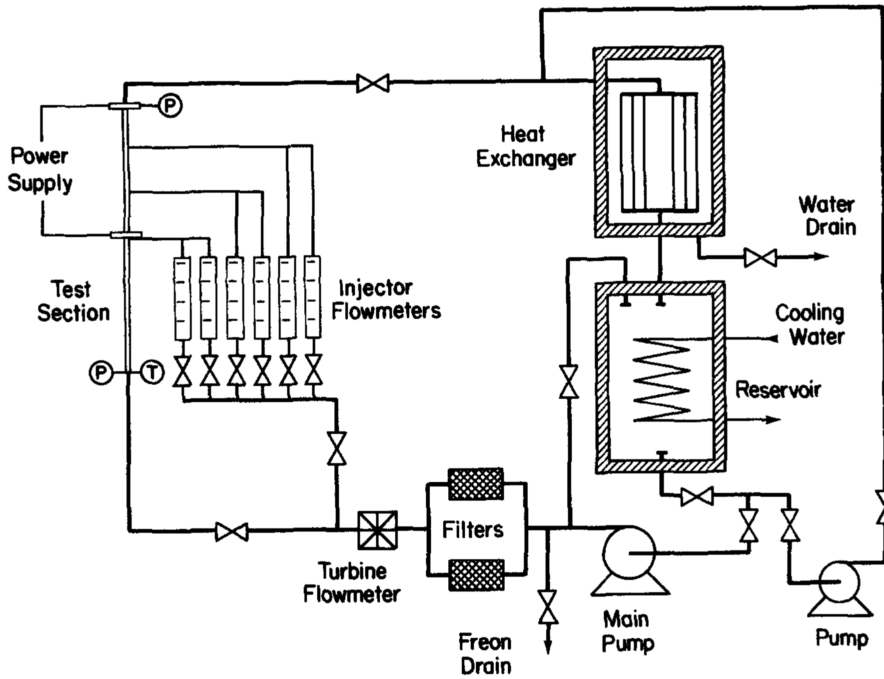


FIG. 1. Experimental flow loop.

The total flow rate through the test section and injectors was measured using a Flow Technology 'Standard Line' turbine flowmeter with an electronic counter for the digital read out of the wave frequency. A correlation of the wave frequency with Freon-113 flow rate was obtained from the manufacturer. The flow rate through each injector was measured using one or more of a bank of Dwyer VFB 'Visi-Float' variable area flowmeters. The test section exit pressure was measured with a Dwyer 'Spirahelic' bourdon tube pressure gage. The pressure difference across the test section was monitored using Dwyer 'Capsuhelic' diaphragm pressure gages with Buna-N parts for Freon compatibility. The reservoir, fluid inlet and test section wall temperature were measured with 30 gage chromel–alumel thermocouples. The thermocouples were attached to the outer surface of the test section using Epoxylite high-temperature epoxy. The epoxy

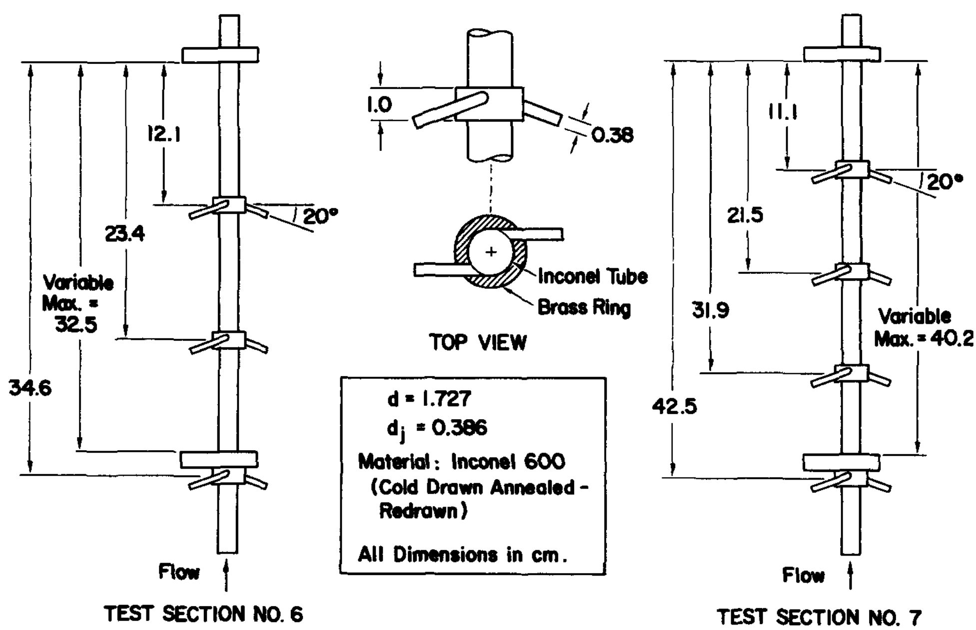


FIG. 2. Details of the test sections.

was chosen for its high electrical resistivity and low thermal resistivity. The output of the thermocouples was recorded on a six channel Brush Mk 200 recorder.

The occurrence of CHF was indicated by a rapid rise in temperature at one or more locations at the tube surface. Although this rise was often slow enough to permit manual power shut off before test section damage occurred, an automatic shut off circuit based on an Athena model 4000-B temperature controller [9] was used as a safety measure. The current through the test section was obtained from the voltage drop measured across a calibrated 1500 A, 50 mV shunt located inside the power supply. This voltage was continuously monitored on a Houston Instrument model 2000 recorder. Test section voltage drop was read on a Hewlett–Packard model 3465A digital multimeter.

Prior to each run, the fluid temperature was adjusted to near the desired level by circulating it through the heat exchanger and/or by running water in the reservoir coils. The main pump was then started. The total flow rate and the individual injector flow rates were adjusted using the upstream gate valves and injector flowmeter valves. The downstream gate valve was used to set the test section exit pressure to the desired value. The d.c. power supply was then activated, and the current through the test section was increased in steps ranging in size from 300 A initially to 10 A as CHF was approached. Care was taken after each increment in power to make sure that test section temperature had leveled off before the current was further increased. This was important because, if heat flux was increased too quickly, the resulting sudden rise in surface temperature would bring about a premature CHF condition. It was assumed that a sudden rise in the output of any of the surface thermocouples indicated occurrence of CHF at that location. Once the CHF condition was recognized, the power was immediately cut off.

Critical heat flux values were calculated based on test section resistance, inside surface area, and measured current at the time of occurrence of the CHF. Test section resistance was found to remain constant as runs were made at any fixed heated length, and resistance measurements were taken after every change of heated length. Values of resistance also remained relatively constant with temperature in the range of interest and were calculated from values of voltage drop and current measured simultaneously near the onset of the CHF condition.

RESULTS AND DISCUSSION

The critical heat flux in 1.73 cm i.d. tubes heated electrically and varying in length from 8.8 to 37.1 cm was measured using Freon-113 as the test liquid. In all of the experiments the exit pressure was held at 2.05×10^5 N m^{-2} while the inlet subcooling parameter, $-x_i$, based on this exit pressure was varied from 0.18 to 0.30. In all of the experiments, the total mass flow rate through the tube was held constant at 2107 kg m^{-2} s^{-1} and the ratio of the mass flow rate through the injectors to the total mass flow rate was varied parametrically. To study the superposition of swirl, the experiments were conducted with one or both injectors operating at one axial location (usually at the inlet). Test section No. 7 was used for studies with one of the twin injectors operating at one location whereas test section No. 6 was used when fluid was injected through both the injectors. Experiments were also performed by having multiple injections along the axis of the tube. In the following, the discussion of the specific features of the swirl flow is preceded by general observation regarding the experiments including correlation of the axial flow CHF data. All of the data are tabulated in ref. [10].

General observations

During the course of the experimental study, it was found that after repeated runs on a test section, the CHF would start to occur prematurely just upstream of the test section exit. Visual observations showed presence of extraneous material at the location of occurrence of CHF. This material could be scraped off. Although it has not been unequivocally substantiated, it is postulated that the extraneous material is NiCl. It is known that at temperatures reached just after occurrence of CHF, this compound could easily form from a reaction between nickel in Inconel and the rather loosely bonded chlorine in Freon. Freon-113, being an organic would not dissolve this salt and crystals could build up locally over the course of several runs. It was found that 3–5 min sponging of the tube interior with 1 M HCl would remove all visible crystals and enable the test section to yield CHF values compatible with those obtained before the build up was observed.

In agreement with the existing evidence in the literature [2, 4], the presence of air in the flow loop was found to lower the critical heat flux. The air in the loop was drawn into the system through a defective seal on the suction side of the pump. After correction of the seal and removal of air from the loop, the critical heat flux was found to increase back to the values obtained prior to failure of the seal.

The cavitation in the injectors was also seen to lower the critical heat flux. The cavitation in the injectors was either caused by the presence of sharp corners in the Swagelok fitting connecting the injector with the feed line or a crimp in the injector tube itself. After remedial measures to eliminate cavitation were taken, the magnitude of critical heat flux reached the values obtained prior to occurrence of cavitation. All of the data reported here are believed to be free of these effects. This is also confirmed by the fact that the axial flow data compare well with the correlation

$$\mathrm{CHF}_a = 1.45 \times 10^{-2} G_T h_{fg} (\sigma \rho_l / G_T^2 L)^{0.25} (L/d)^{-0.05} \times (\rho_v/\rho_l)^{0.133} (1 + 7.25 (L/d)^{0.16} (-x_i)) \quad (1)$$

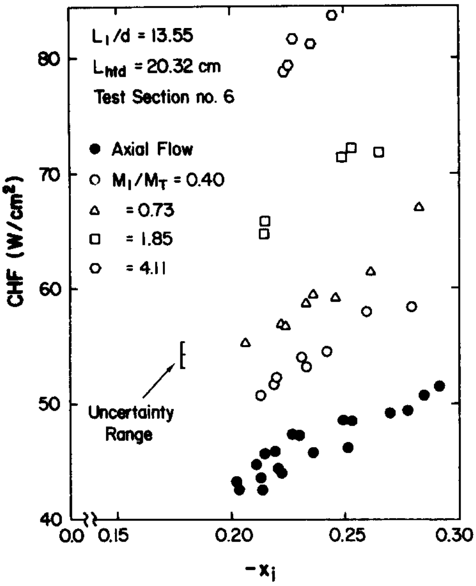


FIG. 3. CHF vs x_i for twin injector entrance injection.

proposed earlier in ref. [1].

It should also be noted here that the presence of brass rings on the tube at the locations where injectors were placed did not influence the magnitude of the critical heat flux in any noticeable way. The observed critical heat fluxes under purely axial flow conditions in tubes with and without injector mountings (brass rings) were about the same.

Injection at one axial location with both or one of the injectors operational

The data presented in this section was obtained when the movable electrode marking the entrance to the heated length was clamped immediately downstream of the operational injector set. Figure 3 shows one set of such data obtained when fluid was injected through both of the injectors. The critical heat flux is seen to increase with liquid subcooling at inlet and with the ratio of injected to total momentum flux. If enhancement in critical heat flux is defined as

$$\Phi = \frac{\mathrm{CHF_s} - \mathrm{CHF_a}}{\mathrm{CHF_a}} \tag{2}$$

the data such as those plotted in Fig. 3 can be replotted. Figures 4 and 5 show the enhancement as a function of the ratio of tube length to tube diameter for several M_I/M_T ratios and a fixed inlet quality. The data plotted in Fig. 4 are for the case when both injectors are operational while the data in Fig. 5 are for a single injector. It is noted that in both cases enhancement decreases with increasing L_I/d but increases with increasing M_I/M_T. However, a comparison of the data (except those for small M_I/M_T) in these two figures shows that enhancement decreases somewhat faster with distance from injection location for a single injector than for the twin injectors. A faster decay of swirl with single injector probably

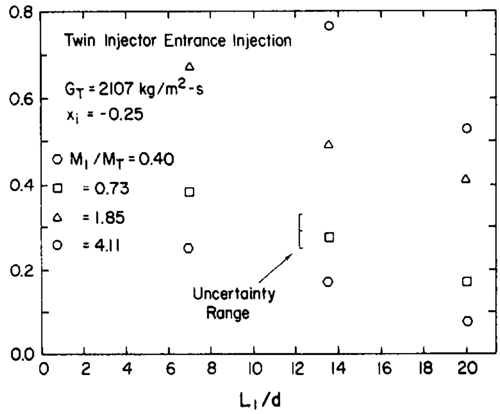


FIG. 4. Enhancement data for twin injector entrance injection.

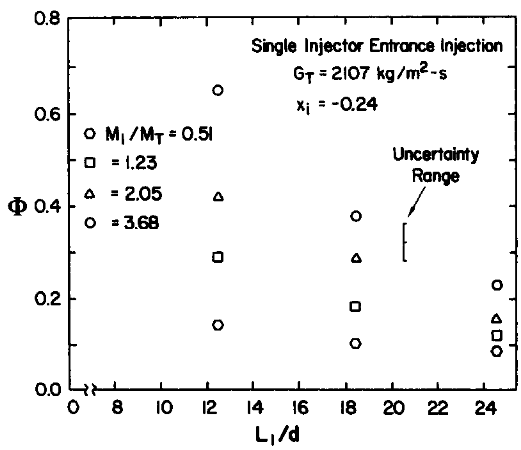


FIG. 5. Enhancement data for single injector entrance injection.

results from the fact that a larger fraction of axially flowing liquid has to be entrained with injection through a single injector than through two injectors.

The enhancement in CHF with both injectors is correlated as†

$$\Phi_I = 0.92(M_I/M_T)^{0.7}(-x_i)^{0.2}\,\mathrm{e}^{-0.059(L_I/d)} \tag{3}$$

and for the single jet case the best fit to the data is obtained as

$$\Phi_I = 0.83(M_I/M_T)^{0.7}(-x_i)^{0.2}\,\mathrm{e}^{-0.074(L_I/d)}. \tag{4}$$

The larger constant in the exponent in equation (4) is indicative of the faster decay of swirl induced by a single jet. The dependence of enhancement on the ratio of the tangential to total momentum and the inlet quality is found to be the same in both cases. However, about a 10% larger constant in equation (3) may be indicative of the fact that even in the limit of $L_I/d \to 0$, the injection through both injectors is more efficient than through one of the injectors. A comparison of prediction from equations (3) and (4)

† The subscript 1 refers to injection at one axial location.

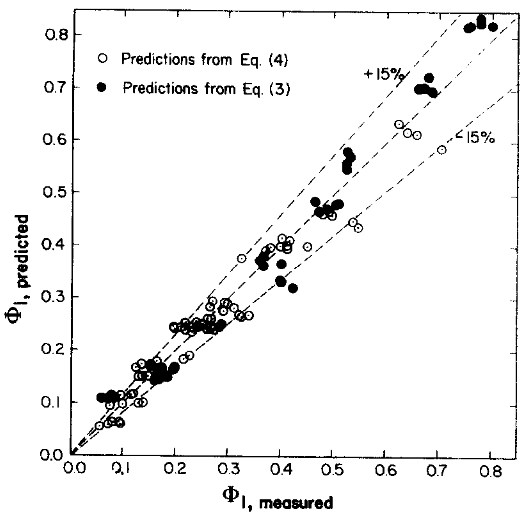


FIG. 6. Comparison of the predictions from the correlation equations (3) and (4) with the data.

with the data is made in Fig. 6. About 85% of the data are correlated within ±15%.

Injection at two axial locations with both injectors operational at each location

From the previous discussion, it can be inferred that increase in enhancement over 'injection at entrance only' values will occur when additional injection takes place within the heated length. Figure 7 shows enhancement data for this situation. In obtaining these data, the ratio of tangential to total momentum flux through the injectors at inlet was kept fixed at 0.9 while the injection rate through the second set of injectors and their location from inlet was varied parametrically. A sketch of the flow configuration is also shown in Fig. 7. In developing a correlation for enhancement in CHF due to superposition of swirl at two axial locations, it is postulated that injection is less effective when it takes place in an already swirling stream. Based on this postulation, the form of correlation chosen is

$$\Phi_{1+2} = 0.92[(M_{1,2}/M_T) + P_2(M_2/M_T)]^{0.70}(-x_i)^{0.2}\,e^{-0.059(L_2/d)} \quad (5)$$

where $M_{1,2}/M_T$ represents the amount of swirl present at the downstream injection location (L_2) due to injection at the entrance (L_1). It is calculated by first using equation (3) to find, Φ_1, the enhancement at the exit of the tube due solely to injection at the entrance. Equation (3) is then reused to find the momentum flux ratio, $M_{1,2}/M_T$ injected downstream at L_2 that will yield the same enhancement at exit, i.e.

$$M_{1,2}/M_T = [1.09\Phi_1(-x_i)^{-0.2}\,e^{0.059(L_2/d)}]^{1.43} = \frac{M_1}{M_T}\,e^{-0.084((L_1-L_2)/d)}. \quad (6)$$

The injection effectiveness parameter P_2 depends on the amount of excess vapor present in the stream. When CHF occurs in a swirling flow, the vapor fraction is larger than that in the pure axial flow case because of the increased amount of vapor that is pushed to the middle of the tube by the swirl induced centripetal force. Since there is a slip between vapor and liquid and bubbles increase agitation in the flow, the presence in swirl flow of this 'excess vapor' will cause the injected fluid to be less effective in supplementing the swirl of the main flow. A phase difference between the swirl associated with the injected fluid and that already existing in the tube can also reduce the effectiveness of the imposed swirl. The amount of 'excess vapor' in the flow at the downstream injection location depends on the same swirling motion as does the enhancement in CHF. Its extent can be obtained simply by integrating the enhancement from the entrance injection location to the second location of injection to form the 'excess vapor' integral, I_{12}, as

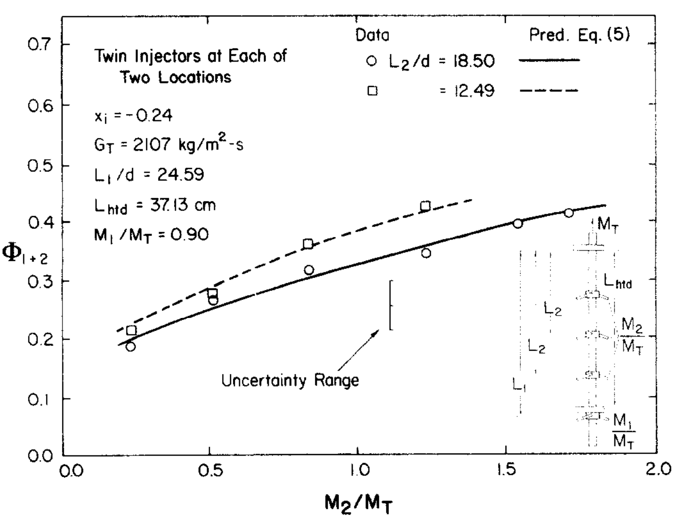


FIG. 7. Enhancement of critical heat flux with injection at two axial locations.

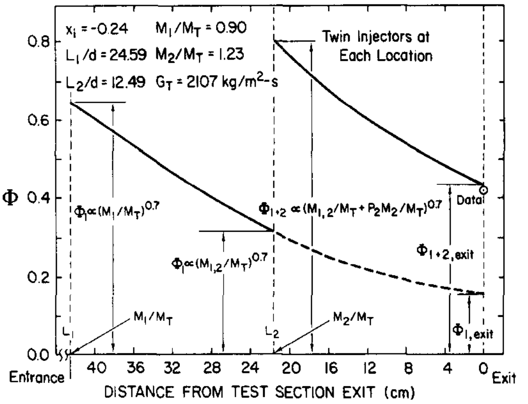


FIG. 8. Superposition of swirl with injection at two axial locations.

$$I_{12} = \int_{L_1/d}^{L_2/d} \Phi \, \mathrm{d}(L/d). \quad (7)$$

Substitution from equation (3) yields

$$I_{12} = 0.92(M_1/M_T)^{0.70} \times (-x_i)^{0.2} \int_{L_1/d}^{L_2/d} \mathrm{e}^{-0.059(L/d)} \, \mathrm{d}(L/d). \quad (8)$$

The swirl effectiveness parameter P_2 which presumably also includes the effect of phase difference is correlated with I_{12} as

$$P_2 = 1.42\,\mathrm{e}^{-0.25 I_{12}}. \quad (9)$$

The dotted and solid lines in Fig. 7 show the predictions made from equation (5) when substitution for P_2 is made from equation (9). Over a ten fold variation in M_2/M_T, the predictions lie within 5% of the enhancement data obtained with $L_2/d = 18.5$ and 12.49. Here it should be pointed out that in the limit of $(L_1 - L_2)/d \rightarrow 0$, $P_2 \rightarrow 1.42$. At first glance, a value of P_2 greater than one may not seem reasonable. However, it should be recognized that in equation (5) the exponent of the group of terms involving P_2 is 0.7 and the effectiveness of the swirl increases as the number of injectors at a given axial location is increased. Figure 8 shows a diagram of the process by which equation (5) takes into account the injection effectiveness to predict CHF enhancement for a typical data point. It should be noted here that CHF will occur at a location along the heated length of the tube where the predicted value of CHF is the lowest and not at a location where enhancement is the lowest.

Extension of the prediction method to three locations when both injectors are operational at each location

The methodology developed above can be easily extended to the case in which injection occurs at three locations along the tube axis. The test section sketch in Fig. 9 shows the flow configuration. As in the two location case, equation (3) is used to find, Φ_1, the enhancement at exit due to injection at L_1. This in turn is used in equation (6) to find the local momentum flux ratio, $M_{1,2}/M_T$ at L_2. The injection effectiveness parameter P_2 is found from equation (9) after calculating the 'excess vapor' integral from equation (8). Equation (5) is then used to find Φ_{1+2}, which in this case is the exit enhancement due to injection at L_1 and L_2. Thereafter, the exit enhancement, Φ_{1+2}, is used in an equation analogous to equation (6) to find, $M_{1+2,3}/M_T$, the injection at L_3 that would yield Φ_{1+2} at exit, i.e.

$$M_{1+2,3}/M_T = [1.09\Phi_{1+2}(-x_i)^{-0.2}\,\mathrm{e}^{0.059(L_3/d)}]^{1.43}. \quad (10)$$

The expression for $M_{1+2,3}/M_T$ can be used in an equation similar to equation (5) to obtain

$$\Phi_{1+2+3} = 0.92[(M_{1+2,3}/M_T) + P_3(M_3/M_T)]^{0.70}(-x_i)^{0.2}\,\mathrm{e}^{-0.059(L_3/d)}. \quad (11)$$

The parameter P_3 in equation (11) is found from the 'excess vapor' integral as

$$I_{13} = \int_{L_1/d}^{L_3/d} \Phi \, \mathrm{d}(L/d) \quad (12)$$

or, because some injection occurs between L_1 and L_3

$$I_{13} = \int_{L_1/d}^{L_2/d} \Phi \, \mathrm{d}(L/d) + \int_{L_2/d}^{L_3/d} \Phi \, \mathrm{d}(L/d). \quad (13)$$

Substituting from equations (7) and (5) into equation (13) yields

$$I_{13} = I_{12} + 0.92[(M_{1,2}/M_T) + P_2(M_2/M_T)]^{0.70} \times (-x_i)^{0.2} \int_{L_2/d}^{L_3/d} \Phi\,\mathrm{e}^{-0.059(L/D)} \, \mathrm{d}(L/d). \quad (14)$$

Figure 9 shows this predictive approach. In this figure a comparison of the predictions with the data of Weede [9] is also made. In the experiment corresponding to that data, the momentum flux ratio was set to be the same at each location. It is seen that the prediction compares with the data within 10%.

Prediction of location of occurrence of CHF. The above discussion was focused on the prediction of enhancement in CHF when the critical heat flux occurred at the exit of the test section. However, depending on the relative spacing of the injectors and the magnitude of the injected momentum, the CHF could occur just upstream of any of the injectors. Knowing the value Φ in each region and combining equations (1) and (2), the magnitude of the predicted critical heat flux along the heated length of the tube can be plotted. The CHF would occur at a location where the predicted magnitude of the critical heat flux is the smallest. Figure 10 shows a comparison of the predictions with one of the data points obtained by Weede [9]. It is seen that the observed location and

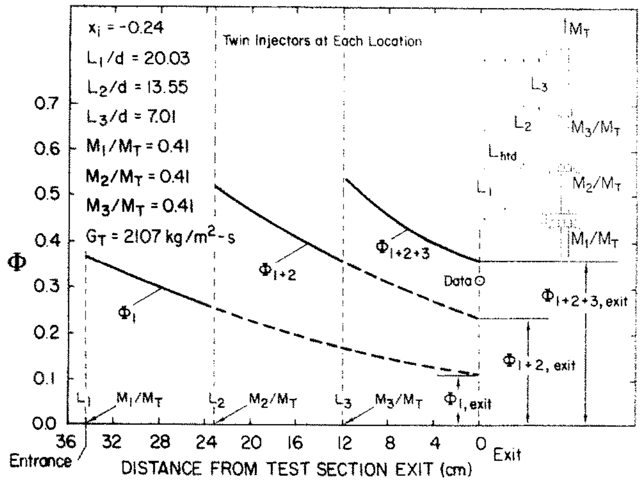


FIG. 9. Superposition of swirl with injection at three axial locations.

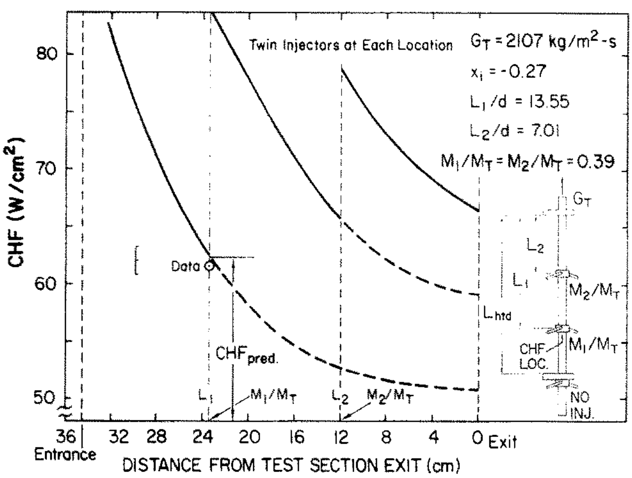


FIG. 10. Comparison of prediction of location of occurrence of CHF with the data.

magnitude of CHF compare quite well with the predictions.

Optimization of enhancement with both injectors operational at three axial locations. The methodology for injection at three axial locations was used to find the spacing of injection locations and the momentum flux through each pair of injectors to maximize the enhancement at the test section exit. A computer program was developed to take the fixed parameters and constraints of the test section as inputs and then calculate the enhancement at exit for each change in flow rate and injection location. Two cases were examined.

(1) Enough pumping power was assumed to be available to force all the flow through one pair of injectors if so desired.

(2) An injected to total mass flow rate ratio of 0.6 was assumed to be the maximum possible for any one pair of injectors. This value was chosen so as to have near maximum enhancement for a given pressure drop.

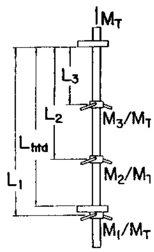
It can be seen from Table 1 that for case (1), the maximum enhancement of 81% is obtained when all of the flow is injected through the injector pair at the entrance. For case (2), the injector spacing and injection rates for the highest enhancement indicate that the maximum enhancement can be achieved by having the maximum injection rate through the farthest downstream injection location possible (L_3) without shifting the location of occurrence of CHF. The remaining flow is divided between the injectors at L_1 and L_2 with the middle injector set (at L_2) placed either near the set at the entrance (at L_1) or near the set closer to exit (at L_3).

In order to insure that CHF occurred only at exit, the CHF location prediction method described earlier was built into the computer program. It is noted from Table 1 that G_0 values are almost zero. It should be

Table 1. Inputs, constraints, and results from enhancement optimization

(a) *Inputs*

$x_i = -0.24$
$d = 1.73$ cm
$d/d_j = 4.47$
$L_1 = 42.5$ cm ($L_1/d = 24.59$)
$L_{htd} = 37.13$ cm
$G_T = 2107$ kg m^{-2} s^{-1}
Number of injection locations = 3
Number of injectors per location = 2



(b) *Constraints*

All flow injected: $G_1/G_T + G_2/G_T + G_3/G_T = 1$
CHF condition always at exit:
$CHF_{s,\,exit} < CHF_{s,\,anywhere\ else}$
$L_{2,\,max} = 39.8$ cm
$L_{2,\,min} = 1.7$ cm
$L_{3,\,max} = 38.8$ cm
$L_{3,\,min} = 0.6$ cm
$P_2 > 0.1$; $P_3 > 0.1$

Perform exhaustive search for maximum Φ:
Increments for L: 1 cm
Increments for G_j/G_T: 0.1

(c) *Results*

Case (1): No constraint on maximum G_j/G_T at any one location:
$\Phi_{max} = 0.81$ with $M_1/M_T = 10.0$ (no injection at L_3 or L_2)
Case (2): $G_j/G_T \leqslant 0.6$ at any one location:
Top six values:

L_2/d	L_3/d	G_0 (kg m^{-2} s^{-1})	M_1/M_T	M_2/M_T	M_3/M_T	Φ
21.54	15.16	$\simeq 0$	0.10	0.90	3.60	0.75
17.20	15.16	$\simeq 0$	0.90	0.10	3.60	0.73
22.99	15.16	$\simeq 0$	0.10	0.90	3.60	0.73
21.54	16.61	$\simeq 0$	0.10	0.90	3.60	0.71
22.99	16.61	$\simeq 0$	0.10	0.90	3.60	0.70
20.09	16.61	$\simeq 0$	0.90	0.10	3.60	0.70

realized that these results are purely theoretical and with no axial flow at inlet. Also, the location of occurrence of CHF may shift away from the test section exit at M_3/M_T values significantly lower than those listed.

CONCLUSIONS

(1) The enhancement in CHF as a result of tangential injection has a power law dependence on the ratio of tangential to total momentum flux and decays exponentially with distance from location of injection.

(2) The enhancement due to injection through one of the injectors at a location decays faster than with injection through both of the injectors at that location.

(3) When tangential injection induced swirl is superimposed on an already swirling flow, the injection is less effective in enhancing CHF.

(4) The superposition methodology developed for multiple injections along the heated length of the tube can be used to predict the magnitude and location of occurrence of CHF in a given flow configuration. The methodology can also be used to maximize the enhancement with respect to flow parameters.

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REFERENCES

1. J. J. Weede and V. K. Dhir, Experimental study of the enhancement of critical heat flux using tangential flow injection. In *Fundamentals of Heat Transfer in Fusion Systems*, ASME HTD 24, pp. 11–18. Seattle, Washington (July 1983).
2. R. D. Boyd, Review of subcooled flow boiling critical heat flux (CHF) and its applications to fusion systems. Part 1. In *Fundamentals of Heat Transfer in Fusion Systems*, ASME HTD 24, pp. 19–30. Seattle, Washington (July 1983).
3. R. D. Boyd, Review of subcooled flow boiling critical heat flux (CHF) and its applications to fusion energy system components, Part 2. In *Fundamentals of Heat Transfer in Fusion Systems*, ASME HTD 24, pp. 31–42. Seattle, Washington (July 1983).
4. G. F. Hewitt, Critical heat flux in flow boiling, 6th International Heat Transfer Conference, Toronto, Vol. 6, pp. 143–172 (1978).
5. Y. Katto, A generalized correlation of the critical heat flux for forced convection boiling in vertical uniformly round tubes, *Int. J. Heat Mass Transfer* **21**, 1527–1542 (1978).
6. W. R. Gambill and N. D. Greene, Boiling burnout with water in vortex flow, *Chem. Engng Prog.* **54**(10), 68–76 (1958).
7. W. R. Gambill, B. D. Bundy and R. W. Wansbrough,

Heat transfer burnout, and pressure drop for water in swirl flow through tubes with internal twisted tapes, *Chem. Engng Prog. Symp. Ser.* **57**(32), 127–137 (1959).
8. F. Kreith and D. Margolis, Heat transfer in turbulent vortex flow, *Appl. Sci. Res.* **A8,** 457–473 (1959).
9. J. J. Weede, An experimental study of the enhancement of critical heat flux using tangential flow injection, M.S. Thesis, University of California, Los Angeles, California (1983).
10. J. H. Scott, An experimental investigation of the superposition of injection induced swirl as applied to the enhancement of subcooled critical heat flux, M.S. Thesis, University of California, Los Angeles, California (1984).

ACCROISSEMENT DU FLUX THERMIQUE CRITIQUE PAR SUPERPOSITION D'INJECTIONS INDUISANT UN TOURBILLONNEMENT

Résumé—On étudie l'accroissement du flux critique, en sous-refroidissement, par utilisation d'un ou plusieurs injecteurs tangentiels placés sur un tube de 1,73 cm i.d. On utilise dans les expériences le Freon 113 comme refrigérant et la longueur chauffée du tube varie entre 8,8 et 37,1 cm. On étudie la superposition du tourbillonnement en utilisant des injecteurs simples et doubles à une position axiale et en faisant varier la distance entre les points d'injection. Les résultats montrent un accroissement du flux thermique critique allant jusqu'à 80%. On trouve que l'injection superposée à l'écoulement diphasique tourbillonnaire est moins efficace que l'injection dans un écoulement non tourbillonnaire.

ZUR ÜBERLAGERUNG VON WIRBELN, ERZEUGT DURCH EINSPRITZUNG, WÄHREND DER ERHÖHUNG DER KRITISCHEN WÄRMESTROMDICHTE BEI UNTERKÜHLTEM SIEDEN

Zusammenfassung—In dieser Arbeit wird die Erhöhung der kritischen Wärmestromdichte bei unterkühltem Sieden durch einzelne oder mehrere tangentiale Düsen, die auf einem Rohr mit 1,73 cm Innendurchmesser montiert sind, untersucht. Die Versuche wurden mit R113 als Kühlmittel durchgeführt; die beheizte Länge des Rohres wurde zwischen 8,8 und 37,1 cm variiert. Die Überlagerung von Drallbewegungen wurde unter Verwendung von Einzel- und Doppeldüsen an einer axialen Position und durch Veränderung des Abstandes zwischen den Düsen untersucht. Die Versuche ergeben eine Erhöhung der kritischen Wärmestromdichte um bis zu 80%. Es zeigt sich, daß die Einspritzung in eine Zweiphasenströmung mit Drall eine geringere Erhöhung bewirkt, als die Einspritzung in eine Strömung ohne Drall.

О ВЛИЯНИИ ОБУСЛОВЛЕННОЙ ИНЖЕКЦИЕЙ ЗАКРУТКИ ПОТОКА ПРИ ИНТЕНСИФИКАЦИИ КРИТИЧЕСКОГО ТЕПЛОВОГО ПОТОКА ПРИ НЕДОГРЕВЕ

Аннотация—Исследуется увеличение критического теплового потока при недогреве за счет использования одной или нескольких тангенциальных инжекторов, расположенных на трубе с внутренним диаметром 1,73 см. В эксперименте в качестве теплоносителя использовался фреон-113, а нагреваемый участок трубы изменялся от 8,8 до 37,1 см. Взаимодействие вихрей изучалось при использовании единичного и двойных инжекторов, расположенных на одной оси, изменяя расстояние между ними. Экспериментальные результаты указывают на увеличение критического теплового потока до 80%. Найдено, что вдув, наложенный на уже завихренный двухфазный поток, менее эффективен для изменения критического теплового потока, чем вдув в незавихренном потоке.