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Critical heat flux on horizontal tubes in an upward crossflow of Freon-113

S. C. YAO
Department of Mechanical Engineering, Carnegie-Mellon University, Pittsburgh, PA 15213, U.S.A.

and

T. H. HWANG
Department of Mechanical Engineering, University of Hawaii at Manoa,
Honolulu, HI 96822, U.S.A.

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Abstract—The critical heat flux (CHF) on horizontal tubes in crossflow of upflowing Freon-113 is obtained under various flow conditions. The effects of the flow field on both the magnitude and the location of the CHF on a horizontal tube are revealed. Data are obtained over a range of mass fluxes (132–560 kg m^{-2} s^{-1}), subcooling (0–6°C), and qualities ($0 < x_{\rm Loc} < 0.143$) at atmospheric pressure. For the case of a tube in a channel, when the mass flux is fixed, the narrower the channel (the smaller the flow area) the lower the CHF. In an in-line bundle the CHF is approximately equal to that of a single tube in an equivalent channel, which has a half width the same as the lateral pitch of the bundle, under the same local mass flux and flow quality. Furthermore, the CHF in this in-line bundle, which has a pitch-to-tube diameter ratio of 1.5, always starts at the upstream stagnation point of the heated tube. This is contrary to the usual situation that occurs on a tube in a channel where the CHF always begins at the downstream portion of the heated tube. This is because, in this in-line bundle, the local quality is highest at the upstream stagnation point of the heated tube due to the presence of the upstream wake. An empirical correlation has been established for the CHF on a horizontal tube in an infinite flow field and in a channel with various channel widths. The correlation also predicts well the CHF on a heated tube in an in-line unheated bundle for the range of conditions examined in this study.

INTRODUCTION

BOILING heat transfer from horizontal tubes in crossflow has received considerable attention as a result of its applications to shell-and-tube heat exchangers, reboilers and evaporators. Leong and Cornwell [1], and Cornwell *et al.* [2, 3] have demonstrated that in Kettle reboilers the upward recirculating two-phase mixture velocities and qualities had a significant effect on the convective heat transfer coefficients over the horizontal bundles. However, no critical heat flux (CHF) data were obtained in those investigations. Palen *et al.* [4] have shown qualitatively that the overall CHF for a large-scale horizontal bundle is, in general, decreased with increasing bundle diameter at constant tube pitch and decreased with decreasing the pitch at a constant bundle diameter. It was also found that the overall CHF of a bundle is lower than that of a single tube. The CHF of an individual tube and the effect of flow qualities were not revealed.

A single tube is the building block of a heat exchanger bundle. Due to the complicated flow and boiling phenomena in Kettle reboilers, extensive efforts have been devoted to study a single horizontal tube in crossflow. A fundamental understanding and parametric effects have been fairly well established for the CHF on a single tube in an infinite pool under pool boiling or single-phase crossflow conditions [5–15]. McKee and Bell [7] performed a study of forced convective boiling on a horizontal cylinder in vertical upflow saturated water at about atmospheric pressure. The electrically heated cylinders of 6.35 and 18.04 mm diameter were used in a 76.2×76.2 mm channel. The low flow velocities were 1.04 and 1.66 m s^{-1}. The forced convective boiling curves were found to be not significantly displaced from the corresponding pool boiling curve. The CHF under forced convection is always initiated near the wake region of the cylinder. They concluded that forced convection substantially increased the CHF on small diameter cylinders but with a much smaller effect on the larger cylinders.

Yilmaz and Westwater [8], and Broussard and Westwater [9] studied experimentally the complete boiling curve for saturated Freon-113 flowing over a horizontal tube at near atmospheric pressure. The upward flow velocities were relatively high; they were 2.4, 4.0 and 6.8 m s^{-1} in ref. [8] and up to 6.0 m s^{-1} in ref. [9]. Steam-heated copper tubes of 6.5 mm diameter [8] and up to 12.7 mm diameter [9] were used. It was found that the boiling curves for different velocities

NOMENCLATURE

d	tube diameter [mm]
G	mass flux [kg m^{-2} s^{-1}]
G^*	gravity influence parameter, $\{(We_g/2R^*)(\rho_f/\rho_g)\}^{1/2}$
H	width of flow channel [mm]
h_{fg}	latent heat of vaporization [J kg^{-1}]
L	heated length of the tube [mm]
p	pitch of the bundles [mm]
q_{max}	CHF [kW m^{-2}]
q_{max}^+	non-dimensional CHF, $q_{max}/(\rho_g h_{fg} U_\infty)$
R^*	square root of the Bond number, $(d/2)/[\sigma/g(\rho_f-\rho_g)]^{1/2}$
U_∞	free stream velocity [m s^{-1}]
We_g	Weber number, $\rho_g d U_\infty^2/\sigma$
X_T	lateral pitch of bundles [mm]
x_{Loc}	local flow quality.

Greek symbols

λ	most dangerous Taylor wavelength [mm]
ρ_f	density of liquid phase [kg m^{-3}]
ρ_g	density of vapor phase [kg m^{-3}]
σ	surface tension of liquid phase [N m^{-1}].

did not intersect or overlap, which is contrary to previous investigators results. The CHF was proportional to the 0.44 power of velocity and inversely proportional to the 0.28 power of diameter.

Extensive studies of CHF on horizontal cylinders in a vertical crossflow in an infinite flow field have been performed by Lienhard and his co-workers [10–13]. They demonstrated that the CHF in forced convective boiling and the CHF in pool boiling can be bridged by the 'mechanical energy stability criterion'. Two different flow patterns of vapor removal from the cylinders were found under forced convection and high heat flux conditions. At very low flow velocity, a three-dimensional 'bubble-like' jet flow pattern is observed, which is similar to that under pool boiling. When the flow velocity is sufficiently high, a two-dimensional 'sheet-like' flow pattern takes place. The transition point between these flow patterns was correlated empirically. They concluded that the low-velocity CHF can be obtained, similar to the CHF of corresponding pool boiling [13], before this transition occurs.

Recently, Katto and Haramura [14, 15] have developed a hydrodynamics instability model of CHF for both pool and flow boiling on submerged bodies in an upward saturated liquid. Two semi-empirical correlations were proposed for two flow regions. In general, the CHF increases weakly with increasing flow velocity in the 'bubble-like' escaped flow region, but strongly to the power of 0.334 of flow velocity at the 'sheet-like' escaped flow region. These two correlations agree fairly well with existing CHF data. However, no distinct criterion was suggested for the transition between these two correlations.

The effect of two-phase oncoming flow on the boiling heat transfer coefficients and CHF on a single tube in a restricted channel has been investigated by Hwang and Yao [16, 17]. They found that the CHF on a single horizontal tube decreases weakly with increasing upflowing Freon-113 qualities. Recently, Jensen and Pourdashti [18] also investigated the low-velocity CHF behavior on a single horizontal tube in a subcooled and low-quality two-phase crossflow of Freon-113. The upflowing Freon-113 velocities were relatively low (up to 0.3 m s^{-1}). It was concluded that CHF decreases linearly with increasing flow quality up to about 10% quality.

The CHF phenomenon for a small array of cylinders in upflowing crossflow under slightly subcooled and high flow velocity conditions was studied in ref. [19]. Hasan *et al.* [19] obtained the experimental results of CHF on a single cylinder subject to the flow interference created by one or more parallel unheated cylinders. The small diameter (up to 1.6 mm) cylinders were nichrome wires held in place under spring tension in upflowing crossflow of methanol or isopropanol. It was observed that at low flow velocities (<0.3 m s^{-1}), the CHF on all the arrays was almost identical to that for a single cylinder. At high velocities, neighboring cylinders had an effect only when the heated cylinder was directly in the wake of an unheated cylinder. Then, the unheated cylinder trapped a large vapor bubble in the gap region and promoted premature CHF. An unheated cylinder, four diameters or less upstream of a heated cylinder, could reduce the CHF by as much as 90% of that for a single heated cylinder. The CHF decreased as the gap became smaller. On the other hand, the heat transfer characteristics of small multitube bundles in pool boiling were studied in refs. [20, 21]. The data showed that within a tube bundle, the vapor rising from lower tubes enhances the CHF on the upper tubes. The results cannot be generalized because the effects of local flow velocity and local flow quality were not separable in refs. [20, 21]. Another interesting study was performed by Meyer *et al.* [22] on the CHF over a cylinder embedded in an array of large diameter (25.4 mm) cylinders in a horizontal crossflow. The horizontal flow of Freon-113 makes the vapor removal path more complicated than for the vertically upflowing condition. An unheated cylinder placed in-line with the test cylinder downstream of the flow at a pitch ratio of 2 showed no influence on the CHF over the test cylinder up to a flow velocity of about 0.4 m s^{-1}. At higher

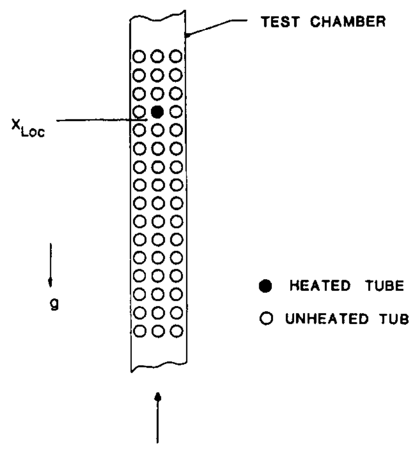

FIG. 1. Schematic diagram of the test bundle.

velocities, the CHF was lower compared with that over the single cylinder.

The search of the recent literature reveals that no published CHF data or correlation is available for a tube in a bundle under low velocities and low quality two-phase crossflow conditions. Therefore, the present study was undertaken to establish further knowledge for these conditions.

THE EXPERIMENT

A simplified sketch of the test bundle is shown in Fig. 1. The test chamber (61.6 × 85.7 × 660.4 mm) is vertically oriented with Freon-113 flowing against gravity. The bundle consists of three columns of in-line tubes with a pitch-to-tube diameter ratio of 1.5. The test chamber has smooth sidewalls with their distance to the adjacent tubes equal to half of the tube-to-tube spacing. The bundle consists of 12 rows of upstream unheated tubes to reduce the entrance effect. All the unheated tubes can be withdrawn from the test section to allow for the investigation of the CHF on a single tube in a channel. The heated tube is made of stainless 304 seamless tubing with a 19.1 mm o.d., a 0.51 mm wall thickness, and a 49.4 mm heated length. This thin-walled tube is heated with direct current which has a 0.6% ripple. The current is obtained from the voltage drop over a shunt. The end effect on the CHF for this short tube will be discussed in the following section.

The heated tube is located at the center of the thirteenth row of the bundle (counted from the bottom). Two J-type, stainless-steel-sheathed, ungrounded thermocouples of 0.81 mm diameter are firmly pressed against the inner wall by plate springs. The thermocouples are also covered with insulating cement to reduce the heat loss through the thermocouples and the natural convection inside the tube. The thermocouples are located at the middle of the heated length and can be rotated circumferentially along the inner wall of the tube. The outer surface temperature is calculated by assuming one-dimensional steady-state heat conduction. The maximum heat loss by natural convection inside the heated tube, and the heat loss through the thermocouples, are estimated [23] to be less than 1.4% of the power applied to the heated tube. The temperature measurement errors resulting from the heat sink effect of thermocouples are estimated [23] to be less than 0.14°C. The circumferential conduction is also negligible due to the thin tube wall and low thermal conductivity of stainless steel. The same heated tube is used for all the tests to eliminate any systematic error. The test tube was polished before each test to assure a consistent surface finish.

During the experiment, the peripheral wall temperatures were measured at 30° intervals with increasing heat flux. The boiling inception was always observed at the bottom portion of the tube. Care has been taken to determine the location of CHF initiation of the test tube. The initiation of the CHF condition was determined by observing the test tube temperatures. When the CHF condition was initiated at a particular region of the tube, the corresponding tube wall temperature would increase drastically. Therefore, at the high heat flux condition (near CHF), the two thermocouples were located at the top and bottom stagnation points to detect the most likely initiated point of CHF. In the present study, the location of CHF initiation was dependent on the flow field as will be discussed in the next section.

The inlet flow quality is established by preheating the fluids and then throttling through a regulating valve located at the entrance of the test section. After the flow passed through the regulating valve, it flows vertically upward through an inlet plenum, which contains a perforated plate to homogenize the incoming vapor and liquid distribution to the test section. The mean flow quality near the test tube, x_{Loc}, can be evaluated through an energy balance of the throttling process.

All the temperatures in the experiment are recorded on an Accurex Autodata Logger (Model Ten/5) with an accuracy of ±0.1°C, and programmed with an interfacing terminal. The range of local flow quality is between 0 and 0.143. For subcooled boiling the local subcooling is fixed at 6°C. The mass flux varies between 132 and 560 kg m^{-2} s^{-1}. The test section was maintained at atmospheric pressure. Details of the experimental apparatus, experimental procedure and error analysis can be found in ref. [24].

RESULTS AND DISCUSSION

A single tube in a channel

In the present study, the surface temperature distribution on the test tube for both subcooled flow and two-phase oncoming flow become uniform with increasing heat flux after boiling inception. In all of the experiments, the highest surface temperature is always detected at the top center of the single test

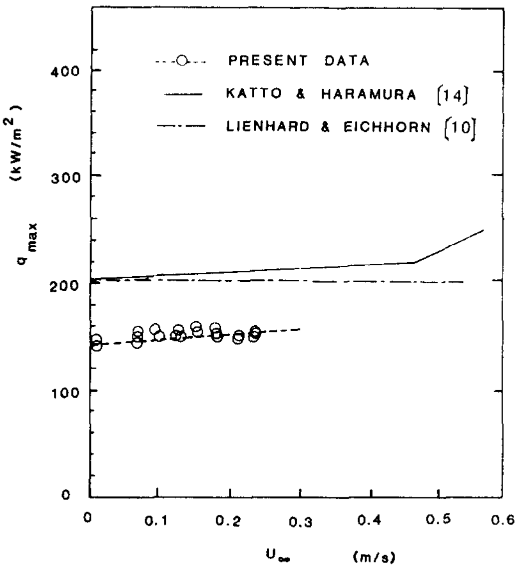

FIG. 2. Variation of the CHF for slightly subcooled Freon-113 flowing across a horizontal single tube.

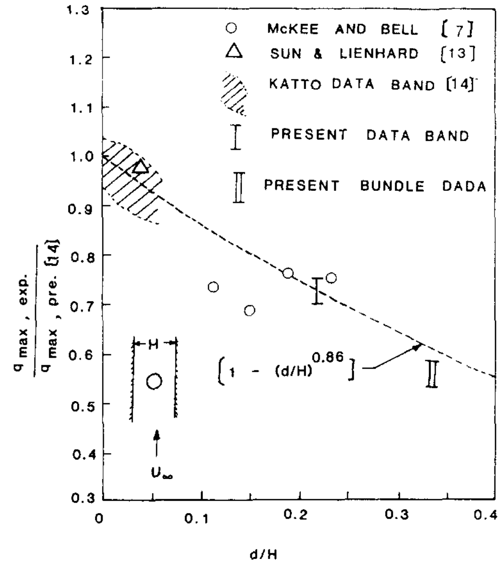

FIG. 3. Comparison of single tube CHF data at various channel blockage ratios.

tube, where burnout begins. This is because when the two-phase mixture passes the 90° position of the tube, the majority of the bubbles leave the tube in a tangential direction upward, while some bubbles are entrained into the downstream wake of the heated tube. The vapor generated in the top portion of the tube has a tendency to be trapped in the downstream wake of the heated tube. Thus, it is hard to rewet the top portion of the tube at high heat flux, and an early burnout is detected there. As will be discussed later, the CHF on a tube in a bundle may begin at the lower portion of the tube because of the different flow field near the tube.

When the flow velocity is relatively low, $G^* < 10$, the CHF is affected by gravity [12]. The gravity influence parameter, G^*, is defined as

$$G^* \equiv \{(We_g/2R^*)(\rho_f/\rho_g)\}^{1/2} \tag{1}$$

where

$$R^* = (d/2)/[\sigma/g(\rho_f-\rho_g)]^{1/2}$$

is the square root of the Bond number, and

$$We_g = \rho_g d U_\infty^2/\sigma$$

the Weber number. In general, the CHF in low velocity flow over a single tube can be expressed in terms of

$$q_{max} = fn(\rho_f, \rho_g, h_{fg}, d, \sigma, U_\infty, g, x_{Loc}, H) \tag{2}$$

where H is the channel width. Equation (2) can be arranged in a dimensionless form as

$$\frac{q_{max}}{\rho_g h_{fg} U_\infty} = fn(We_g, x_{Loc}, \rho_g/\rho_f, R^*, d/H). \tag{3}$$

Figure 2 shows the comparison of CHF predicted by various researchers [10, 14] with the present data for slightly subcooled Freon-113 at low velocity conditions. The present data show that the CHF increases slightly with an increase in flow velocity to the exponent of 0.005. This same trend was also found by Katto and Haramura [14]. However, they are consistently about 28% lower than the predictions by ref. [14], as shown in Fig. 2.

It must be pointed out here that the present study has been performed on a short tube. However, most of the available CHF data for single tubes in crossflows were for large length-to-diameter ratios. The CHF on a short tube may suffer end effects due to the influence of vapor removal behavior. In ref. [25], the size (end) effect on the CHF was discussed for a finite flat plate; it is dependent upon the number of vapor jets $(L/\lambda)^2$ that occurs on the heater surface, where λ is the most dangerous Taylor wavelength and L the heated length of the heater. The wavelength for a large cylinder ($R^* > 1.17$) is found to be $2.5d$ [13]. The value of L/λ of the short tube in the present study is 1.02 and, as expected, just one vapor jet is induced. Therefore, the end effect that resulted from the distortion of the vapor removal mechanism can be considered as insignificant. A similar estimate of the end effect in ref. [7] is found to yield only a 10% reduction of CHF.

Effect of channel blockage ratio on CHF. As shown in Fig. 2, a comparison of the present data with the predictions from the methods shown in refs. [10, 14] for a single tube in an infinite flow field, indicates that the data are much lower. One important parameter that affects the CHF results is the channel blockage ratio (d/H). The higher the blockage ratio, the earlier burnout occurs because of the existence of massive vapor bubbles on the top of the tube. Figure 3 shows the effect of the channel blockage ratio on the measured CHF from different sources. When d/H is low, the CHF is similar to that for a single tube in an

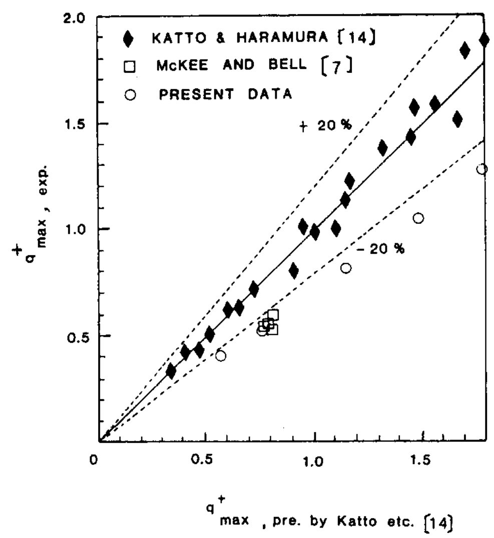

FIG. 4. Comparison of single tube CHF data with Katto and Haramura's correlation [14].

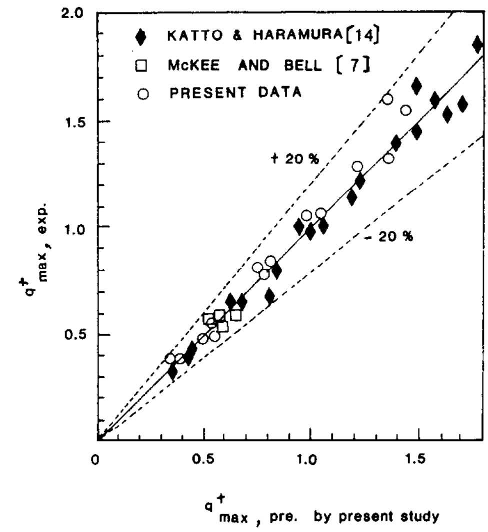

FIG. 5. Comparison of single tube CHF data with equation (4).

infinite flow field. At modest channel blockage ratios, e.g. $d/H = 0.25$, the CHF can be reduced by as much as 30% of that for a single tube in an infinite flow field.

Another way to examine the channel blockage effect is to compare the present data, McKee and Bell's data [7], and existing data at low d/H conditions [14] with Katto and Haramura's prediction [14] for low velocity saturated flow (Fig. 4). In general, the agreement is excellent for the CHF data at low blockage ratio conditions ($d/H < 0.05$). The present data ($d/H = 0.22$) and McKee and Bell's data ($d/H = 0.11$–0.25) are much lower than the predictions. This indicates again that the d/H effect should possibly be considered as an important factor in estimating the CHF on a single tube in a restricted channel at crossflow conditions. The d/H effect is represented by the dashed curve in Fig. 3. Thus, Katto and Haramura's correlation [14] can be modified by a factor of $[1-(d/H)^{0.86}]$ to account for the channel blockage effect.

Effect of local flow quality on CHF. Because of the lack of published CHF data for two-phase oncoming flows, the effect of local flow quality on the CHF has also been investigated. In a conventional in-tube flow, the local flow quality influences the CHF [26]. However, in the present study, the majority of the upstream bubbles leave the tube in a tangential direction upward beyond the 90° position of the heated tube. Some of these bubbles have a tendency to move into the downstream wake of the heated tube and coalesce with the bubble generated at the top portion of the heated tube, so that a slightly lower CHF is observed. Nevertheless, the present data indicate only a weak dependence of the CHF on the local flow quality. For example, a local flow quality of 0.143 will only reduce the CHF by 14% from that in a single-phase oncoming flow. It is noted that Jensen and Pourdashti [18] also found that CHF decreases with increasing flow quality, but linearly up to about 10% quality; then, due to a flow regime transition, the CHF remained relatively constant. Their CHF data at a flow quality of 0.15 was also about 16% lower than that for saturated flow.

CHF correlation. To provide a modified CHF prediction considering the channel blockage ratio and flow quality effects, the following empirical correlation has been established:

$$\frac{q_{\max}}{\rho_g h_{fg} U_\infty} = 0.594 We_g^{-0.476}(1-x_{\text{Loc}})^{0.954}(R^*)^{0.36} \times [2.25+(\rho_g/\rho_f)^{0.15}]^{-1}[1-(d/H)^{0.86}]. \quad (4)$$

This equation is valid for a mass flux higher than 132 kg m^{-2} s^{-1} as limited by the range of the data base, and will not be applicable for pool boiling where $U_\infty = 0$. The comparisons of equation (4) with the available CHF data for single-phase or two-phase oncoming flows are shown in Fig. 5. The local flow quality (x_{Loc}) for slightly subcooled or nearly saturated flow is set equal to zero in the present comparison. Equation (4) fits all the data within $\pm 20\%$. When the blockage ratio is small and the fluid is nearly saturated, the predictions of equation (4) and the correlation in ref. [14] are in agreement within $\pm 10\%$. Although Katto and Haramura's correlation [14] can also be modified to account for the d/H effect and the local flow quality effect separately, the present empirical correlation is much simpler to use because no iteration is required. However, further comparisons of the present correlation with other data should be made to determine the range of applicability.

A heated tube in an unheated bundle

The CHF on a heated tube in an unheated in-line bundle was measured for slightly subcooled flows only. For the present study of the in-line bundle in upward flows with a pitch-to-tube diameter of 1.5, it is

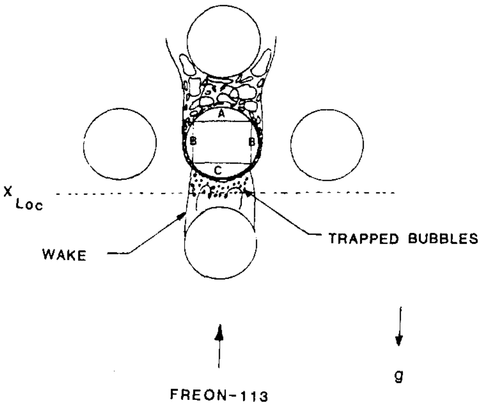

FIG. 6. Schematic representation of boiling phenomenon in an unheated tube bundle.

observed that burnout always begins at the upstream stagnation point of the heated tube. Although only one bundle has been studied, this phenomenon is expected to be generally applicable in industrial bundles where the pitch-to-diameter ratios usually vary between 1.25 and 2.5. This is contrary to that occurring on single tubes in channels where the CHF always starts at the downstream stagnation point of the tube.

In an unheated bundle, the occurrence of CHF at the front stagnation point of a heated tube can possibly be interpreted by the effect of local quality distribution near the tube. While the same phenomenon may be explained by other reasons, e.g. due to the greatly reduced convective heat transfer at region C in the wake, a tentative model is illustrated here. A schematic representation of the boiling phenomenon near the CHF condition in an unheated bundle is shown in Fig. 6. In this tentative model, the flow field near the heated tube is divided into three regions: rear region A, sides region B and front region C as shown in Fig. 6.

At the top portion of the tube, region A, the phenomenon is similar to pool boiling on a horizontal plate facing upward with some recirculating flow above the surface. Small individual bubbles leave the surface and coalesce with others into massive bubbles. The local boiling heat transfer in region A will not be affected whether the tube is in a bundle or in a channel. The downstream unheated tube does not significantly affect the heat transfer in region A. This is similar to the results reported in ref. [27] that an object staying on top of a horizontal heated plate during pool boiling will not affect the CHF of the plate as long as the distance between the object and the plate is larger than the departure bubble diameter. On the left- and right-hand sides of the tube, region B, boiling is similar to that on a vertical wall with upflowing liquids. Thus we expect the CHF in region B to be higher than that in region A because of the forced convective effect.

At the bottom of the tube, region C, the phenomenon is similar to pool boiling on a horizontal plate facing downward with some recirculating flow below the surface. Some of the bubbles generated at region C coalesce and circulate in the upstream wake region which results in a higher local quality near the wall and, finally, a lower CHF as compared with region A. Therefore, early burnout is observed at the upstream stagnation point of a tube in this in-line bundle.

For a wide-spacing tube bundle, the wake of the upstream tube diminishes before arriving at the front stagnation point of the heated tube. Therefore, the CHF may start at the downstream portion of the heated tube in a bundle, similar to that for a single tube in an infinite pool.

Recall the situation of a single tube in a channel as a comparison: the direct impingement of Freon-113 on the upstream stagnation point results in better heat transfer and higher CHF locally as compared with those on the downstream stagnation point of this tube. As a result, burnout is usually observed at the downstream stagnation point of a single tube in a channel.

Overall comparison of CHF data

It is interesting to compare the CHF for a single tube in an infinite flow field, in a channel and in a bundle. Hasan *et al.* [19] concluded that when the flow velocity is low, $G^* < 10$, the CHF on a cylinder in a two or three cylinder array is identical to the CHF on a single cylinder in an infinite pool. In the present study of an in-line bundle with upward flows, G^* is much less than 10. However the data show a significant reduction of the CHF by the surrounding unheated tube bundle.

The significant effect of the channel width on the CHF of a horizontal single tube in a channel has been indicated in equation (4) and Fig. 3. It can be postulated that the side column of the unheated tubes in a bundle can be regarded as imaginary walls. The CHF for a tube in an unheated bundle is therefore, similar to the CHF for a tube in a narrow channel and we expect it to be much lower than the CHF on a single tube in an infinite flow field. Some attempts have been made to choose a suitable hypothetical channel width in the bundle. Two typical cases are considered here. First, the lateral pitch of the bundle is taken as half of the equivalent channel width ($H = 2X_T$) and the resulting channel blockage ratio is 1/3. Second, the equivalent channel width is taken as $H = 2X_T - d$, and the corresponding d/H ratio becomes 0.5. It appears that the first choice of the channel width gives a reasonable prediction of the CHF for a tube in an unheated bundle as shown in Fig. 3. The result of the second choice underpredicted the CHF by about 20%. The comparisons of the present bundle data with the predictions of equation (4) and the predictions of Katto and Haramura's correlation [14] are shown in Table 1. As indicated in Table 1, the present prediction of the CHF for a tube in a bundle is consistently about 10% higher than the data. Further refinement of the selection of the equivalent width of the channel for the bundle may reduce this difference.

Table 1. Comparison of the bundle CHF data

G ($kW\,m^{-2}\,s^{-1}$)	CHF,† Exp. ($kW\,m^{-2}$)	CHF,‡ Equation (4) ($kW\,m^{-2}$)	CHF,§ Katto and Haramura [14] ($kW\,m^{-2}$)	Percentage error $\frac{\text{Exp.} - \text{Equation (4)}}{\text{Exp.}}$
132	105	111.8	205.8	−6.5
242	108	115	209	−6.5
352	108.6	117	210.6	−7.7
462	114.2	118.7	212	−3.9
560	116.5	120	215.2	−3.0

† CHF data for a tube in an unheated bundle.
‡ Prediction of equation (4) for the bundle CHF ($H = 2X_T$).
§ Prediction of CHF for a single tube in an infinite pool [14].

Table 1 also shows that the present data are much lower than the CHF for a single tube in an infinite flow field [14]. This is due to the different vapor flow pattern that results from the combined effects of the side tubes, which provide a narrow flow channel, and the upstream tube, which provides a relatively high flow quality at the upstream stagnation portion of the heated tube. In other words, both the channel blockage ratio and the local flow quality distribution influence the CHF on the heated tube. The higher the channel blockage ratio or the higher the local flow quality at the front portion of the tube, the lower the CHF. As a result, the CHF data for a single tube in an infinite flow field should be modified significantly when they are used to predict the CHF in bundles.

CONCLUSIONS

Experimental studies of the CHF on horizontal tubes in an upward crossflow of Freon-113 have been performed. A single tube was located in a channel and in a 3 × 16 in-line upheated tube bundle. The test tube is heated electrically and the Freon-113 flows upward at various mass fluxes and local flow qualities. The experiment reveals the effects of the flow field on both the magnitude and the location of the CHF for a horizontal tube.

For the case of a single tube in a channel, when the mass flux is fixed, the narrower the channel the lower the CHF. In an in-line bundle the CHF is approximately equal to that of a single tube in an equivalent channel, which has a half width the same as the lateral pitch of the bundle, under the same local mass flux and flow quality. Furthermore, the CHF in this in-line bundle (with a pitch-to-tube diameter ratio of 1.5) always begins at the upstream stagnation point of the heated tube. This is because, in the present in-line bundle, the local quality is highest at the upstream stagnation point of the heated tube due to the presence of the upstream wake. This phenomenon could be a typical situation of industrial tube bundles but is contrary to the usual situation that occurs on a tube in a channel or in an infinite pool where the CHF always starts at the downstream portion of the heated tube. When the pitch-to-tube diameter ratio of the in-line bundle is increased, it is expected that the chance of CHF to occur at the downstream stagnation point of the heated tube will increase.

An empirical correlation, equation (4), has been established for the CHF on a horizontal tube in a channel with various channel widths. The same correlation also predicted well the CHF on a heated tube in an infinite flow field and in an in-line unheated bundle for the range of conditions examined in this study. To determine the range of applicability of the correlation, further measurements should be made to different bundle geometries and flow conditions.

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FLUX THERMIQUE CRITIQUE SUR DES TUBES HORIZONTAUX DANS UN ECOULEMENT FRONTAL ASCENDANT DE FREON 113

Résumé—Le flux thermique critique (CHF) sur des tubes horizontaux dans un écoulement frontal ascendant de Freon 113 est obtenu dans des conditions variées d'écoulement. Les effets du champ d'écoulement sur l'intensité et sur l'emplacement du CHF sont dégagés. Des mesures sont faites pour un domaine de débit (132–560 kg m^{-2} s^{-1}), de sous-refroidissement (0–6°C) et de qualité ($0 < x_{Loc} < 0{,}143$), à la pression atmosphérique. Dans le cas d'un tube dans un canal, lorsque le débit-masse est fixé, plus le canal est étroit, plus le CHF est faible. Dans un arrangement en ligne, le CHF est approximativement égal à celui d'un tube unique dans un canal équivalent qui a une demi-largeur égale au pas latéral du faisceau, avec le même débit-masse et la même qualité. Le CHF dans l'arrangement en ligne avec un rapport pas-diamètre du tube de 1,5, se produit toujours au point d'arrêt amont du tube. C'est le contraire de la situation habituelle pour laquelle le CHF commence toujours sur la portion aval du tube dans un canal. Ceci provient de ce que dans un faisceau de tubes en ligne, la qualité locale est plus élevée au point d'arrêt amont à cause de la présence d'un sillage ascendant. Une formule empirique est établie pour le CHF sur un tube horizontal dans un écoulement infini et dans des canaux avec différentes largeurs. La formule prédit correctement le CHF sur un tube chaud dans un arrangement en ligne non chauffé pour le domaine de conditions considéré dans cette étude.

KRITISCHE WÄRMESTROMDICHTE AN HORIZONTALEN ROHREN BEI AUFWÄRTSGERICHTETER QUERANSTRÖMUNG MIT R113

Zusammenfassung—Die kritische Wärmestromdichte (CHF) an horizontalen Rohren bei aufwärtsgerichteter Queranströmung mit R113 wurde für verschiedene Strömungsbedingungen bestimmt. Es werden die Einflüsse des Strömungsfeldes sowohl auf den Betrag, als auch auf den Ort der CHF aufgezeigt. In einem weiten Bereich der Massenstromdichte (132 bis 560 kg m^{-2} s^{-1}), der Unterkühlung (0 bis 6°C) und des Dampfgehaltes ($0 < x_{Loc} < 0{,}143$) wurden Daten bei Umgebungsdruck aufgenommen. Für den Fall eines Rohres in einem Kanal ergeben sich bei konstanter Massenstromdichte umso niedrigere Werte der CHF, je enger der Kanal ist (kleinerer Strömungsquerschnitt). In einem fluchtenden Bündel ist die CHF bei gleicher lokaler Massenstromdichte und gleichem Dampfgehalt nahezu gleich der CHF eines einzelnen Rohres in einem Kanal, dessen halbe Breite dem Querabstand der Rohre im Bündel entspricht. In einem derartigen Bündel mit dem Teilungsverhältnis 1,5 beginnt die CHF immer am vorderen Staupunkt des beheizten Rohres. Dies steht im Gegensatz zur üblichen Situation eines Rohres in einem Kanal, bei dem die CHF immer auf der von der Strömung abgewandten Seite des Rohres auftritt. Dies ist darauf zurückzuführen, daß in diesem fluchtenden Bündel der lokale Dampfgehalt am vorderen Staupunkt des beheizten Rohres aufgrund der dort vorhandenen Wirbel am größten ist. Eine empirische Korrelation für die CHF an einem horizontalen Rohr in einem unendlichen Strömungsfeld und in einem Kanal mit verschiedener Kanalbreite wird angebegen. Mit der Korrelation läßt sich auch die CHF an einem beheizten Rohr in einem unbeheizten Bündel im untersuchten Parameterbereich wiedergeben.

КРИТИЧЕСКИЙ ТЕПЛОВОЙ ПОТОК НА ГОРИЗОНТАЛЬНЫХ ТРУБАХ В ВОСХОДЯЩЕМ ПОПЕРЕЧНОМ ТЕЧЕНИИ ФРЕОНА-113

Аннотация—При различных условиях течения найден критический тепловой поток (КТП) на горизонтальных трубах в поперечном восходящем течении фреона-113. Выявлено влияние поля течения на величину и положение КТП на горизонтальной трубе. Получены данные для диапазонов массового расхода вещества (от 132 до 560 кг $м^{-2}$ $с^{-1}$), недогрева (от 0 до 6°С) и характеристик потока ($0 < x_{Loc} < 0,143$) при атмосферном давлении. Для случая одной трубы в канале при постоянной величине расхода вещества КТП снижается по мере сужения канала (уменьшения поперечного сечения потока). В коридорном пучке труб КТП приблизительно совпадает с его значением для единичной трубы в эквивалентном канале, полуширина которого равна поперечному шагу пучка, при одинаковых значениях локального массового потока и характеристиках течения. В этом пучке с отношением шага к диаметру, равным 1,5, КТП всегда наблюдается в точке торможения восходящего потока на нагретой трубе. Это противоречит обычной ситуации, возникающей для единичной трубы в канале, когда КТП достигается на участке нагретой трубы, находящемся вниз по течению. Этот факт объясняется тем, что в коридорном пучке труб локальные характеристики течения максимальны в точке торможения восходящего потока на нагретой трубе в силу наличия восходящего спутного следа. Установлено эмпирическое соотношение для КТП на горизонтальной трубе в бесконечном поле течения и в каналах различной ширины. Это соотношение также хорошо описывает КТП на одной нагреваемой трубе, находящейся в коридорном пучке ненагреваемых труб для условий, рассмотренных в данной статье.