EFFECT OF FLOW OBSTACLES WITH VARIOUS LEADING AND TRAILING EDGES ON CRITICAL HEAT FLUX

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KEYWORDS: Flow boiling, critical heat flux, flow obstructions

A joint investigation has been performed by the University of Ottawa and Chalk River Laboratories that examined the effect of the shape of the leading and trailing edges of the turbulence enhancing devices ("flow obstacles") on critical heat flux (CHF). The objective of this study was to gain a better overall understanding of the limit of CHF improvement for various obstacle designs and the impact of flow conditions on the improvements.

The experiments were carried out in a heat-transfer loop at the University of Ottawa. Flow obstacles with a square cross-sectional area and one rounded side (2.9 mm by 3.22 mm) were machined to provide different leading and trailing edges: flat, knife-shaped, wedge-shaped, or rounded surface. Each obstacle was placed at a location 125 mm upstream of the end of a heated tube with an inside diameter of 6.92 mm. To prevent premature dryout from occurring upstream of the obstacle, additional flow obstacles of a simpler ring-type design were installed at various upstream locations. The experiments were performed in R134a at a pressure of 1.67 MPa (10 MPa in water-equivalent value), mass fluxes from 1000 to 3000 kg/m^{2}s (1350 to 4100 kg/m^{2}s in water-equivalent values), and dryout qualities from -5 to +60%.

The results showed that the CHF increase in flow-obstacle equipped tubes was between 0% and 500%, compared to the plain tube at the same dryout conditions. In general, the largest enhancement was observed for an obstacle with the flat leading edge perpendicular to the flow, while the least improvement was observed with an obstacle having knife-shaped leading and trailing edges. The experiments showed that the CHF enhancement ratio depends strongly on the dryout quality; it is considerably

larger at qualities higher than the limiting critical-quality region of a plain tube (the limiting critical-quality region was not observed in the obstacle-equipped tubes). Mass flux and the shape of the leading and trailing edges of the flow obstacle also affect the CHF enhancement: for lower mass fluxes (less than 2000 kg/m^{2}s), the CHF enhancement became negligible for an obstacle with a sharp leading edge.

Introduction

General

The main objective of this experimental research is to study the general flow obstruction effects on CHF for saturated flow boiling conditions. The relevance of this study is that rod spacing devices and other flow-obstructing appendages have been used in nuclear fuel bundles to enhance the CHF.

Ideally, an investigation of the CHF enhancement potential of flow obstruction devices should be studied in full scale test sections that closely simulate the reactor fuel bundles with spacers (appendages). Such experiments are very expensive.

To reduce the expense and complexity of CHF testing of full-scale fuel bundles with high-pressure steam-water, low-latent-heat fluids have been used successfully as modeling fluids. Reliable CHF predictions for water can be made based on CHF measurements in refrigerants at considerably lower pressures, temperatures and powers, resulting in cost savings of around 70% compared to equivalent experiments in water.

Additional savings can be realized by performing tests in a channel simulating a subchannel of a fuel bundle. Since subchannel analysis is frequently used to model the CHF behavior of fuel bundles, this is an acceptable interim approach. The CHF has been measured extensively in simple geometries such as directly heated bare tubes [1-3]. Such measurements have helped to provide a better understanding of the CHF mechanisms.

The approach taken in this investigation is to use a simulation of a subchannel, a directly heated tube equipped with various flow obstruction arrangements to assist in providing a better understanding of the CHF enhancement mechanisms of flow obstructions (it should be noted that the results of this research may not be directly applied to a particular bundle design).

Previous Studies

The objective of using spacers (in our case flow obstructions) is to maintain the desired cross section configuration in fuel assemblies. A wide variety of spacer types have been used in different designs of nuclear reactors.

The effect of spacing devices or flow obstructions on CHF is rather complex and is still under investigation by many scientists and researchers. Recent studies [4-10] all have shown significant spacer effects to be present. The majority of these studies indicate beneficial effects of spacers on CHF, but some researchers have reported detrimental effects [6, 10].

Our previous studies [4-6] on the effect of flow obstructions (rings and bars with different cross sections: circular, segment, sector, rectangular, etc.) on the CHF show a very significant increase in CHF for a tube with flow obstructions, varying from 40% to 600% (and more for twisted plate), based on a constant critical quality approach, and from 10% to 100%, based on inlet conditions approach. For medium mass fluxes, the limiting critical quality phenomenon can be clearly seen for the bare tube data [3]. This phenomenon is less pronounced for the tubes containing flow obstructions. Also, at some flow conditions (R-134a, p=1.67 MPa, G=1000 kg/m^{2}s, x_{cr}=0.25-0.35) CHF for the obstacle equipped tube may be lower, by as much as 2 times than the bare-tube CHF [6]. All these studies were conducted with flow obstructions having only abrupt leading and trailing edges.

The objective of this study was to gain a better overall understanding of the limit of CHF improvement for various obstacle designs (differently shaped leading and trailing edges) and the impact of flow conditions on the improvements in a circular tube.

Nomenclature

D	inside diameter, m
$G=\rho u$	mass flux, kg/m^{2}s
h_{fg}	latent heat of vaporization, J/kg
L	heated length, m
p	pressure, MPa
q	heat flux, W/m^2
u	velocity, m/s
x_{cr}	critical vapor quality,
$x_{cr}^{\lim}$	limiting critical quality,

Greek letters

ε	blockage ratio (flow obstruction cross-section area/channel flow area), (%)
ρ	density, kg/m^3

Abbreviations

DC	Direct Current
ID	Inside Diameter
OD	Outside Diameter

Experiments

Test Facility

The experimental study was performed in a multi-fluid loop using R-134a as a coolant. The experimental loop was designed and built at the Department of Mechanical Engineering, University of Ottawa. The main components of the loop are - test section, condenser (heat exchanger with cold water), pressurizer with electrical heater and coils for cold water, preheater (electrical heater and heat exchanger with hot/cold water), two pumps (connected in series), electrical generator (DC, maximum 40 V × 300 A) and related instrumentation (flow meter, thermocouples, data acquisition system, voltmeter, ammeter, pressure transducer with sensor, etc.). A full description of the experimental loop was presented by Pioro et al. [3, 5]. The test section (Fig. 1) was oriented vertically.

Test section

The test section was a circular tube (ID 6.92 mm, OD 7.93 mm, length 2.1 m), made of Inconel 601 (Fig. 1). The inside diameter was close to the 8 mm standard tube size diameter on which the CHF look-up table [11] is based. The test section was directly heated by DC current with uniform axial and circumferential power profiles. Two types of flow obstructions were used: local obstacles (bars with one rounded side) attached to the wall and concentric rings (Table 1 and Fig. 2) whose OD was equal to the ID of the bare tube. The axial length (in the direction of the flow) of the rings was 3 mm and blockage ratio was 37% (Fig. 1). The local obstacles and the rings were kept in their locations with external magnets. This design allowed movement of any flow obstruction in the axial direction during the experiment. External magnets were electrically isolated with thin Teflon tape from the heating surface of the tube. Additional upstream rings ensured that CHF occurred initially at the downstream end. The flow obstructions were spaced axially by 125 mm.

CHF was detected by fast-response K-type thermocouples attached to the test section by special adhesive just upstream of the upper power terminal, or by miniature probe thermocouples just upstream of flow obstructions. The fast response thermocouples on the circular tube were located in groups of four, 90° apart (rotating clockwise at 0°, 90°, 180°, and 270°) in several planes (three planes at 5, 10, and 15 mm) upstream from the lower edge of the upper power terminal. The probe thermocouples for detecting dryout upstream of the flow obstructions were located upstream of the lower edge of obstructions: for each local obstacle - one thermocouple, for a ring – two thermocouples 180° apart in one cross section.

Test Matrix

Refrigerants have been used successfully in many heat transfer laboratories as the modeling fluids for simulating the CHF of water. It was shown [1-5] that if the Katto similarities are satisfied, then the dimensionless CHF expressed as, $\left(\frac{q_{cr}}{G\, h_{fg}}\right)$ will also be the same for both fluids.

The tests were performed at an outlet pressure of 1.67 MPa; this corresponded to typical Pressurized Heavy Water Reactor's operating conditions (10 MPa water-equivalent). The range of inlet temperature was as wide as possible, but limited at the low end by the temperature of the water in the condenser (that varied from about 2°C in winter to 16°C in mid summer) and at the upper end to just below saturation to avoid a two-phase inlet (~56°C). This corresponded to a maximum inlet quality range of -60% to -2%. It also resulted in a wide range of dryout qualities for a given heated length. The complete test matrix is listed in Table 2.

Test procedure

Before each series of experiments a heat balance test was performed. It showed the heat loss to be less than 1-2% of total power input. Thus, it was decided to run the main series of experiments with the uninsulated test section.

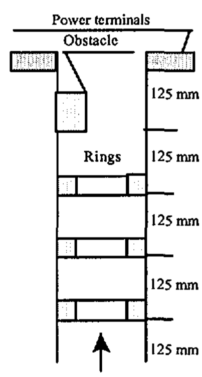

Fig. 1. Test section with flow obstructions.

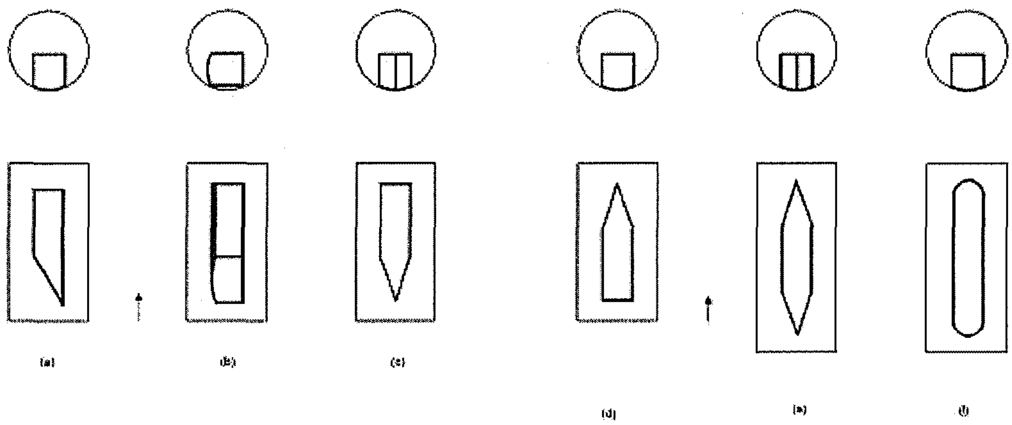

Fig. 2. Flow obstructions – square bars (one side rounded, ε=24%) with various edges: (a) wedge-shaped leading edge directed to side; (b) the same, directed to center; (c) knife-shaped leading edge; (d) knife-shaped trailing edge; (e) knife-shaped both edges; (f) rounded both edges.

Table 1. Obstacles specification.

Figure	Type of obstacle and blockage ratio (%)	Length mm	Width mm	Height mm	Diameter (ID) mm
	Square bars with one rounded side				
-	Square bar, 24%	10	2.9	3.22	-
2a,b	Wedged-shaped edge, 24%	15	2.9	3.22	-
2c,d	Knife-shaped edge, 24%	15	2.9	3.22	-
2e	Knife-shaped both edges, 24%	20	2.9	3.22	-
2f	Rounded both edges, 24%	20	2.9	3.22	-
	Rings				
1	Rings, 37%	-	-	3	5.50

Table 2 Test conditions for the bare tube and enhanced tube.

Flow Parameter	Bare/Enhanced Tube	Water-Equivalent Value
Pressure	1.67 MPa	10 MPa
Inlet Quality	-60% to –2%	Same
Mass Flux	2000 kg/m^2s 3000 kg/m^2s	2826 kg/m^2s 4239 kg/m^2s
Outlet Quality	-5 to +60%	Same
Heated Length	1; 2 m	Same

Just prior to CHF occurrence, all test conditions were stabilized and the power to the test section was raised in small steps. CHF was defined as the first detected occurrence of a wall temperature excursion just below the upper power terminal or just upstream of flow obstructions. At that moment, all values of the parameters and dryout location were recorded and the power to the test section was decreased. In general, after that, a new value of inlet temperature was set up. Once the complete range of inlet temperatures had been covered, (or if the dryout location had changed from the usual location just upstream of upper power terminal to a new location) the flow was changed to the next flow of the test matrix.

In the main series of the experiments, the inlet temperature of the working fluid (R-134a) was usually changed from the minimum value of 38°C to just below the saturation temperature in steps of 2-3°C. Hence, the inlet subcooling varied from the maximum available value to 0, and the inlet quality varied from the minimum available value to 0. Such test procedure, together with a change in heated length (1 m and 1.98 m lengths were usually used for the tube with flow obstructions), allowed for a wider range of critical qualities. Because of the lower CHF with the bare tube, the range of critical qualities was usually lower than that of the obstacle-equipped tubes. Hence, the bare tube critical quality range was extended by using two-phase flow at the test section inlet and performing a heat balance across the preheater as well to determine the critical quality. A comparison with corresponding single-phase flow at the test section inlet results did not reveal any significant differences in CHF due to the two-phase flow inlet [3]. Two-phase flow at the test section inlet was also used for the experiments with flow obstructions [5].

CHF for the bare tube was relatively easy to measure as the CHF always first occurred at the downstream end of the heated length. The tests with the flow-obstruction-equipped test section were more complex as there were several preferential locations of CHF: (i) at the end of the heated length (as for the bare tube), and (ii) upstream of the flow obstruction. The latter CHF occasionally occurred because the flow obstruction usually suppressed any downstream CHF occurrence due to a higher turbulence level. This turbulence level is not present upstream; however, the local quality upstream is lower which results in a higher CHF. An upstream CHF would not permit the quantification of the increase in CHF due to an appendage. To avoid the occurrence of upstream CHF, a series of flow obstructions (10 rings) were installed upstream of the obstruction being studied. They were spaced 125 mm apart. Previous studies by Doerffer et al. [8] and Pioro et al. [4, 5] had shown that the presence of upstream flow obstructions does not have a cumulative effect, i.e., it does not affect the CHF enhancement effectiveness of the most downstream flow blockage.

Experimental errors

A heat balance tests showed that the heat losses were not more than 1-2% (in absolute values not more than 20 W for the test section and 50 W for the preheater) of total power input. CHF measurement errors were not more than 2.5% (4.5% for the experiments with two-phase flow at inlet). Errors for measuring mass flux and pressure were not more than 0.3% and 1%, respectively.

Test results

General

CHF test results obtained in a tube with flow obstructions were compared to corresponding reference CHF values for a bare tube at the same flow, pressure and critical quality. Bare tube results were obtained from two sources: reference tube tests obtained in R-134a from the University of Ottawa experimental loop [3], and the CHF look-up table for water [11]. The CHF look-up table for water was converted into R-134a-equivalent data using the Katto fluid-to-fluid modeling relationships [3]. The CHF values from the look-up table (D=8 mm) were also adjusted to the bare tube diameter of 6.92 mm using the following correlation [11]:

$$\frac{CHF_{8\,mm}}{CHF_{6.92\,mm}} = \left(\frac{8}{6.92}\right)^{-0.5} \quad (1)$$

The CHF data from the look-up table were used to confirm the reliability of our experimental data, and in some cases to extend the range of the R-134a reference CHF values [3].

As had been done previously, the CHF results are presented graphically as CHF vs. Critical Quality and CHF Enhancement Ratio vs. Critical Quality. Previously, it was found [1-5] that presenting experimental data in the form of CHF vs. Critical Quality is the most convenient approach and permits to combine the effects of heated length and inlet temperature. It also permits a direct comparison with the CHF look-up table. The value of critical quality was based on the full heated length because the location of dryout was usually within 5 mm from the upper power terminal.

Bare tube results

The reference CHF results were obtained prior and subsequent to the CHF enhancement tests. The results are summarized in the paper by Pioro et al. [3]. In general, the agreement between the CHF look-up table [11] and the experiment is good. Only at qualities near the so-called limiting quality region (the region where the CHF drops rapidly with increasing quality, due to a transition from an entrainment-controlled-dryout to a deposition-controlled-dryout), do we see a different trend, with the CHF look-up table showing a more gradual variation in CHF.

The CHF look-up table extends over a much wider range of qualities than the experiments. This will permit the use of the look-up table to quantify the CHF enhancement for qualities greater than the limiting critical quality values.

Effect of knife-shaped edges on CHF

Experiments on the enhanced tube were initially performed with the main local obstacles (bars, ε=24%) and ten additional upstream flow obstructions (rings) located in series: the local obstacle (closest to the upper power terminal) was 125 mm upstream of the terminal, and the rings were spaced 125 mm from each other (Fig. 1). The rings had flow blockage ratios of 37%.

In Figs. 3 and 4 the CHF enhancement for the bar with abrupt edges is compared to the same cross sectional shape obstacle with knife-shaped leading and/or trailing edges. Figures 3a and 4a show the CHF results for mass flux values of 2000 and 3000 kg/m^{2}s, while Figs. 3b and 4b show the CHF enhancement ratio (the experimental CHF data points obtained in a bare tube were used as the reference value). Based on these figures the following observations may be made:

- The local flow obstructions (ε=24%) increase the CHF significantly (up to 6 times): no significant effect of heated length on the CHF enhancement (Figs. 3a and 4a) or enhancement ratio (Figs. 3b and 4b) was observed. This is in agreement with our previous observations [4, 5] and the observations of Doerffer et al. [7, 8]. For the lower mass flux (G=2000 kg/m^{2}s) and lower critical qualities the bar with the knife-shaped leading edge shows insignificant CHF enhancement.
- The local flow obstructions with abrupt edges show the highest increases in CHF

(Figs. 3 and 4).

- The shape of the trailing edge does not show any significant effect on CHF enhancement.
- In general, the CHF in an enhanced tube increases significantly over a wide range of critical qualities. For qualities higher than the limiting critical quality, this increase goes up dramatically (Fig. 3). Also, a peak in CHF enhancement can be noticed in the middle range of critical qualities (Figs. 3b and 4b).
- Limiting critical quality region was mainly observed for the bare tube at low mass fluxes (G<3000 kg/m^{2}s).
- No limiting critical quality region was observed for the enhanced tube at G=2000 kg/m^{2}s. It may well be that the turbulence generated by the obstructions homogenizes the flow, thus suppressing the mechanisms responsible for the limiting critical quality (the limiting critical quality phenomenon is thought to be due to a change from entrainment-controlled to deposition-controlled dryout).

Effect of shape of leading edge of flow obstruction on CHF enhancement

Figures 5a and 6a show the effect on CHF of differently shaped leading edge (knife-shaped, wedge-shaped edge directed to side or center) of local flow obstruction (bar, ε=24%) for G=2000 and 3000 kg/m^{2}s. The main obstacle is located 125 mm upstream from the end of the heated length with ten rings (ε=37%) upstream spaced equally 125 mm apart. The wedge-shaped leading edge that directs the flow to the center of the tube shows less enhancement than the other two shapes. For the lower value of mass flux (G=2000 kg/m^{2}s), a wedge-shaped leading edge directed to the side shows a higher CHF enhancement than the other two shapes (Fig. 5).

No clear limiting critical quality region was observed in these test series at G=3000 kg/m^{2}s for the bare tube and at G=2000 and 3000 kg/m^{2}s for the enhanced tube. For qualities higher than the limiting critical quality of bare tube, the increase in CHF goes up dramatically (Fig. 5b). Also, a peak in CHF enhancement can be noticed in the middle range of critical quality (Figs. 5b and 6b).

Effect of shape of leading and trailing edges of flow obstruction on CHF enhancement

Figures 7 and 8 show the effect of differently shaped edges (leading and trailing) of the flow obstruction for two values of mass flux (G=2000 and 3000 kg/m^{2}s) on CHF enhancement (main flow obstruction - bar (ε=24%) and additional flow obstructions - 10 upstream rings (ε=37%)). Figures 7a and 8a show the CHF enhancement and Figs. 7b and 8b - the CHF enhancement ratio.

In general, there is no difference in CHF enhancement for both edges rounded and knife-shaped. Again, a bar with abrupt edges shows higher CHF enhancement compared to the two other shaped edges.

Conclusions

CHF experiments were performed in test sections with four types of flow obstructions and in a bare tube. The CHF enhancement results were compared with those for bare tube and with the CHF data from the look-up table which were converted from water to R-134a and corrected for difference in diameters with the commonly used inverse exponential relationship.

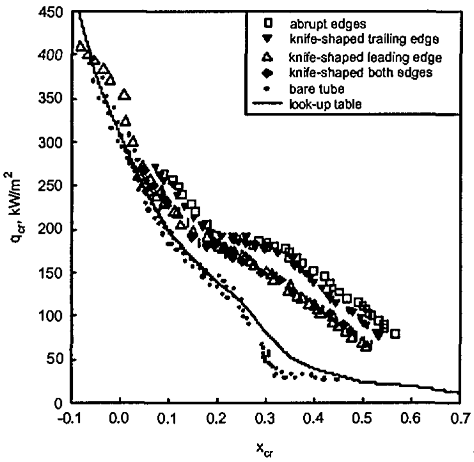

Fig. 3a. Effect of critical quality on CHF in tube with/without flow obstructions: R-134a, p=1.67 MPa, G=2000 kg/m^{2}s, L=0.45-2 m.

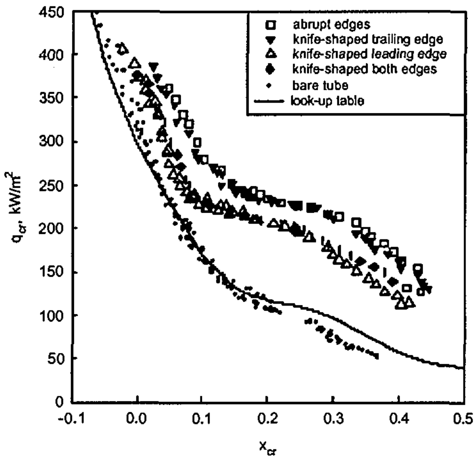

Fig. 4a. Effect of critical quality on CHF in tube with/without flow obstructions: R-134a, p=1.67 MPa, G=3000 kg/m^{2}s, L=0.45-2 m.

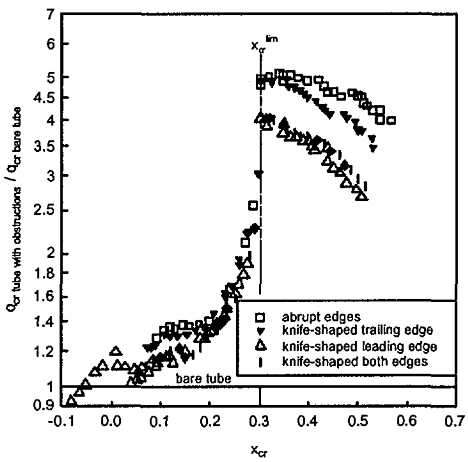

Fig. 3b. Effect of critical quality on CHF enhancement in tube with flow obstructions: R-134a, p=1.67 MPa, G=2000 kg/m^{2}s, L=0.45-2 m.

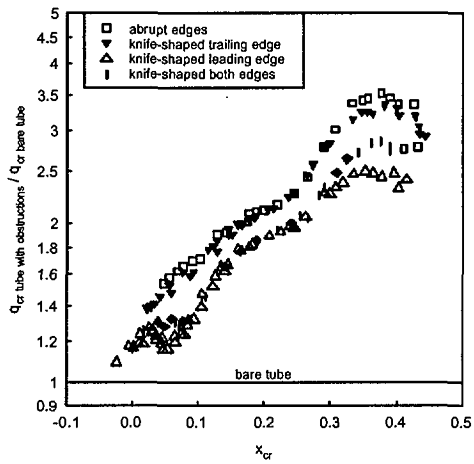

Fig. 4b. Effect of critical quality on CHF enhancement in tube with flow obstructions: R-134a, p=1.67 MPa, G=3000 kg/m^{2}s, L=0.45-2 m.

1. In general, a comparison of the CHF results obtained with the flow-obstruction-equipped tubes to the bare tube data and the look-up table showed that flow obstructions have a significant enhancement effect on the CHF for the conditions tested: the CHF increased up to 6 times, depending on the mass flux, critical quality and shape of the leading edge of flow obstruction. The test results indicate that the largest enhancement occurred for the abrupt leading edge flow obstruction, and higher dryout qualities.
2. It was found that the CHF enhancement is very sensitive to critical quality changes.

For qualities higher than the limiting critical quality, the CHF enhancement is very high. Also, a peak in CHF enhancement can be noticed at the limiting critical quality for G=2000 kg/m^{2}s.

3. The experiments clearly show that at lower mass velocities (G=2000 kg/m^{2}s) the CHF enhancement effect of flow obstructions with knife-shaped and rounded leading edges may disappear at low qualities.
4. No limiting critical quality region was observed for the enhanced tube. It may well be that the turbulence generated by the obstructions suppresses the mechanisms responsible for the limiting critical quality.

Acknowledgements
The financial support provided by AECL and NSERC is gratefully acknowledged.

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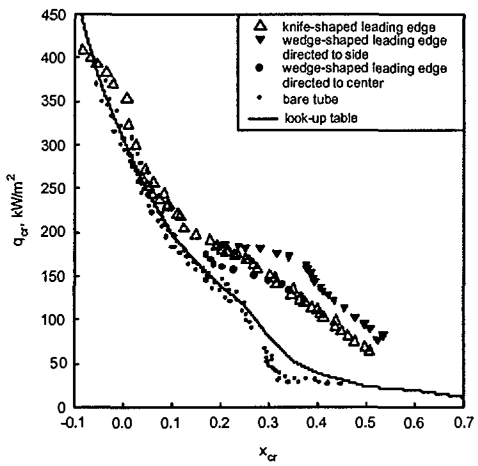

Fig. 5a. Effect of critical quality on CHF in tube with/without flow obstructions: R-134a, p=1.67 MPa, G=2000 kg/m^{2}s, L=0.45-2 m.

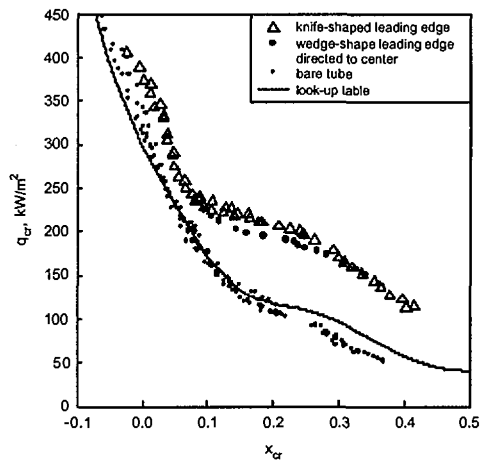

Fig. 6a. Effect of critical quality on CHF in tube with/without flow obstructions: R-134a, p=1.67 MPa, G=3000 kg/m^{2}s, L=0.45-2 m.

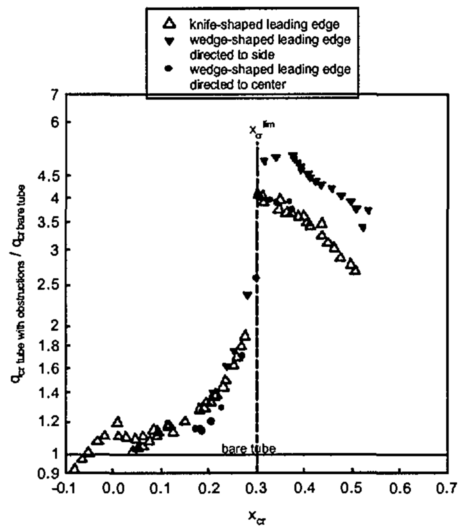

Fig. 5b. Effect of critical quality on CHF enhancement in tube with flow obstructions: R-134a, p=1.67 MPa, G=2000 kg/m^{2}s, L=0.45-2 m.

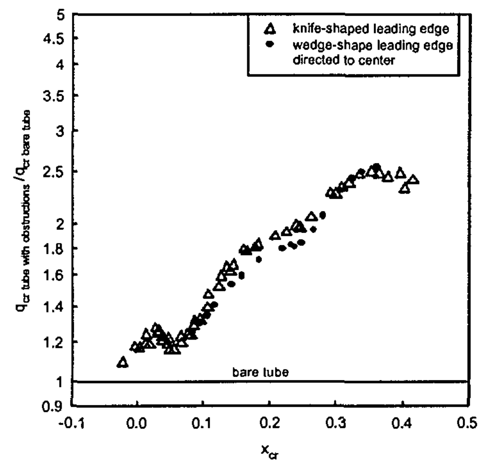

Fig. 6b. Effect of critical quality on CHF enhancement in tube with flow obstructions: R-134a, p=1.67 MPa, G=3000 kg/m^{2}s, L=0.45-2 m.

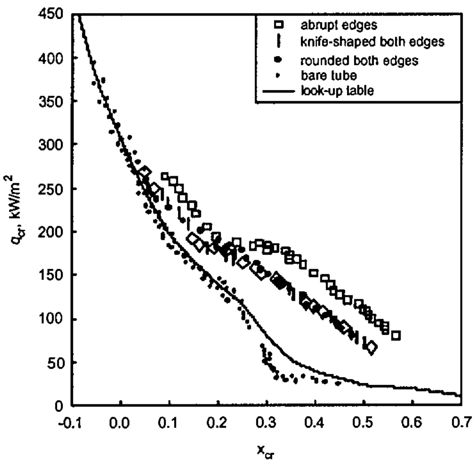

Fig. 7a. Effect of critical quality on CHF in tube with/without flow obstructions: R-134a, p=1.67 MPa, G=2000 kg/m^{2}s, L=0.45-2 m.

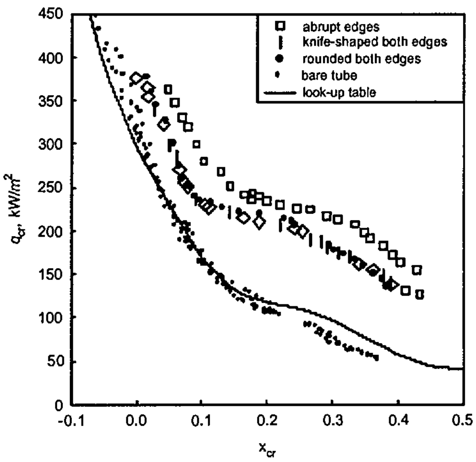

Fig. 8a. Effect of critical quality on CHF in tube with/without flow obstructions: R-134a, p=1.67 MPa, G=3000 kg/m^{2}s, L=0.45-2 m.

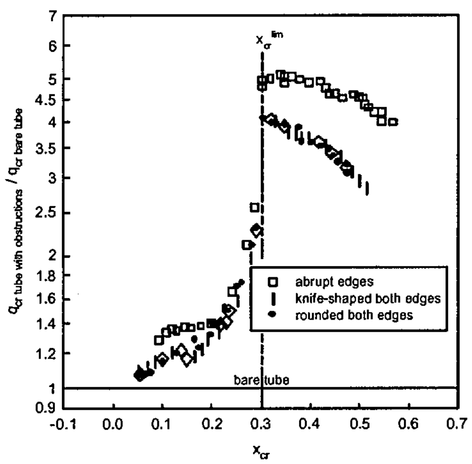

Fig. 7b. Effect of critical quality on CHF enhancement in tube with flow obstructions: R-134a, p=1.67 MPa, G=2000 kg/m^{2}s, L=0.45-2 m.

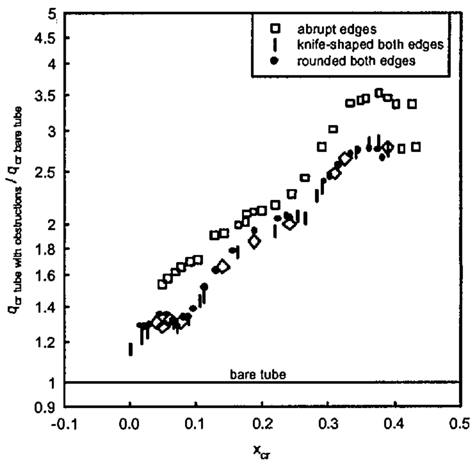

Fig. 8b. Effect of critical quality on CHF enhancement in tube with flow obstructions: R-134a, p=1.67 MPa, G=3000 kg/m^{2}s, L=0.45-2 m.