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Experimental Study for the CHF Characteristics of the Vertical Tube Using R-134a

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Abstract

An extensive experimental study of the critical heat flux(CHF) in the vertical smooth tube and vertical rifled tubes of several different types has been under an investigation. The main objective of this study is to investigate the CHF characteristics of the R-134a for vertical tubes covering a wide range of inlet and critical quality and the CHF enhancement mechanism in a rifled tube. These CHF data are required to develop the rifled tube with enhanced CHF by comparing their CHF data with each other. The correlations for water-to-R-134a fluid modeling are developed and CHF enhancement mechanism in a rifled tube is addressed. The test pressures are 11, 13, 16.5, 23.9, and 29.7 bar and the mass fluxes are 285 – 1300 kg/m^2. The heating length of test section is maximum 3000 mm. Some of CHF test results for smooth tube are presented in this paper. The rest tests including 7 different rifled tubes will be scheduled to be finished by end of this year.

1. Introduction

The Critical Heat Flux(CHF) is the heat flux at which boiling crisis occurs an heat transfer rate deterioration suddenly. Great quantities of experimental and theoretical studies concerning the CHF have been performed over last 40 years. As a results of these efforts, a lot of methodology had been developed to predict the CHF and its characteristics with some uncertainty. These CHF researches and these products had been developed mainly for the nuclear fuel design. Since CHF research for the water involved the enormous cost, the CHF using the Freon instead of water have been researched at the stage of feasibility study to develop the new fuel design. The refrigerants, R-11, R-12, R-21 and R-114 had been used to model the CHF characteristics of water based on the fluid-to-fluid models[1-4].

The CHF phenomenon is a major parameter in designing and operating the heat transfer equipments with a high heat flux. The CHF enhancement will reduce the operating cost and increase safety will be increased at the given operating condition. Particularly, the higher capacity of nuclear reactor and steam generator, the larger boiler needs to maximize the heat transfer rate per unit size and the special cooling device for a divertor in fusion reactor is necessary to remove a very high heat flux. Additionally, the higher energy efficiency, the very effective compact cooling device and the various cooling equipments with very high heat flux have been required to improve the cooling capacity.

Although it is very important to determine the optimum operating condition after considering the effects of main operating parameters on the CHF to obtain the extreme high CHF at the heat transfer equipment, the operating condition shall be determined by complexly considering other design limiting parameters as well as CHF. The CHF enhancement has been recently investigated to extend the region of nucleate boiling which is the best effective heat transfer mechanism [4, 5].

The main objective of this study is to investigate the CHF characteristics of the R-134a for vertical tubes covering a wide range of inlet and critical quality and the CHF enhancement mechanism in a rifled tube. These CHF data are required to develop the rifled tube with enhanced CHF by comparing their CHF data with each other.

The R-134a was selected in consideration of the environmental problem and the following advantages in researching the CHF.

- Test rig designed with low temperature and low pressure due to low critical pressure and temperature
- Very low possibility of tube damage due low latent heat.
- Low operating and facility cost due to low latent heat

2. Experimental Method

2.1 Experimental loop

The experiment on the subcooled flow boiling of R-134a was performed in a wide range of mass fluxes, inlet subcooling and the operating pressure, respectively. The apparatus of the present experiment is shown in Fig. 1. The R-134a experimental loop consists of the following components: a test section for CHF, a mass flow meter, a pre-heater for inlet subcooling control, an accumulator for pressure control, a canned pump for stable mass supply, a condenser with phase change, and a chiller, or chilling system, with R-22 and water-propylene glycol. The chiller used contains a heat exchanger for R-134a cooling, with water-propylene glycol flow via a water pump cooled in a bath with an R22 refrigeration system. The loop is filled with R-134a in the vacuum condition. A data acquisition system is used and electric power to heat the boiling surface of the test section is supplied by a DC power supply, with the maximum capacity of 200 kW (40 V, 5000A).

2.2 Test section

The test sections are shown schematically in Figure 2. They are carbon steel (SA182) and vertical tube with upward flow, and resistance heated via a larger DC current passing through the wall. The heated length of test section is 3000 mm and the inside and outside diameters are 17.04 mm and 22.59 mm. The temperatures of the liquid at the inlet and outlet of the test section were measured with an in-stream T-type sheathed thermocouples. The temperatures of the outside wall were measured at 21 locations along the channel wall, and two K-type thermocouples are installed at each location.

2.3 Test matrix and test procedure

Table 1 summarizes the test matrix and the equivalent water-based conditions. In order to cover the larger range of the critical quality as soon as possible, the inlet heating length is controlled as well as the subcooled temperature. At the given mass flux and system, the subcooled and heating length are changed to get CHF characteristics (critical quality and critical heat flux) and the CHF vs. critical quality relationship which can show whether the heating length can affect the CHF characteristics. It will show that the CHF for this test is only a function of pressure, mass flux, and critical quality (like as look-up table).

Before each series of experiments, a heat balance test was performed. Firstly, the pump starts and the mass flow is controlled by the speed control with the converter and control valve at a certain level. The test pressure in the test loop is increased by turning on the heater. After the pressure in the test loop reaches a pre-determined level, the inlet temperature is controlled by the power control to the pre-heater. The power to test section is increased at first rapidly to about 85% and then slowly. Boiling crisis is considered to occur when one of the thermocouples shows a temperature value 20 higher than the saturated temperature.

Table 1. Test Matrix

Pressure, bar		Saturated Temperature, ^{o}C		Mass Flux at R-134a condition, kg/m^2-sec				
				285	500	712	1000	1300
R-134a	Water	R-134a	Water	Mass Flux at Water Condition, kg/m^2-sec				
11.3	70	44	285.7	402.38	706.6	1006.2	1413.2	1837.2
13.0	80	49.4	295	402.1	705.4	1004.5	1410.8	1834.0
16.5	100	59.2	311	400.4	702.4	1000.2	1404.8	1826.3
23.9	140	75.5	336.6	396.	695.3	990.1	1390.6	1807.7
29.7	170	85.7	352.3	393.2	689.9	982.4	1379.7	1793.6

3. Fluid-to-fluid model

Refrigerants such as R-12, R-22, R-134a have been used successfully in several heat transfer laboratories as modeling fluids for water[1-3]. It has been shown that the following fluid-to-fluid modeling relationships and procedures are satisfied.

1) Calculate the density ratio of liquid to vapor of R-134a. Find out the pressure at which the density ratio of water is equal to that of R-134a.

$$\left[\frac{\rho_f}{\rho_g}\right]_{R-134a} = \left[\frac{\rho_f}{\rho_g}\right]_W$$

2) Calculate the mass index at the equivalent pressure as follows;

$$F_G = \frac{G_W}{G_{R-134a}} = \frac{(\sqrt{\sigma\rho})_W}{\left(\sqrt{\sigma\rho}\right)_{R-134a}}$$

3) Determine the latent index and heat flux index.

$$F_{\Delta h} = \frac{\left(h_{fg}\right)_W}{\left(h_{fg}\right)_{R-134a}} \qquad F_Q = F_G \times F_{\Delta h}$$

4) Calculate the critical heat flux by the boiling number and heat flux index.

$$\left(q_c\right)_W = F_Q \times \left(q_c\right)_R$$

This procedure has been applied to water-to-R-134a using the steam tables for R-134a and for water. The simple correlations are obtained for the pressure scaling, mass flux, subcooling degree and minimum heat flux and summarized in Table 2. Figure 3 shows how the scaling factors depend on the water pressure. In addition, Figure 4 shows the relationship between subcooled degrees for water and R-134a.

Table 2. Scaling factor for water-to-R-134a modeling

	Applicable range		Correlations for scaling factor
	Water	R-134q	
Pressure	$40 \le P_W \le 180$	$7 \le P_R \le 30$	$P_W / P_R = 6.551 - 0.00486 \times P_W$
Mass flux			$G_W / G_R = 1.415 + 0.0002247 P_W - 4.3 \times 10^{-6} P_W^2$
Subcooling	$0 \le dT_W \le 80$	$0 \le dT_R \le 40$	$dT_R = (-0.00472 + 0.0048 P_W - 3.9 \times 10^{-5} P_W^2) + (0.337 + 0.000233 P_W) \times dT_W$
Ciritical heat flux			$CHF_W / CHF_R = 13.57 + 0.01607 P_W - 7.46 \times 10^{-5} P_W^2$

4. CHF enhancement mechanism in rifled tube

It has been shown in some literatures that the rifled tube reveals the significant improvement in heat transfer and critical heat flux. But, the degree of improvement depends greatly on the geometry of the rifle on the inner surface of the tube. It has been explained by a centrifugal action at the fluid flowing near the surface. The rifles have the water near wall be rotated to generate a swirl flow. This results in a centrifugal action which forces the water to the tube wall, retards reentrainment of the liquid, and causes the drift on the radial direction to carry the vapor to the centre. The steam blanketing and film dryout at CHF conditions are thus prevented until substantially higher steam qualities are reached. From some literature, a minimum mass flux is required to generate swirl flow. The limited work of some researchers indicated that at low and moderate qualities, swirling flow was not obtained until a critical liquid superficial velocity was reached[10].

The swirl effect is quantified as the ratio of centrifugal acceleration to the gravity as follows [4-9];

$$\theta = \frac{a_r}{g}$$

where a_r is the centrifugal force, which is expressed by $a_r = \frac{V_r^2}{R}$.

($V_r = \frac{V_a}{\tan(\varphi)}$: circumferential velocity of fluid, R : inside radius, φ: helical angle from horizontal line)

This equation means that the centrifugal acceleration is a function of only one variable, helical angle at the given inside diameter. Figure 5 shows the relationship between helical angle and centrifugal ratio. With decreasing the helical angle, the acceleration ratio is getting higher. But, if the helical angle is lower than some threshold value, the CHF mechanism would be transferred from swirl effect to the turbulent intensity effect.

5. CHF test results in smooth tube

Figure 6 is the test results of the critical heat fluxes at 16.5 bar with the different mass fluxes. Figure 7 is the test results of the critical heat fluxes at 23.9 bar with the different mass fluxes. It is known from both figures that the critical heat flux are linearly increased with increasing the subcooling degree and the slope of higher mass flux is greater than that of lower mass flux.

6. Conclusions

These CHF data are required to develop the rifled tube with enhanced CHF by comparing their CHF data with each other. The correlations for water-to-R-134a fluid modeling are developed and CHF enhancement mechanism in a rifled tube is addressed.

The test pressures are 11, 13, 16.5, 23.9, and 29.7 bar and the mass fluxes are 285 – 1300 kg/m^2. CHF test results for smooth tube shows the consistency of the general CHF characteristics. The rest tests including 7 different rifled tubes will be scheduled to be finished by end of this year.

7. Further study

After completing the CHF tests for smooth, which are addressed in the matrix, the R-134a test data will be compared with corresponding CHF data sets obtained in water-cooled tubes using the lookup table.

To investigate the CHF characteristics and mechanism of rifled tube, 7 different rifled tubes will be tested at the same test matrix.

Acknowledgments

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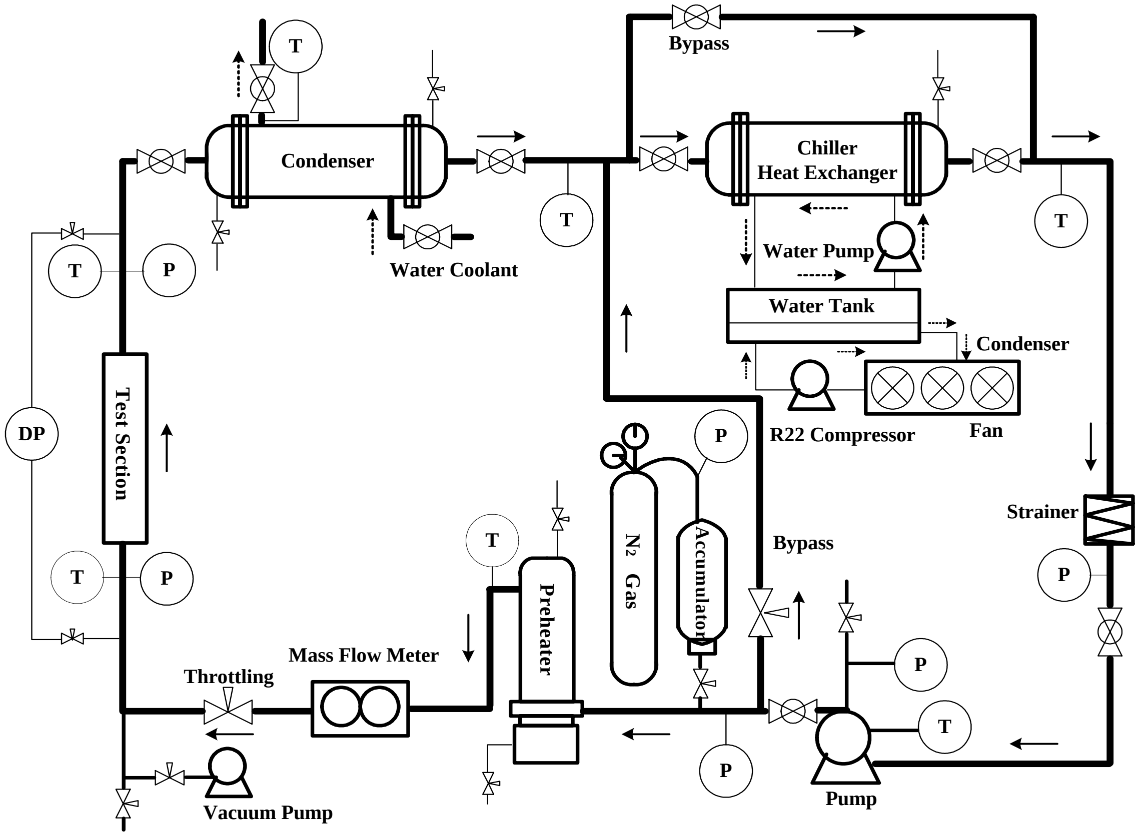

Fig. 1. Schematic diagram of the experimental system

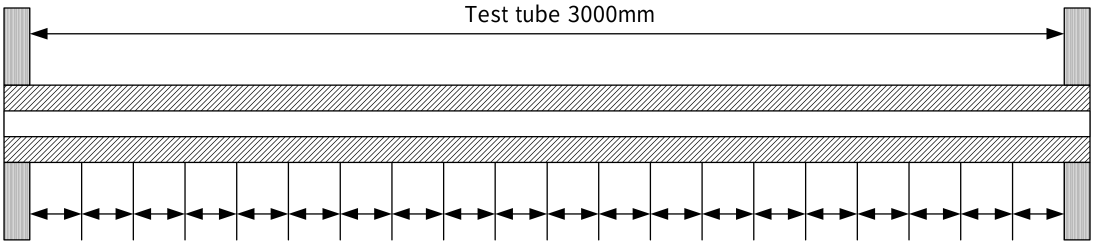

Figure 2. Schematic diagram of test section and distribution of thermal couples along test section

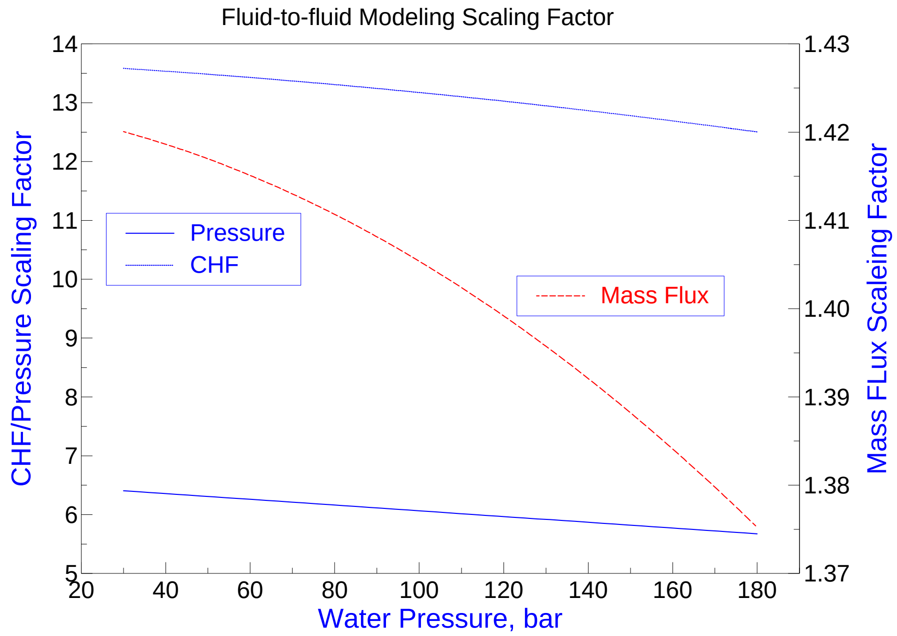

Figure 3. Scaling factors for water-to-R-134a modeling

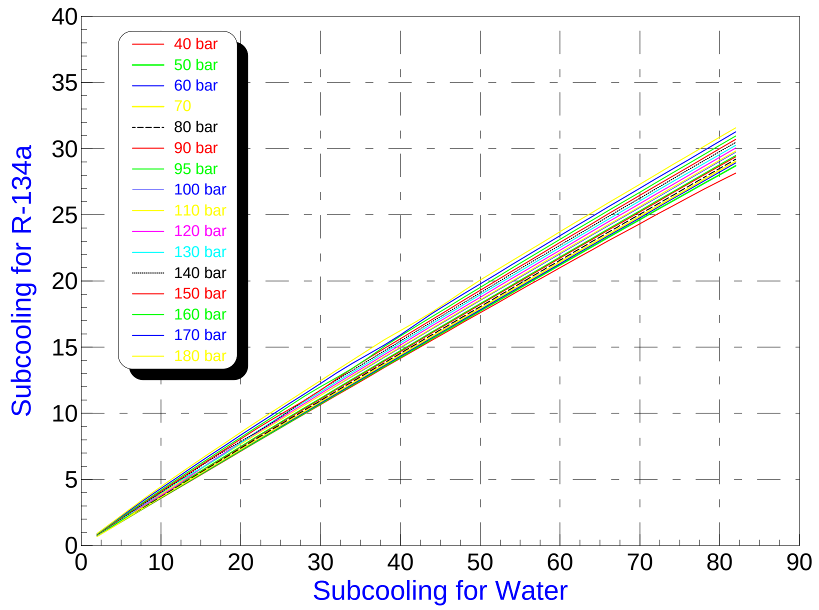

Figure 4. Relationship between subcooling degrees for water and R-134a

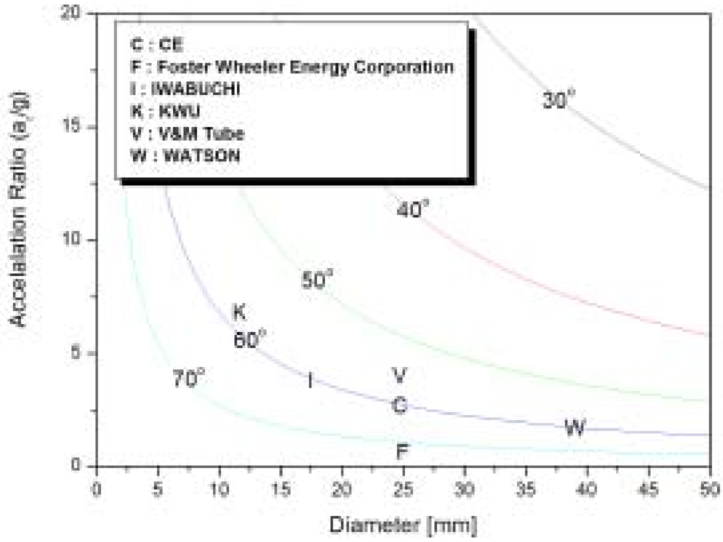

Figure 5. Acceleration ratio vs helical angle in rifled tube

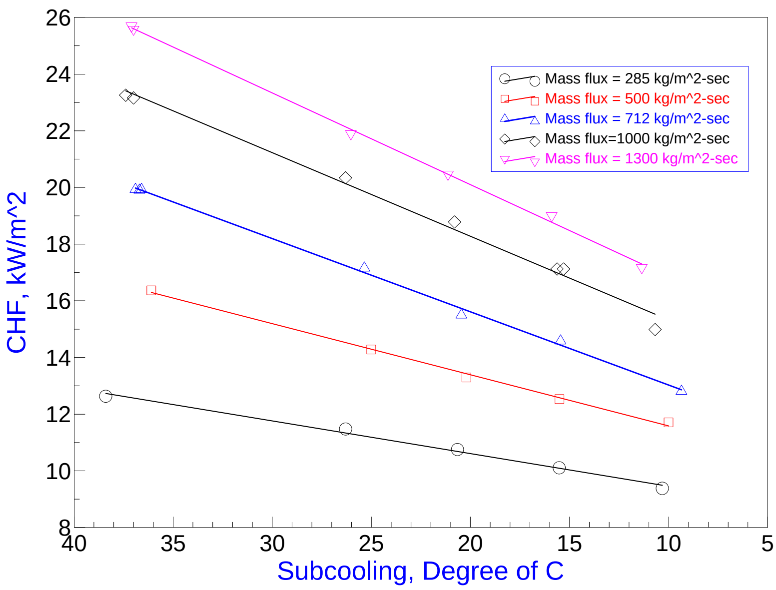

Figure 6. CHF data of R-134a at the operation pressure of 16.5 bar

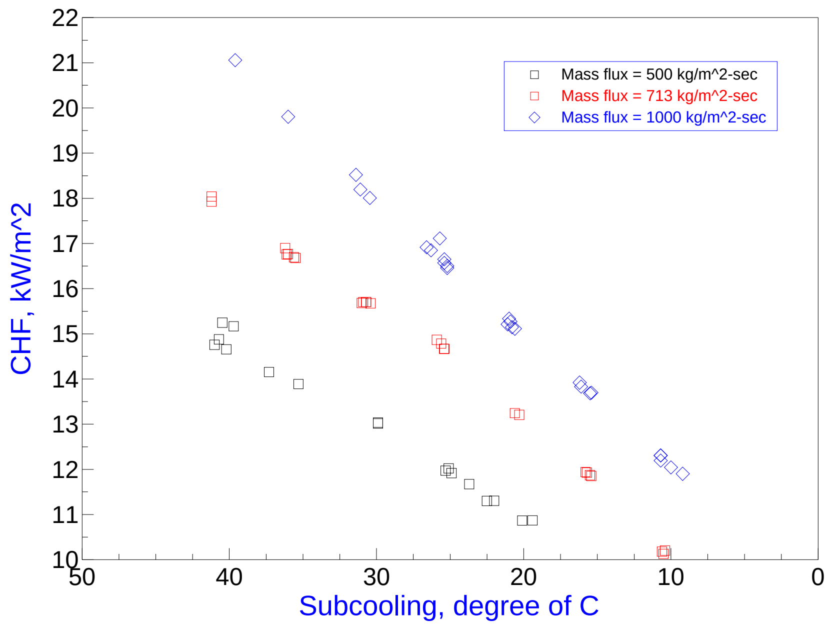

Figure 7. CHF data of R-134a at the operation pressure of 23.9 bar