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The characteristics and visualization of critical heat flux of R-134a flowing in a vertical annular geometry with spacer grids

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Abstract

In the present paper, critical heat flux (CHF) experiments of forced convection boiling were performed to investigate the CHF characteristics of a vertical annular channel with one heated rod and four spacer grids for new refrigerant R-134a. The experiments were conducted under outlet pressure of 11.6, 13, 16 and 20 bar, mass fluxes of 100–600 kg/m^2 s, and inlet temperatures of 25–40 °C. The parametric trend of the CHF data was well consistent with previous understanding in water. The comparison between the present results with effect of the flow obstacle enhancing CHF and water data in similar geometry shows R-134a can be a modeling fluid for simulating water CHF in high pressure and high temperature condition even for annular geometry. The direct observation of flowing bubble behaviors contributes to enhancing our understanding on the effect of flow obstacles for flow boiling heat transfer.

Keywords: R-134a; Flow boiling; CHF; Fluid-to-fluid model; Visualization

1. Introduction

Since industrial revolution of late 18th and early 19th century represented as a boiler, thermal-hydraulic systems using phase change of a fluid or boiling have been steadily studied with considering the economical efficiency of the systems. In particular, the forced convection boiling associated with the change in phase of a fluid and fluid motion driven by an external force is the most preferred heat transfer regime in design of thermal-hydraulic equipments and systems due to its high efficiency of combined latent heat and flow-driven effects. The boiling is faced with the limitation condition called critical heat flux (CHF) that causes an abrupt temperature rise and the physical destruction of the heated surface according to the sudden transition of from efficient wall-liquid zone with nucleate boiling to wall-vapor zone with film boiling.

Therefore, the better understanding of CHF characteristics is very useful and precious for the safety of various high-heat flux thermal-hydraulic systems.

A lot of efforts for experimental and theoretical researches concerning CHF under forced convection boiling have been performed over a few decades. As a result, a lot of models or methods have been developed for prediction of the CHF and its characteristics for various applications [1,2]. Although many aspects of CHF have been understood to some extent, experimental investigations are usually limited to the simplified geometry due to the high expenditure and complexity. Under the absence of a universal CHF correlation commonly usable for various geometries, CHF continue to be studied. Moreover, in recent years, the research activities for the CHF are focused on CHF enhancement techniques to increase the economic efficiency and safety margins of the energy systems. For example, advanced developments of smaller and more powerful electronic devices started to consider dielectric refrigerants with phase changes and refrigeration systems with new refrigerants. In case of nuclear power plant, there is the strong demand of power uprating including new

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Nomenclature

D	inside diameter (m)
F_G	mass flux index
$F_{\Delta h}$	latent heat index
F_Q	heat flux index
G	mass flux (kg/m^2 s)
G_P	mass flux of prototype fluid (kg/m^2 s)
G_M	mass flux of modeling fluid (kg/m^2 s)
h_{fg}	latent heat (kJ/kg)
Δh_i	inlet subcooling enthalpy (kJ/kg)
L	heated length (m)
Min.	Minimum
P	pressure (bar)
T	temperature (°C)
q_c	critical heat flux (kW/m^2)
q_{co}	q_c for $\Delta h = 0$ (kW/m^2)
x	thermodynamic equilibrium quality

Greek symbols

ρ	density of fluid (kg/m^3)
μ	dynamic viscosity of fluid (Pa/s)
σ	surface tension (N/m)

Subscripts

c	critical
e	hydrodynamic equivalent with D or exit with x
f	saturated liquid
g	saturated vapor
h	heated equivalent with D
M	Modeling fluid
P	Prototype fluid

thermal-hydraulic design due to high-density nuclear fuels. Even in case of nuclear fusion development, plasma-facing components have very high heat flux challenges. Super-critical operation of both coal-burned and nuclear power plants is causing the various thermal-hydraulic issues.

However, due to the high latent heat and high critical pressure of water, direct CHF experiments in water are very expensive and limited in scale. Therefore, if there exists a scaling fluid properly to simulate water boiling phenomena even with low latent heat and low critical pressure, demanded experimental data with the cost of experiments reduced significantly can be acquired. While in heat transfer experiments, various kinds of refrigerants are being used for high temperature and high pressure water scaling, those also have been evaluated to be applicable to CHF experiments [3]. For example, in the development of new nuclear fuel design including various turbulence-generation mixing vanes or flow obstacles, CHF using the refrigerants instead of water has been researched because refrigerant CHF test without high experimental cost is preferred as performance comparison test to select mixing vanes or flow promoter showing the best performance of CHF enhancement among various candidate designs [4].

Among CHF scaling fluids, the refrigerant, R-12 had extensively been used to model the CHF characteristics of water due to its low latent heat, low critical pressure, and well known properties [5]. However, the refrigerants such as R-134a and R-152a have been evaluated as an alternative in modeling CHF in water due to its harmlessness on the environment [6,7] because CFC (clorofluorocarbon) family such as R-12, R-22, R-133, and R-144, could deplete the ozone layer. In particular, since the thermophysical properties of R-134a are close to R-12, R-134a is considered to be a new scaling fluid. Tain and Cheng [6] reported that the CHF test data in R-134a agreed very well with the CHF data predicted by converting the standard CHF look-up table from water to R-134a equivalent condition. Also, Pioro et al. [8] reported that the agreement between the CHF look-up table and the experiment is surprisingly good. However, those studies were confined to simple tube geometry.

In order to investigate R-134a CHF characteristics for various geometries, develop new thermal-hydraulic CHF enhancement techniques and run its performance test, KAIST (Korea Advanced Institute of Science and Technology) built a forced convection boiling CHF loop using R-134a as a working fluid and have been studying since 2001. Up to now, KAIST CHF investigations are on such geometries as rectangular channel [9], uniformly heated vertical tube [10], uniformly heated vertical rifled tubes [11].

In particular, the present work is motivated by the following two concerns: (i) the flow boiling CHF characteristics of R-134a for various geometries are not well-known; (ii) for various geometries, phenomenological characteristics or boiling phenomena remain unexplored. Therefore, this study aims to provide R-134a CHF database with the CHF characteristics and bubble behaviors in a new geometry of vertical annular channel including flow obstacles. This schematic CHF test using R-134a is used to examine the forced convection flow boiling, CHF and the suitability of R-134a as a CHF modeling fluid of water in annular geometry. Also, this CHF data will be used as a reference for future post-CHF studies of R-134a and the visualization of flow boiling will be used for understanding the effect of flow obstacles.

2. Experimental method

2.1. Experimental loop

CHF experiments and visualization have been carried out in the R-134a forced convection boiling CHF loop at