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Critical heat flux for flow boiling of water at low pressure in vertical internally heated annuli

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ABSTRACT

Critical heat flux for flow boiling of water at low pressures on technically smooth surface tubes was experimentally investigated. The experiments were performed in a vertical annular test section of two coaxial tubes. The inner Zircaloy-4 tube with an outer diameter of 9.5 mm was directly heated over a length of 326 mm. Outer glass tubes of 13 mm and 18 mm inner diameter formed two different annular assemblies with length to heated equivalent diameter ratios of 39.3 and 13.2. The experimental parameters of inlet subcooling enthalpy, outlet pressure and mass flux were varied in the ranges of 100–250 kJ/kg, 115–300 kPa, and 250–1000 kg/(m^2 s). The resulting critical heat flux values were between 0.66 and 2.83 MW/m^2 depending particularly on the mass flux conditions. The results were compared with literature measurement data as well as with prediction methods using look-up tables for critical heat flux. The length to heated equivalent diameter ratio was found to be one of the important parameters for the comparison between different measurement data. The experimental values were smaller than the calculated critical heat flux values of the predictions methods. The measurements showed better agreement with the more recent CHF look-up tables.

1. Introduction

Boiling of a liquid fluid is used for cooling and/or steam production in many technical applications, like power plants or electronic devices. However, the nucleate boiling process is limited by the critical heat flux (CHF), which is the highest heat flux that can be dissipated into a nucleate boiling system before the local transition to film boiling occurs. This transition at CHF implicates a fast increase of the surface temperature for a heating power driven system because of a significantly reduced heat transfer during the film boiling regime. This can lead to an irreversible thermal damage of the heated surface. Therefore, the knowledge of the CHF is important for a safe operation of a boiling application.

The application of the current work is towards the flow boiling process and safety analysis for nuclear reactors. Experiments of boiling heat transfer and critical heat flux for forced convective flow boiling with regard to the conditions in nuclear reactors and steam generators are generally conducted in modeling test sections with tube, annular or rod bundle geometries. Extensive studies were performed, however particularly for high pressure, high flow conditions and most of them were examined with tubes [1–5]. Critical heat flux at low flow, low pressure conditions is important with respect to accident conditions of boiling water reactors [3,6]. Nevertheless, available experimental data and prediction methods for these conditions are scarce.

The general parametric trends of CHF in annuli in comparison to CHF in a reference tube of 8 mm diameter were discussed by Doerffer et al. [7]. The authors collected experimental data considering the general effects of pressure, mass flux, vapor quality, gap size, and curvature. However, their data covered only high pressures from 980 to 14,100 kPa. Thus, the effects for pressures below 1000 kPa were not included in this study.

Fiori and Bergles [8] performed CHF experiments in annular and tube geometries at low pressures of 148–600 kPa. Using an outer glass tube for the internally heated annulus, they visualized the flow regime and the occurrence of CHF by photographs and video tapes. They identified slug or froth flow prior to CHF in subcooled flow boiling and observed the formation of a very localized dry patch at CHF. Fiori and Bergles [8] developed a model considering the unstable situation of cyclical dry out and quenching of the surface at CHF. However, the authors pointed out that the model could not be used generally since flow structure information such as slug frequency or radius of the initial dry spot was required and basic theoretical models for these phenomena were not available.

Rogers et al. [9] conducted CHF experiments for three different annular gap sizes formed by an inner directly heated Inconel-718 tube and unheated outer glass tubes. The authors presented CHF

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Nomenclature

A_{cross}	cross-sectional area
A_{heat}	heated area
d_{he}	heated equivalent diameter
d_{hydr}	hydraulic diameter
d_i	inner diameter of annular cross section
d_o	outer diameter of annular cross section
f_1, f_4	correction factors for CHF look-up table
F	mass flow rate
G	mass flux
Δh_{in}	inlet subcooling enthalpy
Δh_v	enthalpy of evaporation
L	length of heated channel
p	pressure
p_{out}	pressure at outlet
P_{heat}	heated perimeter
P_{wet}	wetted perimeter
$\dot{Q}_{el}$	electrical heating power
$\dot{q}$	heat flux
$\dot{q}_{chf}$	critical heat flux
$\dot{q}_{chf,f1}$, $\dot{q}_{chf,f4}$	critical heat flux corrected with factors f_1 and f_4
$\dot{q}_{chf,8}$	critical heat flux for 8 mm diameter tube
s	gap width
T	temperature
T_{in}	fluid temperature at inlet
x_{th}	thermodynamic vapor quality
$x_{th,out}$	thermodynamic vapor quality at outlet
Greek letters	
ϵ_{hom}	void fraction for homogeneous two-phase flow
ρ_l	density of liquid phase
ρ_v	density of vapor phase
Abbreviations	
an	annulus
CHF	critical heat flux
COSMOS	Critical-heat-flux On Smooth and MOdified Surfaces
DSM	direct substitution method
HBM	heat balance method
JSME	Japanese Society of Mechanical Engineering
KIT	Karlsruhe Institute of Technology
LUT	look-up table
TS	test section

data for mass fluxes between 60 and 650 kg/(m^2 s) and constant outlet pressure of 156 kPa. Furthermore, they compared their results with four different empirical correlations of Knoebel et al. [10], McAdams et al. [11], Menegus [12], and Katto [13]. All correlations significantly overpredicted the experimental CHF. Rogers et al. [9] emphasized that using empirical correlations all important variables have to be exactly in the range for which the correlation has been developed. Since these correlations were inadequate to describe their experimental data, Rogers et al. [9] developed an individual empirical correlation depending on mass flux and inlet subcooling enthalpy for each tested annular geometry. However, a general use of these correlations is not possible.

El-Genk et al. [14] investigated CHF for water in vertical annuli at low flow and low pressure of 0–250 kg/(m^2 s) and 118 kPa. The inner stainless steel tube was heated directly and three unheated outer tubes of Pyrex with different inner diameters were used. According to their visual observations a two-phase flow transition occurred at CHF from annular to annular-mist flow for the smallest annulus and from slug-churn to churn-annular flow for the two larger annuli. El-Genk et al. [14] developed separate empirical correlations for both flow pattern transitions at CHF conditions. However, the correlations of Rogers et al. [9] and El-Genk et al. [14] are inadequate for general use since they are only valid in the small parameter range of their experimental data.

Schoesse et al. [15] measured also CHF at low mass flux and low pressure conditions of 20–280 kg/(m^2 s) and 128 kPa. The vertical internally heated annular test section consisted of an inner stainless steel tube and an outer Pyrex tube. The authors distinguished between a lower and a higher mass flux range. For mass fluxes lower than 140 kg/(m^2 s) they observed flooding and chugging at the exit at CHF conditions. These fluctuations were not noticeable for mass flux fluxes higher than 140 kg/(m^2 s). The two phase flow pattern was characterized by transitions from bubbly flow to churn flow to annular flow over the heated length of the channel. In the annular flow regime they distinguished between pulsated annular flow where liquid is periodically accelerated through the channel and stable annular-mist flow with a continuous annular flow pattern.

Chun et al. [6] performed CHF experiments in a vertical annular test section for a wide range of pressures from 570 to 15010 kPa. The inner and outer tubes were made of Inconel-600 tube and only the inner tube was heated indirectly. They compared their experimental results with correlations of Doerffer et al. [7], Bowring [16], and Janssen and Kervinen [17]. The Bowring correlation showed satisfying agreement with the experimental data in the complete experimental range whereas the Janssen and Kervinen correlation overpredicted the lower pressure data. Nevertheless, all three correlations tended to overestimate (slightly or significantly) CHF for lower pressures than 10,000 kPa.

Two-phase boiling systems can be affected by various flow instabilities [18]. Particularly systems with narrow channels and low flow and low pressure conditions are susceptible to flow instabilities which can cause remarkably lower CHF values [19,20]. On the one hand, narrow channel systems have a high two-phase pressure drop [21,22] and on the other hand, fluid properties like for example density, viscosity or enthalpy are influenced significantly by variations in the low pressure range [23].

Mishima and Nishihara [24] presented experimental data of a benchmark project of the JSME. CHF experiments at low pressure conditions of 100 kPa with the same geometrical annular test section design have been conducted at several universities and institutions. Although applying the same experimental conditions there was a scatter in the data between the institutions, particularly for low subcoolings. Mishima and Nishihara [24] assumed that the discrepancy could be related to flow instability because of varied pump characteristics and inlet throttling conditions. For instance, Katto [1] mentioned also that experiments on the CHF near atmospheric pressure are often subject to insufficient throttling conditions upstream of the test section.

Pretests in the present test facility COSMOS showed that the flow boiling process without stabilizing precautions was highly affected by instabilities. A pulsating flow boiling process could be observed in case of unstable flow conditions. These oscillations caused premature critical heat fluxes at a much lower power input than for stable conditions. Therefore, the flow stability was experimentally investigated as described in Haas et al. [25] in order to establish stable flow conditions for the CHF experiments.

Table 1 presents the geometry and experimental conditions for the above described investigations of CHF in annuli at low