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Critical heat flux for flow boiling of water on micro-structured Zircaloy tube surfaces

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ABSTRACT

We investigated the influence of surface structure on critical heat flux (CHF) for flow boiling of water. The objectives were to find suitable surface modification processes for Zircaloy-4 tubes and to test their critical heat flux performance in comparison to the smooth surface tube. Surface structures with micro-channels, porous layer, oxidized layer, and elevations in micro- and nanoscale were produced on Zircaloy-4 cladding tube. These modified tubes were tested in an internally heated vertical annulus with a heated length of 326 mm and an inner and outer diameter of 9.5 and 18 mm. The flow boiling experiments with water were performed with mass fluxes of 250 and 400 kg/(m^2 s), outlet pressures between 120 and 300 kPa, and an inlet subcooling temperature of 40 K. Only a small influence of modified surface structures on critical heat flux was observed for the pressure of 120 kPa in the present test section geometry. However, with increased pressure and mass flux, the critical heat flux could be increased up to 29% higher than for the smooth tube using surface structured tubes with micro-channels, porous and oxidized layers. The flow boiling process and the critical heat flux occurrence were visualized by high-speed camera records. Additionally, we characterized the surface wettability behavior of the different tube surfaces using the Wilhelmy method. Concluding from the different characteristics capillary effects and/or increased nucleation site density were assumed to influence the critical heat flux performance.

1. Introduction

The critical heat flux (CHF) of Zircaloy tubes is of particular interest for pressurized water reactors. As a departure from nucleate boiling would damage the fuel claddings, a safety margin from CHF has to be kept during operation, which is limiting the reactor power. Measures to increase the CHF are thus interesting for economic and safety reasons.

Recent studies have shown that modifying surfaces by roughening or micro-structural coating can improve the CHF, thus reaching higher applicable heat fluxes. Poniewski and Thome [1] gave a state-of-the-art on the specific topic nucleate pool boiling for different fluids on micro-structured surfaces. You et al. [2] summarized investigations of heat transfer and CHF on microporous surfaces in pool and flow boiling for highly wetting fluids like FC-72, FC-87 and R-123. Porous coated surfaces were found to influence significantly the pool boiling CHF on flat surfaces with an increase of about 100%. Despite the number of boiling sites, heat transfer in pool boiling also depends on the corresponding rate of bubble formation. These two effects are linked with surface wettability and surface roughness [3]. Ammerman and You [4] reported an increase in CHF between 14 and 36% in comparison to the smooth surface for flow boiling of FC-87 on micro-porous surfaces in a small horizontal square channel. According to the authors the enhancement is smaller than for pool boiling because of the limited liquid amount in the narrow channel geometry used in the flow boiling experiments.

Several studies analyzed the enhancement of the boiling heat transfer and the critical heat flux for hydrophilic and hydrophobic surfaces for pool boiling of distilled water [5–7,3]. On the one hand hydrophobic surfaces release bubbles more frequently resulting in a decreased wall temperature and consequently in a higher effective heat transfer coefficient (HTC). On the other hand hydrophilic surfaces possess a high density of nucleation sites serving to an increased CHF [3,6] fabricated hydrophilic substrates with hydrophobic dots to enhance HTC and CHF. The studies showed that the ratio of the area covered by hydrophobic dots to the heated area is a relevant parameter to influence the CHF behavior, whereas the HTC was dependent on the dot diameter, the number of dots and the pitch distance between the dots. Based on the conducted experiments, the authors recommend a surface with

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Nomenclature

A_{cross}	cross-sectional area
d_{he}	heated equivalent diameter
d_i	inner diameter of annular cross section
d_o	outer diameter of annular cross section
F	mass flow rate
F_{wet}	wetting (or Wilhelmy) force
G	mass flux
Δh_{in}	inlet subcooling enthalpy
L	length of heated channel
L_{wet}	wetted length
P_{el}	electrical power
p_{out}	outlet pressure
$\dot{q}$	heat flux
$\dot{q}_{chf,smooth}$	CHF of smooth surface tube
$\dot{q}_{chf,struct}$	CHF of structured surface tube
$\Delta\dot{q}_{chf}$	difference in CHF between structured and smooth surface tubes
T_{sat}	saturation temperature
T_{sub}	subcooling temperature

Greek letters

θ	contact angle
θ_{adv}	advancing contact angle
θ_{rec}	receding contact angle
$\Delta\theta$	contact angle hysteresis
σ	surface tension

Abbreviations

CHF	critical heat flux
CNT	carbon nanotube
COSMOS	**C**ritical-heat-flux **O**n **S**mooth and **MO**dified **S**urfaces
HTC	heat transfer coefficient
KIT	Karlsruhe Institute of Technology

numerous micro-sized hydrophobic dots to get optimized surfaces concerning CHF and HTC. Additionally the area ratio of these dots should be kept small.

O'Hanley et al. [8] analyzed the single contributions of surface wettability, porosity and roughness on the CHF of water in pool boiling experiments. Therefore different surfaces were designed allowing to evaluate each effect separately by varying the individual parameters. An astonishing result of this study is that the wettability alone shows no effect on the CHF. On different smooth and non-porous surfaces, of which one was uncoated, one hydrophilic and one hydrophobic, the difference of CHF was negligible. A substantial contribution is found for porosity. The increase of CHF for a smooth hydrophilic surface was up to 60% with respect to the reference heater. In contrast, hydrophobic porous surfaces decrease the CHF of up to 97%. The conclusion of these results is that the effect of porosity on magnitude and sign is directly linked with the wettability of the porous layer. In the same study, it was identified that roughness parameters like the arithmetic average of the absolute value of surface feature heights R_a or the average distance of the five highest peaks to lowest fie valley R_z are no reasonable correlating parameters for CHF. There was no difference found in CHF behavior in varying these roughness parameters. In a further study, Tetreault-Friend et al. [9] picked-up the result that the combination of hydrophilicity and porosity leads to an increased CHF. They analyzed the effects of pore diameter and layer thickness on CHF. According to their conclusions, the CHF is determined by the competition of wickability and conduction heat transfer, where the former effect is described by the capillary pressure, liquid viscous pressure drop and momentum change due to evaporation.

Ahn et al. [10] performed pool boiling experiments with water at saturated conditions using Zircaloy plates with different topography and wettability due to an anodic oxidation treatment. The boiling heat transfer curves were almost identical for all samples. However, the CHF values were increased for the treated samples in comparison to the smooth surface. They observed an increasing trend of CHF with decreasing contact angle reaching significantly higher values for contact angles below 10°.

Fong et al. [11,12] investigated the influence of surface roughness on transient CHF in pool boiling for Zircaloy-2 tubes of 19.5 mm outer diameter and 450 mm length. The tube was orientated horizontally in a liquid pool of water at saturated conditions at atmospheric pressure. The power was increased rapidly until CHF was identified visually by video camera when film boiling was observed. The roughness of the outer tube surfaces was modified by glass-peening. Compared to the smooth (un-peened) surface the observed critical heat flux was increased up to a maximum of 57%.

Horizontal cylindrical tubes with smooth and microporous coated surfaces were tested by Chang and Baek [13] in saturated pool boiling of FC-87 and R-123. CHF was similar to smooth tube although heat transfer was enhanced. This behavior was different to investigations on flat surfaces. The authors assumed that the increased void fraction due to the raising bubbles from the bottom surface prevent the liquid from rewetting the surface.

Kim et al. [5] investigated surfaces with coatings of TiO_2 and ZnO that changed their wetting behavior according to the applied superheat conditions. The wetting behavior is hydrophobic for low heat flux region increasing the bubble generation and thus the HTC. For high heat flux region the surfaces becomes hydrophilic to compensate the CHF. The flow boiling experiments were performed on very small heated surfaces (15 mm × 10 mm) respectively very fine tube diameters (0.3 mm). During the experiments, the surfaces improved the HTC but decreased the CHF for mass fluxes below 1000 kg/(m^2 s). For mass fluxes above 1000 kg/(m^2 s) HTC was enhanced without CHF degradation. The authors claimed that for low mass fluxes the wall temperature did not reach the transitional temperature of wettability to become hydrophilic.

The studies of Pioro et al. [14] showed the effect of flow obstacles within a test section consisting of a vertical tube with an inner diameter of 6.92 mm and a length of 2.1 m made of Inconel 601. The directly heated tube was cooled with R134 under a covered pressure range from 9.6 to 23.9 bar, a mass flux range from 500 to 3000 kg/(m^2 s). Different obstacles varying in flow obstruction shape, axial distance, edge shape and degree of flow blockage were used. Pioro et al. [14] showed, that beyond the effects of surface enlargement, variations in surface roughness, changements on the wettability properties and on the nucleation site density, there exists also the effect of flow blockage leading to increased CHF values. This effect only shows for mass fluxes higher than G = 1.000 kg/(m^2 s) a significant CHF increase, which is significantly higher than the mass fluxes used in the present study.

Stein [15] performed CHF experiments on surfaces with porous sinter layers for flow boiling in tubes at mass fluxes of 24–300 kg/(m^2 s) and pressures of 120–700 kPa. Two different lengths (127 mm and 450 mm) were coated with porous layers of Inconel 600 with the same layer thickness of 300 μm, but different particle sizes (30–40 μm, 60–80 μm). The experiments showed