



On post-dryout heat transfer in channels with flow obstacles



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HIGHLIGHTS

- A new methodology to calculate wall temperature for post-dryout heat transfer in channels with flow obstacles was developed.
- The influence of flow obstacle on critical quality was included.
- The effect of developing post-dryout heat transfer was taken into account.
- The predictive capability of the developed correlation was demonstrated.

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ABSTRACT

This paper describes a new approach to predict post-dryout heat transfer in channels with flow obstacles. Using experimental data obtained in annular test sections at prototypical BWR conditions, the existing Saha correlation for post-dryout heat transfer has been modified to account for the presence of obstacles. The obstacle effect is taken into account in the following way: (a) the critical quality downstream of an obstacle is found; (b) an exponential function of equilibrium quality is applied to describe the decrease of heat transfer coefficient in the developing post-dryout region; (c) an additional heat transfer enhancement term is applied downstream of the obstacle. The new approach is applied to annular test sections with various flow obstacles and a significant improvement of accuracy of wall temperature prediction, as compared to reference methods, is shown.

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1. Introduction

Post-dryout heat transfer is defined as the heat transfer regime encountered beyond the boiling crisis occurrence. It could be initiated by an abnormal operation of steam generators, cryogenic facilities or nuclear reactors and is mainly characterized through a dramatic increase of the wall temperature downstream of the point of the onset of boiling crisis, as well as a strong deterioration of the heat transfer coefficient (Chen and Costigan, 1992). In this heat transfer regime, the dominant mechanisms are represented by the convective heat transfer from the heated surface to the vapor and the convective heat transfer from the heated surface to the entrained droplets. It has been shown that the presence of droplets in the vapor stream may increase or decrease the turbulence level of the vapor core while the droplets entering into the liquid boundary layer increase the turbulence level in vicinity of the wall (Yoder et al., 1983). The effect of the entrained droplets is thus essential

and is taken into account in several modeling approaches, such as, e.g., the Saha's correlation (Saha, 1980).

Most of the existing approaches to predict post-dryout heat transfer coefficient are based on the thermodynamic equilibrium assumption and are employing a modified Dittus–Boelter correlation, where the Prandtl number is evaluated at the wall temperature and the Reynolds number is evaluated at the bulk vapor temperature. However, some authors – based on successful experimental work (Nijhawan et al., 1980; Unal et al., 1991) – introduce the non-equilibrium concept in their models, leading to more realistic prediction results (Groeneveld and Delorme, 1976; Saha, 1980).

Anghel and Anglart (2012) compared several existing post-dryout heat transfer correlations and models with their own experimental data obtained recently in annuli with various flow obstacles. They showed that all examined correlations significantly over-estimated the wall surface temperature and argued that the correlations were not applicable to channels with frequently repeating flow obstacles, where fully developed conditions would never exist. They also suggested a correction term to the Saha correlation to account for the developing post-dryout conditions.

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Nomenclature

D_h	hydraulic diameter (m)
G	mass flux ($\text{kg m}^{-2} \text{s}^{-1}$)
h	heat transfer coefficient ($\text{W m}^{-2} \text{K}^{-1}$)
n	number of points
Nu	Nusselt number
Pr	Prandtl number
q''	heat flux (W m^{-2})
Re	Reynolds number
T	temperature (K)
x	quality
z	distance downstream of obstacle location (m)

Greek symbols

λ	thermal conductivity ($\text{W m}^{-1} \text{K}^{-1}$)
μ	viscosity (Pa s)
ρ	density (kg m^{-3})
σ	surface tension (N m^{-1})

Subscripts

C	calculated
e	equilibrium
E	experimental
f	saturated liquid
g	saturated vapor
sat	saturation
w	wall

The effect of obstacles located inside of flow channels has been investigated by many researchers for several decades. The influence of obstacle positions and geometry on heat transfer downstream of their locations has been studied both experimentally and theoretically. The experiments have been performed mainly in three different types of test sections: in tubes, in annuli and in rod bundles. Most of the experiments were carried out for single phase flow conditions (Holloway et al., 2008; Marek and Rehme, 1979; Rehme, 1977; Yao et al., 1982). The general finding was that flow obstacles strongly enhanced heat transfer downstream of their locations, but the level of influence varied with geometry details. Only few attempts were made to investigate this effect for two-phase flow conditions (corresponding to post-dryout heat transfer to water at high pressure). Nagayoshi and Nishida (1998) measured the effect of the flow obstacle on the droplet deposition rate and quantified the turbulence enhancement due to the obstacle. Leung et al. (2005) investigated the effect of three different flow obstacles placed in a tube and using HFC-134a as the working fluid. They reported a strong heat transfer enhancement effect due to obstacles and developed a correlation to capture it using their own data. Recently, experiments with water at high pressures have shown quenching of the heated wall due to flow obstacle presence (Anglart and Persson, 2007; Anghel and Anglart, 2012). A direct connection between the quenching and a flow blockage area was indicated by Hochreiter et al. (1992), who concluded that the effects of flow blockage were multi-folded and mainly present due to: de-superheating of the vapor, changes at boundary layer level, droplets break-up, and turbulence increase. All of the above-mentioned phenomena are enhancing heat transfer at the post-dryout conditions.

Significant effort has been devoted to development of correlations and models to describe the influence of flow obstacles on post-dryout heat transfer. Theoretical models and empirical correlations were proposed by e.g. Yao et al. (1982), Kim and Korol'kov (1991), Groeneveld et al. (1999), Sergeev (2005), Anglart (2006) and Miller et al. (2011). These approaches are mainly based on

experimental data obtained in tubes, where fully-developed post-dryout heat transfer conditions prevailed. In the present paper, experimental data obtained in annuli with various flow obstacles are used (Anghel and Anglart, 2012). In these experiments, special care was taken to measure the wall surface temperature in the transition region between convective boiling heat transfer and post-dryout heat transfer. As demonstrated in the experiments performed by Anghel and Anglart (2012), this type of heat transfer, referred to as the trans-dryout heat transfer regime, is expected to prevail in fuel assemblies of boiling water reactors (BWRs) when the total power of the assembly exceeds the critical one.

In this paper a new method is developed to evaluate wall superheat in the post-dryout heat transfer regime. For this purpose 1211 data points were selected from the experimental work of Anghel and Anglart (2012). About 660 points were selected to develop a correction function to the Saha correlation to calculate the Nusselt number in the trans-dryout region. Since in this region the wall temperatures are rather moderate, it is assumed that the convective boiling heat transfer is prevailing and the radiation heat transfer effects may be neglected. The remaining 511 points were used to optimize the coefficients of the correlations which calculate the enhanced Nusselt number downstream of flow obstacles. To demonstrate the applicability of the method to post-dryout heat transfer conditions, a simple correlation to predict critical quality in an annular test section with flow obstacles is used. One of the main features of the presented methodology is that it can be applied to any configuration of flow channels and obstacles. However, a relevant experimental data set is needed to derive the correlation coefficients, as shown in this paper using the data of Anghel and Anglart (2012).

2. Analysis of post-dryout heat transfer

In the experimental work presented in Anghel and Anglart (2012) the test sections with pin spacers only was referred to as test section A, the test section with pin spacers and cylindrical obstacles was referred to as test section B and test section with pin spacers and grid spacers was referred to as test section C. The test section consisted of an annulus made of two concentric tubes, where both the inner and the outer wall were heated using direct current. The inner pipe of the annular test section was referred to as a rod while the outer pipe as a tube. The test sections are schematically shown in Fig. 1.

The blockage-area ratio of the flow obstacles is: 10.13% in case of pin spacers, 7.3% in case of cylindrical obstacles and 10.07% in case of grid obstacles. The post-dryout transition region is defined as the axial distance in the channel starting from the point of the onset of the dryout toward the maximum measured wall temperature. The same definitions are used in the present paper. Fig. 1 shows the three test sections together with pin spacers and flow obstacles used in the experiments.

The effect of a pin spacer in test section A is shown in Fig. 2, where the ratio of the measured and calculated heat transfer coefficients is plotted against non-dimensional distance L/D_h , where L is an axial distance downstream of the pin spacer and D_h is the hydraulic diameter. The reference heat transfer coefficient is estimated from the Groeneveld (1975) correlation. The figure shows the effect of the last pin spacer for two different mass fluxes and four different heat fluxes. The zero value on the horizontal axis indicates the location of the pin spacer. In case of low mass flux the wall surface is quenched over a distance of ~ 10 hydraulic diameters while in case of higher mass flux this distance is ~ 17 hydraulic diameters. The values of the heat transfer coefficients in all four cases became nearly equal to each other at the exit from the test section, their magnitude being closer to the one calculated from the

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