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Analysis and modeling of post-dryout heat transfer in upward vertical flow

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ABSTRACT

An analytic model has been developed for the whole post-dryout region based on the analysis of the main heat and mass transfer mechanisms in this region. The whole post-dryout flow region is divided into two regions: the developing region and the fully developed region. Both the definition and the determination method of these two regions are proposed in this paper. A correction factor K_1 is proposed to represent the heat transfer enhancement in the developing region. Meanwhile in the fully developed region, the cross-section of the flow is divided into a film region and a central region to account for the impact of the droplets' volumetric concentration on the interfacial heat transfer between vapor and droplets. A correction factor K_2 for modeling the distribution of the droplets on the cross-section is proposed. Finally, the current model developed in this study is verified by comparing with five theoretical models and five experiment databases, which cover the geometry from round tube channel to annuli channel, and cover following ranges of parameters: pressure 3–20.5 MPa, mass flux 500–4472 kg/(m^2 s), heat flux 90–2000 kW/m^2, hydraulic diameter 2.5–24.69 mm. The results indicate that the current model could provide a very good agreement in the prediction of the post-dryout heat transfer.

1. Introduction

The research of post-dryout heat transfer has generated great interest both in the academic and industrial field because of its importance in determining maximum surface temperature, which is one of the key factors for steam generator design, safety analysis of nuclear reactor loss-of-coolant accidents, and performance evaluation of some advanced nuclear fuels. A post-dryout heat transfer region can be encountered once the surface temperature becomes too high to maintain a continuous liquid contact, and the surface becomes covered by a continuous or intermittent vapor blanket. Though sometimes, the term post-dryout is used to denote the general heat transfer deterioration in flow boiling process, that liquid could be in the form of dispersed spray of droplets, continuous liquid core, or transition between the former two cases (Groeneveld and Freund, 1973), we would prefer commonly to refer post-dryout to the heat transfer deterioration in the condition when liquid is only in the form of dispersed droplets, and denote the other cases by the term post-DNB (departure from nucleate boiling).

The study on post-dryout heat transfer mechanisms and its predicting method development have been conducted for over half a century. Excellent reviews of these works can be found in articles by Groeneveld (1975), Chen (1986) and Andreani and Yadigaroglu (1994). Numerous types of models and correlations have been developed and implemented to achieve varying ranges of success. And these works can be classified as,

- correlative works,
- and analytical works.

Most of the correlative works usually originate with a single-phase wall-vapor convective heat transfer correlation which is in a similar form with the Dittus-Boelter equation:

$$Nu_{w-v} = 0.023 Re_v^{0.8} Pr_v^{0.4} \tag{1}$$

and coefficients in the correlation are modified to include the impact of dispersed droplets on the convection. The initial correlative works were conducted by the representatives, Dougall (1963) and Groeneveld and Moeck (1969), assuming the vapor is in an equilibrium state, namely, the vapor is considered having no superheat. With more findings confirmed the existence of thermal non-equilibrium in the post-dryout regime (Laverty and Rohsenow, 1964; Mueller, 1967), relation between the actual and equilibrium qualities is vastly developed to estimate the vapor superheat at any location downstream of the dryout point. Examples of models

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Nomenclature

x	quality [–]
α	void fraction [–]
Z	elevation [m]
D_T	tube diameter [m]
d	droplet diameter [m]
q''	heat flux [W m^{-2}]
G	mass flux [kg m^{-2} s^{-1}]
i_{vd}	latent heat of vaporization [J kg^{-1}]
ρ	density [kg m^{-3}]
μ	dynamic viscosity [kg m^{-1} s^{-1}]
σ	surface tension [N m^{-1}]
h	heat transfer coefficient [W m^{-2} K^{-1}]
T	temperature [K]
k	thermal conductivity [W m^{-1} K^{-1}]
Cp	specific heat capacity [J kg^{-1} K^{-1}]
K_1	correction factor in Eq. (10) [–]
K_2	correction factor in Eq. (22) [–]
S_f	shielding factor, defined in Eq. (18) [–]
ψ	length ratio in Eq. (12) [–]
ε	effectiveness in Eq. (14) [–]
S	slip ratio [–]
U	axial velocity [m s^{-1}]
V_d	droplet deposition velocity [m s^{-1}]
g	gravitational acceleration, in Fig. 1
Re	Reynolds number [–]
We	Weber number [–]
Pr	Prandtl number [–]
Gz	Graetz number [–]
Bo	boiling number [–]
Nu	Nusselt number [–]

Subscripts

do	dryout point
reg	region line
poi	point of interest
s	saturation
a	actual, or real
e	equilibrium
–	means “between”
d	droplets
w	wall
v	vapor
vf	vapor in the film region
vc	vapor in the central region
vb	vapor at the bulk temperature
vs	vapor at the saturation temperature
1	developing region
2	fully developed region
NB	nucleate boiling

include such a relation are Groeneveld model (Groeneveld and Delorme, 1976), and CSO model, developed by Chen et al. (1979). Usually, these correlations are derived from a limited amount of data without revealing the mechanisms inside and are not appropriate for using outside their database.

Most of the analytical works attempt to predict the wall temperature by considering three-path heat transfer that involves heat transfer from the heated wall to vapor, from vapor to droplets and from wall to droplets, including direct contact and thermal radiation. Such models adopt assumptions concerning the local values of certain variables, typically are the velocity slip ratio and droplet diameter. Some of the models require the quality at the dryout point, a variable depends on its upstream flow regime and has great influence on the model’s accuracy. In general, many early-stage investigations (Hill and Rohsenow, 1982; Jeong and No, 1996; Moose and Ganić, 1982; Saha, 1980; Varone and Rohsenow, 1986; Yoder and Rohsenow, 1980) are based on one-dimensional separated flow model and differs only by the selection of empirical correlations for heat transfer, or by selection of models for calculating droplet size. One of such models named “Local Conditions Solution” (Hill and Rohsenow, 1982) is found in this study to be good in agreement with the wall temperature magnitude, but poor in the prediction of the wall temperature profile. Furthermore, computational fluid dynamics (CFD) approach has been employed in recent years to capture more detailed phenomena (Li and Anglart, 2016, 2015; Shi et al., 2016; Torfeh and Kouhikamali, 2015), e.g. the vapor-droplet interface, the droplet concentration distribution, and local vapor superheat. However, CFD is computationally expensive and the models applied in CFD still need a quite extensive knowledge of the physical phenomena to improve the prediction.

On the side of application in the nuclear engineering industry, one example of the widely accepted system codes is ATHLET (2012). The latest version of ATHLET code adopts three alternative models for post-dryout heat transfer, named modified Dougall-Rohsenow model (Liesch et al., 1975), Groeneveld model (Groeneveld and Moeck, 1969), and Condie-Bengston IV model (Vojtek, 1978), respectively. These models are simple equilibrium correlations and are confirmed with limited accuracy in this study. Therefore, developing an accurate and easy-to-implement post-dryout model for ATHLET code is one of the potential desires of the current work.

2. Analysis of the post-dryout heat transfer

Fig. 1 depicts the flow patterns and wall temperature profile of a typical post-dryout flow. In the pre-dryout region, an annular liquid flow is formed by continuous evaporation of the liquid phase, and the liquid phase on the heated wall could be a very thin film, especially in the upstream of the dryout point. Immediately after the dryout point, a short transition regime develops, in which liquid in the form of filaments or droplets, is ejected into the vapor core. Heat transfer coefficients are reduced significantly in this region, with an accompanying steep rise in wall surface temperature. While liquid film on the heated wall dries out, the near-wall vapor temperature rises sharply. As a result, droplets near the wall are quickly evaporated, and the direct wall-droplets contact becomes less frequent. In this region, vapor temperature structure and droplets distribution on the cross-section of the tube are well rearranged, finally develop into a relatively stable state, which is called fully developed post-dryout region, characterized by a stable mist flow pattern and none wall-droplets wet contact.

2.1. Determination of the flow regions

The post-dryout flow consists of a developing region and a fully developed region, and the developing region could be further subdivided into a short sputtering zone and a flow rearrangement zone. Definitions of the terms post-dryout developing region and fully developed region are proposed in this paper as follows,

Developing region: The region starts from the liquid film dryout point, ends at where wall surface is fully covered by stable vapor blanket. Flow structure develops to be stable in this region and