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A simplified energy dissipation based model of heat transfer for post-dryout flow boiling

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ABSTRACT

A model for post dryout mist flow heat transfer is presented based on considerations of energy dissipation in the flow. The model is an extension of authors own model developed earlier for saturated and subcooled flow boiling. In the former version of the model the heat transfer coefficient for the liquid single-phase convection as a reference was used, due to the lack of the appropriate model for heat transfer coefficient for the mist flow boiling. That issue was a fundamental weakness of the former approach. The purpose of present investigation is to fulfil this drawback. Now the reference heat transfer coefficient for the saturated flow boiling is that corresponding to vapour flow the end of the mist flow. The wall heat flux is based on partitioning and constitutes of two principal components, namely the convective heat flux for vapour flowing close to the wall and two phase flow droplet–vapour in the core flowing. Both terms are accordingly modelled. The results of calculations have been compared with some experimental correlations from literature showing a good consistency.

1. Introduction

The flow boiling for a long time has been perceived as one of the most effective ways of removal of large heat fluxes. The phenomenon found applications in various areas of technology where efficient cooling is required. Examples of such applications are nuclear reactor cooling, medical applications where cooling of neutron generators used in treatment of tumours is necessary, testing of materials, cooling of electronic equipment or cooling of gas turbine nozzles.

In the annular-mist flow with heated walls, the liquid film is depleted by both the entrainment of liquid droplets and by the evaporation. When the liquid film experiences almost complete depletion and no longer covers the wall, the heat transfer between the fluid and the channel wall deteriorates, leading to the onset of boiling crisis called dryout. As the flow develops further downstream in the post-dry out region, the liquid flows only as droplets in the core flow, and the channel wall temperature increases to a higher level. This phenomenon has made the prediction of the heat transfer in mist (dispersed) flow regime more complicated and more difficult. In the case of the post-dry out heat transfer, where droplets are travelling in the core of the flow forming the mist with vapour, due to the fact that heat is not transferred directly from the heated wall to the liquid droplets; instead, the heat is first transferred to the vapour next to the wall. Subsequently only a part of that heat is transferred from the vapour to the liquid droplets, which leads to different temperatures between liquid droplets and the vapour phase. In such case, significant amounts of liquid droplets may exist even though the equilibrium quality exceeds unity. As a result of that temperature of non-equilibrium vapour becomes superheated, where superheat of vapour phase may reach few hundreds Kelvins. The dryout occurrence and the downstream post-dry out wall temperature excursion could damage the channel wall. Because of this reason, exact mechanisms for the heat transfer process are still poorly understood and reliable prediction models are still being sought. Such situation is present even though numerous experimental measurements and prediction models have concentrated on the dispersed flow heat transfer.

A number of papers in the literature are devoted to this issue but the complexity of the process makes the analysis of that case very challenging. Several modelling approaches have been developed to predict the heat transfer rate during mist flow boiling. Such models can be generally divided into two categories, namely purely empirical correlations for heat flux calculations or the formulas based on mechanistic models. The empirical approaches express the wall heat flux or partitioning of the wall heat flux. Non-consistent empirical correlations for heat transfer coefficient

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Nomenclature

Bo	Boiling number, $B = q/(G\ h_{lv})$
c	specific heat [J/(kg K)]
C	constant
D_h	hydraulic diameter [m]
E	energy dissipation [W/m^3]
f	friction factor
g	gravitational acceleration [m^2/s]
G	mass velocity, [kg/(m^2 s)]
h_{lv}	latent heat [J/kg]
$\dot{m}$	mass flow rate, kg/s
p	pressure [N/m^2]
P	empirical correction, perimeter
R	tube radius [m]
q	heat flux [W/m^2]
r	radius [m]
Re	Reynolds number, $Re = G\ D_h/\mu_l$
T	temperature [°C]
x	quality [–]
z	wall normal coordinate [m]

Greek symbols

α	heat transfer coefficient [W/(m^2 K)]
λ	thermal conductivity [(W/m K)]
μ	dynamic viscosity [kg m/s]
ρ	density [kg/m^3]
σ	surface tension [kg/s^2]
τ	shear stress [N/m^2]

Subscripts

A	annular
AV	annular vapour
c	core
e	equivalent
l	liquid phase
K	two-phase core
M	mist
O	reference
p	constant pressure
Pb	pool boiling
ref	reference
sat	saturation
TP	two-phase
TPB	two-phase flow boiling
v	vapour
w	wall

Superscript

+	non-dimensional

are used for expressing a particular wall heat flux partitioning. Non-consistency partially stem from the fact that empirical correlations are generally limited to particular flow conditions. Hence empirical correlations do not include modelling of the heat transfer mechanisms. The alternative are the mechanistic models which are capable of determining the particular heat flux components individually. Usually main aspects of the problem are studied. Firstly the distance from the dryout conditions to the complete evaporation of the drops in the core flow and, secondly, heat transfer from the wall to fluid. Hence empirical correlations for wall heat flux partitioning can only provide information regarding how the wall heat flux is to be partitioned. They cannot be used for the prediction of the wall heat flux itself. The mechanistic models, on the other hand, which are based on the relevant heat transfer mechanisms occurring during the boiling process, have the capability for individual determination of each of the relevant heat flux components. Hence the mechanistic models can be used for both the prediction of the wall heat flux and the partitioning of the wall heat flux between the liquid and vapour phases. An excellent review of literature on the topic of empirical correlations for heat flux, empirical correlation for partitioning of wall heat flux and mechanistic models for prediction of wall heat flux and partitioning can be found in [1].

The region of the mist zone can be either large or small in relation to the fluid properties, mass flux, pressure and heat flux. It is a non-equilibrium region in which the quality and void fraction are positive non-zero values but the vapour temperature is above the saturation temperature. Modelling of such phenomenon represents significant difficulties.

Nishikawa et al [2] investigated critical heat flux and heat transfer coefficient in relation to the safety and performance of vapour generators at high subcritical pressure with refrigerant R22 as working fluids. They introduced the Knudsen number Kn to take account of the thermodynamic non-equilibrium between the vapour and the liquid droplets, correcting in such way the wall temperature distributions. The proposed model predicted satisfactorily heat transfer to R22 at high subcritical pressures.

Jones Jr. and Zuber [3] shown that the non-equilibrium component of the total energy can be expressed as a first-order, inhomogeneous relaxation equation in terms of the newly introduced parameter named the superheat relaxation number. That model proved to show that the effects of mass velocity and heat flux along the length of the tube for equilibrium qualities from 0.13 to over 3.0.

Terekhov et al [4] studied the steam-drop flow in a tube. Authors postulated the factors influencing the heat and mass transfer process in steam-drop flow. These were initial mass concentration of liquid droplets, their initial diameter, mixture velocity, heat flux, initial temperature of steam flow. They found that the evaporation rate of particles increases with increasing heat flux and initial vapour temperature, whereas the decreasing trend is observed with increasing droplet size. Considerations enabled to estimate the distance over which all droplets evaporated.

Guo and Mishima [1] claim that it is impossible to predict accurately the heat transfer in the mist flow without considering the thermal non-equilibrium between droplets and vapour. Authors considered five configurations of interaction between vapour, liquid droplets and the wall. These were forced convection of vapour phase to the wall, the direct contact heat transfer of droplets to the wall, the interfacial heat transfer between vapour and droplets and the radiation between the wall, droplets and vapour. It resulted from this study that the heat transfers by radiation and by direct droplet contact to the wall are important under low pressure and low mass flow conditions. Neglecting these two heat transfer paths may lead to an unacceptable error in wall temperature prediction. Nevertheless the vapour convection is the dominant heat transfer mechanism.

Liu and Anglart [5] suggested an integrated CFD model to include both the pre-dryout annular-mist flow and the post-dryout mist flow, with post-dryout heat transfer accounted for. The three-field annular-mist CFD model couples the thin liquid film model with the two-field two-fluid model of the gas core flow including the gas phase and the droplets. The dryout occurrence was predicted using a critical film thickness model. The various