International Journal of Heat and Mass Transfer 103 (2016) 66–76

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Prediction of dryout and post-dryout wall temperature at different operating parameters for once-through steam generators

Jianxin Shi, Baozhi Sun *, Guolei Zhang *, Fuyuan Song, Longbin Yang

College of Power and Energy Engineering, Harbin Engineering University, Nantong Street, Harbin 150001, PR China

ARTICLE INFO

Article history:
Received 15 March 2016
Received in revised form 8 July 2016
Accepted 9 July 2016

Keywords:
Once-through steam generator
Dryout
Post-dryout
Flow boiling
Heat transfer deterioration

ABSTRACT

A three-dimensional "unit tube" physical model is established by simplifying the once-through steam generator (OTSG) designed by B&W and a three-dimensional two-fluid three-flow-field mathematical model that takes into account the interactions between liquid droplets and other flow-fields (steam and liquid film) and the interactions between liquid droplets and the wall in liquid deficient regions is introduced. The results of a numerical simulation using the developed OSTG model conducted at different operating parameters show that the three-dimensional two-fluid three-flow-field mathematical model used in this paper can accurately predict the dryout and post-dryout wall temperature distribution of the OTSG at different operating conditions. The simulations also show that the post-dryout wall temperature decreases along the height of the heat transfer tube at low mass fluxes while gradually increases at high mass fluxes, which is opposite to the changes in wall temperature seen in post-departure from the nucleate boiling region. Furthermore, dryout occurs later as pressure increases, with a smaller soaring maximum of the wall temperature. Dryout will occur when the wall temperature gradient reaches or exceeds 250 K/m as the heat flux increases.

1. Introduction

The main heat transfer method in the secondary side of a steam generator (SG) which undertakes the heat transfer between primary side and secondary side is two-phase flow boiling heat transfer [1,2]. To achieve higher power generation efficiency with such a design, it is necessary to improve the outlet temperature of the fluid in the secondary side of the SG. However, due to the nature of two-phase boiling heat transfer, deterioration in the flowing boiling heat transfer inevitably occurs in the secondary side of the SG when the outlet water is in a superheated condition, which is also known as a boiling crisis [3,4]. A boiling crisis is usually divided into two categories: the pool boiling crisis and flow boiling crisis. A pool boiling crisis means that the bubbles generated near the wall are too numerous to spread into the main stream when the heat flux increases to a certain value in the pool boiling process, resulting in the wall being covered with a layer of steam film. This steam film sometimes does not break and still covers the wall, which leads to a rapid decline in heat flux and a rapid rise in wall temperature, causing a deterioration in the boiling heat transfer process.

Two forms of heat transfer deterioration that can typically occur in the flow boiling process. The first kind of heat transfer deterioration occurs when the heat flux exceeds the critical heat flux, namely when the heat transfer transforms from nucleate boiling to film boiling. Again, the bubbles generated near the wall are too numerous to adequately spread out so that the wall is covered by a steam film, which causes a rapid rise in wall temperature. The flow boiling enters into an anti-annular flow after this type of deterioration occurs, and will not resume annular flow and mist flow. Furthermore, the quality is low when this occurs, which is commonly referred to as a departure from nucleate boiling (DNB) crisis. The DNB crisis is similar to the heat transfer deterioration experienced in the pool boiling process. The second kind of heat transfer deterioration occurs when the quality is high in the boiling process. The adherent liquid film is torn or evaporated due to acceleration of the core steam, i.e., the flow pattern transforms from an annular flow to a mist flow, which leads to heat transfer deterioration. This is known as dryout, and it usually occurs in a once-through boiling tube where the wall temperature soars at the dryout location [5,6].

It is important to note that wall temperature will rapidly rise regardless of what kind of heat transfer deterioration occurs. If effective methods are not taken to mitigate the rising maximum

* Corresponding authors. Fax: +86 0451 82519305 (G.L. Zhang), fax: +86 0451 82569229 (B.Z. Sun).

E-mail addresses: sunbaozhi@163.com (B. Sun), zhangguolei@hrbeu.edu.cn (G. Zhang).

http://dx.doi.org/10.1016/j.ijheatmasstransfer.2016.07.027
0017-9310/

Nomenclature

t	time, s
α	volume fraction
ρ	density, kg/m^3
∇	gradient
$\vec{U}$	velocity vector, m/s
Γ_l	mass transfer rate between liquid film and steam, kg/(m^3 s)
Γ_d	mass transfer rate between droplets and steam, kg/(m^3 s)
S_E	droplet entrainment rate, kg/(m^3 s)
S_D	droplet deposition rate, kg/(m^3 s)
p	pressure, MPa
g	gravity, m/s^2
F_{vd}	drag force between steam and droplets, N/m^2
F_{vl}	drag force between steam and liquid film, N/m^2
$\vec{F}_{lift}$	buoyancy lift, N/m^2
τ	shear stress, N/m^2
τ^{Re}	Reynolds stress, N/m^2
h	enthalpy, kJ/kg
q	heat flux, W/m^2
q_{vl}	heat flux per unit volume between steam and its interface with the liquid film, W/m^3
q_{vd}	heat flux per unit volume between steam and its interface with the droplets, W/m^3
χ_c	heating perimeter, m
A	flow area, m^2
q_{wv}	heat flux between wall and steam, W/m^2
q_{lv}	heat flux per unit volume between liquid film and its interface with the steam, W/m^3
q_{wl}	heat flux between wall and liquid film, W/m^2
q_{dv}	heat flux per unit volume between droplets and their interface with the steam, W/m^3
q_{wd}	heat flux between wall and droplets, W/m^2
q_{wil}	heat flux between wall and the interface of the steam with the liquid film, W/m^2
q_{wid}	heat flux between wall and the interface of the steam with the droplets, W/m^2
δ	liquid film thickness, m
u	velocity, m/s
C_l	lift coefficient
f	drag function
d	diameter, m
ν	kinematic viscosity, m^2/s
μ	dynamic viscosity, Pa s
Re	Reynolds number
λ_{RT}	Rayleigh - Taylor instability wavelength, m
D_h	hydraulic diameter, m
λ	thermal conductivity, W/(m·K)
Nu	Nusselt number
T	temperature, K
Pr	Prandtl number
x	quality
z	the height of heat transfer tube, m

Subscripts

v	steam
l	liquid film
d	droplet
i	$i = v, l, d$
q	$q = l, d$
vo	vorticity
k	$k = v, l$
w	wall
DO	dryout

of wall temperature, the heat transfer deterioration location and changes in the wall temperature in the post-deterioration region, the damage to the operating devices will occur. Thus, more and more researches have focused on understanding and mitigating this heat transfer deterioration.

Bennett et al. [7,8] and Becker et al. [9] established experimental flow boiling systems based on vertical uniform and non-uniform heating tubes, and conducted post-DNB (the outlet quality was lower and approximately 0.45) experiments at different operating parameters. Both groups found that the post-DNB wall temperature rose along the height of the heat transfer tube at low mass fluxes and decreased at high mass fluxes. Zhao et al. [10] studied the variation of surface heat transfer coefficient in pre-critical heat flux regions by changing the inlet pressure, mass flux and heat flux of a single horizontal coil tube. Jayanti and Valette [11] developed a one-dimensional three-fluid model and a set of closed correlations to simulate the flow boiling heat transfer process of a steam-water mixture in an electrically heated vertical tube, and predicted the experimental DNB results of other researchers using the model. The group found that the post-DNB wall temperature rose along the height of the heat transfer tube at low mass fluxes and decreased at high mass fluxes with their model, showing that numerical results were basically consistent with experimental data. Then, Jayanti and Valette [12] used the modified one-dimensional three-fluid model to predict heat transfer deterioration among rod bundles in a reactor, and compared the simulation results of transfer deterioration location, bundle temperature with the experimental data from other researchers. The group found that the model properly predicted the phenomenon when the operating conditions were 0.3–13.5 MPa of pressure and 50–800 kg/m^2·s of mass flux. Ha et al. [13] applied the three-fluid model using the SPACE code and simulated flow boiling in an electrically heated vertical tube to obtain pressure drop, temperature, void fraction and heat transfer deterioration location data under certain conditions by solving conservation equations for each phase based on the finite volume, they found that the simulated results were in good agreement with the experimental data of the open literature. In the same year, Li et al. [14] extended nucleate boiling to DNB of the RPI wall boiling model considering liquid film in the vicinity of wall, used computational fluid dynamics (CFD) software Fluent to simulate flow boiling and critical heat flux in a uniformly heated vertical tube and obtained the DNB location and axial distribution of the wall temperature. Talebi et al. [15] simulated the thermal-hydraulic process from single-phase liquid heat convection to post-DNB heat transfer region in a uniformly heated vertical tube (the outlet quality was about 0.5) by combining the film thickness model with wall heat flux partition model, and then evaluated the deviation from thermodynamic equilibrium in post-DNB critical region by wall heat flux partition model. The researchers found that the post-DNB wall temperature increased along the height of the heat transfer tube at low mass fluxes and decreased at high mass fluxes, verifying the feasibility and accuracy of the model through comparison with the experimental data of Bennett et al. [8].

Note that the outlet qualities were relatively low in the above studies, with a maximum value of about 0.5. This means that the occurred heat transfer deterioration belonged to the first kind of heat transfer deterioration (DNB). However, the heat transfer