Applied Thermal Engineering 105 (2016) 132–141

Contents lists available at ScienceDirect

Applied Thermal Engineering

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

Research Paper

Numerical simulation of dryout and post-dryout heat transfer in a straight-pipe once-through steam generator

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HIGHLIGHTS

- Two-fluid three-flow-field model is developed to predict dryout in steam generator.
- The empirical correlation is used to correct dryout criterion.
- The interactions between three-flow-fields and the wall are considered.
- Dryout and post-dryout heat transfer mechanisms are discussed through the results.

ARTICLE INFO

Article history:
Received 2 March 2016
Revised 19 May 2016
Accepted 24 May 2016
Available online 24 May 2016

Keywords:
Once-through steam generator
Vertical pipe
Flow boiling
Dryout
Heat transfer characteristic

ABSTRACT

Accurately predicting dryout and post-dryout heat transfer characteristics is critical for proper design of once-through steam generators. This paper provides a reasonable and simple method for this prediction by introducing a two-fluid, three-flow-field mathematical model and improving the dryout criterion-critical quality, and conducts a numerical simulation of dryout and post-dryout heat transfer in a once-through steam generator to prove the model's performance. The results show that the critical quality in a once-through steam generator is about 0.82, with the heat transfer capacity significantly reducing and the wall temperature sharply increasing in a non-linear form by approximately 30 K when dryout occurs. Part of the steam is superheated in the post-dryout region, resulting in a deviation from thermodynamic equilibrium between the vapor and liquid phases. Dryout and post-dryout heat transfer in the once-through steam generator operate between complete deviation from thermodynamic equilibrium and complete thermodynamic equilibrium. Therefore, the presence of droplets has a significant influence on the mass, momentum and energy transfer between the film and vapor phases.

1. Introduction

Compared to traditional natural circulation steam generators, a once-through steam generator (OTSG) used in the nuclear power plant with pressurized water reactor (PWR) generates superheated steam at the outlet, which provides the design good economical efficiency, compactness, modular construction, high power generation efficiency and good thermal heating effect. Because of these advantages, more and more researchers have focused on studying OTSG in recent years. In a OTSG, the working fluid in the secondary side experiences a complex vapor-liquid two-phase flow and heat transfer process that includes preheating and boiling until overheating. Deterioration in the heat transfer occurs when the steam quality reaches a certain value, which has a major influence on the safe and reliable operation of the equipment. This heat transfer deterioration can be divided into two types according to its cause:

(1) DNB (departure from nucleate boiling): DNB occurs when the heat flux exceeds the critical heat flux such that the flow pattern changes from nucleate boiling to film boiling. This means that bubbles near the wall are generated too late to spread to the main stream, causing the wall to be covered with a vapor film.
(2) Dryout: This phenomenon occurs when the steam quality reaches a sufficiently high value, that the adherent annular liquid film is torn by the steam—that is, the flow pattern changes from an annular flow to a mist flow [1,2].

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http://dx.doi.org/10.1016/j.applthermaleng.2016.05.145
1359-4311/

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)
$\vec{F}_{vl}$	drag force between steam and liquid film (N/m^2)
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)
D_h	hydraulic diameter (m)
λ	thermal conductivity (W/(m K))
Nu	Nusselt number
T	temperature (K)
Pr	Prandtl number
x	steam quality
z	the height of heat transfer tube, m

Subscripts

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

The heat transfer deterioration that occurs during operation of a OTSG is dryout.

Liquid films disappear when dryout occurs as the wall is no longer wetted in this state (i.e., there is no liquid contact with the wall), which results in a significant reduction in the surface heat transfer coefficient and a sharp rise in wall temperature. If effective control of this situation is not taken, wall temperature may exceed the maximum allowable limit, posing a security threat to running equipment. To describe this phenomenon, researchers have conducted a great deal of research and proposed two different models: a liquid film thickness model and a two-fluid three-flow-field model. Whalley et al. [3] proposed a liquid film thickness model based on a flow analysis approach, used the model to calculate the liquid film flow rate of an unbalanced flow (such as evaporation flow) through a uniformly heated straight pipe, then extended the model to predict the dryout and post-dryout heat transfer phenomenon. Azzopardi [4] studied the impact of the initial entrainment fraction and mass flow rate on dryout position for an electrically heated vertical tube using the liquid film thickness model. Chong et al. [5] modified the model in [4] and used it to predict dryout in a serpentine reboiler passage. Adamsson and Anglart [6] combined the liquid film thickness model with a sub-channel model of a nuclear reactor fuel assembly and captured the effect of shaft power distribution on dryout position.

However, it is worth noting that the liquid film thickness model only considers the steam and the liquid film when predicting the dryout and post-dryout heat transfer, and there is presently no mature film thickness measurement method. Thus, it is difficult to verify the model. At the same time, some scholars have instead turned to conducting OTSG simulations by simplifying the flow boiling process. Li et al. [7] adopted a moving boundary lumped parameter method to investigate the change of inlet and outlet parameters in HTR-10 that considered the preheating, boiling and superheating regions. Li and Ren [8] studied the influence of heating power on the outlet steam temperature and the length of each heat transfer region by using a lumped parameter method to divide the heat transfer region into preheating, boiling and superheating regions based on the moving boundary model. Zhu et al. [9] established a dynamic mathematical model of the preheating, boiling and superheating regions based on lumped parameters and a moving boundary, and then conducted both steady and dynamic simulations. Wang et al. [10] studied the flow and heat transfer characteristics of the preheating and nucleate boiling regions in a OTSG using a two-fluid model and an RPI thermal phase change model built with CFX software. However, this study was limited by the method itself, as the simulation was only concerned with the inlet and outlet parameters of the OTSG and ignored local changes in the axial direction, and there exists dryout, heat transfer deterioration and wall temperature increases in localized regions. Generally speaking, the lumped parameter method will invariably ignore these factors when determining the thermal-hydraulic characteristics of a OTSG.

To predict dryout more accurately, Thurgood et al. [11] considered liquid films, droplets, steam flow-fields and the interactions between these states in 1983. Based on their analysis, the group proposed a two-fluid three-flow-field model that used the easily measured steam quality as the dryout criterion, then implemented the model with COBRA-TF software to predict dryout-induced leakage accidents in the primary side cooling system of a nuclear reactor. Hoyer [12] applied a one-dimensional two-fluid three-flow-field model to MONA code and simulated the flow boiling of an electrically heated vertical tube in an experimental database. The results of the simulation showed that the model could accurately predict dryout and post-dryout heat transfer. Hoyer and