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Development of void fraction-quality correlation for two-phase flow in horizontal and vertical tube bundles

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ABSTRACT

A steam generator thermal-hydraulic code based on homogeneous flow model has been useful based on its numerical stability and simpler formulation. One of key parameters for a steam generator thermal-hydraulic analysis is void fraction which determines two-phase mixture density and affects two-phase mixture velocity. These parameters are important for a heat transfer tube vibration analysis. A void fraction-quality correlation is very important to accurately convert the quality into the void fraction. The void fraction-quality correlation should preferably be applicable to parallel and cross flows in rod or tube bundles since two-phase flow in the steam generator encounters flow configuration change from the parallel flow along the tube bundle in the riser section of the steam generator to the cross flow in the U-bend section of the steam generator. A set of correlations depending on flow configuration such as parallel and cross flows, rod or tube array pattern and mass flux is developed based on legacy Smith correlation. The correlation agrees with the parallel and cross flow data with the mean absolute error (or bias) of 0.117% and the standard deviation (random error) of 2.26% and with the mean absolute error (or bias) of 0.760% and the standard deviation (random error) of 6.21%, respectively. The correlations are further simplified to a single correlation applicable for parallel and cross flow in rod or tube bundles. The Smith correlation with a modified constant entrainment parameter e being 0.5 is recommended for predicting void fraction in the steam generators. The Smith correlation with $e = 0.5$ is expected to be applicable for parallel and cross flows with various rod or tube array patterns including normal square, parallel triangular and normal triangular arrays.

1. Introduction

A steam generator is a type of heat exchanger. Water that has passed through a nuclear reactor core ("the primary fluid") is carried through the steam generator within thousands of metal tubes, known as "heat transfer tubes." Some of the heat contained in the primary fluid is conveyed through the walls of the heat transfer tubes to water flowing outside of the tubes ("the secondary fluid"). The secondary fluid is water at the steam generator inlet, but the water boils into a two-phase mixture (steam/water) as heat transfers from the primary fluid to the secondary fluid, so that a good portion of the secondary fluid has become steam as it reaches the steam generator outlet. After leaving the steam generator, the steam is the driving force that rotates a turbine to generate electricity.

Some of steam generators have experienced some problems such as tube support corrosion, tube-sheet corrosion, tubing corrosion, fretting fatigue cracking and impingement, which have led to unplanned outages (Green and Hetsroni, 1995). To avoid these problems, a steam generator is designed with an input based on detailed three-dimensional local thermal-hydraulic conditions computed by steam generator thermal-hydraulic codes. A porous media approach is usually utilized in the steam generator thermal-hydraulic codes. A control volume in the porous media approach includes volumes of structures and flow channels. The porosity is defined by the ratio of volume of flow channels to total volume. Various reliable steam generator thermal-hydraulic codes have been developed based on different two-phase flow porous media formulations.

CAFCA code developed by EDF (Electricite de France in France), THIRST code developed by AECL (Atomic Energy of Canada Limited) and FIT-III code developed by MHI (Mitsubishi Heavy Industries,

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Nomenclature

a	gap between tubes
B_1	parameter
B_2	parameter
C_0	distribution parameter
C_1	parameter
c_1	parameter
c_2	parameter
D	tube (or rod) diameter
D_C	flow path diameter
e	entrainment factor defined as ratio of mass of liquid droplets entrained in gas core to total mass of liquid
e^V	volume porosity
f	friction force per unit volume exerted on secondary-side fluid by embedded solids
G	mass flux
G_H	mass flux based on hydraulic equivalent diameter
G_P	mass flux based on minimum pitch between rods (or minimum gap between rods)
g	gravitational acceleration
h_{fg}	latent heat
h_m	mixture enthalpy of secondary fluid
j	mixture volumetric flux
j_g	superficial gas velocity
j_g^+	non-dimensional superficial gas velocity
j_g^*	non-dimensional superficial gas velocity
$j_{g,crit}$	critical superficial gas velocity
K_0	parameter
L	parameter
La	Laplace length scale
m_d	mean absolute error
m_{rel}	mean relative deviation
$m_{rel,ab}$	mean absolute relative deviation
N	number of sample
N_{Ca}	Capillary number
N_{Fr}	Froude number
N_G	non-dimensional mass flux
$N_{G,H}$	non-dimensional mass flux based on hydraulic equivalent diameter
$N_{G,P}$	non-dimensional mass flux based on minimum pitch between rods (or minimum gap between rods)
N_{La}	non-dimensional Laplace length scale
N_{Re}	Reynolds number
N_{Ri}	Richardson number
N_{We}	Weber number
$N_{\mu f}$	viscous number
P	tube (or rod) pitch
p	pressure
p_{crit}	critical pressure
$\dot{q}_s$	heat source (rate of heat transfer) per unit volume
S	slip ratio
s_d	standard deviation
t	time
V_{gj}	drift velocity
$V_{gj,B}$	drift velocity computed by Ishii's bubbly flow correlation
$V_{gj,P}$	drift velocity computed by Kataoka-Ishii's correlation
V_{gm}	relative velocity of vapor with reference to mixture velocity
v_f	liquid velocity
v_g	gas velocity
v_m	mixture velocity
x	quality

Greek symbols

α	void fraction
γ	parameter
$\Delta\rho$	density difference
μ_f	absolute viscosity of liquid phase
ρ_g	gas density
ρ_f	liquid density
ρ_m	mixture density
σ	surface tension

Subscripts

cal.	calculated value
exp.	experimental value

Ltd.) adopt homogeneous flow model composed of three transport equations such as mass, momentum and energy conservation equations (Boivin et al., 1987; Carver et al., 1981; Hirao et al., 1993). The velocity slip is considered through a void fraction-quality correlation. ATHOS code developed by EPRI (Electric Power Research Institute) utilizes algebraic slip model composed of three transport equations such as mass, momentum and energy conservation equations (Singhal et al., 1982). The velocity slip is considered through the momentum equation with a drift-flux type correlation. PORTHOS code developed by EPRI uses two-fluid model composed of six transport equations such as mass, momentum and energy conservation equations for gas and liquid phases (Chan et al., 1986). The outputs of the steam generator thermal-hydraulic codes are utilized for improving the steam generator design and stability analysis of fluid-elastic vibration.

In order to enhance the code prediction capability, reliable constitutive equations are indispensable. Among the constitutive equations, void fraction correlation is very important, because void fraction affects two-phase mixture density directly and two-phase mixture velocity. Void fraction constitutive correlations are often given for each flow regime, each channel geometry, and each channel orientation, but it is preferred to use a single void fraction constitutive correlation in the code. However, since the two-phase flow structure changes from parallel flow along tube bundles in a vertically straight section to cross flow in a U-bend tube section, it is challenging to develop a single void fraction constitutive correlation which is applicable for all void fraction range in the steam generator.

From this point of view, this study aims to develop a void fraction-quality correlation for maintaining the prediction accuracy of steam generator thermal-hydraulic codes developed based on homogeneous flow model. First, basic two-phase flow porous media formulations are reviewed to highlight the importance of void fraction correlations. A brief literature survey on existing void fraction correlations and tube (or rod) bundle data for parallel and cross flows follows. Then new void fraction correlation is developed for parallel and cross flows encountered in a steam generator.