International Journal of Heat and Fluid Flow 34 (2012) 85–97

Contents lists available at SciVerse ScienceDirect

International Journal of Heat and Fluid Flow

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

Measurement and modeling of two-phase flow parameters in scaled 8 × 8 BWR rod bundle

X. Yang, J.P. Schlegel, Y. Liu, S. Paranjape, T. Hibiki, M. Ishii *

School of Nuclear Engineering, Purdue University, 400 Central Dr., West Lafayette, IN 47907-2017, USA

ARTICLE INFO

Article history:
Received 2 December 2011
Received in revised form 2 February 2012
Accepted 6 February 2012

Keywords:
Rod bundle
Pressure loss
Void fraction
Drift-flux models
Interfacial area concentration
Axial development

ABSTRACT

The behavior of reactor systems is predicted using advanced computational codes in order to determine the safety characteristics of the system during various accidents and to determine the performance characteristics of the reactor. These codes generally utilize the two-fluid model for predictions of two-phase flows, as this model is the most accurate and detailed model which is currently practical for predicting large-scale systems. One of the weaknesses of this approach however is the need to develop constitutive models for various quantities. Of specific interest are the models used in the prediction of void fraction and pressure drop across the rod bundle due to their importance in new Natural Circulation Boiling Water Reactor (NCBWR) designs, where these quantities determine the coolant flow rate through the core. To verify the performance of these models and expand the existing experimental database, data has been collected in an 8 × 8 rod bundle which is carefully scaled from actual BWR geometry and includes grid spacers to maintain rod spacing. While these spacer grids are ’generic’, their inclusion does provide valuable data for analysis of the effect of grid spacers on the flow. In addition to pressure drop measurements the area-averaged void fraction has been measured by impedance void meters and local conductivity probes have been used to measure the local void fraction and interfacial area concentration in the bundle subchannels. Experimental conditions covered a wide range of flow rates and void fractions up to 80%.

1. Introduction

The next generation of advanced water reactors will be licensed using, in part, safety analyses developed using the results of advanced best-estimate computer codes for thermal–hydraulic analysis. These codes, such as TRACE and RELAP5, utilize the one-dimensional two-fluid model for the prediction of two-phase flows. This model treats the liquid and gas using separate mass, momentum and energy transport equations and is therefore often called the six-equation model. Time averaging the local instant formulation of the two-fluid model gives rise to terms describing the transfer of mass, momentum and energy between the phases. These interfacial transfer terms must be predicted using constitutive relations, and the development of these constitutive relations has been the most significant challenge in the use of the two-fluid model for predicting reactor behavior.

One of the most critical reactor components in advanced analysis codes is the rod bundle, which is used to predict the behavior of the flow in the reactor core. Rod bundles present many challenges due to their complex geometry and the presence of spacer grids which help maintain rod spacing. This prevents criticality accidents and ensures open flow channels for coolant. Current approaches for predicting flow behavior in rod bundles use correlations selected using flow regime maps to predict the interfacial transfer terms. Often, these correlations and flow regime maps are developed only for fully-developed flows. Because of this the models may not be applicable to transient situations or developing flows and their use may result in numerical oscillations or bifurcations, limiting the use of advanced computer codes. For this reason, it is essential to develop more accurate and robust models for the interfacial transfer terms (Ishii and Hibiki, 2010). Of special interest is the prediction of interfacial drag, which has a significant effect on the prediction of void fraction. Accurate void fraction prediction is essential in the prediction of flow rate as well as pressure drop. The presence of grid spacers further complicates the prediction of pressure drop in rod bundle systems.

The interfacial area transport equation promises to address some of these shortcomings by providing a method to model the dynamic development of two-phase flows, however this approach is still under development (Hibiki and Ishii, 2009). In the meantime it is desirable to have the optimum models for interfacial transfer and other quantities required for accurate predictions using the two-fluid model such as the grid spacer pressure loss. In order to improve the current approach for rod bundles an extensive database

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* Corresponding author.
E-mail address: ishii@purdue.edu (M. Ishii).

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doi:10.1016/j.ijheatfluidflow.2012.02.001

Nomenclature

Latin characters

A	coefficient matrix (–)
a_i	interfacial area concentration (m^{-1})
C	constant (–)
D_H	hydraulic diameter (m)
DP	differential pressure (Pa)
f	friction factor (–); distribution function (–)
g	Gravitational acceleration ($\mathrm{m/s^2}$)
j	superficial velocity (m/s)
K	pressure loss coefficient (–)
L	length (m)
n	exponent in friction loss correlation (–); number of grid spacers
m	exponent in friction loss correlation (–)
P	coefficient matrix (Pa)
p	pressure (Pa)
P_0	pitch (m)
R_0	rod diameter (m)
r	radial distance (m)
Re	Reynolds number (–)
V	voltage (V)
v	velocity (m/s)
X	solution matrix (Pa)
X	Lockhart–Martinelli correlation parameter (–)
x	variable (kPa)
y	variable representing grid loss (kPa)
z	axial location (m)

Greek Characters

α	void fraction (–)
Δp	pressure drop (Pa)
Δz	elevation difference (m)
φ_f^2	two-phase friction multiplier (–)
μ	dynamic viscosity (Pa s)
ρ	density ($\mathrm{kg/m^3}$)

Sub/superscripts

1	value at Port 1
2	value at Port 2
3	value at Port 3
4	value at Port 4
5	value at Port 5
6	value at Port 6
7	value at Port 7
f	quantity for liquid phase
g	quantity for gas phase
m	mixture value

Operators

$\langle\rangle$	area-averaged quantity
$\ll\gg$	void-weighted area-averaged quantity

of area-averaged void fraction data and pressure loss data are required. The void fraction data is useful for evaluating drift-flux models, which are often used in the prediction of interfacial drag in two-phase systems. Many previous studies (Rehme, 1973; Chun and Seo, 2001; Schikorr et al., 2010; Yano et al., 2001) have focused on the measurement of pressure drop and the prediction of Critical Heat Flux (CHF). Some studies have also concentrated on measurement of the local void fraction profiles within the rod bundle. Some information on the area-averaged void fraction (Julia et al., 2009) or on the effect of grid spacers on void fraction change and pressure losses is available (Coddington and Macian, 2002). Additionally, these studies have generally been limited to small rod bundles with few rods, which may not be representative of prototypic Boiling Water Reactor (BWR) or Pressurized Water Reactor (PWR) models.

In light of these shortcomings, work has been undertaken to measure the area-averaged void fraction and two phase pressure losses under a wide variety of flow conditions in an 8 × 8 rod bundle geometry. This rod bundle has been scaled from an actual BWR rod bundle and includes spacer grids (Chen et al., 2012).

2. Previous work

Many studies have been performed to measure the void fraction and identify the flow regimes in rod bundles. A thorough review of these studies was performed by Julia et al. (2009).

The frictional pressure loss in two-phase systems is generally modeled using a formulation similar to that developed by Lockhart and Martinelli (1949). According to this formulation, the frictional pressure drop is given by

$$\Delta p_f = 4\varphi_f^2 \frac{fL}{D} \frac{\rho_f \langle j_f \rangle^2}{2} \tag{1}$$

where Δp is the pressure drop, φ_f^2 is the two-phase friction multiplier, f is the single-phase friction factor, ρ_f is the liquid density and j_f is the superficial liquid velocity. Quantities in brackets, $\langle\rangle$, indicate area-averaged quantities. In order to use this formulation, the two phase friction multiplier and friction factor must be defined. For the friction factor, Cheng and Todreas (1986) proposed a model of the form

$$f = \frac{C}{\mathrm{Re}^n} \tag{2}$$

with Re the liquid-phase Reynolds number. C and n are empirical constants. Based on the model developed by Rehme (1973) for rod bundles, the value of the constant is 0.152 and the exponent n is 0.18. The Reynolds number is defined as

$$\mathrm{Re} = \frac{\rho_f D_H \langle j_f \rangle}{\mu_f}. \tag{3}$$

where μ_f is the liquid viscosity. One of the most commonly used models for the two phase friction multiplier is given by Chisholm (1967).

Generally the pressure drop in an air–water rod bundle system is composed of three significant terms: gravitational pressure drop, friction pressure drop, and grid loss pressure drop. To accurately measure grid loss data it is necessary to separate the pressure loss into these three parts. The term representing the frictional pressure loss is determined using a friction loss correlation. The void fraction is measured experimentally. Thus the grid spacer pressure loss can be computed from the measured void fraction and pressure loss as well as the boundary condition. This procedure is detailed in Appendix A.

To develop a model for the grid spacer pressure drop, it remains to find a loss coefficient, K, and the two-phase multiplier. It can be assumed that K has much the same form as that given for f by Cheng and Todreas (1986), that is

$$K = \frac{C}{\mathrm{Re}^n} \tag{4}$$