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Two-phase flow structure in large diameter pipes

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ABSTRACT

Flow in large pipes is important in a wide variety of applications. In the nuclear industry in particular, understanding of flow in large diameter pipes is essential in predicting the behavior of reactor systems. This is especially true of natural circulation Boiling Water Reactor (BWR) designs, where a large-diameter chimney above the core provides the gravity head to drive circulation of the coolant through the reactor. The behavior of such reactors during transients and during normal operation will be predicted using advanced thermal–hydraulics analysis codes utilizing the two-fluid model. Essential to accurate two-fluid model calculations is reliable and accurate computation of the interfacial transfer terms. These interfacial transfer terms can be expressed as the product of one term describing the potential driving the transfer and a second term describing the available surface area for transfer, or interfacial area concentration. Currently, the interfacial area is predicted using flow regime dependent empirical correlations; however the interfacial area concentration is best computed through the use of the one-dimensional interfacial area transport equation (IATE). To facilitate the development of IATE source and sink term models in large-diameter pipes a fundamental understanding of the structure of the two-phase flow is essential. This understanding is improved through measurement of the local void fraction, interfacial area concentration and gas velocity profiles in pipes with diameters of 0.102 m and 0.152 m under a wide variety of flow conditions. Additionally, flow regime identification has been performed to evaluate the existing flow regime transition criteria for large pipes. This has provided a more extensive database for the development and evaluation of IATE source and sink models. The data shows the expected trends with some distortion in the transition region between cap-bubbly and churn-turbulent flow. The flow regime map for the 0.102 m and 0.152 m diameter test sections agree with the existing flow regime transition criteria. It may be necessary to perform further experiments in larger pipes and at higher gas flow rates to expand the range of conditions for which models can be developed and tested.

1. Introduction

Two-phase flows occur in a wide variety of common industrial applications. Many of these applications involve large diameter pipes. This is especially true of the chemical and petroleum industries, where bubble column chemical reactors and large pipe pumping systems are quite common. In the nuclear industry, two phase flows often occur in large channels. For this reason a lack of fundamental knowledge in this area can have significant ramifications for nuclear safety. In next-generation BWR systems, for example, the flow through the reactor is driven by natural circulation. This requires a large diameter chimney section above the core to provide the necessary gravity head (Ishii et al., 1998). This region is very sensitive to variations in the two-phase flow, especially during reactor startup. Flow in large pipes has several significant differences from flow in small pipes. Once the flow channel diameter is larger than the maximum cap bubble size, which is defined by Kataoka and Ishii (1987) as

$$D_H^* = \frac{D_H}{\sqrt{\frac{\sigma}{g\Delta\rho}}} \geq 30 \tag{1}$$

a variety of fundamental changes to the flow occur. Here, D_H is the hydraulic diameter, σ is the surface tension, g is gravitational acceleration, and $\Delta\rho$ is the density difference between the liquid and gas phases. First slug bubbles bridging the entire pipe cross-section can no longer be sustained due to Taylor instability, which causes the upper surface of larger bubbles to distort and collapse, breaking the large bubble into two or more daughter bubbles. This results in significant three-dimensional recirculatory behavior as the liquid flows around the cap bubbles rather than being forced out of the way, as is the case with slug bubbles. This causes significant changes to the void fraction and velocity profiles and can result in very different behavior from flow in smaller pipes, where slug bubbles can be sustained. For reactor safety it is vitally important that

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Nomenclature

Latin Characters

a_i	interfacial area concentration (1/m)
C	constant
D	diameter (m)
d	diameter (m)
F	fraction of eddies causing breakup (–)
g	gravitational acceleration (m/s^2); breakup frequency (s^{-1})
h	enthalpy (J/kg)
K_g	constant (–)
L	length (m)
M	interfacial momentum transfer (kg/m^2 s^2)
$N_{\mu f}$	viscosity number (–)
n	concentration (m^{-3})
p	pressure (kPa)
q	heat transfer (W/m^2)
r	radial location of measurement (m)
R	pipe radius (m)
r	radius (m)
S	collision cross-sectional area (m^2)
t	correlated time (s)
t_b	breakup time (s)
u	velocity (m/s)
V	volume (m^3)
v	velocity (m/s)
We	Weber number (–)

Greek Characters

α	void fraction (–)
β	PDF of daughter particle size (–)
ε	turbulent dissipation rate (m^2/s^3)
θ	collision frequency (s^{-1})
Γ	interfacial mass transfer (kg/m^3 s)
λ	coalescence efficiency (–)
μ	viscosity (Pa s)
Φ	energy source due to turbulent dissipation (W/m^3)
φ	source or sink term for IATE (1/ms)
$\Delta\rho$	density difference between phases (kg/m^3)
ΔT	time interval (s)
τ	characteristic time (s)
ρ	density (kg/m^3)
σ	surface tension (N/m)
$\sigma_v{}^2$	variance
τ	shear force (N/m^3)

Superscripts and Subscripts

*	non-dimensional value
b	bubble
c	critical value
h	hydraulic
i	interfacial value; bubble index
j	bubble index
k	value for phase k
T	value due to turbulence
t	turbulent fluctuation
ted	value for turbulent Eddy
v	value for velocity
w	value at the wall
z	denotes axial direction

Operators

$\sum$	summation
$\langle\rangle$	area-averaged quantity
$\langle\langle\rangle\rangle$	void-weighted area-averaged quantity
$-$	time-averaged quantity

the capability to accurately model and predict two-phase flows in such systems be developed.

These models will be integrated into existing thermal–hydraulic analysis codes for use in predicting system behavior. The most accurate way of predicting system behavior is full-scale testing, however in the nuclear industry full-scale tests are expensive and often impractical. In place of full-scale tests, a variety of scaled, separate effect, and local phenomena studies are used to develop mathematical models for the prediction of flow behavior under a wide variety of conditions. These models are then solved numerically using a computer. For this approach, reliable models with appropriate constitutive relations are essential for accurate predictions of the behavior of two-phase flow systems.

Most of these analysis codes make use of the two-fluid model, which is currently the most practical model for two-phase flow because it is more detailed than other models while using fewer resources than DNS or LES. This two-fluid model is the most detailed two-phase flow model currently used in system analysis codes. This model treats each phase separately, resulting in two sets of balance equations for mass, momentum and energy. The one drawback to this model is its complexity, which is largely introduced by the terms representing the transfer of mass, momentum and energy across the gas–liquid interface. Mathematically, the one-dimensional version of the two-fluid model is given as (Ishii and Hibiki, 2010):

$$\frac{\partial\langle\alpha_k\rangle\rho_k}{\partial t}+\frac{\partial}{\partial z}(\langle\alpha_k\rangle\rho_k\langle\langle v_{zk}\rangle\rangle)=\langle\Gamma_k\rangle \tag{2}$$

$$\begin{aligned}\frac{\partial\langle\alpha_k\rangle\rho_k\langle\langle v_k\rangle\rangle}{\partial t}+\frac{\partial}{\partial z}C_{vk}\left(\langle\alpha_k\rangle\rho_k\langle\langle v_{zk}\rangle\rangle^2\right)&=-\langle\alpha_k\rangle\frac{\partial\langle\langle p_k\rangle\rangle}{\partial z}+\frac{\partial}{\partial z}\langle\alpha_k\rangle\langle\langle\tau_{kzz}+\tau^T_{kzz}\rangle\rangle-\frac{4\alpha_{kw}\tau_{kw}}{D}+\langle\alpha_k\rangle\rho_k g_z\\&\quad+\langle\langle v_{ki}\rangle\rangle\langle\Gamma_k\rangle+\langle M_{ik}-\nabla\alpha_k\cdot\tau_i\rangle_z+\left\langle(p_{ki}-p_k)\frac{\partial\alpha_k}{\partial z}\right\rangle\end{aligned} \tag{3}$$

$$\begin{aligned}\frac{\partial\langle\alpha_k\rangle\rho_k\langle\langle h_k\rangle\rangle}{\partial t}+\frac{\partial}{\partial z}C_{hk}(\langle\alpha_k\rangle\rho_k\langle\langle v_{kz}\rangle\rangle\langle\langle h_k\rangle\rangle)&=\langle\alpha_k\rangle\frac{D_k}{Dt}\langle\langle p_k\rangle\rangle-\frac{\partial}{\partial z}\langle\alpha_k\rangle\langle\langle q_k+q_k^T\rangle\rangle+\frac{\xi_h}{A}\alpha_{kw}q''_{kw}+\langle\langle h_{ki}\rangle\rangle\langle\Gamma_k\rangle\\&\quad+\langle q''_k a_i\rangle+\langle\Phi_{ik}\rangle\end{aligned} \tag{4}$$

$$\sum_k\langle\Gamma_k\rangle=0 \tag{5}$$

$$\sum_k\langle M_{ik}-\nabla\alpha_k\cdot\tau_i\rangle_z=0 \tag{6}$$

$$\sum_k\left(\langle\Gamma_k\rangle\langle\langle h_{ki}\rangle\rangle+\langle q''_k a_i\rangle\right)=0. \tag{7}$$

Here, Γ_k, $\overline{M}_{ik}$, τ_i, q''_{ki}, and φ_k are the mass generation, generalized interfacial drag, interfacial shear stress and interfacial heat flux, which are key parameters in the interfacial transfer of mass, momentum and energy. Definitions of other quantities can be found in the nomenclature.