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Flow regime, void fraction and interfacial area transport and characteristics of co-current downward two-phase flow

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HIGHLIGHTS

- Downward flow regime maps and models were studied for 25.4 to 101.6 mm pipe diameters.
- Effect of flow inlet on flow transition, void & interfacial area profile were studied.
- Bubble void profiles were associated with the interfacial forces for downward flow.
- Flow regime pressure drop and interfacial friction factor were studied.
- The most applicable and accurate downward drift-flux correlation was determined.

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ABSTRACT

Downward two-phase flow is observed in light water reactor accident scenarios such as loss of coolant accident (LOCA) and loss of heat sink accident (LOHS) due to loss of feed water or a secondary pipe break. Hence, a comprehensive literature review has been performed for the co-current downward two-phase flow with information on the flow regime transitions and flow characteristics for each regime in the downward flow. The review compares the experimental data of the flow regime map and the current available transition models. Objectivity of the data varies on the method utilized as a certain degree of subjectivity is still present in the most objective method. Nevertheless, experimental data through subjective methods such as direct visualization or analysis of a wire mesh sensor (WMS) data were still studied in this review. Despite the wide range of flow regime data for numerous pipe sizes, a consensus was not reached for the effect of pipe sizes on flow regime transition. However, it is known that a larger pipe results in greater degree of coalescence at lower gas flow rates (Hibiki et al., 2004).

The introduction of a flow straightener at the inlet led to less coring and fluid rotation and inevitably, reduced bubble coalescence. This also resulted in the disappearance of the kinematic shock wave phenomenon, contrary to an inlet without a flow straightener. The effect of flow inlet, flow location, pipe diameter and bubble interfacial forces on the radial distribution as well as bubble coalescence and breakup rate are studied. Moreover, the interfacial area concentration and the bubble coalescence and breakup mechanisms are shown to vary in the axial direction as well as with flow rate, flow area and pressure drop. The liquid velocity field, bubble shape and shear stress are studied for a stationary slug bubble with downward liquid flow. Furthermore, the relationship between the plug and foam flow shape profiles, relative velocity, void fraction and gas slug velocity at an elevated pressure of 0.2 MPa studied by Sekoguchi et al. (1996) are also analyzed, together with the five plug flow sub-regime groups located in the low slip and high slip velocity regions. For the annular flow, the relationship between liquid film thickness, entrainment mechanisms, film velocity and shear stress are studied as well. Alike to plug flow, five sub-regimes in the annular flow are also examined along with the bubble and droplet entrainment mechanisms.

The paper also discusses the pressure drop for bubbly, slug, foam, falling film and annular flow regimes, with a particular focus on the most accurate interfacial friction factor correlation for annular flow and its applicability for a wide range of pipe diameters. The flow instability of a system such as static and dynamic instability in the presence of a downcomer, for both single and parallel heated channels are examined too. Finally, the most accurate and versatile drift-flux correlation applicable to all downward

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Nomenclature

a_i	interfacial area concentration [1/m]
A_{lf}	$=\pi(D\delta-\delta^2)$ liquid film wetted cross-sectional area [m^2]
Bo	$=\Delta\rho g D^2/\sigma$, Bond number [–]
D	diameter [m]
f	interfacial friction factor [–]
Fr_f	$=j_f/\sqrt{gD(\Delta\rho)/\rho_f}$, Froude number [–]
Fr_g	$=j_g/\sqrt{gD}$, gas Froude number [–], $=j_g^2/gD$, gas Froude number [–] (Crawford et al. (1985))
g	gravitational constant [m/s^2]
h	mean film thickness [m]
Δi_{fg}	latent heat of vaporization [J/kg]
Δi_{sub}	fluid inlet subcooling [J/kg]
Δi_λ	subcooling at point of net vapor generation [J/kg]
j	mixture volumetric flux [m/s]
Lo	Laplace length [m^2]
L_h	heated length [m]
N_{sub}	$=(\Delta i_{sub}/\Delta i_{fg})(\Delta\rho/\rho_g)$, subcooling number [–]
P	pressure [Pa]
r	radius [m]
R	pipe radius [m]
Re_f	$=uD/\upsilon_f$ fluid Reynolds number [–]
Re_g	$=u_g(D-2\delta)/\upsilon_g$, gas Reynolds number [–]
Re_{lf}	$=4u_{lf}A_{lf}/\pi D\upsilon_f$, liquid film Reynolds number [–]
Re_{sg}	$=u_g D/\upsilon_g$, superficial gas Reynolds number [–]
Re_{sf}	$=u_f D/\upsilon_f$, superficial liquid Reynolds number [–]
u	velocity [m/s]
z	axial pipe direction [m]

Greek symbols

δ	liquid film thickness [m]
σ	surface tension [N/m]
v	kinematic viscosity [m^2/s]
α	void fraction [-]
ξ_h	heated perimeter [m]
λ	non-equilibrium non-boiling length [m]
ρ	density [kg/m^3]
φ	interfacial area concentration source or sink term [1/m-s]
θ	$=(v_f^2/g)^{1/3}$, reduced liquid film thickness [m]
Ψ	factor depending on the shape of a bubble ($1/36\pi$ for a spherical bubble) [–]
$\Delta\rho$	density difference [kg/m^3]
τ	shear stress [Pa]

Subscripts

b	bubble
$crit$	critical
f	fluid
g	air
H	hydraulic
lf	liquid film
i	interfacial
in	inlet
r	relative velocity
s	single phase
sm	Sauter mean
t	turbulent
w	wall
0	rise velocity of bubbles (Harmathy, 1960)

Superscript

$*$	non-dimensional term

flow regimes is highlighted and compared to drift-flux type correlations as it will be a stepping stone to attain a more accurate co-current downward flow transition model. Further experimental effort is essential to achieve a strong foothold in the understanding of co-current downward two-phase flow, as it is vital for nuclear engineering applications.

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