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Review

A critical review of flow maps for gas-liquid flows in vertical pipes and annuli

Benjamin Wu[a,1], Mahshid Firouzi[a,1,*], Travis Mitchell[b], Thomas E. Rufford[a], Christopher Leonardi[b], Brian Towler[a]

[a] School of Chemical Engineering, The University of Queensland, St. Lucia 4072, Australia
[b] School of Mechanical and Mining Engineering, The University of Queensland, St. Lucia 4072, Australia

HIGHLIGHTS

- Critical review and analysis of 3947 flow regime data points for vertical flows.
- Assessment of the available models for prediction of upward flow regime transition.
- Generation of a universal flow map for upward flows based on Reynolds numbers.

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ABSTRACT

The accurate prediction of two-phase gas and liquid flow regimes is important in the proper design, operation and scale-up of pressure management and fluid handling systems in a wide range of industrial processes. This paper provides a comprehensive review of 3947 published experimental data points for gas-liquid flow maps in vertical pipes and annuli, including a critical analysis of state-of-the-art measurement techniques used to identify bubble, slug, churn and annular flow regimes. We examine the critical factors of pipe geometry (diameters, deviation from vertical), fluid properties and flow conditions that affect the transition from one flow regime to another. The review surveys the theoretical models available to predict flow regime transitions, and we validate the accuracy of these models using the published experimental data. The most reliable flow regime transition models for upward co-current flows are analytically shown to be: (i) Barnea 1987 for dispersed bubble to bubble flow, (ii) Taitel et al. 1980 for bubble to slug flow, (iii) Barnea 1987 for slug to churn flow, and (iv) Mishima and Ishii 1984 for churn to annular flow regime transition.

Moreover, based on the review we provide an outlook on the research needs and important developments in prediction of two-phase flow in vertical pipes including the use of computational fluid dynamics (CFD) techniques to simulate gas-liquid flows in vertical geometries.

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[*] Corresponding author.
E-mail address: m.firouzi@uq.edu.au (M. Firouzi).

[1] First authors.

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Nomenclature

A_p	projected bubble area (m^2)
C	empirical constant
C_K	empirical constant
C_M	empirical constant
C_0	approximate ratio of centreline velocity to average velocity (dimensionless)
D	pipe inner diameter (m)
D_b	bubble diameter (m)
D_C	casing inner diameter (m)
$D_{critical}$	critical pipe inner diameter (m)
D_H	hydraulic diameter (m)
D_T	tubing outer diameter (m)
D_{32}	Sauter mean bubble diameter (m)
F_i^{inter}	interfacial forces (N/m^2)
H_L	liquid holdup (dimensionless)
l_E	entry length (m)
m	empirical constant
$N_{\mu l}$	liquid viscosity number
s_G	gas specific density (dimensionless)
s_L	liquid specific density (dimensionless)
SL	slippage number (dimensionless)
T_i	viscous stress tensor (dimensionless)
U_0	bubble rise velocity (m/s)
U_G	Taylor bubble rise velocity (m/s)
u_{bS}	Taylor bubble superficial velocity (m/s)
u_{FS}	liquid film superficial velocity (m/s)
u_{GS}	gas superficial velocity (m/s)
u_{GS}^*	dimensionless gas superficial velocity
u_{KS}	phase superficial velocity (m/s)
u_{KS}^*	dimensionless phase superficial velocity
u_{LS}	liquid superficial velocity (m/s)
u_{LS}^*	dimensionless liquid superficial velocity
u_M	mixture superficial velocity (m/s)
u_∞	rise velocity of fairly large bubbles (m/s)

Greek symbols

α	void fraction (dimensionless)
α_{avg}	average void fraction (dimensionless)
α_b	bubble void fraction (dimensionless)
α_{bs}	bubble-slug void fraction (dimensionless)
α_{mean}	mean void fraction (dimensionless)
δ	liquid film thickness (m)
ε_c	critical void fraction (dimensionless)
μ_G	gas viscosity (mPa.s)
μ_L	liquid viscosity (mPa.s)
μ_S	liquid specific viscosity (dimensionless)
ρ_G	gas density (kg/m^3)
ρ_H	homogenous or no-slip density (kg/m^3)
ρ_L	liquid density (kg/m^3)
ρ_M	mixture density (kg/m^3)
σ	surface tension (N/m)
σ_S	liquid specific surface tension (dimensionless)

Non-dimensional parameters

$Fr_M = u_M/\sqrt{Dg}$

$\mathrm{Re}_{GS} = \frac{\rho_G u_{GS} D}{\mu_G}$

$\mathrm{Re}_{LS} = \frac{\rho_L u_{LS} D}{\mu_L}$

$We_{GS} = \frac{\rho_G u_{GS}^2 D}{\sigma}$

$We_{LS} = \frac{\rho_L u_{LS}^2 D}{\sigma}$

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1. Introduction

Gas and liquid are required to flow simultaneously inside vertical pipes and vertical annuli in a wide range of industrial and engineering processes. Two-phase gas and liquid flows manifest in steam boilers, condensers, chemical reactors and associated process piping [1–4] in petrochemical plants, food-processing plants and in nuclear energy facilities [5,6]. The proper design and operation of these two-phase fluid systems requires accurate prediction of pressure drops in the system, and that prediction relies on understanding the nature of the flow regimes that could manifest in a two-phase system. This review paper surveys the published experimental data and mathematical models that describe two-phase flows in (a) vertical pipes and (b) vertical annuli, which is