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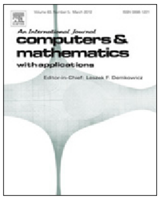

Unified graph-based multi-fluid model for gas–liquid pipeline flows

B. Krasnopolsky [a,b,*], A. Starostin [c], A.A. Osiptsov [b]

[a] *Institute of Mechanics, Lomonosov Moscow State University, Russia*
[b] *Schlumberger Moscow Research Center, Russia*
[c] *Schlumberger Abingdon Technology Center, United Kingdom*

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ABSTRACT

We present a novel model of transient multiphase flow for gas–liquid mixtures in long pipelines. The study develops a general flexible formulation of a one-dimensional flow for complex multiphase mixtures in the presence of slip and mass exchange. Multi-fluid and drift–flux approaches are combined. The multi-fluid model governs the momentum balance for the fluids, and drift–flux correlations are used for modelling of the slip between individual components. A tree-like graph is introduced to describe the hierarchy of fluids and components within the mixture. The numerical implementation for an arbitrary number of components is based on the extension of the Semi-Implicit Method for Pressure-Linked Equations. Imbalances of equations are selected as criteria for iteration convergence. Specific corrections are discussed, including those proposed for the equilibrium gas-release model.

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1. Introduction

Transient multiphase flows in circular pipes are encountered in various industrial applications, including hydrocarbon production and transport, chemical engineering, nuclear energy, and biomechanics. The key motivation for this work comes from the oil and gas industry, where accurate and robust modelling of multiphase flows is required for the design, execution, and control of a number of technologies, including wellbore startup and cleanup after drilling. Commonly, the initial wellbore flow involves several fluids of different properties, such as mud, cushion, brine, reservoir oil, gas, and water, and possibly other liquids, which are left in the wellbore and near-wellbore zone after drilling and completion. The first priority for engineers is to make sure the wellbore is cleaned of non-reservoir liquids and a stable flow of hydrocarbons is established. To protect safety and environment, an accurate and predictive model is required to prevent undesired events such as unstable flow regimes or unexpected long slugs of non-hydrocarbon liquids (e.g., reservoir water), which may kill the flare during well testing on an offshore rig and result in a serious environmental accident. Effective management of multiphase pipeline flows in industrial applications requires corresponding software based on fast and reliable physical models and numerical methods. They typically operate with one dimensional models, utilizing asymptotic long-channel approximation based on the large aspect ratio of the pipe. Derivation of these models and governing equations from the first principles of fluid mechanics with cross-section averaging procedure can be found in [1,2].

There are two most widely-accepted approaches to continuum modelling for complex multiphase mixtures in one-dimensional approximation: the "simplified" drift–flux model [3–5] and the "full" multi-fluid model [6–10]. The drift–flux

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[*] Corresponding author at: Institute of Mechanics, Lomonosov Moscow State University, Russia.
E-mail addresses: krasnopolsky@imec.msu.ru (B. Krasnopolsky), AStarostin@slb.com (A. Starostin), AOsiptsov@slb.com (A.A. Osiptsov).

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model is based on a single momentum conservation equation written for the mixture. The phase velocities are expressed explicitly by the algebraic formulae through the mixture velocity, weighted by a profile parameter, and a phase drift velocity.

In the drift–flux approach, the algebraic expressions for phase velocities follow from the corresponding momentum conservation laws. These expressions can be derived from an analytical solution of a particular flow structure under specific assumptions and then calibrated against the experimental data. The no-slip velocity condition between two chemically similar fluids is the most simple relationship commonly used to track miscible fluids as tracers in the liquid phase. Originally, the drift–flux model was formulated for gas–liquid flow, where liquid is a continuous phase and gas is dispersed in the form of bubbles. From the momentum conservation equation for the dispersed phase, it follows that under the balance of the gravity, Stokes, and Archimedes forces exerted on the bubble, the velocity of bubbles can be expressed analytically through the mixture velocity and the slip (drift) velocity [11]. In [12], the correlation for bubble velocity was proposed for freely rising bubbles. This correlation was used in [13] to study bubble column dynamics.

Whereas originally the drift–flux model was proposed for a specific bubbly gas–liquid flow regime, it was later extended to cover the entire range of flow regimes that may occur in a two-phase gas–liquid flow in an inclined pipe. A series of experimental studies propose the correlations between phase and mixture velocities over a wide range of flow rates. Drift–flux correlations for gas–liquid and oil–water slip and a two-stage approach to model three-phase gas–oil–water flows were proposed in [4].

The drift–flux model is applicable to a wide range of flow regimes with non-inertial interphase slip [11]. The variety of flow regimes in the multiphase pipe flows is a challenging issue, which complicates the numerical modelling. According to [14], it is possible to recognize different flow regimes for high-contrast density of fluids: annular, stratified smooth, rolling waves, dispersed flow, and slugging. The drift–flux model is not applicable to predict the stratified-wavy and hydrodynamic slugging flow regimes, yet it captures the terrain-induced slugging. The particular relationships of the drift–flux model cover restricted intervals of parameters: pipe inclination angle and diameter, surface tensions, temperatures, densities and other. The limits of applicability for some correlations are discussed in [15]. To model flows beyond these limits, the parameters of the corresponding relationships should be tuned against experimental data.

On the contrary, in the multi-fluid model, each phase is treated as a separate continuum described by a momentum equation. In [6,7,16], the multi-fluid model was developed and applied for cooling problems. Paper [17] considers the modelling of oil–water emulsion and gas mixture in application to hydrocarbon transportation. Three-fluid models are formulated, when it is necessary to consider several immiscible liquids or to take into account dispersed phases. In near-horizontal pipes the gas–oil–water mixture may flow in separate layers. It is found that oil–water slip is significant and can provoke transition from stratified smooth regime to slugging [18]. The authors also offer the criteria for identification of flow regime in gas–oil–water flows and choice of friction terms. In [17,19], a momentum equation for droplets is introduced, so the droplets are considered as a third phase. As a result, the precise prediction of the pressure drop and other properties of the annular flow regime becomes possible. In [9], the authors considered four continua: gas, liquid, droplets and bubbles. The model contains the most comprehensive experimentally-calibrated closure relations for friction and interphase mass exchange.

The first generation of closure correlations for multi-fluid models was related to the flow regimes [6,7,16,17], which were identified in experiments. Once the flow regime is identified, the correlations for friction forces can be specified. The flow patterns for hydrocarbons and air–water flows are constructed, for example, in [17,20]. In [21], the authors proposed the criteria of the transitions between flow regimes. The criteria are based on the stability analysis of two-phase flows and validated with the patterns from [20].

Starting from [22], the next generation of multi-fluid models is constructed to be flow-regime independent. The following extension of the model in [9] introduces bubbles and droplets to predict the transitions from slugging to dispersed flow or annular flow. The model covers the transitions between all flow regimes.

To our knowledge, the most complex formulation of the multi-fluid model is realized for three fluids (gas, oil, and water) and an arbitrary number of components in the dynamic pipeline flow simulator OLGA [17]. In [9], the two-fluid model is proposed in a regime-independent formulation for four fields (continuous and dispersed gas and liquid). In applications, however, the number of fluids may significantly exceed three. Besides, each fluid may be present in the form of a continuous layer and dispersed droplets or bubbles. The model needs closure relations for friction with the walls and between layers and for interphase mass exchange. Hyperbolicity analysis of the resulting equations is important to ensure well-posedness of the initial–boundary value problem and stability of its numerical solution.

In this work, we propose a model that covers an arbitrary number of phases and is based on the combination of the multi-fluid and the drift–flux approaches. We will use a tree-like graph representation for the complex structure of the mixture. A SIMPLE-like iterative algorithm is adopted to solve the governing equations. The numerical method operates with the model graph, hence it is possible to simulate mixture of any complexity.

The outline of the paper is as follows. Section 2 describes the unified mathematical model for multiphase flow based on a tree-like graph and examples of the graphs for the well-known models presented in the literature. Section 3 provides examples of closures for the mathematical model, typical for the flow of gas–oil–water mixtures in oil and gas applications. Section 4 presents the numerical method based on the SIMPLE-like approach. The section with validation cases follows.

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