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Review

# A review on mechanisms and models for the churn-turbulent flow regime

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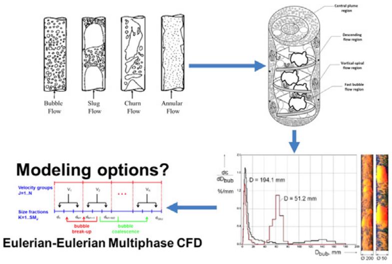
## GRAPHICAL ABSTRACT



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## ABSTRACT

The modeling of two-phase flows has always been limited to special cases due to the very complex nature of its interface. When considering vertical pipe flows with low gas volume flow rates, bubbly flow occurs. With increasing gas volume flow rates larger bubbles are generated by bubble coalescence, which further leads to transition to slug, churn-turbulent, and annular flow. Considering, as an example, a heated tube producing steam by evaporation, as in the case of a vertical steam generator, all these flow patterns including transitions are expected to occur in the system. Despite extensive attempts, robust and accurate simulations approaches for such conditions are still lacking. This paper summarizes the state-of-the-art on the understanding of the physics behind churn-turbulent flow, and transitions to and from this flow pattern. Both, benefits and limitations of the existent experimental approaches and their usefulness for model development and validation at these high void fraction conditions are discussed. Limitation of both, low-dimensional approaches (0D, 1D, and 2D), and high resolution approaches such as Direct Numerical Simulations (DNS) are analyzed. Averaging procedures, such as the Eulerian–Eulerian approach including the interfacial momentum closures which has been used in the past for simulating churn flow, are review thoroughly. Finally, possible improvements are proposed.

**Contents**

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## 1. Introduction

Two-phase gas–liquid flows are usually observed in a large range of industrial applications, including the petrochemical, pharmaceutical, biochemical, nuclear, and metallurgical industries. Bubbly flow conditions, are often useful in the cultivation of bacteria and mold fungi, production of cell proteins, animal cell cultures, and treatment of sewage in the biochemical industry. Higher-turbulent flows, as for example the churn-regime, are frequently used in highly exothermic processes such as liquid phase methanol synthesis, Fischer–Tropsch synthesis, and hydrogenation MAC. The understanding of these flow regimes is also very important in the nuclear industry, for example in Boiling Water Reactors (BWR), where the accurate knowledge of the correct distribution of the void fraction allows the prediction of moderator density curves, which strongly influence the neutronics performance and local power production, as well as the heat transfer within the reactor core. Highly turbulent two-phase flows can also be relevant in nuclear reactor safety analyses,such as in the case of the investigation for the manifestation of flashing instabilities in the riser of passive systems during startup conditions, which are a potential occurrence in the German BWR concept known as KERENA (Leyer and Wich, 2012). Similarly, studies based on hot leg models of Pressurized Water Reactors (PWR) have shown that churn-turbulent and slug flows play an important role in the evolution of Counter Current Flow Limitation (CCFL) during the depressurization accident scenario identified as Loss of Coolant Accident also known as LOCA (Navarro, 2005; Deendarlianto et al., 2011; Montoya et al., 2012; Al Issa and Macian-Juan, 2013).

Extensive experimental studies have been conducted in support of the understanding of two-phase flows. These studies include visual observations and application of various linear and non-linear time-series techniques such as spectral analysis, chaos analysis, stochastic modeling, and multi-resolution analyses. Still, empirical correlations have shown large discrepancies in their predictions for the same operating and design conditions. Although large advances have been made in theoretical and computational methods, progressing from one-dimensional models to full 2D and 3D approaches, capable of accounting for non-uniformities in radial gradients for heterogeneous flows, the modeling is still limited by the accuracy of the interfacial momentum representation.

Most of the experimental work on two-fluid approaches, as well as the development of closure models, has been largely focused on low gas volume fractions typical of bubbly flow. The behavior of the small bubbles in this flow regime has been extensively studied and characterized by various authors including, as representative, the work of Walley (1987) on drag forces, and the extensive experimental and theoretical studies on drag and non-drag forces of Tomiyama et al. (2002). At the same time, these closure laws have been applied on a wide regime of scenarios, with acceptable agreement against experimental results (Ziegenhein et al., 2015; Rzehak and Krepper, 2013; Rzehak et al., 2014; Liao et al., 2015).

The complexity of the two-phase flows increases with the rise in void fraction, where countering mechanisms induce on the one side coalescence of the small bubbles into larger ones, and on the other breakup of the large structures. Furthermore, the increase in bubble sizes also introduces a higher level of complexity at the interface, as a consequence of the increasing turbulent conditions of the liquid phase. The increased deformability makes the theoretical modeling of the large bubbles particularly difficult.

The challenges of modeling high void fraction regimes increases due to the very limited information that can be extracted from experimental data. While local and transient information has been obtained for the small and large bubble mixtures (Prasser et al., 2007; Lucas et al., 2005), churn-like bubbles are extremely unstable and therefore not prone to separate analysis, which would be essential, for developing appropriate lift closure relations.

The lack of data and insufficient understanding of the physics behind churn-turbulent flows, have brought discrepancies in its definition starting from Vermeer and Krishna (1981) who expressed that no interaction exist between large and small bubbles. In turn, Chen et al. (1994), defined that small and large bubbles do interact in a mostly chaotic scenario, and that a transitional flow between bubbly and churn-regime occurs, where large bubbles are mostly in the center, while small bubbles are entrained at the wall of the pipe recirculating due to a liquid downward flow. Later experimental data (Beyer et al., 2008; Lucas et al., 2010) showed that a combination of both scenarios occurs in churn-turbulent flow. In reality, this flow regime is characterized by large spiraling, transient, vortex-like structures which move throughout the system. These vortices contain large, highly distorted bubbles that concentrate in the core of the pipe and draw small bubbles in their wake (Fig. 1). At low liquid flow rates, close to bubble column conditions ($V_l = 0$), due to buoyancy forces, the void fraction maximum in the pipe or column center induces a liquid recirculation with the water rising at the center and falling in the wall region.

Due to its characteristically transient behavior in both space and time, 0D and 1D methods are not truly applicable for these highly turbulent regimes. Furthermore, usefulness and applicability of Computational Fluid Dynamics (CFD) codes in this type of flow regime suffer from incomplete understanding of the complex counteracting physical mechanisms. The lack of complete understanding, together with the absence of reliable experimental data for churn-like and slug bubbles, render the modeling via the Eulerian–Eulerian approaches extremely challenging due to the difficulty of assembling robust closure models for the deformable