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Algebraic turbulence modeling in adiabatic gas–liquid annular two-phase flow

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ABSTRACT

The study considers algebraic turbulence modeling in adiabatic gas–liquid annular two-phase flow. After reviewing the existing literature, two new algebraic turbulence models are proposed for both the liquid film and the droplet laden gas core of annular two-phase flow. Both turbulence models are calibrated with experimental data taken from the open literature and their performance critically assessed. Although the proposed turbulence models reproduce the key parameters of annular flow well (average liquid film thickness and pressure gradient) and the predicted velocity profiles for the core flow compare favorably with available core flow velocity measurements, a more accurate experimental database is required to further improve the models accuracy and range of applicability.

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1. Introduction

Annular two-phase flow is one of the most frequently observed flow regimes in gas–liquid two-phase flow systems encountered in the chemical, nuclear and oil industries. Due to its practical interest, annular flow has been the subject of extensive research in the last decades, both experimentally and theoretically. The number of proposed studies dealing with annular flow is actually so huge that no attempt is made here to review the existing literature. Annular flow is characterized by the presence of a thin, wavy liquid film dragged along the channel wall by the shear force exerted by the gas phase, which flows in the center of the channel carrying a part of the liquid phase as entrained droplets. Since the interface between the liquid film and the gas core is highly dynamic and irregularly shaped, gas bubbles occasionally become entrained in the liquid film. The structure and morphology of the interface between the liquid film and the gas core, which is intrinsically time-dependent, strongly affects all transport processes taking place between the phases, thus playing a central role in the overall transport mechanisms and fluid dynamics of annular flow.

Schematically, two types of surface disturbance are typically considered to characterize the interface morphology in annular flow: ripple waves and disturbance waves. Ripple waves are low amplitude and low velocity ripples that appear on top of the liquid film. They are typically short-lived and do not appear to carry liquid mass in the direction of the flow. Disturbance waves, also called roll waves, also appear periodically on the surface of the liquid film and slide on top of the liquid film at a velocity much higher than that of the liquid film surface. The front of disturbance waves rises sharply from the liquid film while their rear tapers off more gradually. The surface of disturbance waves is highly irregular and ruffled, which can result in a characteristic milky appearance as a result of light scattering. Disturbance waves typically form complete rings in the channel, their amplitude can be several times the average liquid film thickness and they tend to live for long axial distances, actively carrying liquid mass in the direction of the flow. If the hydrodynamic conditions are appropriate, the crests of the disturbance waves are sheared-off by the gas flow and liquid droplets become entrained in the gas flow.

Theoretically, annular two-phase flow is particularly difficult to analyze due to the large number of comparable dynamic forces that influence its hydrodynamics. In particular, viscous, inertia and gravity effects are important inside the liquid film, while the drag of the gas flow and surface tension influence the morphology of the liquid–gas interface. Inertia is relevant inside the droplet laden gas core, together with the drag exerted by the gas carrier phase on the entrained liquid droplets which move at a reduced speed in comparison with the gas flow. Droplets are continually entrained from the top of disturbance waves travelling on the liquid film and are eventually redeposited back onto the liquid film. Under steady-state adiabatic flow conditions, the rate of droplet entrainment is balanced by the rate of droplet deposition, so that no net mass transfer takes place between the liquid film and the gas core. Nonetheless, a net exchange of momentum from the gas core to the liquid film is always taking place, since the droplets

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that are entrained leave the liquid film with a velocity that is typically lower than the velocity of the droplets that are redeposited after being accelerated in the gas core. As such, a tight mass and momentum coupling exists between the phases, further complicating the picture. The above considerations explain why basic modeling of annular two-phase flow is still very limited (Tong and Tang, 1997; Levy, 1999), and presently reliance has to be placed largely on empiricism.

Turbulence is the most common and most complicated form of fluid motion and is one of the last subjects of classical theoretical physics that is still not completely resolved (Bradshaw, 1997; Schmitt, 2007). The correct way to treat turbulent flows is to solve the 3-D time-dependent Navier–Stokes equations, which are currently believed to give an adequate description of turbulent flows (Bradshaw, 1997). This approach, however, is at present too computationally demanding for general engineering applications. Besides, the interest in engineering is typically restricted to a few time-averaged and frequently also space-averaged flow parameters. In order to provide a mean turbulent solution that meets typical engineering needs instead of an instantaneous and local one, the Navier–Stokes equations are typically averaged out in time. The non-linearity of the original system yields a system of averaged equations that contains terms that depend on the small-scale instantaneous turbulent fluctuations. Such terms are collected in the turbulent shear stress tensor which is then related to the average flow quantities, thus providing a turbulence model to properly close the time-averaged system.

Several turbulence models have been proposed so far (Wilcox, 2002), with algebraic models being the simplest of all. Algebraic models utilize the Boussinesq assumption that considers the turbulent shear stress to be proportional to the symmetric part of the gradient of the mean velocity field. The constant of proportionality, which is referred to as the turbulent viscosity or eddy viscosity, depends upon the flow and is expressed by an empirical algebraic relation that involves the length scales of the mean flow. Notwithstanding the limitations of the Boussinesq assumption (Schmitt, 2007) and its highly simplified character, algebraic models are easy to use, easy to implement and typically are reasonably accurate for many engineering applications (Tannehill et al., 1997; Wilcox, 2002). Being empirical, these models typically work well only within the limits of the original experimental database they have been fine-tuned with.

Numerous studies have addressed turbulence in annular two-phase flow (Anderson and Mantzouranis, 1960; Hewitt and Lacey, 1965; Levy, 1966; Moeck and Stachiewicz, 1972; Butterworth, 1974; Ueda and Nose, 1974; Ueda and Tanaka, 1974; Levy and Healzer, 1981; Dobran, 1983; Tandon et al., 1985; Abolfald and Wallis, 1986; Oliemans et al., 1986; Jensen, 1987; Bellinghausen and Renz, 1992; Malamatenios et al., 1994; Jayanti and Hewitt, 1997; Azzopardi, 1999; Kaji et al., 1999; Trabold and Kumar, 1999; Vassallo, 1999; Kumar and Trabold, 2000; Kishore and Jayanti, 2004; Pu et al., 2006; Peng, 2008), both experimentally and theoretically. Most of the time, turbulence modeling has been dealt with indirectly, as an intermediate step in the context of general annular flow modeling for experimental data reduction and/or the prediction of hydraulic parameters.

Turbulence in the liquid film has attracted particular interest, due to its connection with the theoretical prediction of the heat transfer coefficient and the onset of dryout in boiling channels. Due to the highly dynamic morphology of the liquid film, the experimental investigation of turbulence is particularly challenging. Vassallo (1999) experimentally investigated the turbulence structure in the wall region of air–water annular flow. For thin liquid films, Vassallo (1999) found that the turbulence structure was similar to that of single-phase wall-bounded flows. For thick liquid films, however, the turbulence structure was found to be modified by the highly dynamic character of the gas–liquid interface. Numerical simulations performed by Jayanti and Hewitt (1997) suggest that disturbance waves may behave as packages of turbulence sliding on top of a laminar substrate liquid film. Turbulence in the liquid film, therefore, seems to be strongly linked to the liquid film morphology in general and to the disturbance wave dynamics in particular.

In the majority of the available studies, turbulence modeling in the annular liquid film has been carried out by extrapolating the results of algebraic turbulence modeling in single-phase wall-bounded flow (Anderson and Mantzouranis, 1960; Hewitt and Lacey, 1965; Levy, 1966; Butterworth, 1974; Ueda and Nose, 1974; Ueda and Tanaka, 1974; Tandon et al., 1985; Abolfald and Wallis, 1986; Oliemans et al., 1986; Kishore and Jayanti, 2004; Pu et al., 2006; Peng, 2008), with some researchers (Kaji et al., 1999; Vassallo, 1999) proposing slight modifications to the single-phase flow theory to better capture the unique features of annular flow. On the basis of direct observations of annular flow, some researchers (Moeck and Stachiewicz, 1972; Ueda and Nose, 1974; Ueda and Tanaka, 1974) proposed that the liquid film might be decomposed into two sub layers: a continuous liquid base layer in contact with the channel wall below an intermittent and wavy liquid layer extending to the liquid-gas interface. Accordingly, two-layer turbulence models for the liquid film have been proposed (Moeck and Stachiewicz, 1972; Levy and Healzer, 1981; Dobran, 1983), providing a potentially superior description of the liquid film turbulence structure. The two-layer algebraic model proposed by Dobran (1983), in particular, is probably the most successful (Jensen, 1987; Malamatenios et al., 1994). The increased accuracy of two-layer models comes about at the expense of an increased number of empirical correlations required to actually implement these models. In the model of Dobran (1983), besides the correlations for predicting the turbulent viscosity in both the continuous base liquid layer and in the intermittent liquid layer, a further correlation is provided to estimate the thickness of the continuous base liquid layer. Typical values for this key parameter are in the range of 10^{-5}–10^{-4} m, small enough to make experimental measurements to verify the existence of two sub layers particularly challenging and their outcome potentially questionable, due to several second-order effects that might influence the measurements and should therefore be taken into account, such as the radial swelling of the tube under pressure load or misalignments and meniscus occurrence if the needle contact measuring technique is used. Since algebraic turbulence modeling is empirical in nature, the possibility to easily collect experimental data to fine-tune the models is of crucial importance. In this respect, the smaller the number of empirical correlations required to feed an algebraic turbulence model, the better. Besides, having to rely on challenging and potentially questionable experiments to collect the required data is a significant drawback that severely limits the usefulness of an algebraic turbulence model and should be avoided, even perhaps at the expense of lower accuracy in the model predictions.

The available experimental studies that address turbulence in the gas core of annular two-phase flow (Azzopardi, 1999; Trabold and Kumar, 1999) seem to indicate a higher turbulent intensity in annular flow with respect to a comparable single-phase gas flow. This enhancement of turbulence can be traced to the interaction of the gas flow with both the liquid film and the entrained liquid droplets. In particular, the highly irregular liquid film that surrounds the gas core is believed to act as a sort of surface roughness that affects the gas flow, increasing the turbulence intensity. The entrained droplets move slower than the carrier gas, are present in a broad distribution of sizes, can be highly deformed and are believed to actively shed vortices, thus increasing the turbulence intensity in the gas core. In analogy with what was already discussed for the liquid film, turbulence modeling in the gas core

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