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An experimental study of stratified–dispersed flow in horizontal pipes

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ABSTRACT

The tracer method has been adopted to study stratified–dispersed flow in a horizontal pipe, 80 mm in diameter and 50 m long, operating at 5 Bar with nitrogen–water mixtures. The use of the tracer method in a horizontal pipe required the development of a specially designed test section, the related electronics and a data acquisition system. It has also been necessary to develop a tracer injection system, which has been designed in order to obtain uniform tracer concentration in the liquid film immediately after its injection. The main flow parameters which can be measured with the present experimental set-up are the circumferential distribution of the film height, flow rate and tracer concentration, the rates of droplet entrainment and deposition and the split of the liquid phase between the wall layer and the entrained droplets. The average tracer concentration data have been interpreted with a new three-field model of the liquid phase in the stratified–dispersed flow pattern. In the present formulation, the model holds for steady, fully developed flow conditions and is based on a one-dimensional description of the flow system. The data cover a limited number of flow conditions.

Introduction

Pipeline transportation over long distances of natural gas in presence of a liquid phase (light hydrocarbons and/or water) is becoming common practice in the oil industry. When this happens for a subsea gathering and transportation system, the risks associated with the Flow Assurance issues and the high investment costs oblige to a very careful design of the flow lines. In these near horizontal pipes the choice of the diameter often leads to a flow pattern characterized by a continuous liquid layer flowing at the pipe wall, while the remaining liquid is entrained by the gas in the form of fast moving droplets which tend to deposit back on the wall layer.

At large gas velocities, the liquid film may cover the entire pipe wall and the resulting flow pattern becomes similar to annular flow in vertical pipes. Horizontal annular flow typically occurs in heat transfer equipment, when small diameter pipes are employed. Also most of the available data are relative to small diameter pipes operating with air and water at atmospheric pressure. In natural gas pipelines the pipe diameter and the gas velocity are such that the continuous liquid phase mainly flows at the bottom of the pipe and the resulting flow pattern can be better classified as Stratified–Dispersed (SD) flow.

Multi-field, gas–liquid models reported in the literature (see for instance, Bendiksen et al., 1991) are based on a set of one-dimensional mass, momentum and energy conservation equations. The integration of these equations requires empirical methods or correlations to predict the transitions among the different flow patterns and to estimate flow parameters such as the rates of droplet entrainment and deposition. Recently, Bonizzi et al. (2009) have shown that the integration of conservation equations directly provides a reliable detection of flow pattern transitions. In both models cited above, SD and annular flows are described by a similar set of conservation and closure equations. One of the objectives of the present work is to verify if the one-dimensional description of SD flow adopted by the existing models of pipeline flow is acceptable or if a different approach is required.

When dealing with SD flow in near horizontal pipes, the main problem is that there are almost no data available for the development or the validation of the model. These data should include the measurement of the pressure gradient, the liquid hold-up, the fraction of entrained droplets and, possibly, the rates of droplet entrainment and deposition. These data are also lacking under conditions far from those of industrial interest, as far as pipe diameter and gas and liquid physical properties concern.

The critical flow parameter to be predicted is the fraction of liquid entrainment. This is because the split of the liquid phase determines the overall liquid hold-up in the pipe and the value

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of the frictional pressure losses. Besides the fluid dynamic issue, a better understanding of the flow behavior of the dispersed phase has a wide number of implications in heat transfer and in the Flow Assurance studies.

The models developed for the prediction of liquid entrainment are based on the observation that in fully developed SD or annular flow the rate of droplet deposition becomes equal to the rate of entrainment and the entrained liquid fraction becomes approximately constant along the pipe. This allows the measurement of the entrained liquid and also the development of independent correlations for the deposition and entrainment rates.

The methods originally developed to measure the liquid entrainment can be divided into two main groups: isokinetic sampling of the dispersed phase (Wallis, 1962) and extraction of the wall layer with a porous section of the pipe (Cousins and Hewitt, 1968). Both these methods present advantages and disadvantages. In particular, due to the loss of circular symmetry which obliges to sample in the entire cross-section, the sampling probe method becomes more difficult to be used, and less accurate, in a horizontal pipe rather than in a vertical one. However, most of the data relative to horizontal flows have been obtained by the sampling probe method (Paras and Karabelas, 1991; Williams et al., 1996; Tayebi et al., 2000).

The rates of droplet entrainment and deposition have been measured under developing or fully developed flow conditions. However, the situation reported by Hewitt (1979) more than 30 years ago is still actual: there are no well established techniques for measuring these quantities even in a vertical pipe and very few new methods have been proposed in recent years. In the past, mainly two methods have been used: the double film extraction method (Cousins and Hewitt, 1968), already mentioned as a technique adopted to measure the liquid entrainment, and the tracer method (Quandt, 1965). The film extraction method suffers of a number of limitations and potential inaccuracies, but the main problem is that the deposition rate is measured under developing flow conditions. This makes the data analysis and the development of correlations a difficult task. The tracer method has been perceived to be cumbersome and inaccurate, as also recently reported by Han et al. (2007). For this reason it has never been adopted for the study of SD flow and very few times for vertical annular flows.

Among the new techniques, recently Damsohn and Prasser (2011) proposed a conductance method based on a sensor able to detect the impact of droplets on a thin horizontal liquid film. In order to detect smaller droplets, the droplet conductivity has been increased. In principle, the sensor developed by these authors allows the droplet deposition rate to be determined, but it seems difficult that this method be able to deal with thick films and/or large deposition rates, unless the method evolves towards the tracer method. In this respect the tracer method still appears as the only viable technique to study complex flow patterns such as annular or SD flow in near horizontal pipes. This explains why the tracer method has been adopted in the present work: this choice has been made due to the lack of any possible alternative. As it will be clear from this work, the tracer method is really cumbersome and not particularly accurate, but it allowed an unexpected insight into the structure of SD flow. This is because the tracer is a passive scalar and its transport in a complex flow system may reveal more details than the ones for which its use has been originally planned. Moreover, the experimental system developed to measure the tracer transport allows also different data to be taken.

The tracer method was originally proposed by Quandt (1965) and has been adopted by Cousins et al. (1965), Jagota et al. (1973), Andreussi (1983) and Schadel et al. (1990) for the study of vertical annular flow. This method provides a fairly accurate measurement of the fraction of entrained liquid, and good estimates of the entrainment and deposition rates, also under developing flow conditions, as shown by Leman et al. (1985). The tracer method consists of the continuous injection into the wall layer of a tracer, which, in air–water flow, can be a salt solution. The salt concentration in the film is then measured at different distances downstream from the injection point. The salt concentration in the wall layer immediately after the injection allows the base film flow rate, and consequently the liquid entrainment, to be determined. Mass balances are then used to relate the measurements of salt concentration along the pipe to the rate of droplet interchange between the film and the initially unsalted liquid droplets carried by the gas. In the original applications of the method, film samples were extracted and analyzed. The use of conductance probes allowed salt concentration to be detected in situ, as reported by Schadel et al. (1990), with a noticeable simplification of the method.

As mentioned above, to our knowledge the tracer method has never been adopted for the analysis of SD flow in near-horizontal pipes or for fluids other than water, but there are no reasons to suspect that the method will not be as effective in these cases. The main problem when dealing with SD flow is the asymmetric distribution of the liquid layer, which requires, on one hand, a circumferential distribution of the inlet tracer flow rate proportional to the local liquid film flow rate. On the other hand, that the tracer concentration be measured not only at various distances from the tracer injection, but also around the pipe wall. The latter issue has been faced with the development of a newly designed test section. This test section can be used for a number of different applications and is based on a set of non-conventional conductance probes which allow the local film thickness and, in present experiments, the tracer concentration around the pipe wall to be measured at a number of axial locations. The present paper deals with the application of the tracer method to horizontal SD flow. The data regard a limited set of flow conditions as the description of the experimental method is the main objective of the present work.

Model of tracer transport

Tracer transport in vertical annular flow has been described by one-dimensional tracer conservation equations based on the assumption that tracer mixing in the wall layer after its injection is almost instantaneous (Quandt, 1965). The experiments reported by Cousins et al. (1965) and Jagota et al. (1973) apparently contradict this assumption. The theoretical analysis of tracer mixing in a turbulent liquid film reported by Andreussi and Zanelli (1976) and a set of experiments described by Andreussi (1983) indicate that tracer mixing in the radial direction is very efficient, while the circumferential liquid film distribution and tracer concentration can be poor, even in vertical flows. These effects may explain the experimental observations of Cousins et al. (1965) and Jagota et al. (1973).

The tracer conservation equations proposed by Quandt (1965) are based on the assumption that fully developed flow conditions are reached. These conditions can be approached in long insulated pipes, when a gas–liquid mixture flows at thermodynamic equilibrium under a moderate pressure gradient.

In fully developed annular flow, the rate of droplet deposition becomes equal to the rate of entrainment and the liquid film and the entrained droplets flow rates tend to assume a constant value along the pipe. When a tracer is injected into the wall layer, the mass balances relative to tracer transport can be written as:

$$\rho_L \alpha_F u_F \frac{dC_F}{dz} = -\Phi_I (C_F - C_D), \tag{1}$$