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Measurement of liquid film distribution in near-horizontal pipes with an array of wire probes

P. Andreussi [a,*], E. Pitton [b], P. Ciandri [c], D. Picciaia [c], A. Vignali [c], M. Margarone [d], A. Scozzari [e]

[a] University of Pisa, Italy
[b] University of Udine, Italy
[c] TEA Sistemi spa, Italy
[d] ENI E&P, ENI spa, Italy
[e] CNR-ISTI, Pisa, Italy

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ABSTRACT

A test section consisting of a circumferential array of conductance probes has been developed to measure the thickness distribution around the pipe wall of a liquid layer flowing in near horizontal pipes. When the film thickness is known, the array can be employed to measure the local film flow rate by injecting a high conductivity tracer into the liquid flowing at pipe wall.

The test section consists of a short pipe made of a non-conducting material installed in a flow rig designed to operate at an appreciable pressure (40 bar). The flow loop is made of metallic pipes connected to the electrical earth. The conductance probes are made of three parallel, rigid wires spaced along the flow direction and are used to measure the height or the electrical conductivity of the liquid layer. The three-electrode geometry is aimed at minimizing current losses toward earth. The simultaneous operation of all the probes of the array, without multiplexing, allows a substantial reduction of current dispersion and a good circumferential resolution of film thickness or conductivity measurements. The probe geometry may generate an appreciable disturbance to the gas–liquid interface. This aspect of the proposed method has been studied with an experimental and numerical investigation relative to free falling liquid layers.

1. Introduction

Pipeline transportation over long distances of natural gas or saturated steam in presence of a liquid phase is a common practice in the oil and in the geothermal industry and can be extremely challenging when major flow assurance issues, such as solid formation and deposition or pipe wall corrosion, arise. In near-horizontal pipes, stratified flow conditions are encountered at moderate phase velocities. At higher gas velocity, only part of the liquid flows at the pipe wall, while the remaining liquid is entrained by the gas in the form of droplets which tend to deposit back onto the wall layer. The competing phenomena of droplet entrainment and deposition determine the liquid holdup, which is the fraction of the pipe cross-section occupied by the liquid phase. The resulting flow pattern is usually classified as stratified-dispersed flow.

In one-dimensional gas–liquid flow models (see for instance [1]), stratified and stratified-dispersed flow in inclined pipes and annular flow in a vertical pipe are described by the same set of conservation equations. The closure equations required for these two regimes are quite different, due to the different effects of gravity, but while the data and correlations relative to vertical annular flow are abundant, there are almost no correlations for horizontal or inclined flow and very few data are available for the development or validation of flow models. The main objective of the present work is the development of a new experimental method able to provide these data.

The critical flow parameters to be measured in stratified-dispersed flow are the flow rate and the circumferential thickness distribution of the liquid layer flowing at pipe wall. This is because these parameters determine the overall liquid hold-up in the pipe and the value of the frictional pressure losses. Besides to the fluid dynamic issue, a better knowledge of the flow behavior of the wall layer has a wide number of implications in heat transfer and flow assurance studies.

Many authors measured the liquid film thickness by determining the electrical conductance between either two parallel wires or two flush-mounted electrodes. Wire probes have been introduced by Miya et al. [2] and studied in details by Brown et al. [3]. Flush-mounted probes have been first described by Coney [4].

* Corresponding author. Present address: Department of Civil and Industrial Engineering, University of Pisa, Largo L. Lazzarino, 56100 Pisa, Italy.
E-mail address: paolo.andreussi@tea-group.com (P. Andreussi).

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The two-ring probe is a particular type of flush-mounted probe and has been used to measure the mean thickness of liquid films flowing in a vertical pipe [5]. Among the numerous applications of conductance probes, the work by Geraci et al. [6] is significant because these authors used both wire and flush-mounted probes for the measurement of the circumferential liquid film thickness distribution in stratified-dispersed flow. Multiple ring probes have been used to study slug flow in inclined pipes [7]. Zhao et al. [8] used a set of four flush-mounted probes to study the flow of large disturbance waves in a vertical film. The electrical behavior and the application of ring probes to other flow patterns has been described in details by Andreussi et al. [9] and Fossa [10]. Barral and Angeli [11] studied the fine interfacial structure of water–oil flow in a horizontal pipe with two double-wire conductance probes. These authors report that the disturbances generated by these probes on liquid flow are negligible.

Along with the development of multiple probe test sections, advanced conductance methods have also been proposed, such as the wire mesh sensor (WMS) [12]. This technique provided good results when studying bubble or slug flow and, in a recent paper, Vieira et al. [13] adopted a WMS to study stratified-dispersed flow in a horizontal pipe. As stated by these authors, they were not able to detect thin liquid films flowing in the upper part of the pipe. Therefore, in their experiments the crossing points of the WMS closer to the wall than 1 mm were disregarded. The case of thin films has been faced by Damsohn and Prasser [14] with the development of a sensor based on the wire mesh approach for the analysis of the electrical signals generated by a matrix of flush-mounted electrodes.

This sensor is characterized by high time and spatial resolution, but its use is limited by the saturation of the electrical response at increasing the film thickness. According to these authors, the maximum film thickness that can be measured with their sensor is 0.8 mm. The measuring range of flush-mounted electrodes has been extended by Tiwari et al. [15], who developed a test section of flush-mounted electrodes spaced at different distances among them. With this set-up, the maximum film height which was possible to measure, with an acceptable accuracy, was equal to 3.5 mm. This value still appears to be unsatisfactory when studying stratified flow in a horizontal pipe in presence of large disturbance waves, whose height can largely exceed 3.5 mm [16]. In principle, the limiting value of the film height reported by Tiwari et al. [15] can be extended by increasing the distance between the electrodes. This requires the simultaneous acquisition of signals generated by sensors operating in different height ranges.

The liquid film thickness in annular or stratified flows has also been measured with other techniques. Some of these methods, such as the γ-ray or the X-ray tomography [17,18], the Laser Induced Fluorescence [19] or other optical methods can be quite expensive. However, the main reason to disregard these methods for the present application is that it may be difficult to use the same method to measure both the film thickness and the concentration of an appropriate tracer.

In the present work, a conductance method based on the use of an array of non-conventional wire probes has been developed to measure the local thickness or the conductivity of a liquid layer flowing at pipe wall. In general, the conductivity of a liquid can be modified by increasing its salinity and, at low salinity, the conductivity is proportional to the salt concentration. When the film thickness is known, a salt solution can be used as a tracer to measure the flow rate of a liquid film by continuously adding the solution to the film and measuring the liquid conductivity. The smooth injection of a very small tracer flow rate does not modify the film flow characteristics or alter the linear relation between liquid conductivity and salt concentration. In order to perform this type of measurements, the film thickness distribution around the pipe wall can be measured in the absence of tracer injection, while the local film flow rate can be derived from the variation of the probe conductance when the tracer inlet flow is switched on. Alternatively, two consecutive probe arrays, with tracer injection between the arrays, can be used to perform simultaneous measurements of the local film thickness (with the first array) and flow rate (with the second).

Tracer injection experiments can be performed both under developing or fully developed flow conditions and, in developed flow, the tracer method can be used to measure also the rate of droplet exchange between the wall layer and the gas core for vertical annular flow [20,21]. To this purpose, it is necessary to measure the tracer concentration in the liquid film at a number of locations along the pipe. These measurements can be made with a set of conductance probes, combining film thickness and conductivity measurements [22]. Recently, the complex application of the tracer method to stratified-dispersed flow in a horizontal pipe has been reported by Pitton et al. [23]. The combined use of the tracer injection system and the measuring sections described in the present paper allowed these authors to measure the local film flow rate and the rates of liquid exchange between the wall layer and the gas core.

The range of liquid thicknesses that we expect to measure in an 80 mm pipe goes from a minimum of 0.05 mm to a maximum of 50–60 mm. Having this objective in mind, wire probes appear to be a better choice than flush-mounted probes, due to their intrinsic linearity, which allows the height of both thin and thick liquid layers to be measured with good accuracy. The expected measuring range of the proposed test section is very wide, but it can easily be attained using the same electronics by properly choosing the liquid conductivity. This represents a major advantage of wire probes when compared with flush-mounted probes or other methods adopted in the literature to measure the thickness of a liquid layer.

The main disadvantage of wire probes is that they are intrusive. The same problem arises with WMS and recently a study on the intrusiveness of a three layer WMS has been presented by Ito et al. [24]. These authors observed an appreciable effect of the wire mesh on the velocity of gas bubbles crossing the mesh. This flow condition is quite different from the case of film flow, but the work of Ito et al. [24] represents a serious warning against the use of intrusive probes. This potential limitation of wire probes is examined into details in the present paper, with a careful computation of the flow and the electrical fields around the electrodes.

The conductance probes proposed in the present work are made of three rigid wires spaced along the flow direction. A circumferential array of such probes is installed in a test section made of a non-conducting material which is part of a flow rig designed to operate at an appreciable pressure, composed of metallic pipes electrically connected to the earth potential. A common excitation signal is fed to all the central electrodes (transmitting electrodes) of the array, while the external electrodes (receiving electrodes) are actively kept at the same, earth potential. This allows to minimize current losses towards earth and to mitigate possible interferences between adjacent probes. The simultaneous operation of all the probes of the array, without multiplexing, is also useful to obtain a good circumferential resolution of film thickness or conductivity measurements.

A three electrode geometry of conductance probes has been used by other authors. For instance, Kim et al. [25] developed a three electrode flush-mounted probe to compensate the temperature effects on thickness measurements. A three layer wire mesh has been developed by Richter et al. [26] to measure the velocity of the gas bubbles crossing the mesh. In both cases, the objectives of these authors were substantially different from those of the present method.