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International Journal of Multiphase Flow 34 (2008) 1161–1174

International Journal of Multiphase Flow

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Experimental analysis of flow regimes and pressure drop reduction in oil–water mixtures

G. Sotgia [a], P. Tartarini [b], E. Stalio [b,*]

[a] Dipartimento di Energia, Politecnico di Milano, Italy

[b] Dipartimento di Ingegneria Meccanica e Civile, Università degli Studi di Modena e Reggio Emilia, Via Vignolese 905/B, 41100 Modena, Italy

Received 20 December 2007; received in revised form 29 May 2008; accepted 1 June 2008
Available online 17 June 2008

Abstract

The physical understanding of two-phase flow characteristics in horizontal pipes is of importance in the petroleum industry since significant savings in pumping power can be derived from the water-lubricated transportation of crude oil.

An experimental study of water continuous oil–water flow in horizontal pipes is performed using mineral oil and tap water of viscosity ratio about 900 and density ratio 0.9. A set of seven different pipes of Pyrex and Plexiglas where used, with diameters ranging between 21 and 40 mm. Pressure drop measurements, flow pattern maps and clear pictures of the oil–water flow are reported in this article together with comprehensive comments. The results obtained are compared to empirical laws, theoretical findings and experimental results by different authors in the literature.

In order to identify the regions with operational conditions that are suitable for applications, a novel criterion for the location of the annular/stratified transition is proposed which is based only on experimental observations.

Keywords: Oil–water; Annular; Stratified; Transitional boundary; Pressure drop reduction

1. Introduction

The widespread occurrence of multiphase flows in pipes has motivated extensive research in the field; a number of practical applications in the petroleum industry involve oil–water two-phase flow phenomena. Significant savings in the pumping power required for oil transportation can be attained when water flows in the pipeline together with the oil, especially when the highly viscous phase is surrounded by a water annulus, giving place to the core annular flow configuration. As the establishment of a particular flow regime depends upon the interaction of gravitational, inertial and surface tension forces, annular flow is observed only under particular combinations of the oil and water flow rates.

A large body of literature is presently available on the two-phase flow of oil and water in pipes. A thorough report of industrial applications and annular flow studies made before 1997 is provided in the review by Joseph et al. (1997). The same group published a book on the topic (Joseph and Renardy, 1993) and a number of papers ranging from the linear stability analysis for the pipe flow of two liquids (Joseph et al., 1984) to an experimental study including results from a 0.6-m diameter, 1000-m-long pipeline (Joesph et al., 1999). Measurements of pressure drop and holdup for water lubricated transportation of oil in a 15.9 mm glass pipeline are presented by Arney et al. (1993) together with a friction factor formula based on concentric cylindrical core annular flow theory and an empirical equation for the holdup volume fraction.

Ooms and co-workers analyzed the case of a wavy, eccentric core annular flow with a rigid core and a thin annulus; they interpreted the balancing of buoyancy with laminar (Ooms, 1972; Ooms and Beckers, 1972; Oliemans

* Corresponding author. Tel.: +39 059 2056144; fax: +39 059 2056126.
E-mail addresses: giorgio.sotgia@polimi.it (G. Sotgia), tartarini.paolo@unimore.it (P. Tartarini), enrico.stalio@unimore.it (E. Stalio).

0301-9322/$ - see front matter © 2008 Elsevier Ltd. All rights reserved.
doi:10.1016/j.ijmultiphaseflow.2008.06.001

and Ooms, 1986; Ooms and Poesio, 2003) and turbulent (Oliemans et al., 1987) hydrodynamic lifting. The theory requires the knowledge of the wavy interface shape and is not easily applied for practical purposes. A two-fluid model which is instead commonly used to predict pressure gradient and holdup in liquid–liquid annular flows was devised by Brauner (1991). The following year Brauner and Maron (1992a) proposed a set of criteria for the transition between stratified, annular and dispersed flow patterns and tackled (1992b) the stability of stratified liquid–liquid flow. Recently Brauner developed a model for the dispersed flow regime (2001).

Angeli and Hewitt (1998) performed measurements on the flow of a low viscosity oil and tap water in two 25.4-mm pipes of stainless steel and acrylic resin; they noticed a large difference between pressure gradients measured in the two pipes and ascribed the effect to different wettability characteristics of the pipe walls. Also flow patterns were found to be substantially dependent on the pipe material, the flow structure being investigated through video recording and the use of a high frequency impedance probe (Angeli and Hewitt, 2000). The flow pattern maps provided by Angeli and Hewitt (2000) and Lovick and Angeli (2004) and the transition criteria introduced by Brauner and Maron (1992a) are compared by Chakrabarti et al. (2007) to their own map. This was compiled using quantitative indications coming from a newly designed, non-intrusive optical probe in a 25.4-mm Perspex pipe. The comparisons between maps in the papers by Angeli and Hewitt (2000) and Chakrabarti et al. (2007) reveal a marked sensitivity of liquid–liquid flow results to the many experimental parameters.

When annular flow is used for the lubricated transportation of a highly viscous oil, the liquid–liquid system is more conveniently operated far from the transition boundary with the stratified flow. The reasons are twofold, first the pressure drop reduction is larger for higher oil flow rates and second, the undesired occurrence of the transition to the stratified configuration would lead to a sharp increase in the pressure drop. The accurate and reliable prediction of the transitional boundaries between annular flow and the stratified configuration is therefore of recognized importance for applications. Bannwart (2001) reports two necessary requirements for the occurrence of annular flow. The first comes from the paper by Joseph et al. (1984) but was derived under very specific conditions for density-matched liquids, the other was suggested by the Eötvös number classification of liquid–liquid systems but fails even to follow the trends observed experimentally. On the other hand the equations for the identification of annular/stratified transitional boundaries provided by Brauner and Maron (1992b) are not straightforward to use for engineering applications because only implicitly defined functions are provided. Moreover while the holdup ratio of the flow is needed to perform the required calculations, the holdup itself depends on the flow pattern.

This paper presents an experimental study of water continuous oil–water flows; the oil used in the experiments is very viscous, with properties similar to crude oil transported in industrial pipelines. The liquid–liquid pressure drop behavior is related to the superficial velocities of the two phases and their configuration; results are compared with empirical and theoretical models in the literature. Discussion is made of the influence on the two-phase flow features of the inlet mixer, the pipe material and its history; flow pattern maps are compiled for two different pipe diameters displaying results from a large number of experiments, together with clear pictures of the wide variety of flow configurations. A criterion for the location of boundaries between annular and stratified flow is provided. In contrast with other criteria for the annular/stratified transition (Joseph et al., 1984, 1992b, 2001), the condition presented here arises only from experimental observation and does not include indications for the transition of different fluids over a very wide range of diameters. However the use of the suggested condition in applications is viable, requiring only a preliminary test to be performed using the same fluids. This would ensure an accurate indication of the most suitable flow parameters for lubricated transportation of highly viscous liquids over a wide range of conditions.

2. Experimental apparatus

The experiments reported in this paper were performed in the two-phase thermo-fluid dynamics laboratory of the *Politecnico di Milano*, in the liquid–liquid flow facility shown schematically in Fig. 1.

2.1. Description of the test facility

Oil and water are pumped separately from their storage tanks; in transit to the test section their flow rates are mea-

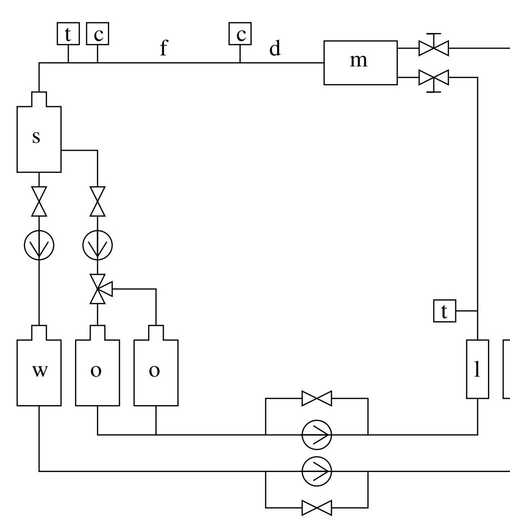

Fig. 1. Schematic representation of the oil–water loop, (o) oil Reservoir, (w) water reservoir, (l) laminar flowmeter, (e) electromagnetic flow meter, (t) thermocouple, (m) two-phase mixer, (d) flow development region, (f) fully developed flow, (c) capacitance pressure transducer, (s) separator tank.