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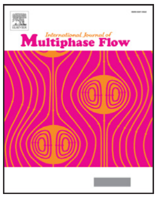

Measurement and prediction of droplet size in annular gas–liquid flows in aero-engine oil systems

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ABSTRACT

Two-phase gas–liquid annular flows are encountered in ventless aero-engine oil system pipes. The droplet size in the flow has an important impact on the performance of downstream equipment as breathers and de-aerators. However, literature studies present semi-empirical models that are not in the range of operating conditions of the oil system. To investigate the effect of the use of lubrication oil on the droplet sizes, this paper presents experimental results of annular flow with oil flow rates from 160 to 640 l/h and air flow rates from 60 to 120 Nm^3/h. Comparison of the Sauter–Mean Diameter predicted by existing correlation show an error of minimum 30% compared to experimental values for higher oil flow rates, which are the most important in oil systems. To address this issue, correlations were adapted to fit experimental results. With the new set of parameters, the Sauter-Mean Diameter is estimated with an error of maximum 18% for higher oil flow rates. Results analysis illustrate that the main difference between existing and new correlations could be due do the surface tension and viscosity of lubrication oil, which are very different from water at low temperature. The results are also consistent with the transition between bag and ligament break-up droplet generation mechanism at a flow rate of 80 Nm^3/h.

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1. Introduction

Two-phase annular flows in pipes are widely encountered in numerous environments. In this type of flows, constant topology changes of the interfaces and complex energy, mass and momentum interactions complicate modelling efforts (Boulesteix, 2010; Hanratty et al., 2003; Liles, 1981). Small-scale interactions between the phases have important effects on the macroscopic properties of the flow (Hanratty et al., 2003). Detailed physical models are thus not easy to build. Therefore, a part of research efforts is focused towards semi-empirical models and experimental data collection. This is especially true for fluids, working conditions, and pipe diameters that have not been tested in the literature, as Mobil Jet Oil II in aero-engine oil systems, which is of interest in this study.

The need to reduce engine fuel and oil consumption deeply changes the architecture and the working conditions of aero-engine oil systems (Flouros and Streifinger, 2012). Labyrinth seals, sealing engine bearing chambers, are being replaced by brush seals (Flouros et al., 2015; Kanarchos and Flouros, 2010). They reduce the air flow rate and change the nature of the two-phase flow in the bearing chambers (Chandra et al., 2010; Farrall et al., 2006; Streifinger, 1998). With these seals, ventless systems, in which the vent lines are removed are feasible (Raimarckers, 2011). Kanarchos and Flouros (2010) show that in this case the standard configuration is an annular flow. This will affect engine piping, pumps and separator design (Steimes et al., 2013).

To investigate the effect of the use of lubrication oil on the droplet sizes in annular flow, this paper presents experiments in a pipe with a mixture of oil flow rates from 160 to 640 l/h and air flow rates from 60 to 120 Nm^3/h. These conditions are representative of ventless oil systems. The experimental results highlight that existing correlations fail to predict correctly droplet sizes. To tackle this problem, this paper proposes an updated version of these semi-empirical correlations to predict the Sauter-Mean Diameter in aero-engine oil system annular flows.

2. Gas–liquid annular flows

In two-phase flows in pipes, an annular flow is established when the velocity of the gas dominates gravity effects. The liquid runs on the external part of the pipe and the gas flows in the central core. This flow regime is stable and therefore often desired in two-phase flow processes (Thome, 2010). The phenomenon leading to droplet creation by instability waves is called entrainment. At very high gas flow rates, the annular film is destroyed and all the liquid is entrained as droplets (mist or dispersed flow). Two

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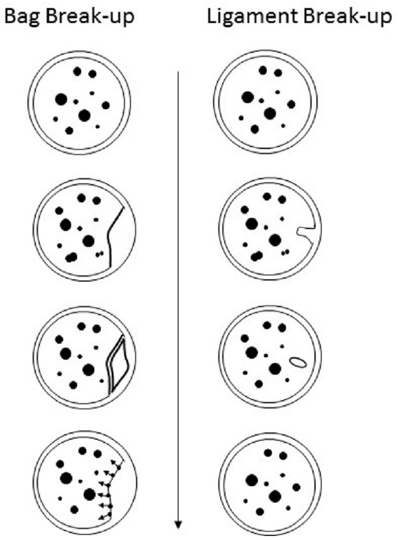

Fig. 1. Droplet generation by bag and ligament break-up, as originnaly developped by Azzopardi (1997).

parameters define annular gas–liquid flows: the entrainment rate and the particle-size distribution.

2.1. Entrainment rate

The entrainment rate E is defined as the fraction of liquid entrained as droplets to the total liquid mass flow rate. It is computed as Eq. (1)

$$E = \frac{\dot{m}_{oil} - \dot{m}_{oil\ film}}{\dot{m}_{oil}} \tag{1}$$

with E the entrainment rate, $\dot{m}_{oil}$ the total oil mass flow rate and $\dot{m}_{oil\ film}$ the oil film mass flow rate. The entrainment rate is a result of the atomization and deposition processes between the air flow and the liquid film surrounding the pipe of the annular flow. The atomization finds its origin in the instability waves running in the pipe. Ishii and Grolmes (1975) showed there is a strong link between the creation of waves and the entrainment of droplets, and that the wave frequency increases with the gas and liquid flow rates. Azzopardi (1997) identified two droplet generation mechanisms, also illustrated on Fig. 1:

- The bag break-up that occurs at low gas and liquid flow rates. The liquid wave is undercut by the gas flow and forms a bubble. The pressure in the bubble increases until it bursts and creates a number of small droplets.
- The ligament break-up that occurs at higher gas and liquid flow rates. The crest of the liquid wave elongates into liquid ligaments. The gas flow then separates these ligaments from the liquid film and breaks them into drops.

Azzopardi (1997) shows that the deposition rate of droplets on the liquid film is increased by low gas velocities, small tube diameters and high surface tension. Jepson et al. (1989) measured a reduction of the entrained liquid fraction with the gas density (lower shear stresses $\rho_g u_g^2$). Considerable uncertainties affect experimental results and contradictory results are found for measurements at same workings conditions (Azzopardi, 1997). Many researchers tackled the semi-empirical modelling of entrainmnent rate (Al-Sarkhi et al., 2012; Cioncolini and Thome, 2010; Ishii and Grolmes, 1975; Ishii and Mishima, 1989; Pan and Hanratty, 2002a; 2002b; Sawant et al., 2009). A maximum entrainment rate is found in every study. It is the working conditions for which the atomization and deposition are in equilibrium and no more additional droplets are entrained in the gas flow. Different semi-empirical correlations lead up to a difference of 50% in estimated entrainment rate. The operating conditions of these studies are given in Table 1 and compared to the present paper.

Cioncolini and Thome (2010) proposed an innovative approach to estimate the entrainment rate based on measurements of 8 different gas–liquid combinations and 19 pipe diameters (for a total of 1504 measurements collected from the literature). They consider the atomization process as a high velocity confined spray, flowing in a channel and atomizing the annular liquid film. Their correlation between the entrainment rate and a core Weber number (We_{ci}) fits a sigmoid function. The entrainment rate is modelled as Eq. (2):

$$E = \left(1 + 13.18 We_{ci}^{-0.671}\right)^{-3.582} \tag{2}$$

with We_c the core Weber number defined on the basis of the central core flow of the pipe and computed as:

$$We_{ci} = \frac{\rho_{ci} V_{ci}^2 d_{ci}}{\sigma} \tag{3}$$

with ρ_{ci} the droplet laden gas density (taking into account the presence of droplets), V_{ci} the core flow velocity, d_{ci} the core flow hydraulic diameter and σ the surface tension. These values depend on the thickness of the liquid film and iterative computations are used to resolve this set of equations. More information on these parameters is found in Cioncolini and Thome (2010).

2.2. Droplet sizes

The central part of an annular flow is made of a mixture of gas flow and liquid droplets. These droplets are characterised by a particle size distribution (PSD), which is defined around the Sauter-Mean diameter (d_{32}).

Several researchers studied annular flow experimentally and varying measurement techniques were used to measure the PSD: photography, electrical capacitance, laser diffraction, phase Doppler anemometry, etc. A part of these studies where performed using early laser diffraction systems that distorted results (Azzopardi, 1997; Simmons and Hanratty, 2001). Older experimental results should thus be taken with care. However, the trends identified are still correct.

Previous experiments highligthed that at low air flow rates, an increase in liquid flow rate results in d_{32} decrease down to a minimum value. If the liquid flow rate is further increased, d_{32} increases. This behaviour is not observed at higher air flow rates, for which d_{32} continuously increases linearly with the entrained liquid mass flux (Azzopardi, 1985; Azzopardi et al., 1991; Fore and Dukler, 1995; Jepson et al., 1989). According to Azzopardi (1985), this behaviour is due to the two droplet creation mechanisms: the bag break-up, occurring at low gas and air flow rates, creates larger drops than ligament break-up. When the two phenomena are acting together, in transition phases when liquid flow rate increases, smaller droplets are first created and d_{32} decreases. When the liquid flow rate increases further, only the ligament break-up mechanism operates. The size of the created droplet does not change, but the increasing number of droplet leads to coalescence and to an increase of d_{32}. PSD in vertical and horizontal pipes are different. In the latter, larger drops are concentrated in the bottom half of the pipe. Azzopardi (1997) and Simmons and Hanratty (2001) assume this dispersion finds its origin in droplet gravitational settling and liquid film asymmetry. If the gas velocity is sufficiently high, the same particle size distribution is found in vertical and horizontal flows.

Variation of gas and liquid characteristic influence d_{32}. Azzopardi (1997) found that increasing gas density increases

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