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Atomisation rate and gas/liquid interactions in a pipe and a venturi: Influence of the physical properties of the liquid film

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ABSTRACT

The aim of this study is to better understand and model atomisation phenomena occurring in a venturi metre under air/oil and air/water annular flows. First, the structure of the liquid film was observed using a high-speed video camera in the pipe section upstream of the venturi, and along the convergent section: the surface waves and regimes visualised were described and compared with the literature, which highlighted the influence of the liquid film physical properties. Some of these surface waves, corresponding to disturbance waves as described in the literature, seem to be at the origin of consequent atomisation. These disturbance waves were then characterised through calculation of their velocities and comparison with the literature: a calculation procedure was defined and showed the influence of parameters such as air superficial velocities, wave height, liquid viscosity, interfacial friction velocity and flow regimes. Another aspect of the atomisation modelling consists in modelling both the location of the beginning of atomisation and the atomisation rate inside the venturi. The video records showed that, contrary to what is often assumed in some studies, a consequent atomisation may start at the middle of the convergent section, depending on the surface waves occurring at that time. Finally, a correlation law for the atomisation rate is proposed, based on the literature and measurements on air/water and air/oil flows.

1. Introduction

In the oil and gas industry, venturis are mainly used to measure liquid and gas flow rates: following ISO standard 5167, in monophase flows, differential pressure measurement between the upstream and the throat section enables the liquid or gas flow rate crossing the venturi meter to be determined in-line. The addition of a liquid phase in the gas flow gives rise to an extra pressure loss. At low liquid loading (GVF > 95%) and in the presence of annular two-phase flows, Azzopardi and Govan (1984) and then Lupeau et al. (2007) observed that this phenomenon is mainly due to the atomisation of the liquid film flowing on the pipe wall inside the venturi meter. Consequently, it appears very important to correctly model the entrainment mechanisms appearing inside the venturi, in order to improve the accuracy of the predicted gas and liquid flow rates at low liquid loading. This model needs to predict both:

- The diameter of droplets resulting from this entrainment (D_p).
- The entrained fraction of liquid (E_f).

In order to better model the diameter of entrained droplets, numerous investigations have been carried out with the aim of understanding how they are formed from a planar liquid film sheared by gas. Liquid film atomisation results from the propagation of surface waves leading to the breaking of the film into droplets. Hong et al. (2002) suggests that two kinds of instabilities are involved (Fig. 1): in the longitudinal direction the shearing between the gas and the liquid induces Kelvin–Helmholtz instabilities linked to the formation of waves progressing axially along the liquid film. The acceleration of the liquid into the gas then gives rise to a Rayleigh–Taylor instability in the transverse direction. The combination of these instabilities forms regularly-spaced transverse ligaments which under the acceleration of the gas, are stretched until they burst into droplets. Marmottant (2001), Varga (2002), Hong et al. (2002), Lalo et al. (2006), Ben-Rayana et al. (2006) relate the droplet sizes to the longitudinal and transverse wavelengths (λ_L and λ_T) of the instabilities and the gas velocity.

In annular flows different types of waves have been identified in the literature (Azzopardi (2006)): ripples, disturbance waves, ring waves, ephemeral waves and "huge" waves. Some authors (Cooper et al. (1963), Jacowitz and Brodkey (1964), Arnold and Hewitt (1967), Azzopardi and Whalley (1980)) observed from photographs and video records that almost all the droplet entrainment is related to the presence of disturbance waves. These waves correspond to a

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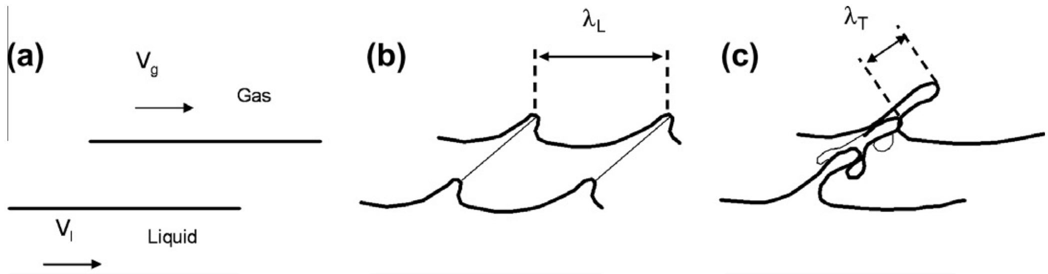

Fig. 1. Destabilisation of a liquid film flowing on a wall by an air flow Hong et al. (2002).

local thickening of the film travelling at a velocity significantly greater than that of the film. Azzopardi (2006) suggested that these waves originate in bursts appearing in the liquid film layer which cause the interface to bulge locally. This initial thickening of the film is then amplified by the shear induced by the gas flow. Mori et al. (2007) studied the influence of viscosity on the inception of these disturbance waves and their relation to droplet formation. They observed that disturbance waves appear for a liquid Reynolds number, based on the liquid superficial velocity, of around 200. They noticed that the influence of the superficial gas velocity on the inception of these waves is small. In order to characterise these waves, various parameters were studied in the literature. One of these is their velocity. Observation shows that theses disturbance waves are moving with a velocity much greater than the ripple waves. Some authors have proposed correlations. From a theoretical analysis based on momentum and mass balances, Pearce (1979) suggested relating this velocity to the velocities and densities of the gas and the liquid phase, and the height of the disturbance wave:

$$V_{DW} = \frac{A.\overline{V_{LF}} + \overline{V_{s.g}} \cdot \sqrt{\rho_g/\rho_l}}{a + \sqrt{\rho_g/\rho_l}} \tag{1}$$

$$A = \frac{\bar{\delta}}{\sqrt{\delta_b \delta_p}} \cong 0.8 \tag{2}$$

where δ_b represents the minimum film thickness of the liquid film, δ_b the maximum film thickness and $\bar{\delta}$ the mean film thickness. $\overline{V_{LF}}$ corresponds to the bulk velocity in the liquid film ($\overline{V_{LF}} = \dot{m}_l/\rho_l \cdot S_{FL}$); S_{FL} is the average area of the liquid film. $\overline{V_{s.g}}$ is the superficial velocity of the gas phase. For air/water flows, Pearce (1979) gives $A = 0.8$. This model has been compared with experimental data from various pipe diameters: the agreement is better for the highest tested diameters (between 25 and 42 mm).

Sawai et al. (1989) proposed that the disturbance wave velocity is proportional to the interfacial friction velocity.

Published results show that atomisation of the film begins only under given conditions (Ishii and Grolmes (1975), Hewitt and Govan (1990), Nigmatulin et al. (1996), Lopez de Bertodano and Assad (1998), Alipchenkov et al. (2002), Lopez de Bertodano et al. (2001)). The two parameters defining this limit are the Reynolds number of the film and a Weber number. The first is an indicator of the appearance of small instabilities on the film surface and the second characterises the competition between the stabilizing and the destabilizing forces.

Hewitt and Govan (1990) suggested using a critical Reynolds number for the liquid phase. Nigmatulin et al. (1996) add a criterion based on a Weber number using the interfacial friction stress and the film thickness. For water flows, Mori et al. (2007) observed that atomisation appears simultaneously with the disturbance waves. Nevertheless, as the liquid viscosity increased, they observed that droplets appeared before the inception of the disturbance waves. In order to correlate their observations, they introduced a Weber number based on the interfacial shear stress, the amplitude of the waves and the surface tension. A critical value of 0.025 is obtained for the start of the atomisation. Many correlations were provided for the prediction of the entrainment rate in an annular pipe flow (Azzopardi (2006)). Some of these depend on the deviation of the Reynolds number or the Weber number from their respective critical values (Hewitt and Govan (1990), Nigmatulin et al. (1996), Lopez de Bertodano et al. (2001), Alipchenkov et al. (2002)). From these different correlations, it is possible to define the relationship between the liquid and gas flow properties and the rate of atomisation.

$$Ra \approx (\rho_g^n U_g^p)(\rho_l^m U_l^k \sigma^s \mu_l^r) \tag{3}$$

where the coefficients *n, p, m, k, s, r* are defined in Table 1.

Some specific studies were performed for the prediction of the entrained fraction of liquid in a venturi meter. Azzopardi and Govan (1984) suggested that an extra entrainment occurs at the beginning of the throat section and is due Eq. (3) to a radial component of the velocity of the liquid film. They proposed the following expression:

$$Q_{v,p2} = \left(\frac{\tan\theta}{1+\tan\theta}\right) \cdot \frac{Q_{v,LF}}{\pi \cdot d \cdot \delta z} \tag{4}$$

where θ is the convergent angle, *d* the throat diameter and δz represents the length of the film element where atomisation occurs.

Fernandez-Alonso et al. (1999) performed a specific study on a venturi with a β ratio (=d/D) of 0.6 where *D* in the pipe diameter. They examined the influence of the throat length on the atomisation process and observed that atomisation mainly occurs at the inlet of the throat section. They observed that the correlation proposed by Azzopardi and Govan (1984) over-predicts the fraction of liquid entrained by the gas flow. They proposed a correlation with a wider range of validity.

$$E_f = 1 - \left(\frac{We_{crit}}{We}\right)^n \tag{5}$$

With:

$$We_{crit} = 0.1857 \cdot \left(90 - \frac{\theta}{2}\right) - 5.17 \text{ and } We = \frac{\rho_g V_{sg}^2 \delta}{\sigma} \tag{6}$$

The exponent *n* depends on the convergent angle.

The Weber number is defined from the mean film thickness δ and the gas superficial velocity V_{sg} at the throat section inlet.

Finally, Lupeau et al. (2007) suggest another correlation, established in air/water flow at atmospheric pressure and with a convergent angle of 10.5°.

$$Q_{\text{atomised}} = k_c We^{3.4} \tag{7}$$

where k_c is a constant equal to 10^{-9} (m^3/s).

However, it can be seen that most of the previous observations and correlations on the prediction of the entrained rate have been