Experimental and theoretical investigation on the annular-intermittent flow transition in upward-vertical liquid/dense-gas two-phase flow experiments

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Abstract. The present work aims to theoretically predict and experimentally investigate the transition boundary from annular to intermittent flow for mixtures of sulfur hexafluoride and oil flowing into a 24.35 mm i.d. pipe in the upward-vertical direction. An experimental laboratory facility having a closed one-inch pipe loop was employed to operate at the absolute pressure of 15 bar over a wide range of operating flow rates. The film instability mechanism indicates that the critical superficial gas velocity required for the transition to annular flow is 1.82 m/s for low values of superficial liquid velocity and the experimental results revealed that the transition occurs in the range between 1.5 m/s and 2 m/s for two sets of data points corresponding to low superficial oil velocities. Therefore, a relatively good agreement is verified between the results from the experiments and theoretical results, so that the transition is in fact governed by the reversal motion of an unstable oil film in the wall region, as it has been visually observed with a high-speed camera in experiments.

Keywords: *annular flow, two-phase flow transition, dense gas, upward-vertical flow, interfacial shear stress*

1. INTRODUCTION

Annular flow is a separated two-phase gas-liquid flow pattern in which the liquid phase flows as a continuous, wavy film positioned at the channel perimeter and also as droplets carried by the turbulent gas stream in the pipe center (core region). Boilers, condensers, refrigerators and nuclear reactors are among the pieces of industrial equipment where the flow pattern can be observed under high levels of pressure. Typical annular flow operating conditions are advantageous because of relatively low-pressure variations in comparison with dynamic fluctuations of intermittent flows. Despite that, the presence of interfacial waves and the simultaneous occurrence of entrainment and deformation of fluid portions imply a flow scenario of great complexity, mainly in a two-phase flow transition, which makes the physics-based modeling of two-phase flows more complicated, although a good predictive performance of the resulting models is required.

In the transition from annular flow, it is known that the interfacial shear stress exerted by the turbulent gas core plays a major role in sustaining the liquid film in the upward motion along the vertical pipe wall. Based on the physical mechanism of film stability proposed by Barnea (1986), the present work aims to theoretically predict and experimentally investigate the transition boundary from annular to intermittent (A-I) flow for mixtures of sulfur hexafluoride (around 100 kgm^{-3}), also referred to as dense gas, and mineral oil (867 kgm^{-3}) with surface tension (0.03215 Nm^{-1}) at the absolute pressure of 15 bar and 31°C inside a 24.35 mm i.d. stainless-steel pipe.

2. EXPERIMENTAL FACILITY

The facility located at LEMI is pressurized to operate with either gas-liquid mixtures or separate flow of each individual fluid phase, and presents a measurement section equipped with flow meters and pneumatic control valves, a test section having a flow visualization window that allows the use of a high-speed camera, differential pressure transducers, a single-beam gamma densitometer and quick-closing valves, as well as a peripheral set of separators, compressors, storage tanks and a three-spindle screw pump for the mineral oil (LUBRAX Turbine 22). Designed to operate at low liquid/gas density ratio in a hydrodynamic similarity relation with the offshore gas-oil production industry, Quintino et al. (2023) were pioneering to use the LEMI's facility, performing horizontal experiments inside a 50.8 mm i.d. pipe, and investigated the effect of gas density on the transitions from stratified to non-stratified flow patterns.

3. RESULTS AND DISCUSSION

The theoretical transition model has been reformulated identifying dimensionless numbers that influence the transition to annular flow. Momentum balance over the liquid film yields Eq. (1) that relates the interfacial shear stress (τ_i) to the nondimensional liquid film thickness $\left(\tilde{\delta} = \delta/D\right)$ for fixed values of the liquid phase Froude number $\left(Fr_f\right)$ and the liquid phase Reynolds number $\left(Re_f\right)$ by keeping the superficial liquid velocity $\langle j_f \rangle$ unchanged. On the other hand, τ_i can be defined for a turbulent gas core in terms of the superficial gas velocity $\langle j_g \rangle$ and the interfacial friction factor, Eq. (2), for which the Wallis (1969) correlation for completely rough film regime is assumed to be applicable to dense-gas/oil. In this case, τ_i in function of $\tilde{\delta}$ for fixed values of the gas phase Froude number $\left(Fr_g\right)$ and the gas phase Reynolds number

(Re_g). Figure 1 shows a solid-line family of inverted-bell-shaped curves and a dashed-line family of ascending curves for fixed $\langle j_f \rangle$ and $\langle j_g \rangle$, respectively, relating a dimensionless form of τ_i with $\tilde{\delta}$. On the theoretical basis satisfying the film flow instability criterion, i.e. $\tilde{\delta} < 0.064$, the critical value of $\langle j_g \rangle$ is predicted to be about 1.82 m/s for the A-I flow transition boundary, which corresponds to the dashed, black ascending line going through the minimum points of those bell-shaped curves for low fixed values of $\langle j_f \rangle$.

$$\frac{\tau_i}{(\rho_f-\rho_g)gD} = \left[(\tilde{\delta}-\tilde{\delta}^2)^3 \sin\beta + \frac{1}{32}C_f\left(\frac{\rho_f}{\rho_f-\rho_g}\right)\frac{{Fr_f}^2}{{Re_f}^n}\right]\left[\frac{1-2\tilde{\delta}}{(\tilde{\delta}-\tilde{\delta}^2)^2}\right] \qquad (1)$$

$$\frac{\tau_i}{(\rho_f-\rho_g)gD} = \frac{1}{2}\left(\frac{\rho_g}{\rho_f-\rho_g}\right){Fr_g}^2\frac{0.046}{{Re_g}^{0.2}}\left[\frac{1+300\tilde{\delta}}{(1-2\tilde{\delta})^4}\right] \qquad (2)$$

Figure 1 also displays a plot of experimental data points that presents the expected trend between the total pressure drop and the superficial gas velocity for two low values of $\langle j_f \rangle$ in the churn-annular flow region. It can be noted that the minimum pressure drop occurs at $\langle j_g \rangle$ placed between 1.5 and 2 m/s for both the green and red curves, above of which the annular flow pattern is experimentally verified to become stable for mixtures of sulfur hexafluoride and mineral oil within a 1-inch i.d. vertical pipe.

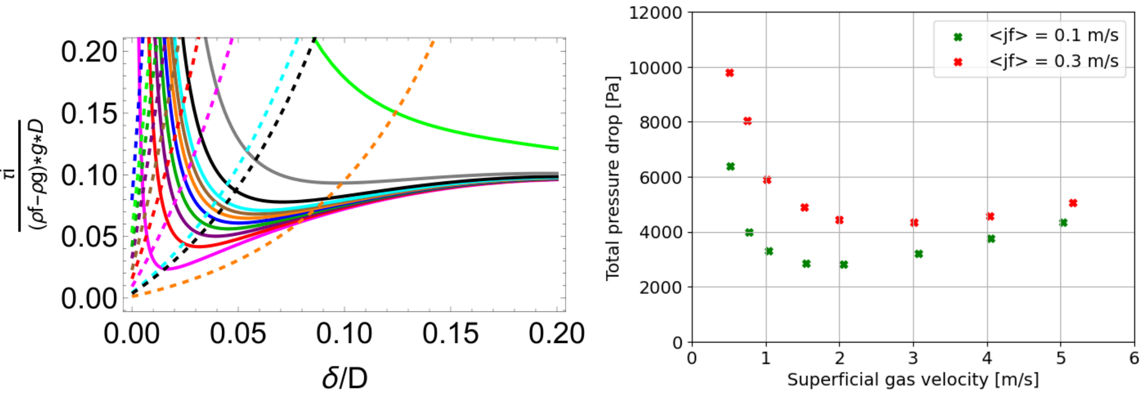

Figure 1. A dimensionless form of τ_i versus $\tilde{\delta}$ (left) and the total pressure drop [Pa] versus $\langle j_g \rangle$ (right)

4. CONCLUSIONS

The transition boundary to annular flow has been theoretically predicted and experimentally investigated for oil/dense-gas mixtures and the experimental results agree relatively well with the film instability mechanism originally proposed by Barnea (1986) to account for the reversal motion of the film, as it has been visually observed during the experiments.

5. REFERENCES

BARNEA, D. Transition from annular flow and from dispersed bubble flow – unified models for the whole range of pipe inclinations. **International Journal of Multiphase Flow**, v. 12, n. 5, p. 733-744, 1986.

QUINTINO, A. M.; JUNIOR, R. F.; RODRIGUEZ, O. M. H. Experimental study of liquid/dense-gas pipe flow. **Geoenergy Science and Engineering**, v. 230, p. 1-13, 2023.

WALLIS, G. B. **One-dimensional two-phase flow**. Dover Publications, 1969. 410 p. (revised republication in 2020).

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