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# AIR ENTRAINMENT DUE TO A PLUNGING FREE-SURFACE FLOW

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## ABSTRACT

The air entrainment due to a plunging free-surface flow in the Inverted-Shroud gravitational gas-liquid separator (IS-separator) is studied in order to determine bubble size. This kind of flow system is an unconventional one. After air entrainment happens, the continuous liquid phase tries to carry the generated bubbles downstream into the IS-separator. We describe the equipment features and outline that its performance depends on the size of the generated bubbles formed during the air entrainment process. It is also shown that bubble diameter can be expressed as a function of the free-surface velocity and a characteristic length $L_{dis}$, where the kinetic energy of plunging free-surface flow is dissipated. Some $L_{dis}$ correlations from literature are used to determinate bubble diameter as a function of flow conditions, fluid properties and geometry of the IS-separator. The predictions are compared with reported experimental results showing good agreement. On the other hand, it is shown that bubble diameter predictions using classical models are not suitable. The results suggest that the models based on $L_{dis}$ are appropriate, however more comparison are needed in order to get conclusive results.

**KEY WORDS:** Plunging free-surface flow, air entrainment, energy dissipation, bubble distribution, bubble size

## 1. INTRODUCTION

The air entrainment due to plunging jets or at the interface of a turbulent free-surface flow has been broadly studied [1]–[5]. The phenomenology of typical industrial applications, such as oxygenation in spillways, is well understood and proper designs can be performed. However, there are unconventional flow systems that need more research in order to be fully understood. This is the case of air entrainment due to a downward-inclined free-surface annular-duct flow impacting against a quasi-static gas-liquid interface confined in an annular channel. The described flow configuration occurs inside the Inverted-Shroud gravitational gas-liquid separator (IS-separator), with application in the oil industry.

### 1.1 The Inverted-Shroud Separator

The Inverted-Shroud separator is made of a sealed-bottom tube installed between casing and tubing as shown in Fig 1a. Four different kinds of flows are identified in the separator [6]–[8]. First, the mixture flows in an upward gas-liquid annular-duct flow inside the channel formed by casing and IS-separator (A, Fig. 1a). At the inlet of the IS-separator, after a gas-liquid segregation process, the liquid enters to the inner annular-channel, flowing in a downward free-surface flow (*B*, Fig. 1a). The latter impacts against the quasi-static liquid surface at the Inner Annular Level (IAL) causing air entrainment (*C*, Fig 1a). Bubbles are generated mainly due to dissipation of turbulent kinetic energy. If the IS-separation works properly, a liquid single-phase pipe flow should be observed at the tubing (*D*, Fig. 1a). Recent studies, [6] and [9], suggest that the performance of the equipment depends on a length associated with the parabolic trajectory traveled by bubbles to reach the top of the IS-separator, $L_{Stokes}$. Red line in Fig. 1b represents the longer possibly

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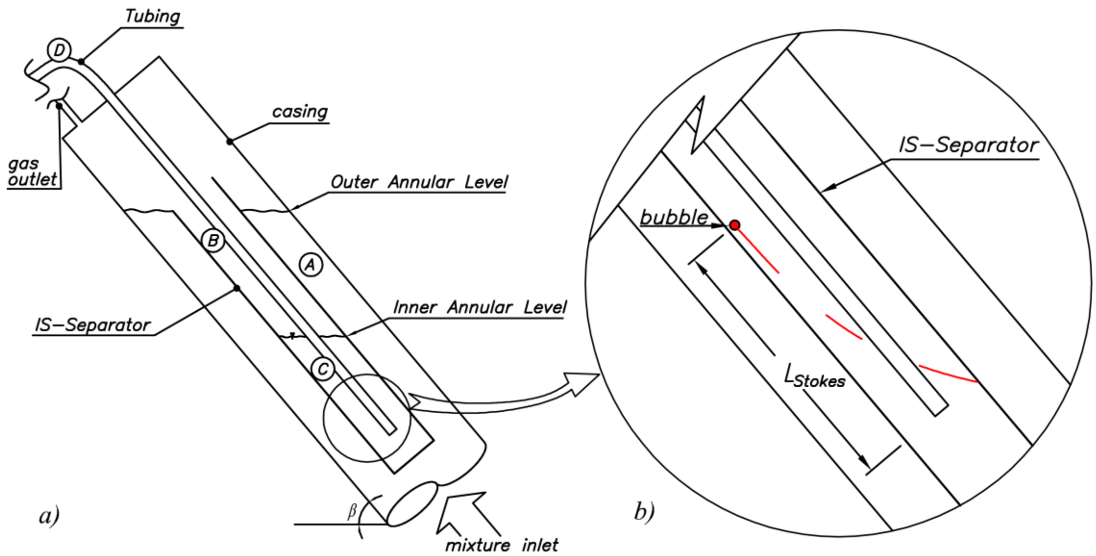


**Fig. 1** Schematic representation of (a) Inverted-Shroud separator and (b) critical trajectory of a typical generated bubble (red line).

trajectory. According to Ortiz-Vidal *et al.* [9], this length is a function of IS-geometry, liquid flow rate and Stokes' terminal velocity ($V_{ter}$). The latter, in turn, depends on bubble diameter ($d_b$) and physical properties of the fluids. Eqs. (1)-(2) can be used to determinate $L_{Stokes}$ and $V_{ter}$,

$$L_{Stokes} = \frac{\pi}{2} ID_{separator} \left( \frac{V_{IA} - V_{ter} Sin\ \beta}{V_{ter} Cos\ \beta} \right) \tag{1}$$

$$V_{ter} = \frac{\rho_L - \rho_G \ \ g d_b^2}{18 \mu_L} \tag{2}$$

where $ID_{separator}$ and $\beta$ are inner diameter and inclination of the separator. $V_{IA}$ is the inner annular-channel liquid velocity. Symbols $\rho$ and $\mu$ represent density and dynamic viscosity, respectively. The subscripts $L$ and $G$ refer to liquid and gas phases, respectively.

## 2. AIR ENTRAINMENT PHENOMENON

The air entrainment phenomenon inside the IS-separation occurs when the plunging free-surface flow impacts on the receiving liquid at the IAL (see Fig 1a). Bubbles are generated due to the dissipation of kinetic energy [10]. Initially the phenomenon is dominated by turbulence forces where the generated bubbles are subjected to breakup and coalescence processes. After that, the smaller bubbles may follow the streamlines of the inner annular-channel flow in direction to the tubing inlet. However, depending on the bubble size, many of them can reach the top of IS-separator before the tubing inlet. According to literature [10], the maximum diameter of the bubbles generated due to a process dominated by dissipation of turbulent kinetic energy can be expressed by,

$$d_b = 1.15 \left( \frac{\sigma}{\rho_L} \right)^{0.6} E_{dis}^{-0.4} \tag{3}$$

where $\sigma$ is the surface tension. $E_{dis}$ represents the rate of turbulent kinetic energy dissipation per unit mass. Ortiz-Vidal *et al.* (see [6], [11]) modelled this parameter considering that all available kinetic energy of the plunging free-surface flow is dissipated within an specific length, measured from the IAL, called dissipation length $L_{dis}$,

$$E_{dis} = \frac{1}{2}\frac{V_{FS}^3}{L_{dis}} \tag{4}$$

where $V_{FS}$ is the plunging free-surface flow velocity. Several correlations for $L_{dis}$ have been proposed. Ortiz-Vidal [7] presented one considering only turbulent flow inside the separator (Eq. (5)). Mendes [12] proposed the correlation shown in Eq. (6), for both laminar and turbulent flow based on the Weber number. According to that author, the coefficients $n$ is equal to 2 and $m$ is 1500 for turbulent flow regime or 0.008 for laminar flow. More recently, Barbosa [13] has improved Mendes' correlation, from a broader experimental database. That author suggested values of $n$ = 1.5 and $m$ = 1500 for turbulent flow or 50 for laminar flow. It is important to notice that all these correlations have been adjusted based on experimental results of IS-separator gas-separation efficiency.

$$L_{dis} = 0.1\left(\frac{Q_{TR}}{Q_L}\right)^{4\sqrt{Sin(\beta)}} \tag{5}$$

$$L_{dis} = ID_{separator}\left[m\ We*^{\,-n}\right] \tag{6}$$

In Eqs (5), $Q_L$ is the volumetric flow rate of liquid. Symbol $Q_{TR}$ represents the critical value of $Q_L$ for which laminar-turbulent flow transition at the inner-annular channel happens. In Eq. (6), $We*$ represents a modified version of Weber number [12]. This is evaluated for conditions of plunging free-surface flow by,

$$We* = \frac{\rho_L S_{FS} V_{FS}^2}{48\sigma} \tag{7}$$

where $S_{FS}$ is the gas-liquid interfacial perimeter of the plunging free-surface flow.

## 3. RESULTS AND DISCUSSION

Bubble size predictions using models based on $L_{dis}$ correlations (Section 2) are compared against experimental results and the classical models presented in Table 1. The Hinze's and critical diameter are included for comparison purposes. The former represents the maximum diameter size of a bubble under turbulence and it was derived for flow in bubble columns [14]. For calculations it is considered the hydraulic diameter of the plunging free-surface flow ($HD_{FS}$). On the other hand, the latter represents the critical diameter to prevent bubble coalescence [14]. The expression only depends on physical properties of the fluids and predicts small diameters compatible with the size of spherical bubbles. The experimental results have been extracted from [15]. The measurements were performed in the IS-separator using a 3D ORM probe at a constant volumetric water flow rate of 60 l/min and 45º of inclination angle. The inner diameter of the shroud and the hydraulic diameter of the

**Table 1** Classical models for bubble diameter.

| Model | Bubble diameter, $d_b$ |
|---|---|
| Hinze's diameter | $= 1.14\left(\frac{\sigma}{\rho_L}\right)^{0.6}\left(\frac{2\cdot 0.046 V_{FS}^{2.8}}{HD_{FS}^{0.8}}\left(\frac{\mu_L}{\rho_L}\right)^{0.2}\right)^{-0.4}$ |
| Critical diameter | $= \sqrt{\frac{0.4\sigma}{\rho_L - \rho_G\ \ g}}$ |

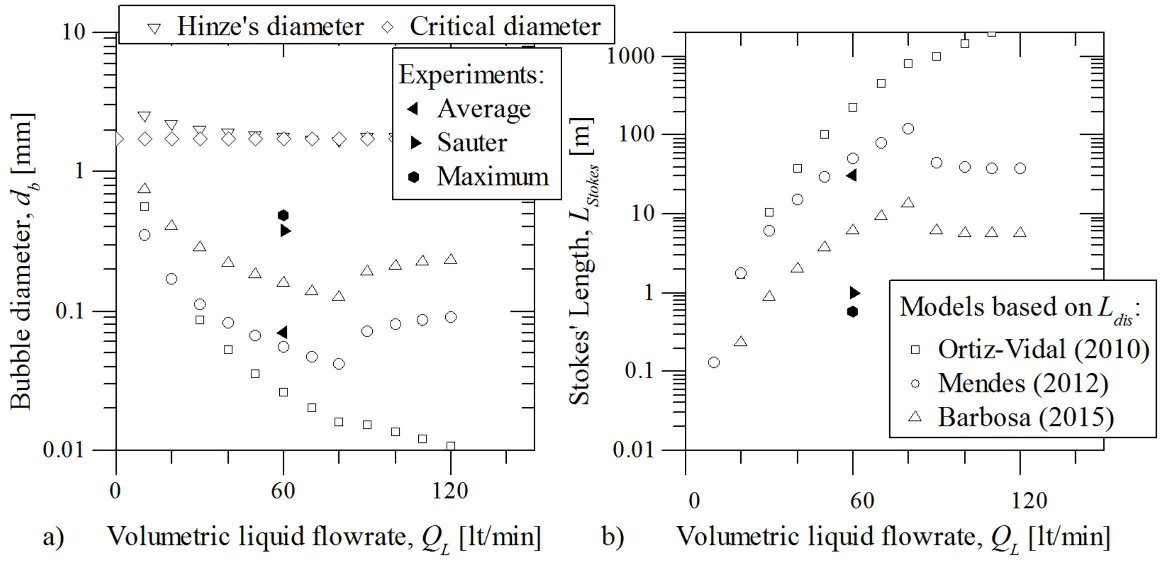


**Fig. 2** Predictions of (a) $d_b$ and (b) $L_{stokes}$ as a function of volumetric liquid flow rate for water flow and 45° of inclination angle. The solid symbols are the experimental results extracted from [15].

inner-annular channel are 53 mm and 21 mm, respectively. Those authors provided the average, Sauter and maximum diameters of the bubbles.

One can see in Fig. 2a results of bubble diameter as a function of volumetric liquid flow rate. The models consider the physical properties of air and water and the IS-separator geometry, as reported by [15]. The models based on $L_{dis}$ correlations predict bubble sizes in the same order of magnitude than the experiments. Moreover, the fact that the predicted diameters are smaller than 1 mm is in agreement with Ortiz-Vidal's experimental observations [16]. The results depend on which experimental diameter is adopted as standard, *i.e.* Average, Sauter or Maximum. If the Average diameter is considered, the correlation of Mendes presents very good agreement with experiments. If the Maximum or Sauter diameter is considered, Barbosa's correlation gives the best results, but with a relative error of about 60%. On the other hand, Ortiz-Vidal's correlation provides the worst results, predicting a too small bubble diameter. The comparison of the experimental results with the predictions of the classical models suggest that on average (Sauter or Average bubble diameter) the bubbles are non-coalescent and have diameters significantly smaller than the maximum possible one due to turbulence. On the other hand, the measured Maximum bubble diameter is significantly smaller than the one predicted by Hinze's. A possible explanation is a technical limitation of the 3D ORM technology, which might have been incapable of measuring the diameter of the bigger bubbles.

The Stokes' length $L_{Stokes}$ was calculated for both experimental and predicted bubble diameters using Eqs.(1)-(2). Results are shown in Fig. 2b. If the Average bubble diameter is considered as the standard one, the Mendes' correlation provides excellent predictions for practical applications of the IS-separator. Barbosa's correlation provides the best results if the Sauter or Maximum diameter is used as standard. Ortiz-Vidal's correlation do not provide practicable lengths. The limitations of this correlation may be related to the fact that it was adjusted based on a restricted experimental database.

The small amount of experimental data makes it impossible to characterize the trend of $L_{Stokes}$ as a function of the experimental bubble diameter. Therefore, more experiments are needed to measure the bubble diameter and, consequently, to evaluate properly the air entrainment phenomenon. The experimental results can be also used to validate the $L_{dis}$ correlations or propose new ones.

## 6. CONCLUSIONS

In general, for plunging jet systems, bubble diameter is a function of energy dissipation and physical properties of the fluids. It was also demonstrated that for plunging free-surface flow this energy dissipation can be expressed as a function of free-surface velocity and a characteristic length within which kinetic energy is dissipated, called dissipation length, $L_{dis}$. Models based on $L_{dis}$ correlations appear to be proper to predict the size of bubbles generated during air entrainment due to an unconventional plunging free-surface flow. The latter occurs inside the Inverted-Shroud separator and the performance of the equipment depends on the average diameter of the generated bubbles. Bubble diameter predictions are in agreement with experiments reported in the literature. The performance of $L_{dis}$-correlation approach is appropriate for the conditions tested. The results, although promising, are not conclusive because the experimental database is limited. More experiments are needed.

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