Petroleum 5 (2019) 178–182

Contents lists available at ScienceDirect

Petroleum

journal homepage: www.keaipublishing.com/en/journals/petlm

High efficiency gas-liquid separation system for pumped wells

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A R T I C L E I N F O

Article history:
Received 10 August 2017
Accepted 31 January 2018

A B S T R A C T

Gas-liquid separation is a very common process in industrial plants, where often high Efficiency of Gas Separation (EGS) is demanded. In the upstream oil industry, gas separation is also crucial for the proper operation of Electrical Submergible Pumps (ESP). Recent studies report the excellent performance of a gravitational separator known as Inverted-Shroud separator (IS-separator). Laboratory results indicate that this kind of separator can achieve total gas separation for a wide range of operation conditions under continuous two-phase flow. The original intent is to use the IS-separator for downhole gas separation in oil production wells. However, by account of its simple design and relatively compact size, it may be suitable for using in industrial plants. In this paper, we present the IS-separator in details, including geometry characteristics and phenomenology. The equipment performance is also discussed. In addition, the challenges related to the deep understanding of the gas separation process inside the IS-separator and the possible practical solutions are outlined.

1. Introduction

Gas-liquid separation is an important issue in Oil & Gas industry when oil wells are explored by means of any Electrical-Submergible-Pump (ESP) technique. This is the case of the Brazilian scenario where the ESP technique is used as artificial lift method in more than 50% of production wells. In the presence of high quantities of free gas upstream of the pump, the latter exhibits efficiency losses and dynamic failures due to surge. Gas separators are employed to avoid that.

Significant efforts have been spent in the last decades on designing efficient downhole gas separators. The technical literature indicates that centrifugal, helical-fix and gravitational gas separators can be used in association with ESP technique [1–4]. The studies show that these kind of equipment are high-efficiency gas separators [2,4–6]. However, some problems were pointed out. For example, centrifugal separators have serious difficulty with slug flow pattern, besides the moving parts, which increases the maintenance frequency and consequently the costs. Helical-fix separators reduce the casing cross-sectional area, decreasing liquid flowrate production. Recent studies on the Inverted-Shroud gas separator (IS-separator) show that this equipment has high-efficiency performance, without moving parts or reducing cross-sectional area. However, further validations are needed, mainly related to details of the gas-separation process, specifically the proper knowledge of the local flow structures inside the IS-separator.

In this paper we present the IS-separator, its geometry characteristics, phenomenology and performance. The challenges related to the understanding of the gas separation process inside IS-separator are also presented. Finally, we propose the proper instrumentation for studying local flow structures inside the equipment, the advantages and the potential use.

2. Inverted-Shroud gas seperator

2.1. Description and phenomenology

Fig. 1 shows a schematic description of the Inverted-Shroud (IS)

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Peer review under responsibility of Southwest Petroleum University.

Production and Hosting by Elsevier on behalf of KeAi

https://doi.org/10.1016/j.petlm.2018.01.006

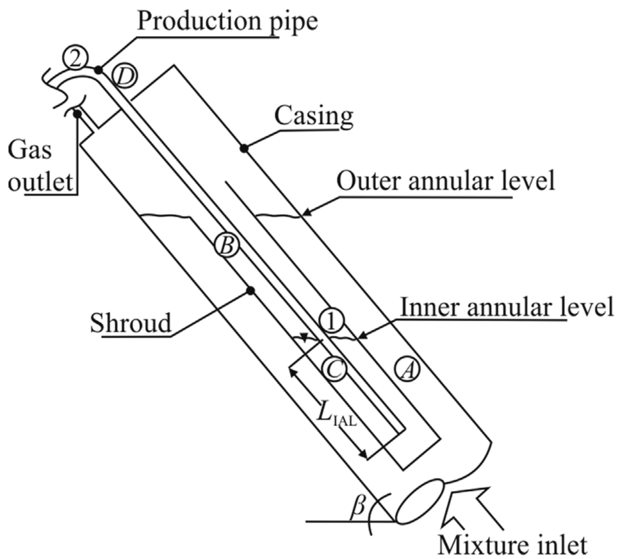

Fig. 1. Schematic description of the Inverted-Shroud Separator. Adapted from Ref. [4].

separator. The IS-separator is a sealed-bottom tube (shroud) installed between the casing and the production pipe. The presence of the separator forms two well-defined annular channels. According to Ortiz-Vidal et al. [4,7], the gas-liquid mixture flows through the outer annular channel in several flow patterns, like slug and bubbly (*A*, Fig. 1). At the beginning of the shroud (Outer Annular Level, Fig. 1) a segregation process occurs due to gravity force and gas flows out. When the separator is installed in inclined position, liquid enters inside the separator flowing as free-surface annular-channel flow (*B*, Fig. 1). The latter impacts on the Inner Annular Level (IAL) of liquid and an aeration process occurs due to kinetic energy's dissipation (*C*, Fig. 1). Bubbles are generated and entrained in the liquid present in the inner annular channel. By account of gravity, buoyancy and drag forces, the bubbles can either flow towards the production pipe's inlet or reach the top side of the shroud. Coalescence can happen along the bubbles trajectory and as a consequence gas flows upwards. If the IS-separator operates properly, only liquid should reach the production pipe's inlet (*D*, Fig. 1).

Two main stages of separation can be identified in the operation of the IS-separator. The first stage occurs immediately after the gas-liquid mixture reaches the beginning of the shroud, when the main body of gas segregates itself and then flows upwards through the annular channel formed by casing and production pipe. The gas can be collected through the gas vent connection. The second stage of gas separation happens inside the inner annular channel. The entrained bubbles try to reach the top side of the shroud, describing quasi-parabolic trajectories. The gas separation is ensured when the latter occurs before the bubbles reach the production pipe entrance.

2.2. Performance

The performance of the IS-separator depends on the L_{IAL} length between the IAL and the production pipe entrance [4,7]. The larger L_{IAL} lengths, the higher the ratios of Efficiency of Gas Separation (EGS). The former implies more bubbles reaching the top side of the Inverted Shroud before they enter to production pipe. Furthermore, Total Gas Separation (TGS) or 100% EGS can be reached under certain conditions, as reported in some studies [4,8,9]. For example, EGS experimental data for different geometries and 45° are shown in Fig. 2. Two regions can be recognized, a region of Total Gas Separation (TGS) and another of Partial Gas Separation (PGS). It is clear that TGS occurs at larger dimensionless L_{IAL} lengths. In Fig. 2, L_{IAL}, normalized by the hydraulic diameter of the inner-annular channel (d_{IA}), is presented as a function of a modified version of the Weber number (We^*, Eq. (1)) [8]. The dimensionless We^* number is evaluated for conditions of free-surface annular-channel flow,

$$We^* = \frac{\rho_L S_i V_{FS}^2}{48\sigma} \tag{1}$$

where ρ_L is the liquid specific mass and σ is the liquid-gas interfacial tension. S_i and V_{FS} are the perimeter and mean velocity of the semi-circular jet related to the free-surface flow, respectively. It is important to note that 100% EGS depends on inclination. For constant values of fluids properties, liquid flow rate and geometry, TGS L_{IAL} length increases with increasing inclination (β) [4,8–10]. Vertical IS-separator need larger L_{IAL} lengths for reaching high-efficiency performance. The inclination of IS-separator is taken into account in the free-surface velocity [11],

$$V_{FS} = \sqrt{\frac{2gD_{FS}Sin(\beta)}{f_{FS}}} \tag{2}$$

where D_{FS} and f_{FS} are hydraulic diameter and friction factor. The subscript *FS* indicates free-surface annular-channel. It can be observed that viscosity is considered by means of friction factor. Therefore, the dimensionless We^* number seems to be a proper parameter to represent the IS-separator performance, as it considers inclination and fluid properties.

The location of IAL determines L_{IAL}. As EGS is a function of L_{IAL}, there is an IAL location related to a minimal L_{IAL}, at which TGS is ensured. That criterion established by Ortiz-Vidal et al. [10] has been used to study gas separation in IS-separators [4,8,12]. Fig. 2 is drawn based on this principle. The IAL location is mainly function of inclination angle, casing pressure, wellhead pressure, liquid

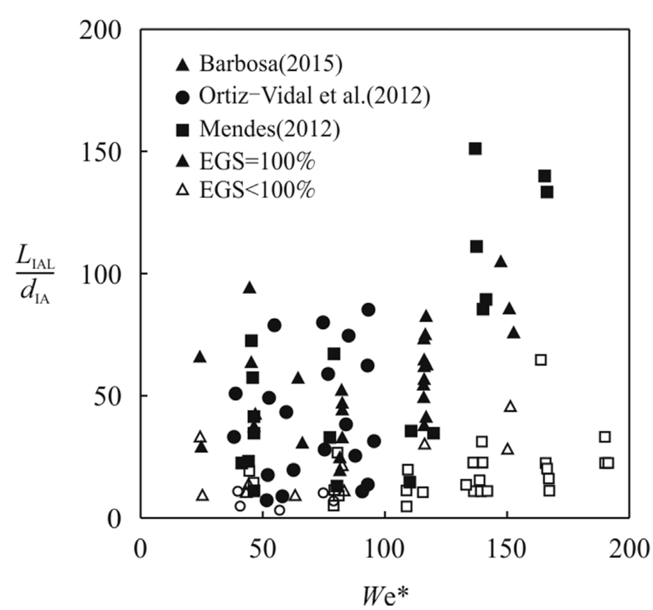

Fig. 2. Efficiency of Gas Separation (EGS) as a function of dimensionless L_{IAL} and *We* for inclination angle of 45°. Solid and open dots correspond to Total Gas Separation and Partial Gas Separation data, respectively. Triangular, circle and square dots correspond to experimental data by Refs. [9,4] and [8], respectively.

flowrate, liquid physical properties, separator geometry and pump power [4,9,11]. For a defined IS-separator, IAL is altered by changes in: (i) the liquid flowrate, (ii) the difference between casing pressure and wellhead pressure and (iii) ESP pump power.

In order to predict the minimal L_{IAL} length a prospective phenomenological model has been developed (see Refs. [11,13,14]). The model is based on the criterion described above and incorporates the experimental findings. The minimal L_{IAL} length to ensure TGS is the sum of two lengths (L_{TGS}, Eq. (3)). a_{dev} is the minimum length to reach fully-developed flow after the collision of the free surface flow against IAL. Eq. (4) can be used for turbulent flow in the inner-annular channel. a_{Stokes} is a length associated to the quasi-parabolic trajectory of the entrained bubbles inside the inner-annular channel. The Eq. (5), proposed by Ref. [11], can be used to evaluate a_{Stokes}. It considers fluids properties and inclination. The model has been tested against experimental data and it has shown physical consistency [10,11], but it needs experimental adjustment of bubble diameter for predicting the minimal L_{IAL} length.

$$L_{TGS} = a_{dev} + a_{Stokes} \tag{3}$$

$$a_{dev} = 4.4 Re_{IA}^{1/6} D_{IA} \tag{4}$$

$$a_{Stokes} = \frac{\pi}{2} D_{IS} \left(\frac{V_{IA} - V_{ter} Sin(\beta)}{V_{ter} Cos(\beta)} \right) \tag{5}$$

$$V_{ter} = \frac{\Delta\rho g D_b^2}{18\mu_L} \tag{6}$$

where Re_{IA}, D_{IA} and V_{IA} represent Reynolds number, hydraulic diameter and mean velocity evaluated in inner-annular channel, respectively. D_{IS} represents the inner diameter of the separator. V_{ter} is the Stokes' terminal velocity. $\Delta\rho$ and μ_L are liquid-gas density difference and dynamic viscosity of liquid, respectively.

Bubble diameter is a key parameter in the model (D_b, Eq. (6)). The bubbles diameter is function of the kinetic-energy dissipation, which in turn takes place within a specific length called dissipation length [13]. The bubble diameter can be modeled by Hinze's diameter, as noted by Ref. [15]. Two correlations for the dissipation length have been proposed so far. Ortiz-Vidal et al. [7,11] proposed a correlation for a constant dissipation length and for the case of turbulent flow. Mendes [8] developed a correlation for both laminar and turbulent flows. The correlations can be used to predict the diameter of the entrained bubbles, but they were adjusted based on gas-separation experimental data.

2.3. Challenges

Understanding the process of the energy dissipation, and, consequently, bubble generation due to the collision of free-surface annular-channel flow against the liquid at the inner-annular channel, (IAL, *C*, Fig. 1), is the main challenge in the study of gas-liquid separation using the IS-separator. A reduced model is the case of plunging-jet phenomenon. Ortiz-Vidal et al. [4] compared the main differences between separation phenomenon in a IS-separator and in similar situations reported in the literature, and they state the needed of further studies. According to those authors, the studies on plunging jets have been motivated by the problem of improving aeration, in contrast to the IS-separator phenomenology, where aeration should be minimized. Therefore, the particular problem of kinetic-energy dissipation in IS-separator deserves a study of its own. In practical terms, as far as the IS-separator is concerned, there is a lack of information on bubbles diameter, size distribution and penetration depth.

Specific experimental methods and advanced instrumentation are needed for studying the local flow structures inside the IS-separator. It should be also considered that the local characteristics of the generated bubbles depend on the measurement point or distance from the L_{IAL} length. Considering that it is difficult to move the instrumentation from one point to another due to practical purposes, we propose the configuration shown in Fig. 3. There is a fixed point for instrumentation and it is the IAL that is moved up and down in order to collect data along the dissipation length, L_{IAL}. Measurements of bubbles characteristics along L_{IAL} will allow the direct verification of the proposed correlations for predicting the Efficiency of Gas Separation (EGS). Consequently, experimental adjustment will be no longer necessary for predicting the minimal L_{IAL} length.

3. Instrumentation and experimental methods

In this section, the proper instrumentation and experimental methods to study gas separation in the IS-separation is outlined, with description of advantages and limitations.

3.1. Reflectance-measurement-based probes

The techniques Optical Reflectance Measurement (ORM) and Focused Beam Reflectance Measurement (FBRM) have been shown to be useful in bubble and dispersed-droplet size measurement in cases where these particles must be measured *in situ*. Both technologies use a revolving laser beam to measure one or more reflecting particles. The FBRM probe measures chord length distributions that must be then translated into actual diameter distributions through statistical analysis. Similarly, the 3D ORM probe uses a laser with a dynamically adjustable focal point, allowing it to track a three-dimensional area (Fig. 4) to measure chord length distributions and automatically convert them to diameter distributions. It will be used for measuring diameter and size distribution of the bubbles by varying the IAL location, as suggested at section 2.3.

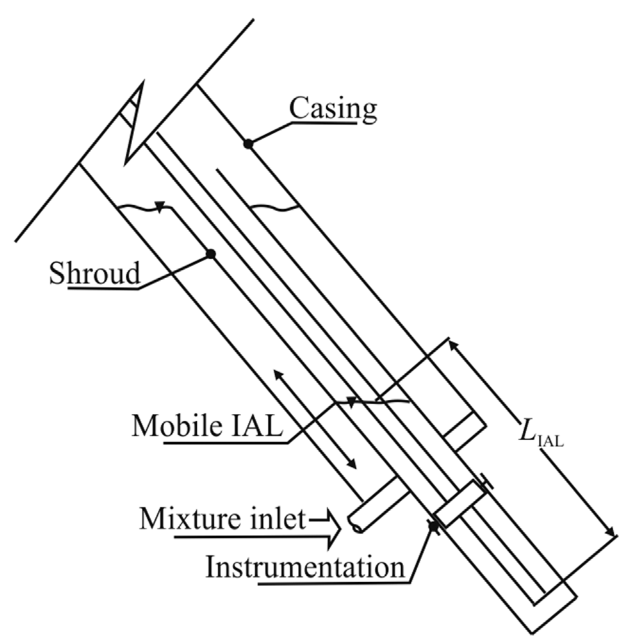

Fig. 3. Schematic experimental configuration for the new instrumentation.

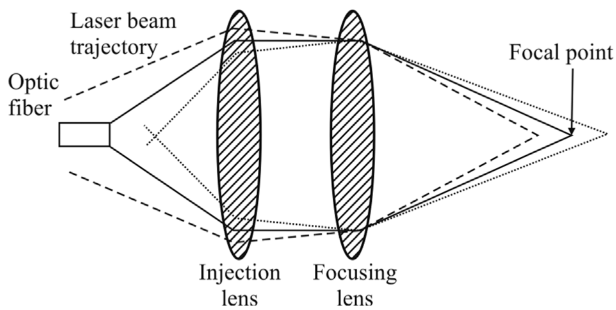

Fig. 4. Diagram of an ORM probe. Adapted from SEQUIP (www.sequip-particle-technology.de/english/).

These techniques allow for rapid acquisition of a large amount of data, which can then be translated into different forms of average particle size. Equation (7), proposed by Azzopardi [16], represents a generic equation for particle size, in which d are measured diameters and m, n are parameters subject to change according to the phenomenon. One relevant pair of parameters is $m = 3$ and $n = 2$, which give us the Sauter average diameter used in experiments with particle atomization in carburetors. This diameter is most useful when the volume and interfacial area of particles are relevant variables.

$$\overline{d}_{m,n} = \frac{\sum d_i^m}{\sum d_i^n} \tag{7}$$

The literature reports studies of the possible applications of the cited reflectance measurement techniques. Lovick et al. [17] and Yusoff [18] obtained accurate measurement for diameter of liquid droplets using the 3D ORM and FBRM technologies, respectively. Authors such as Li et al. [19] achieved good results recently using an FBRM probe to measure micron-sized bubbles. Similarly, Barbosa [9] performed measurements of air bubble diameter in the IS-separator with a 3D ORM probe. However, Barbosa's results are not conclusive due to problems with the validation of the 3D ORM measurements. According to that author, in the process of validation, using hollow glass microspheres of known sizes (mean diameter of particles between 8 and 11 μm), the equipment provided average size similar to what was informed by the particles' manufacturer. On the other hand, for larger particles (<3 mm) the 3D ORM results were inconclusive.

Efforts are being performed in the Industrial Multiphase Flow Laboratory (LEMI) of the University of Sao Paulo (USP) at Sao Carlos campus to get a conclusive validation of 3D ORM equipment, and consequently verify the capability of the instrumentation for measuring bigger bubbles. Specifically, experiments with bubbles generated by a vertical plunging jet, similarly to Evans et al. [20]. Results from a high-speed camera will be compared to data obtained with the 3D ORM probe.

3.2. Wire-mesh sensor

The Wire-Mesh Sensor (WMS) is an intrusive electrical-impedance-based tomographic instrument used to measure phase fraction in multiphase flows [21]. A typical WMS consists of two planes of wires. The wires are parallel in each plane. The planes are rotated 90°, containing at each plane the transmitter and receiver wires, as shown in Fig. 5a. In operation, the electrical properties (conductivity or permittivity) of a multiphase mixture present at each crossing point (16 for the case of 4 × 4 WMS) are directly measured and related to the phase fraction using permittivity models. It is important to note that even the WMS being

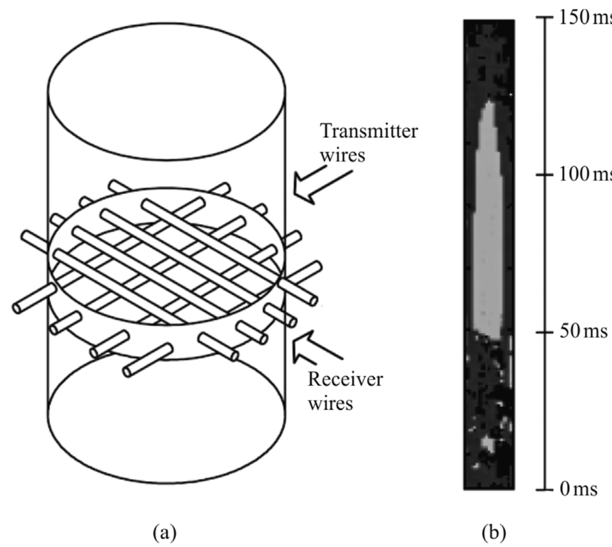

Fig. 5. a) Schematic view of 4 × 4 WMS located in a pipeline. b) Reconstructed slug passing in gas-liquid pipe flow using a 16 × 16 WMS; adapted from Ref. [22].

intrusive, affecting the measurement at some degree, the technique can deliver a tomographic image with an acceptable benefit-cost ratio compared to other instruments [21]. Thus, the WMS would be used for measuring penetration depth of bubbles inside IS-separator by means of phase fraction measurements at different IAL locations, as suggested at section 2.3.

Previous studies on gas-liquid, liquid-liquid and gas-liquid-liquid multiphase flows have shown good agreement between measurements by WMS and traditional techniques, such as quick closing valves [22,23]. One can see in Fig. 5b a reconstructed slug passing in air-water vertical pipe flow with 50 mm ID. It is important to note that the WMS can be also used in the presence of oil. Further work is to adapt the WMS to annular-channel configuration, according to IS-separator geometry.

3.3. Image-based technique

Among the many techniques used for entrained-particle analysis in two-phase flow, by far the most common is filming, coupled with image processing. Filming is a versatile and cost-efficient technique as long as it is possible to see through the pipe wall and two-phase mixture. Many variables must be accounted for, such as sufficient illumination, the correct calibration of the measurement scale, the curvature of the test section tube (when tubes are present) and the location of the focal point. Another obvious advantage in comparison to techniques such as ORM is the greater array of available data. When analyzing a plunging jet there are many variables of interest besides bubble size, such as penetration depth, rate of bubble generation and bubble speed. This technique would be used for measuring these parameters inside IS-separator for different IAL locations.

Many studies on measurement of bubble size using filming techniques are reported. For example, Evans et al. [20] obtained accurate bubble size measurements in vertical plunging jet through filming techniques. Later, Bongiovanni et al. [24] were able to point out some sizing bias issues that can arise when trying to measure moving bubbles. Marmottant and Villermaux [25] performed an in-depth analysis of liquid jets and the way as they are formed. In the case of bubble size, a commonly used option is the Hough transform algorithm, which was originally developed for identification of lines in an image and later modified for identifying the positions of any arbitrary shape (circles, in the case of bubble measurement).

To work with image-based techniques requires the use of proper filming and lighting methods, besides a consistent objective manner to process the images. Currently, a multitude of computer algorithms are available for image processing through software, such as ImageJ and LabVIEW™. For example, for the case of bubble size, the Hough transform algorithm is frequently used. Software such as ImageJ®, MATLAB® or LabVIEW®, when used with image batch-processing algorithms, allow us to obtain data from a much larger amount of images in comparison to a subjective, hand-made analysis. This method results in a more precise final result through one or more of the possible average sizes calculated with Eq. (1). LEMI has at its disposal a set of in-house routines developed in LabVIEW® for processing images in multiphase flows (*e.g.* see Ref. [26]).

4. Conclusions

Reflectance-measurement-based probes, Wire-Mesh Sensor and Image-based techniques can be employed as proper instrumentation for studying local flow structures inside the Inverted-Shroud gravitational gas separator (IS-separator). These flow structures are responsible by the performance of the IS-separator in terms of Efficiency of Gas Separation, where the length between the Inner Annular Level of liquid and the production pipe entrance is a key parameter. Experimental measurements of the flow structure for various lengths are a requirement in order to understand better and model the gas-separation process. From a phenomenological point of view, these flow structures are related to the kinetic energy dissipation and bubble generation process. In practical terms, the characteristics of the flow structures are reflected by means of the diameter, size distribution and penetration depth of the generated bubbles. We analyze the cited instrumentation, their advantages and limitations in the context of the IS-separator and conclude that they are able to assist in the measurement of the cited practical parameters.

Acknowledgements

The authors acknowledge ANP, Petrobras and CNPq (contracts 164211/2015-2, 501443/2014-2 and 151317/2014-3) for the financial support. L. Enrique Ortiz Vidal is also grateful to FIPAI.

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