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EXPERIMENTAL EVALUATION OF EFFICIENCY OF GAS SEPARATION IN AN INVERTED-SHROUD GAS-LIQUID SEPARATOR IN VERTICAL POSITION

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Abstract. We evaluated experimentally the efficiency of gas separation (EGS) in a vertical Inverted-Shroud gas-liquid separator. A pilot facility was constructed in order to simulate the operational conditions in the production wells. Water and air were chosen as working fluid. Observations showed the vertical Inverted-Shroud separator has different behavior when compared to its inclined operation, where the free-surface flow characteristic of the IS-separator inclined becomes either in a thin film flow or a cascade-shaped flow depending on the liquid flow rate and the interfacial instabilities. High air entrainment phenomenon and turbulent kinetic energy dissipation were obtained, thus the swarms of bubbles generated in the inner annular channel were larger than the swarms of bubbles seen in the separator inclined. A map of efficiency of gas separation as a function of dimensionless parameters is presented. The higher dimensionless internal annular level, the greater EGS. In addition, the greater liquid flow rates, the lower EGS. The results obtained are in agreement with data reported in the literature.

Keywords: Gas-separation, Inverted-Shroud separator, air entrainment, energy dissipation, swarm of bubbles.

NOMENCLATURE

Acronyms

EGS	Efficiency of gas separation [%]
IS	Inverted-Shroud
SCP	Submerged centrifugal pump
I.A.L.	Inner annular level
E.A.L.	External annular level
I.A.C.	Inner annular channel
O.A.C.	Outer annular channel

Greek symbols

β	IS separator inclination [$^{\circ}$]
ρ	Density [kg/m^3]
μ	Dynamic viscosity [$Pa.s$]
σ	Superficial tension [N/m]

Latin symbols

\dot{m}	Mass flow [kg/h]
Q	Volumetric flow [L/min]
We^*	Modified Weber number [-]

P	Pressure [kPa]
S	Length [m]
V	Velocity [m/s]
L	Length [m]
d	Diameter [m]

Subscripts

g	Gas phase
l	Liquid phase
j	Downstream of the separator
e	Upstream of the separator
fs	Thin film
i	Gas-liquid interface
iah	Internal annular hydraulic
ial	Inner annular level
ch	Swarm of bubbles
cas	Casing

1. INTRODUCTION

The presence of free gas upstream of any pumping system reduces its pumping efficiency, decreasing the production rate and bringing technical problems, such as, parts replacement high frequency and maintenance shutdowns (Rondy *et al.*, 1993; Harun *et al.*, 2000; Souza *et al.*, 2003; McCoy *et al.*, 2007; Bohorquez *et al.*, 2009).

To avoid that free gas reaches the pump, reducing its performance and its lifetime, in the oil industry, *e.g.*, gas separators are installed upstream of the pump in the downhole (Bohorquez *et al.*, 2009). There are different gas separators, depending on the geometry and technique used to the separation process. Among these, centrifugal and Inverted-Shroud gravitational separators stand out. The first ones have high maintenance cost due to the movable parts that make them up, nevertheless, they have better separation efficiencies, but they do not handle high void fraction. On the other hand, studies indicate that gravitational separators with annular geometry show great performance, *i.e.*, efficiency of gas separation (EGS) greater than 97%, without moving parts, thus avoiding production stops for maintenance of the submerged centrifugal pump (SCP) (Rondy *et al.*, 1993; Bohorquez *et al.*, 2009; Ortiz Vidal, 2010; Mendes, 2012; Barbosa, 2016).

Researchers of the Industrial Multiphase Flow Laboratory (LEMI) designed an Inverted-Shroud gravitational separator (IS-separator) composed by a sealed-bottom tube, when it is installed in inclined way, it transforms a chaotic flow into a free-surface flow. The components of the IS-separator are represented in Fig. 1(a).

Developed studies in the IS-separator indicate that it is possible to reach total gas separation provided that it is ensured that the length between the inner annular level (I.A.L.) and the inlet of the production tube is greater than swarm of bubbles generated by the turbulent kinetic energy dissipation in the inner annular channel, *i.e.*, $L_{ial} > L_{ch}$ as shown in Fig. 1(b). Experimental data have been collected in different inclinations respect to the horizontal, as well as analytical models have been proposed to describe the phenomenology of the IS-separator (Ortiz Vidal, 2010; Mendes, 2012; Barbosa, 2016). Thus, the goal of this work is to collect experimental data with the IS-separator in vertical position to evaluate the EGS and to study the influence of the liquid flow rates on the gas-separation process.

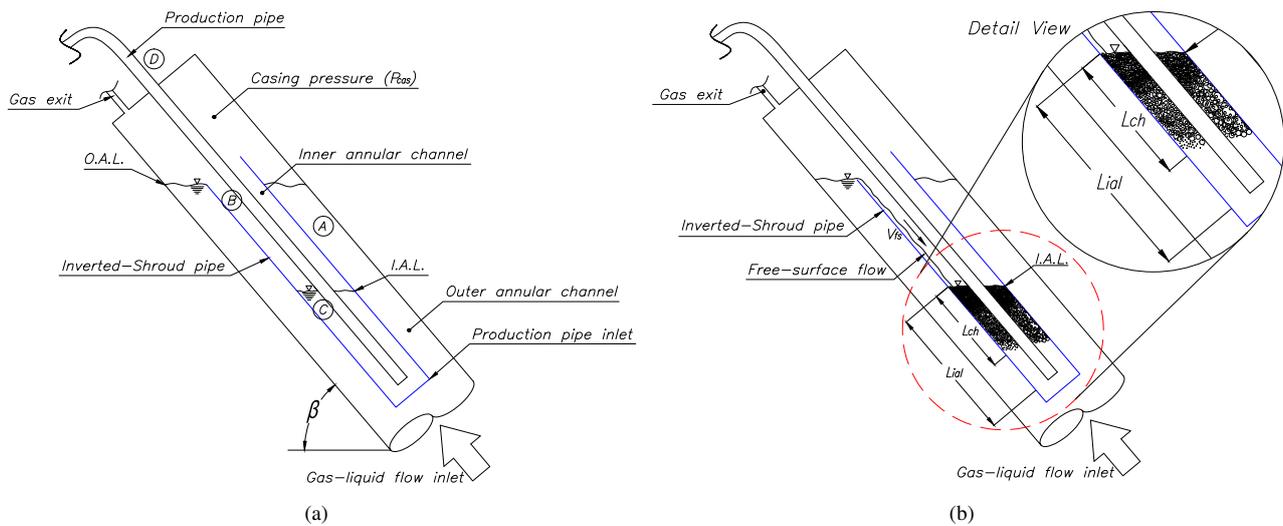


Figure 1. (a) Components of the IS-Separator with different flows (b) Swarm of bubbles generated in the inner annular channel (I.A.C.). Adapted from Ortiz-Vidal *et al.* (2012)

2. EXPERIMENTAL WORK

2.1 Experimental setup

To evaluate experimentally the EGS in an IS-separator in vertical position, the facility shown in Fig. 2 was installed and adapted at LEMI-EESC-USP. The components and measuring instruments that make up this experimental circuit are indicated and listed by letters and numbers in Tab. 1. This installation simulates the operational conditions in the production wells.

The experimental installation consist of a PVC production pipe covered by two concentric borosilicate-glass tubes, an internal pipe called Shroud and an external pipe called Casing, with the configuration showed in Fig 3(a), creating an outer annular channel (O.A.C.) between the casing and the Shroud tubes through which the gas-liquid mixture enters the separator and an inner annular channel (I.A.C.) composed by the Shroud and production pipes, where the process of turbulent kinetic energy dissipation occurs. The length of the IS-separator is 10.50 m. The internal and external diameters of the I.A.C. are 32 mm and 75 mm, while for the O.A.C. are 85 and 105 mm, respectively, *vide* Fig. 3(b).

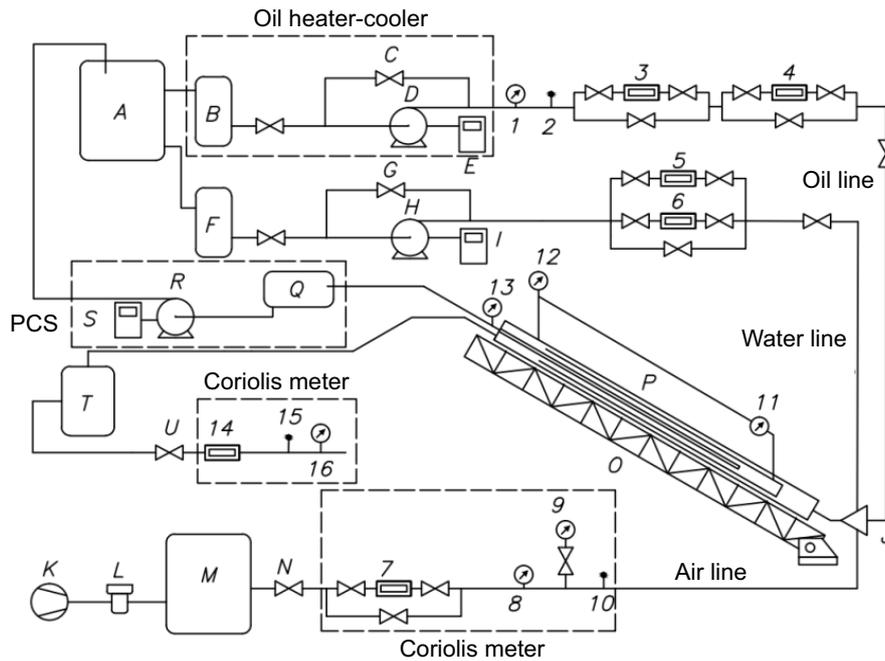


Figure 2. Schematic representation of the IS-Separator installed at LEMI-EESC-USP.

Table 1. Components and measuring instrument of the facility.

Component	Measuring instrument	Range	Accuracy
A Oil/water separator	1 Pressure transducer	0–5 bar	0,25% FE
B Oil reservoir	2 Temperature transmitter	-20–140 °C	0,5 °C
C Oil pump bypass valve	3 Oil flowmeter	0,05–8 L/min	1% FE
D Oil screw pump	4 Oil flow meter	2,5–106,7 L/min	0,5% RD
E Frequency shifter	5 Water flow meter	1–35 L/min	0,75% RD
F Water reservoir	6 Water flow meter	30–1200 L/min	1% RD
G Water pump bypass valve	7 Coriolis meter	0,01– 81.6 kg/h	0,25%RD
H Water screw pump	11 Pressure transducer	1–50 kPa	0,075% spam
I Frequency shifter	12 Pressure transducer	0–5 bar	0,25% FE
J Gas-liquid mixer	13 Pressure transducer	-1–1 bar	0,3% FE
K Air compressor	14 Coriolis meter	0,01– 81.6 kg/h	0,25%RD
L Air filter			
M Air pneumatic tank			
N Flow control valve			
O Steel structure (0-90 °)			
P Test section			
Q Liquid outlet tank			
R Screw pump			
S Frequency shifter			
T Gas-liquid separator			
U Needle valve			
V Heating-cooler system			
W Screw pump			

2.2 Efficiency of gas separation (EGS)

The EGS of the IS-Separator is calculated by the ratio between downstream and upstream air mass flows, Eq. 1.

$$\eta = \frac{\dot{m}_{g,j}}{\dot{m}_{g,e}} \quad (1)$$

Where $\dot{m}_{g,j}$ and $\dot{m}_{g,e}$ refer to the air mass flows downstream and upstream of the IS-Separator, respectively. Both flows are measured experimentally using two Coriolis meters installed on the air line, as indicated by 7 and 14 in Fig. 2.

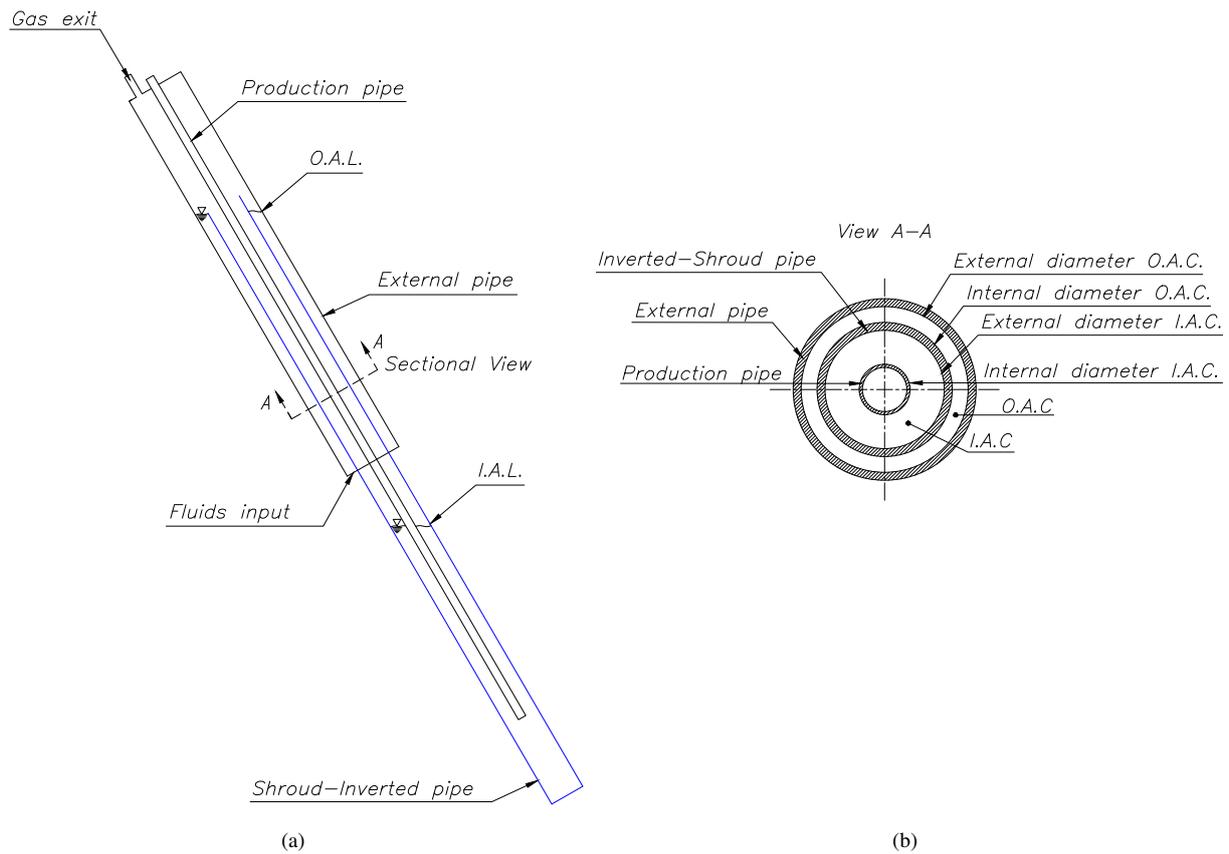


Figure 3. (a) Configuration of the test section (b) Inverted-Shroud separator diameters and annular channels.

2.3 Experimental matrix

According to Ortiz-Vidal *et al.* (2012), EGS is directly related to the I.A.L. position and it is a function of global parameters, such as, liquid flow (Q_l) and IS-Separator inclination (β). In addition, Mendes (2012) reported that EGS is also a function of the liquid-phase viscosity (μ_l). To carry out this work, we propose an experimental campaign in the IS-separator in vertical position, following the experimental matrix showed in Tab. 2.

The liquid and gas flow ranges were defined according to the limit of the installation whereas the separation efficiency ranges were chosen in order to obtain experimental data with low efficiencies, that complement the data collected in the Ortiz-Vidal *et al.*, Mendes and Barbosa's studies, where most of the points gathered correspond to high separation efficiencies, *i.e.*, higher than 90%, once they were focused on reaching the total gas-separation.

Table 2. Experimental matrix proposed for the evaluation of EGS in a vertical IS-separator.

Factor	Limtis	Factor number
Liquid viscosity, (μ_l)	Water (1cP)	1
Air flow upstream, (\dot{m}_e)	2 kg/h	1
Liquid flow, (Q_l)	25, 40, 55 and 75 L/min	4
Separation efficiency*, (EGS)	<50%	8
	50%–75%	
	75%–97%	
	>97%	
Total experimental points		32

* Two experimental points were collected to each range.

2.4 Collection, processing and data analysis

To carry out the experimental campaign, we started the air compressor and the downstream and upstream pumps in parallel by means of the frequency shifters. The air flow regulating valve upstream of the IS-Separator (N, Fig. 2) was actuated until reaching the desired mass flow, the lowest EGS value was defined by closing the air flow regulating valve downstream of the IS-Separator (U, Fig. 2). Once the system achieved the steady-state flow, condition defined by the constant value of the casing pressure (P_{cas}), we collected the first experimental point. After the acquisition time was completed, the separation efficiency was increased, by opening the needle valve downstream of the separator, until reaching a new ESG value according to the experimental matrix. This process was repeated for each liquid flow showed in Tab. 2.

An acquisition program was implemented using a G language of LabVIEW ® 8.6 platform; An acquisition rate of 2500 Hz was chosen to avoid aliasing in reading the signals. We checked in real time some parameters, such as, liquid and gas flows (Q_l , \dot{m}_e), inner and outer annular levels (I.A.L., O.A.L.), efficiency of gas separation (EGS), casing pressure (P_{cas}) and other. All these were adjusted either by the program or manually.

The software Wolfram Mathematica ® was used to process and analyze the data. The mathematical model proposed by Ortiz-Vidal *et al.* (2012) and Mendes (2012) was adapted to our separator geometry and operational conditions describe in Fig. 3(b) and Tab. 2, respectively. In this way, we computed the length of dimensionless internal annular level (L_{ial}/d_{iah}) and the modified Weber number (We^*) given by Eq. 2.

$$We^* = \frac{\rho_l S_i V_{fs}^2}{48\sigma} \quad (2)$$

Where, V_{fs} is the velocity of a thin film flow, S_i is the gas-liquid interfacial length in the inner annular, ρ_l and σ are the liquid density and the superficial tension between the two phases, respectively.

3. RESULTS AND DISCUSSION

3.1 Efficiency of gas separation (EGS)

Aiming at scaling of the IS-separator to field use, the experimental data was represented in a map of efficiency of gas separation as a function of the dimensionless internal annular level length (L_{ial}/d_{iah}) and the modified Weber number (We^*), see Fig. 4. This Figure shows four ranges of the efficiency of gas separation with a variable thickness, where all the tracks have a growing trend with both the dimensionless parameters. We noticed that the highest efficiency values are in the upper region of the chart, *i.e.*, the higher dimensionless internal annular level, the greater EGS. It is explained because of the larger length of L_{ial} , so the bubbles generated by the air entrainment phenomenon and turbulent kinetic energy dissipation inside the IAC must travel a longer path to reach the production pipe inlet, as showed in Fig. 1. However, we realized during the experiments that, even with large L_{ial} , low efficiencies of gas separation were obtained when the liquid flow rates increased, this fact is observed in the central region of the chart where the EGS keeps around 75% for relative large values of L_{ial}/d_{iah} . In these cases, L_{ial} reached values of the order of 8 m depending on the liquid flow rate.

Figure 4 also indicates that the greater We^* , *i.e.*, larger liquid flow rates, the lower EGS, once the drag forces increase taking the bubbles to the entrance of the production pipe. In these cases, we noted that the swarm of bubbles length (L_{ch}) was greater, sometimes with almost the same size of the internal annular level length (L_{ial}). Furthermore, Figure 4 shows that for Weber numbers less than 50, EGS values greater than 50% were obtained. For greater Weber numbers, the EGS dropped to a minimum value of 30%. These results were observed during the experiments and were also reported by Ortiz-Vidal *et al.* (2012), Mendes (2012) and Barbosa (2016).

4. CONCLUDING REMARKS

After this experimental work, we concluded that the efficiency of gas separation (EGS) is related to the inner annular level position (I.A.L), well as it is a function of the liquid flow rate. Experimental results showed that, depending on the operational conditions, the Inverted-Shroud separator in vertical position has efficiency of the order of 30%, nevertheless, large lengths of L_{ial} solve this problem, increasing costs in the design and installation of the separator. According to observations during the experiments, the vertical IS-separator works completely different when compared to its operation in the inclined position. Both the air entrainment phenomenon and the turbulent kinetic energy dissipation are greater in the vertical IS-separator than in the inclined position. Furthermore, the drag forces increases have an important role in the EGS once they take the bubbles to the production pipe inlet and there is no effect of the radial component of gravity.

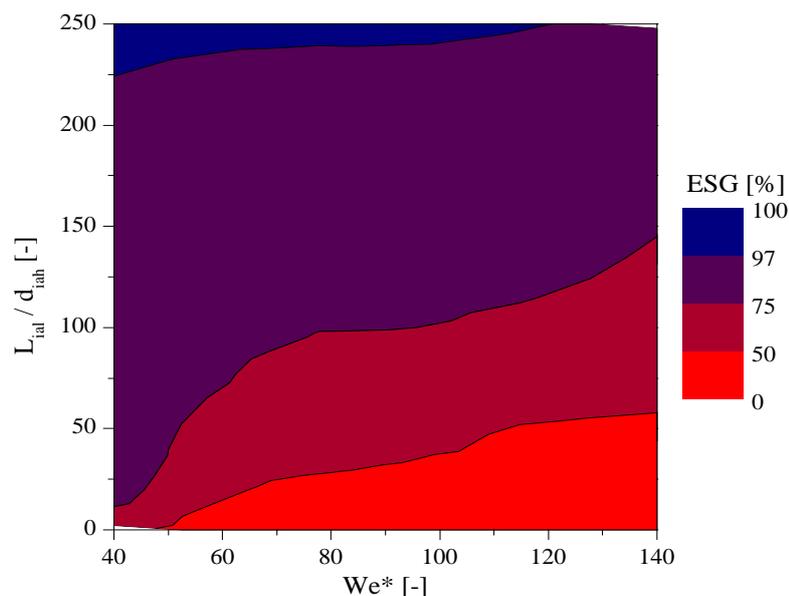


Figure 4. Variation of the efficiency of gas separation with the dimensionless internal annular level and modified Weber number.

5. ACKNOWLEDGEMENTS

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