Numerical Simulation of Single-Phase and Two-Phase Flows in Separator Vessels with Inclined Half-Pipe Inlet Device Applied in Reciprocating Compressors

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Abstract—**This paper aims to apply computational fluid dynamics (CFD) to simulate air flow and air flow with water droplets, as a reasonable hypothesis for real flows, in order to evaluate a vertical separator vessel with inclined half-pipe inlet device (slope inlet). Thus, this type was compared to a separator vessel without inlet device (straight inlet). The results demonstrated a different performance for the two types in terms of air distribution and liquid removal efficiency.**

Keywords-inlet device; separator vessel; computational fluid dynamics; reciprocating compressor; single and two-phase flow

I. INTRODUCTION

The reciprocating compressor is widely used in industry, being an important machine to compress all gas types. However, the liquid fraction ingestion is one of the main causes of unavailability problems due to the "liquid hammer effect" that increases, quickly, the loads in the piston, piston rod, connection rod, crosshead, crosshead pin and other parts. As result, it can lead to their mechanical failure. According to [1], liquid can enter the compressor cylinder due to the impurity from other systems, the gas condensation in the suction piping or by handling low boiling point gas or wet gas during compression process. This context motivated the API-618 code (reciprocating compressors for petroleum, chemical and gas industry services) to recommend the use of separator vessels, in the suction of first stage and between stages, for removing 99% of droplets of 10µm or larger since the dispersed flow (or mist flow) is the most typical standard flow present in compressor unit. Therefore, separator vessels have two important devices in order to capture all droplets through the gravitational deposition and inertial impaction mechanisms. The first, called inlet device, minimizes the droplet shearing, improves the downstream gas velocity distribution and, thus, maximizes the liquid removal efficiency, mainly in the gravitational deposition area [2]. The second, known as mist eliminator (or demister), removes the droplets in three steps: inertial impaction, coalescence and detaching of the droplets from the surface of wire due to the gravitational force [3]. This paper investigated numerically a vertical separator vessel, with inclined half-pipe inlet device and wire mesh mist eliminator, through single-phase and two-phase simulations, and finally the results were compared to a vertical separator vessel without inlet device and the same design of wire mesh mist eliminator.

II. MATERIALS AND METHODS

A. Governing Equations

The following equations were used in the mathematical model of the numerical simulation [4]. The mass equation can be described as:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho U) = 0 \tag{1}$$

where ρ (kg/m^3) is the fluid density, U (m/s) is the fluid velocity and t is time. The momentum equation is:

$$\frac{\partial}{\partial_t}\left(\rho U\right) + \nabla(\rho U U) = -\nabla P + \nabla \tau + F \tag{2}$$

where τ (N/m²) is the viscous stress tensor, F (N) is the air-water droplets interaction force and P (Pa) is the air pressure.

B. Souders-Brown Equation

This equation is the most common method to sizing separator vessels and can be defined by the force balance applied on a droplet in an upwards-flowing in a fluid field, as described (Figure 1) [5].

$$v_{\max.} = K \cdot \sqrt{\left(\frac{\rho_l - \rho_{air}}{\rho_{air}}\right)} \tag{3}$$

where K(m/s) is the separation factor (or Souders-Brown velocity), ρ_l and (kg/m³) ρ_{air} are the water and air density respectively and v_{max} is the maximum air velocity. Maximum air velocity from (3) can be used to define the internal diameter of the separator vessel for the proposal air flow. The other dimensions (length and nozzles) were defined by practical methods from reciprocating compressors manufacturers.

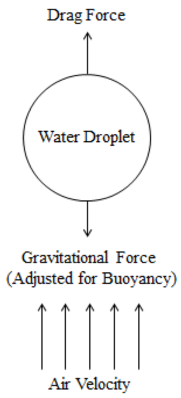

Fig. 1. The forces acting on a droplet in a upwards-flowing

C. *CFD Modeling*

The commercial CFD package ANSYS® CFX 15 was used in the present study, for solving the governing equations and the geometry was made in computer-aided design (CAD) software. A PC processor with four cores was used, with 3.4GHz processor frequency and 8GB RAM. The typical run times were around 7h. The mesh generated has unstructured tetrahedrons grids with 1,115,883 nodes and an inflation was considered close to the surface of the fluid volume to capture the details of the flow. The gas phase was taken to be air, with ρ_{air}=1.07kg/m³, q_{air}=0.07m³/s and T_{air}=25ºC. The liquid phase was assumed to be water and, thus, it was considered m_{water}=2.78E-3kg/s. 1,000 water droplets were divided in five diameters: 10µm, 50µm, 100µm, 150µm and 200µm. For the air and water droplets flow, the restitution coefficient was 0.15 for perpendicular collision and 0.30 for parallel collision. The values were defined based on the Weber number according to [6]. Figure 2 shows the separator vessel used in the CFD simulation for the present work.

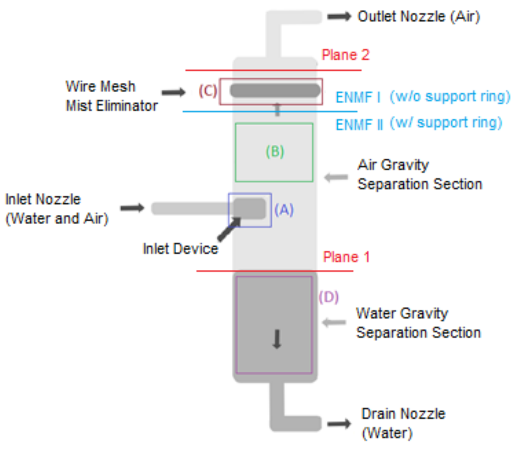

Fig. 2. The separator vessel sized for the CFD simulation

The study concentrated in the open space between "Plane 1" and "Plane 2" (Figure 2). Thus, the wire mesh mist eliminator was included in the modeling as a porous body with a resistance factor that lead to a pressure drop according to Hazen-Dupuit-Darcy equation [7].

$$\frac{\Delta P}{h} = \frac{\mu}{K} \cdot v + C \cdot \rho \cdot v^2 \qquad (4)$$

where ΔP (Pa) is the pressure drop, h (m) is the mist eliminator thickness, ρ is the air density and K and C are dimensionless coefficients (obtained experimentally). Figure 3(a) shows the computational domain for a separator vessel without inlet device and Figure 3(b) shows the computational domain for the same separator vessel, but with inclined half-pipe inlet device.

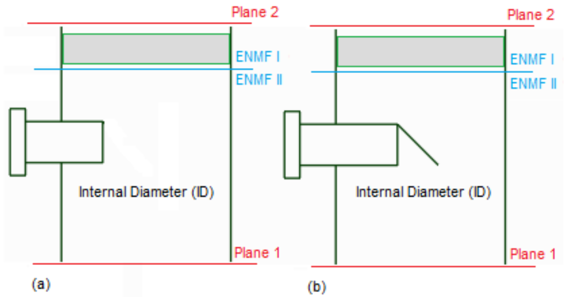

Fig. 3. Computacional domain for a separator vessel: (a) without inlet device and (b) with inclined half-pipe inlet device.

The dimensions of the vessel are described in Table I and the boundary conditions used in the CFD simulation are described in Table II.

TABLE I. DIMENSIONS OF THE MODEL

Dimension (Figure 3)	**Value**	**Unit**
Internal Diameter	400	mm
"Plane 1" to "Plane 2"	887.32	mm
"Plane 1" to "ENMF I"	700	mm
"Plane 1" to "ENMF II"	712.32	mm

TABLE II. BOUNDARY CONDITIONS

Boundary	**Position**	**Boundary Condition**
Inlet	Cross section through the inlet nozzle	Uniform velocity profile, turbulence model (k-ε)
Outlet	Cross section of the separator vessel, some space above the packing bed (Plane 2 of Figure 3)	Free outlet
Water Sump	Liquid surface considered flat (Plane 1 of Figure 3)	No shear
Wall	Vessel wall and nozzle wall	Adiabatic for mass and energy.
Porous Body	Plane ENMF I or ENMF II	Pressure Drop Model

III. SIMULATION RESULTS AND DISCUSSION

A. Effect of the Inlet Device on Uniformity of Air Flow

The profile of air velocity was numerically determined for both types of separator vessels. The first type is the vessel without the inlet device, also called straight inlet, and the second type is the vessel with the inclined half-pipe inlet device, also called slope inlet. In this step of simulation, the support ring, used to assembly the wire mesh mist eliminator in the vessel, was not considered. Thus, the vessel section has 400mm internal diameter, being the plane "ENMF I" (Figure 3) the aimed section to evaluate the air distribution. Figure 4 shows the air vertical velocity for the two types of separator vessels.

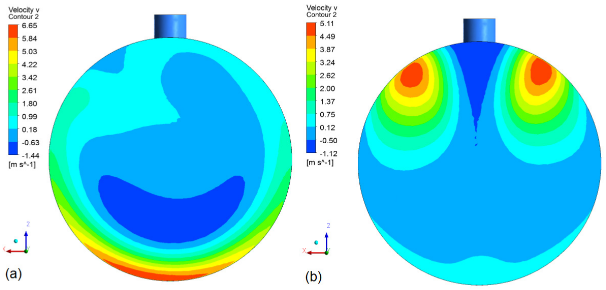

Fig. 4. Distribution of the air vertical velocity in the section "ENMF I" placed 10.32mm below the wire mesh mist eliminator for: (a) the straight inlet and (b) the slope inlet.

It is clear that both types presented a concentrated air flow along the wall which created a non-uniform air flow. However, it is necessary to quantify this distribution by the variation coefficient, widely used in the chemical process industries to evaluate structured, unstructured packing and distributor, with the following equation [8-10]:

$$C_V = \left[\frac{1}{A_t} \sum_{i=1}^{N} A_i \left(\frac{u_i - \bar{u}}{\bar{u}} \right)^2 \right]^{0,5} \qquad (5)$$

where C_v (dimensionless) is the variation coefficient, N is the number of the cells, A_i (m²) is the area of the cell i, A_t (m²) is the total area of the transversal section, ui (m/s) is the air velocity in cell I and $\bar{u}$ is the average air velocity:

$$\bar{u} = \frac{1}{A_t} \sum_{i=1}^{N} A_i u_i \qquad (6)$$

The obtained variation coefficients were 2.67 and 2.34 for the straight and slope inlet respectively. Thus, the results showed that the vessel with the inclined half-pipe inlet device (slope inlet) allowed a slightly better air distribution compared to the straight inlet. However, both types presented a high air velocity in some areas, above the limit of 3.25m/s (3). This condition is undesirable for phase separation.

B. Effect of the Support Ring on Uniformity of Air Flow

Figure 5 presents the air vertical velocities for the separator vessels considering the support rings of wire mesh mist eliminators. It can be observed that maximum velocities decreased, but the straight inlet obtained a lower value compared to the slope inlet. The variation coefficients were 0.34 and 0.81 for straight and slope inlet, respectively. Thus, it is clear that the support rings influenced the air distribution, mainly for the straight inlet due to the deviation of the air flow along the wall. The air velocity in the straight inlet remained below the limit of 3.25m/s. Therefore, this configuration presented better results for the two parameters: air distribution and good condition for phase separation.

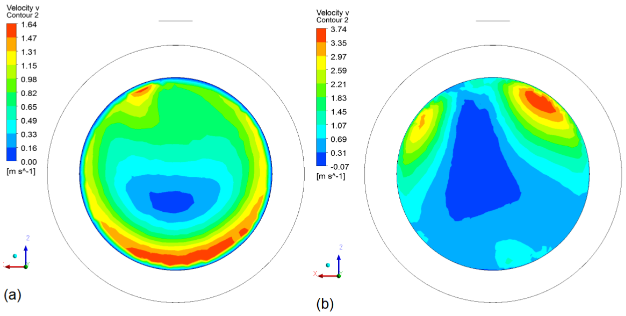

Fig. 5. Distribution of the air vertical velocity in the section "ENMF II" placed 1.0mm below the wire mesh mist eliminator for: (a) the straight inlet and (b) the slope inlet.

C. Effect of the Inlet Device on Liquid Removal Efficiency

The path lines of water droplets for two kinds of inlets were determined by CFD analysis and the results are shown in Figure 6. As observed, the slope inlet removed almost all water droplets above 10μm due to the coalescence of them in the bottom of the vessel. Table III shows a lower number of droplets escaped for the vessel with slope inlet. It is important to explain that the number of droplets that escaped, described in Table III, represents the phase separation in the sections "A" and "B" in Figure 2. In real conditions, the remained droplets will be removed by the wire mesh mist eliminator.

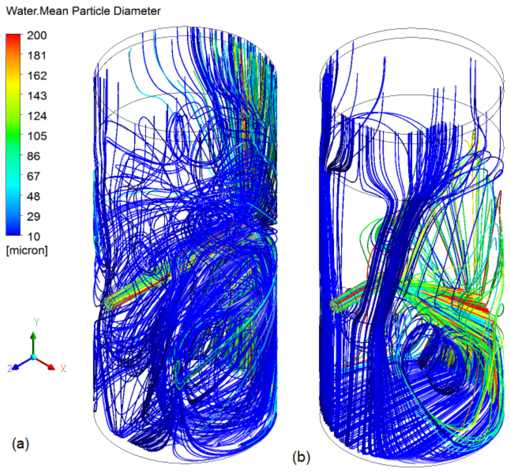

Fig. 6. The path lines of the water droplets for: (a) the straight inlet and (b) the slope inlet.

TABLE III. NUMBERS OF WATER DROPLETS THAT ESCAPED FROM THE SEPARATOR VESSELS

Droplet Diameter	Numbers of Water Droplets (Straight Inlet)	Numbers of Water Droplets (Slope Inlet)
10 μm	121	152
50 μm	48	0
100 μm	17	1
150 μm	8	0
200 μm	2	0
Total	196	153

D. Effect of the Inlet Device on Liquid Removal Efficiency

The slope inlet presented a better efficiency compared to the straight inlet (Table IV).

TABLE IV. LIQUID REMOVAL EFFICIENCY FROM THE SEPARATOR VESSELS

	Water Mass Flow (Straight Inlet)	Water Mass Flow (Slope Inlet)
Input (kg/s)	2.78E-3	2.78E-3
Output (kg/s)	5.45E-4	4.25E-4
Removed (kg/s)	2.23E-3	2.35E-3
Efficiency (%)	80.38	84.69

E. Effect of the Support Ring on Liquid Removal Efficiency

The liquid removal efficiency of the slope inlet was increased after the inclusion of the mist eliminator support ring (Table V).

TABLE V. LIQUID REMOVAL EFFICIENCY FROM THE SEPARATOR VESSELS WITH SUPPORT RINGS.

	Water Mass Flow (Straight Inlet)	Water Mass Flow (Slope Inlet)
Input (kg/s)	2.78E-3	2.78E-3
Output (kg/s)	2.67E-4	1.92E-4
Removed (kg/s)	2.51E-3	2.59E-3
Efficiency (%)	90.39%	93.09%

IV. CONCLUSIONS

In this study, CFD simulation was employed to simulate an air flow through the separator vessels with straight inlet and slope inlet (or with inclined half-pipe inlet device). The results showed that the uniformity of air flow and the liquid removal efficiency in a separator vessel were affected by the inlet device and the support ring of the mist eliminator. The slope inlet improved the liquid removal efficiency in the air gravity separation section. In the other hand, the straight inlet had a better air distribution with a suitable vertical velocity for phase separation. In this type of vessel, the internal diameter may be minimized since the air velocity (1.64m/s) stayed below the limit of 3.25m/s. The obtained results showed that the computational fluid dynamics is an important approach to evaluate the performance of separator vessels.

REFERENCES

[1] B. G. S. Prasad, "Effect of Liquid on a Reciprocating Compressor", Journal of Energy Resources Technology, Vol. 124, No. 3, pp. 187-190, 2002

[2] M. Bothamley, "Gas/Liquid Separators: Quantifying Separation Performance - Part 1", Society of Petroleum Engineers, Vol. 2, No. 4 2013.

[3] H. T. El-Dessouky, I. M. Alatiqi, H. M. Ettouney, N. S. Al-Deffeeri, "Performance of wire mesh mist eliminator", Chemical Engineering and Processing: Process Intensification, Vol. 39, No. 2, pp. 129-139, 2000

[4] F. M. White, Viscous fluid flow, McGraw-Hill, Inc., 1991

[5] M. Souders, G. G. Brown, "Design of Fractionating Columns I. Entrainment and Capacity", Industrial & Engineering Chemistry, Vol. 26, No. 1, pp. 98-103, 1934

[6] B. P. V. D. Wal, Static and Dynamic Wetting of Porous Teflon® Surfaces, Department of Polymer Chemistry, University of Groningen, Nova Zelândia, 2006

[7] T. Helsør, H. Svendsen, "Experimental Characterization of Pressure Drop in Dry Demisters at Low and Elevated Pressures", Chemical Engineering Research and Design, Vol. 85, No. 3, pp. 377-385, 2007

[8] S. R. Darakchiev, "Gas flow maldistribution in columns packed with HOLPACK packing", Bulgarian Chemical Communications, Vol. 42, No. 4, pp. 323–326, 2010

[9] Z. Olujic, "Comparison of Gas Distribution Properties of Conventional and High Capacity Structured Packings", Chinese Journal of Chemical Engineering, Vol. 19, No. 5, pp. 726-732, 2011

[10] T. Petrova, N. V. Bancheva, S. Darakchiev, R. Popov, "Quantitative estimates of gas maldistribution and methods for their localization in absorption columns", Clean Technologies and Environmental Policy, Vol. 16, No. 7, pp. 1381-1392, 2014