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Vianney Atim-Kokondji, Sofiane Khelladi, Florent Ravelet, Farid Bakir, Robert Yu. Performance assessment of an horizontal air / water separator deflector with low volume fraction of air. 2013. hal-00804447

HAL Id: hal-00804447

<https://hal.science/hal-00804447>

Submitted on 25 Mar 2013

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Performance assessment of an horizontal air / water separator deflector with low volume fraction of air

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Abstract

The purpose of the present work is to study the performance of a separator deflector for specific applications under severe constraints of size and low costs. This device separates air and water in an horizontal flow. The efficiency of the separator is defined as the ratio of the mass flow rate of air separated from the liquid and the mass flow rate of air at inlet. The effects of the tilt angle of the deflector and of the absolute inlet pressure are compared for various mixture velocities and air volumetric concentrations. The efficiency strongly depends on the horizontal two-phase flow regime and on the inlet pressure. There exists a unique optimal tilt angle of the deflector for all flow-regimes. The experiments are supplemented with numerical simulations that allow to better understand the flow patterns in the separator. Through this analysis, it is demonstrated that two parameters are needed to fully characterize the performances of the separator. Moreover, it is shown that there exists only one design point where the separator is very efficient and that it is very sensitive to small variations around this design point.

Keywords: Two-phase horizontal flow, Two-phase separator, Separator deflector, Two-phase flow regime.

1. Introduction

The problem of phase separation in a gas / liquid two-phase flow—in particular air and water—is a tremendous issue in many industrial applications. This technological challenge often directly affects the operation of mechanical systems and has an impact on the performance of related processes. Separation of multiphase flows in an industrial process may be intrinsic to the system, as in the offshore and chemical industry where often only one phase represents a market value. In other cases, the presence of two-phase flow is the result of phase changes due to rapid modifications of the thermodynamical operating conditions of the process, such as the cavitation and degassing phenomena.

Until the 1980s, most technologies of separation were based on gravity. Considerations of compactness and cost reduction, especially in the offshore industry, have led to the development of compact active separation processes. For instance, the works of Nebrensky et al. (1980), Kouba et al. (1995), Movafaghian et al. (2000) and Rosa et al. (2001) widely contributed to the development of the cyclone separator. Other examples of active separation devices have been studied by Muschelknautz and Mayinger (1990) (separator with wheels) and Gregory (1989), Entress et al. (1991) and Creutz and Mewes (1999) (separation by the action of a centrifugal pump).

To date, these technologies are essentially intended for offshore and chemical applications, in steady flow with high mixture velocity. High economical value of the product are necessary to justify the use of strongly mechanical energy consuming technologies.

Specific applications appeared recently that deal with intermittent two-phase flows with low mixture velocities under severe constraints of compactness. In aeronautics, there are sometimes vapor in the fuel system, which can reduce the pump efficiency and more generally the mechanical propulsion system. The present work directly concerns the automotive sector. The recent years have been marked by the development of various technologies of improvement of the automotive engines efficiency, among which various processes of valuation of calories contained in the cooling liquid: two-phase cooling, starting up without liquid cooling, starting at useless flow, emptying and filling of the engine,...

For some of these applications, it is necessary to purge the cooling circuit to ensure the smooth operation of the engine. The design of two-phase separators in this context have to be completely rethought to adapt to the new constraints of the environment of use. For flows at low velocity and low proportion of air, most authors have focused on the separation of air-water flow in Y and T-junction as, for instance, Honan and Lahey (1981); Hwang et al. (1988) who worked on turbulent flows in bubbly and churn-flow regimes, or Azzopardi and Whalley (1982) who studied annular flow in T-junctions for horizontal and vertical directions.

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Another device that can be used is the compact separator deflector. It consists of a diverging and converging chamber equipped with an adjustable deflector. One advantage is a low-pressure drop, a low volume and the use of one or more traps for extraction of air out of the mixture. It is of great interest in the following situations:

- The compactness and weight are of particular importance, which excludes the use of separation pumps. This is the case of embedded systems in aeronautics and more recently in the automotive industry;
- The dynamic instabilities and vibrations inherent in moving devices do not allow the use of a cyclone separator.

This paper proposes to evaluate numerically and experimentally a compact separator with deflector in horizontal air-water flow with low volume proportion of air. The main phase that is water flows at a superficial velocity between 1 m.s^{-1} and 3 m.s^{-1} and the volume quality of air is between 1% and 4%. The performance of the separator is defined as its ability to separate air from water. It is evaluated with two coefficients that measure respectively the air flow-rate in the purge and the water flow-rate in the main outlet relatively to the inlet flow-rates. The effects of the angle of the deflector and of the inlet pressure are experimentally studied in a dedicated test bench. This was built on purpose in order to explore various air-water two-phase flow regimes in horizontal configuration. Numerical simulations that give details on local quantities are also performed.

The concept and design of the separator deflector is first described in § 2. Then the performance assessment tools are presented in § 3: the experimental set-up is detailed in § 3.1, the control parameters are introduced in § 3.2, the numerical methods are then presented in § 3.3 and the two coefficients that characterize the performances are defined in § 3.4. The experimental results are presented in § 4. The main results are finally discussed in § 5.

2. Separator deflector: description and operation

2.1. Phase separation in two-phase horizontal flow

Several studies of air-water two-phase flow separation in horizontal configurations (for instance the works of Homan and Lahey, 1981; Azzopardi and Whalley, 1982; Saba and Lahey, 1983; Hwang et al., 1988) have shown that the separation process strongly depends on two physical mechanisms. It first depends on the two-phase flow regime (see, e.g. Hetsroni, 1982; Andreussi et al., 1999). It also depends on the turbulent processes that control the bubble size distribution (see, e.g. Kolmogorov, 1949; Thomas, 1981; Razzaque et al., 2003). And finally, the details of the separator geometry (Y or T-junctions,...) have a strong influence on the separation process.

The flow regimes that are relevant to the application considered hereafter are characterized by the presence of

air plugs or bubbles that are mainly localized in the upper part of the pipe (Hetsroni, 1982; Andreussi et al., 1999). Saba and Lahey (1983) and Hwang et al. (1988) have developed a model for phase separation based on the concept of “dividing streamlines” between “zones of influence”. The principles of operation of the separator deflector that is sketched in Fig. 1 benefit from these ideas.

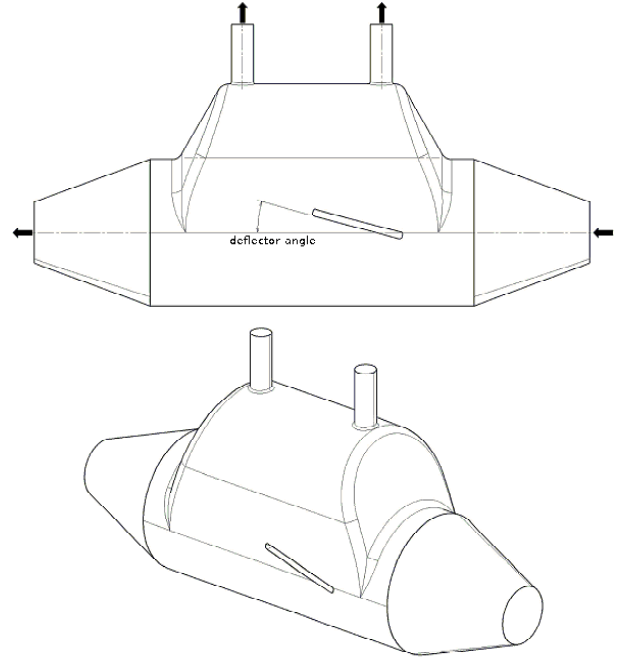


Figure 1: Sketch of the separator. The angle of inclination of the deflector is θ .

2.2. Principle of the separator deflector

The separator deflector consists of a gradual expansion at flow inlet, a deflector on the axis of the pipe, two traps with smaller diameter at the top of the separation chamber and a converging pipe at the flow outlet. The process of separation within the separator deflector combines three mechanisms. First, the traps are situated in the upper part in order to extract air mainly by buoyancy. Then, the gradual increase of the inlet section of the separator results in a decrease of flow velocity. The balance of the forces that act on a bubble is first changing to the benefit of buoyancy. The work of Razzaque et al. (2003) on the distribution of bubble size in horizontal air-water flow have moreover shown the predominant role of coalescence when the flow velocity declines: within the separator, the decrease in flow velocity promotes the coalescence of bubbles and their rise to traps because of enhanced buoyancy. Finally, the inclination of the deflector should create a slight pressure drop that would increase the flow rate in the traps and should create recirculation zones within the separator. The local recirculations may trap air bubbles and help in reducing the active length of the separator. Therefore, the volume of a separator deflector is relatively low.

3. Performance assessment tools

3.1. Test bench

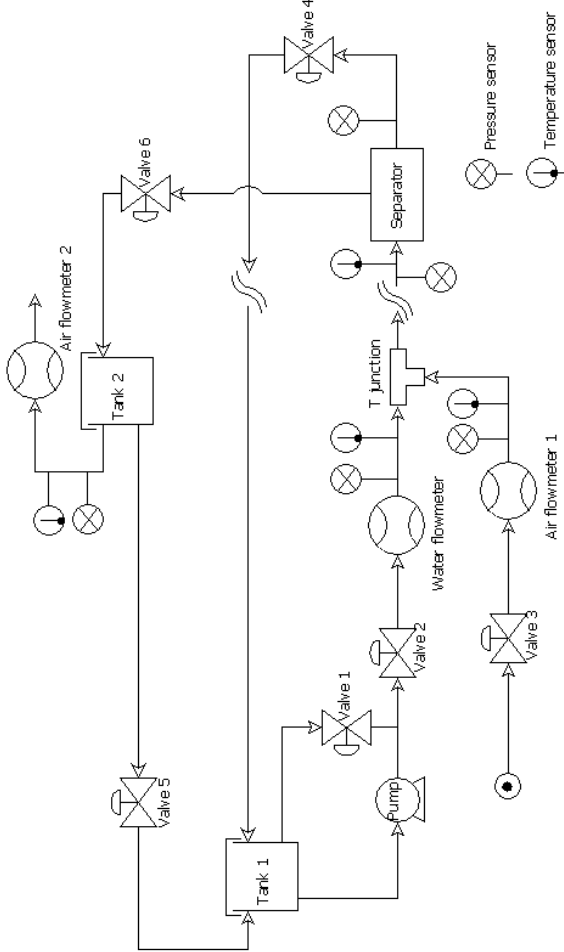


Figure 2: Sketch of the test loop (see § 3.1 for details).

The experimental set-up consists of a closed loop made of pipes of diameter $D = 26$ mm, designed for air-water two-phase flow in which different separators can be included. The test loop is sketched in Fig. 2. The water is moved from the main tank (Tank 1, of capacity 60 L) by a centrifugal pump controlled by an inverter (not shown in the sketch). The water then flows in a tube of diameter $D = 26$ mm where the water volume flow-rate $Q_{w,up}$ is measured.

Air is injected through a tee of diameter 26 mm with several calibrated air inlet passages of diameter 1 mm. A valve and an air flow-meter upstream of the tee are used to set the air volume flow-rate $Q_{air,up}$. The temperature $T_{air,up}$ and the pressure $P_{air,up}$ are also measured, with, respectively a K-type thermocouple and a 4 bars relative pressure transducer.

The injection of air is situated 2 m upstream of the separator. At the inlet of the separator, the pressure P_{in} and the temperature T_{in} are measured. The loop then splits into two branches: a return line to Tank 1 and a branch for the separated flow (purge). This last branch consists of two traps of diameter 9 mm at the top of the separator that are connected to Tank 2, of capacity 20 L. This tank allows a complete separation necessary to measure the air volume flow-rate $Q_{air,purge}$ and the water volume flow-rate $Q_{w,purge}$ in the purge. The air flow is discharged into the atmosphere. The pressure and temperature $P_{air,purge}$ and $T_{air,purge}$ are also measured at this point. The water volume flow-rate in the purge is measured by closing Valve 5 and by watching the time required to fill the tank with 2 L. Otherwise the water returns by gravity from Tank 2 to the main tank (Tank 1).

The pressure at the outlet of the separator P_{out} , on the return line, is also measured. Valve 4 is used to adjust the pressure in the separator.

3.2. Control parameters and operating conditions

The two-phase flow of air and water that enters the separator is characterized by a given pair of mass flow-rates of air and water:

$$(M_{air}; M_w)$$

In the present article, the following equivalent parameters are used:

- The water superficial velocity J_w ;
- The volume quality of air in the mixture β_{in} .

The water superficial velocity is the flow velocity that water would have if it were flowing alone in the pipe. The variations of the density of water ρ_w with temperature are negligible. Thus $Q_{w,in} = Q_{w,up} = M_w/\rho_w$, and:

$$J_w = \frac{Q_{w,in}}{(\pi D^2/4)}$$

The volume quality β depends on the position in the pipe. The density of air indeed varies with the pressure and thus the volume flow-rate of air is not constant. Nevertheless, the air volume flow-rate at the inlet of the separator can easily be computed from the measured volume flow-rate upstream of the tee junction $Q_{air,up}$, assuming the air behaves as a perfect gas. At the separator inlet:

$$\beta_{in} = \frac{Q_{air,in}}{Q_{air,in} + Q_{w,in}}$$

In the present study, the separator performance is studied for the following parameters:

- Three water superficial velocities: $J_w = 1, 2$ and 3 m.s^{-1} ;
- Four volume quality: $\beta_{in} = 1, 2, 3$ and 4% ;

- Angle of the separator deflector: $\theta = 45^\circ$;
- Three levels of absolute pressure at the separator inlet for $J_w = 2 \text{ m.s}^{-1}$: $P_{in} = 1.17, 1.24$ and 1.63 bars.

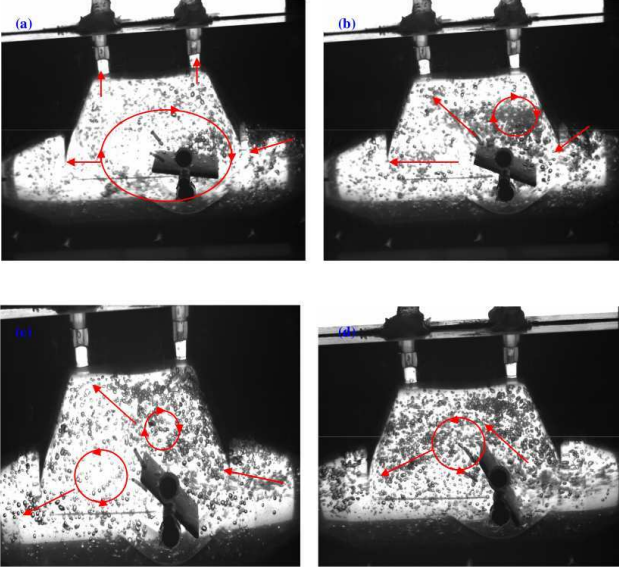


Figure 3: Two-phase flow inside the separator deflector for $J_w = 2 \text{ m.s}^{-1}$ and $\beta_{in} = 1\%$. Deflector angle: (a) $\theta = 15^\circ$, (b) $\theta = 30^\circ$, (c) $\theta = 45^\circ$ and (d) $\theta = 60^\circ$.

The angle of the separator deflector has been chosen after a few tries. Four pictures of the two-phase flow in the separator for the same conditions but with four different deflector angles are displayed in Fig. 3. The angle $\theta = 45^\circ$ leads to optimal separation. For this angle the flow is deflected towards the purges and one can moreover observe the presence of a recirculation loop in the shape of a vortex, close to the inlet of the separator that may enhance the residence time and the coalescence of bubbles. For lower deflector angles, a large amount of bubbles flow beyond the deflector, whereas for larger deflector angles the backflow recirculation disappears.

A multiphase flow in a pipe can exhibit several flow patterns that differ in the spatial organization of the phases. In the case of gas / liquid cocurrent horizontal flow, several flow maps exist and a general method of flow patterns prediction has been developed by Taitel and Dukler (1976). According to this prediction, the present parameters are very close to the transition between bubbly flow and intermittent flow (plug or slug). It is thus very difficult to tell precisely what the flow-regime at separator inlet is, especially since the flow regime may strongly depends on the length of establishment ($80 D$ in the present case). Nevertheless, for $J_w = 2$ and $J_w = 3 \text{ m.s}^{-1}$, the prediction is that the flow should be bubbly and for $J_w = 1 \text{ m.s}^{-1}$ it may be intermittent.

Visualizations with a high-speed camera just before the flow separator inlet may help to clarify this point. Three pictures are shown in Fig. 4.

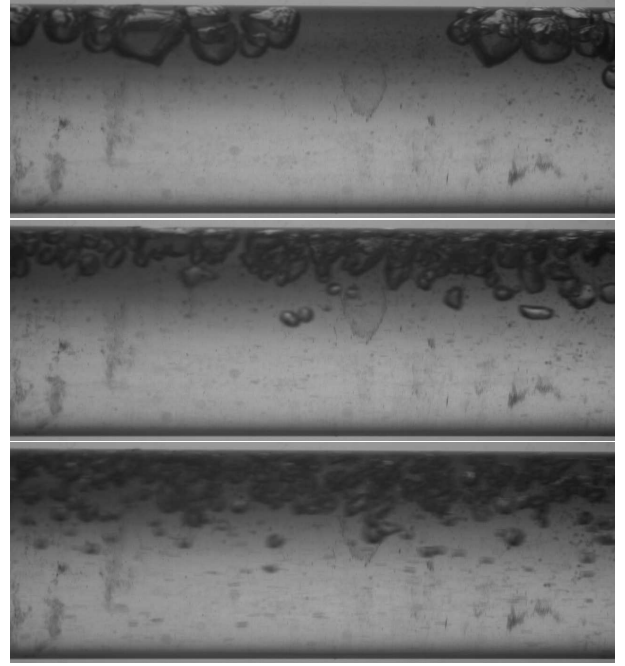


Figure 4: Picture of the flow just upstream of the separator inlet. $J_w = 1 \text{ m.s}^{-1}$ and $\beta_{in} = 2\%$: slug flow. $J_w = 2 \text{ m.s}^{-1}$ and $\beta_{in} = 2\%$: bubbly flow. $J_w = 3 \text{ m.s}^{-1}$ and $\beta_{in} = 2\%$: bubbly flow.

For a low fluid velocity of $J_w = 1 \text{ m.s}^{-1}$ and a low air volume quality $\beta_{in} = 2\%$ (Fig. 4, top), the flow resembles a slug flow regime, with large air pockets that are located mostly at the upper half section of the pipe. Increase the flow velocity actually results in a transition to a dispersed regime with small bubbles that are still concentrated in the upper half part of the pipe (Fig. 4, bottom), as reported by Thomas (1981) and Simmons and Azzopardi (2001).

3.3. Numerical approach

The aim of the numerical simulations presented here is to allow a qualitative analysis of the phenomenon of separation in view of the optimization in future design process. The quantitative analysis of the effects of the water superficial velocity, the inlet volume quality and of the inlet pressure is based on the experimental results.

The numerical analysis of the fluid flow into the separator is based on the Volume of Fluid (VOF) model. This multiphase model is based on an Eulerian approach particularly adapted to this kind of systems since it gives access to the spatial repartition of the phases. The phases are considered immiscible in the present case.

The recommendations for this type of numerical analysis are widely discussed in the literature, (see, e.g. Hirt and Nichols, 1981; Scardovelli and Zaleski, 1999). In the present case, the geo-reconstruct method is used for the phase interface representation. This method is derived from the Piecewise Linear Interface Calculation (PLIC) method (Youngs, 1982). A standard $k - \epsilon$ model for the turbulent flow modelling is used. The only volume force acting on the separator is gravity.

Solver parameters - The CFD solver is FLUENT (Fluent Inc., 2006). The time scheme is 2nd order implicit, with a time step of 0.001 s corresponding to a CFL number close to 0.25. The spatial scheme is a 2nd order upwind scheme for the momentum equations and the pressure-velocity coupling is addressed with a transient PISO algorithm.

Inlet boundary condition - The inlet boundary condition consists of a “velocity inlet” with a spatial distribution of the air fraction that best mimics the experimental observations of Fig. 4. This spatial distribution is imposed through the use of a partition of the inlet boundary into two parts.

Outlet boundary conditions - The outlet boundaries are of “pressure outlet” type: the static pressure is imposed at these boundaries.

Meshing - The computational grid is presented in Fig. 5. The mesh is of hybrid type, with structured cells upstream and downstream of the separator deflector and unstructured cells in the bulk of the separator zone. A grid convergence test has been performed: the final grid contains 10⁶ cells.

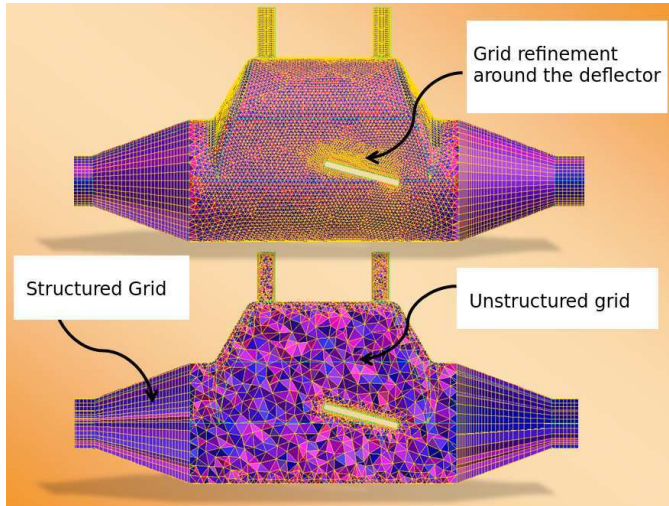


Figure 5: 3D mesh used for the numerical simulations.

3.4. Definition of the performance of a separator

A two-phase separator consists of one inlet and two outlets. A mixture of air and water flows through the inlet and in an ideal case, all the air would flow out through one outlet (the purge) and all the water would flow out through the other outlet (the main branch). Owing to this remark, we introduce *two* quantities that will characterize the overall performance of a separator. The first one is called the *efficiency* and is of classical use in the Literature. The second one is called the *water conservation coefficient* and is not usually considered.

The efficiency is the ratio of mass flow-rate of purged air to the mass flow-rate at inlet:

$$\epsilon = \frac{M_{air,purge}}{M_{air,in}}$$

This efficiency only considers the air flow in the purge. It varies between 0 and 100%. One can imagine two situations where all the air would flow through the purge, leading to an efficiency $\epsilon = 100\%$: one where no water would flow through the purge, and the other one where all the water would flow through the purge. The second separator is obviously of extremely poor performance. For this reason, we introduce the water conservation coefficient W_{con} that vary between 0 and 100%. This quantity is the symmetric of the efficiency, with air \rightarrow water and purge \rightarrow outlet: it is a measure of the water mass flow-rate in the main branch relative to the water mass flow-rate at inlet.

$$W_{con} = 1 - \frac{Q_{w,purge}}{Q_{w,in}}$$

This last quantity is of great interest for the specific automotive application, where the purge is connected to an expansion tank of limited capacity.

4. Results

4.1. Effects of the flow velocity and of the inlet volume quality

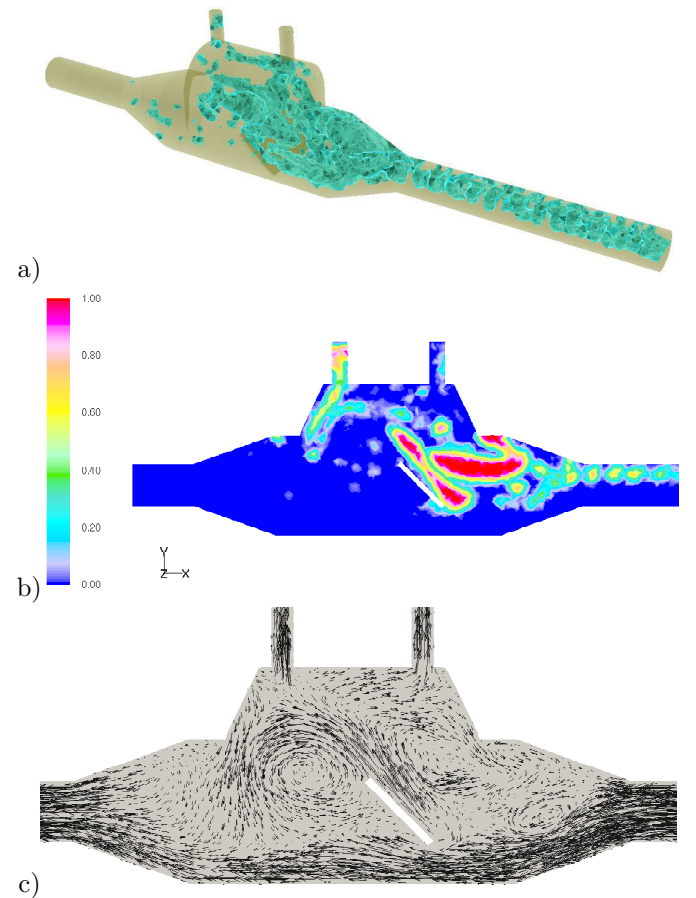


Figure 6: 3D CFD results of the separator at $\theta = 45^\circ$ for $\beta_{in} = 1\%$ and $J_w = 2 \text{ m.s}^{-1}$. a) Iso-surface of air volume fraction α at $\alpha = 0.5$, b) Contours of air volume fraction α in the symmetry plane of the separator, and c) Velocity vectors in the same plane.

The instantaneous air volume fraction and flow velocities obtained by the numerical approach are presented in Fig. 6 for $\beta_{in} = 1\%$ and $J_w = 2 \text{ m.s}^{-1}$.

The flow features that are observed in the numerical analysis of the separator are in relatively good accordance with the actual experimental observations (see Fig. 3c). The recirculation zones that are highlighted in Fig. 3c are indeed very well reproduced by the numerical simulation. One can observe the presence of the same two zones in the vector field displayed in Fig. 6c. The first vortex is close to the inlet, on the right side of the deflector in the figure, and the other one is on the left side of the deflector. As observed experimentally, the right side vortex enhances the residence time and then contributes to the promotion of the coalescence of air bubbles which may explain the presence of the large air-pockets that can be observed in Fig. 6b. Moreover, it is also observed that most of the air bubbles are oriented toward the left side purge as in the corresponding experiment. Nevertheless, the size of the air bubbles is clearly overestimated in the numerical simulation with respect to the experiments. This could mainly be due to the two-phase inlet boundary condition that expresses the air amount in terms of a volume fraction in a mixture rather than in terms of localized bubbles of pure air.

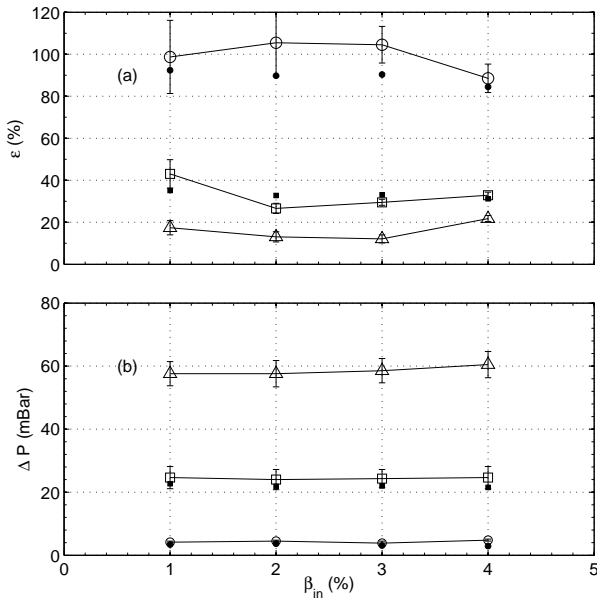


Figure 7: Efficiency ϵ (a) and pressure drop Δp (b) as a function of the air volume quality β_{in} for three velocities: \circ : $J_w = 1 \text{ m.s}^{-1}$, \square : $J_w = 2 \text{ m.s}^{-1}$ and \triangle : $J_w = 3 \text{ m.s}^{-1}$. Closed symbols stand for the numerical results.

The figure 7 presents the evolution of the efficiency ϵ and of the pressure difference between the inlet and the outlet of the separator Δp as a function of the volume quality at inlet β_{in} for three water superficial velocities at inlet. The closed symbols stand for the numerical results and the open symbols stand for the experimental results. Valve 4 is fully open in each case. The errorbars show

the standard deviation of the results, computed on several realizations of the same experiment.

The numerical results match quite well the experimental results. The efficiency is however slightly underestimated at the lowest water velocity: this parameter is indeed very sensitive to the choice of boundary conditions of the numerical model. It is especially necessary to describe accurately the distribution of air in the inlet section of the separator.

The experimental efficiency is close to 100% for the low velocity $J_w = 1 \text{ m.s}^{-1}$ (\circ in Fig. 7a). It is fairly independent of the volume quality in the explored range. One can notice a small decrease to $\epsilon \simeq 95\%$ for the highest volume quality $\beta_{in} = 4\%$. The pressure drop in the separator is of the order of 4 mbar and does not depend on β_{in} .

The efficiency suddenly drops to $\epsilon = 32\% \pm 7\%$ for $J_w = 2 \text{ m.s}^{-1}$ (\square in Fig. 7a) and to $\epsilon = 15\% \pm 4\%$ for $J_w = 3 \text{ m.s}^{-1}$ (\triangle in Fig. 7a). It is still independent of the volume quality. The pressure drops are respectively 24 and 58 mbars. The pressure drop in the separator thus does not scale with J_w^2 as would be expected for a singular pressure drop in a turbulent single-phase flow, but increases faster: a fit with a power law gives a $a = 2.4 \pm 0.1$ exponent ($\Delta p \propto J_w^a$).

The flow velocity thus has a strong effect on the efficiency whereas the variation of the volume quality between 1% and 4% only leads to second-order effect. The steep decrease of the efficiency ϵ between $J_w = 1$ and $J_w = 2 \text{ m.s}^{-1}$ may be related to the change of flow regime of the incoming two-phase flow from a plug flow to a bubbly flow.

4.2. Effects of the inlet pressure

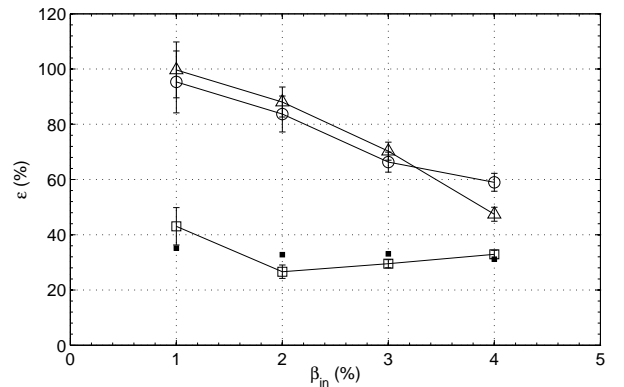


Figure 8: Efficiency ϵ as a function of the air volume quality β_{in} at a velocity of $J_w = 2 \text{ m.s}^{-1}$ for three inlet pressures: \square : $P_{in} = 1.17 \text{ bars}$, \circ : $P_{in} = 1.24 \text{ bars}$ and \triangle : $P_{in} = 1.63 \text{ bars}$. Closed symbols stand for the numerical results.

The figure 8 presents the evolution of the efficiency ϵ as a function of the volume quality at inlet β_{in} for $J_w = 2 \text{ m.s}^{-1}$ and different inlet pressures that have been set with different closings of Valve 4.

When Valve 4 is fully opened, the inlet pressure for this velocity is $P_{in} = 1.17 \text{ bars}$ (\square) and one recovers the

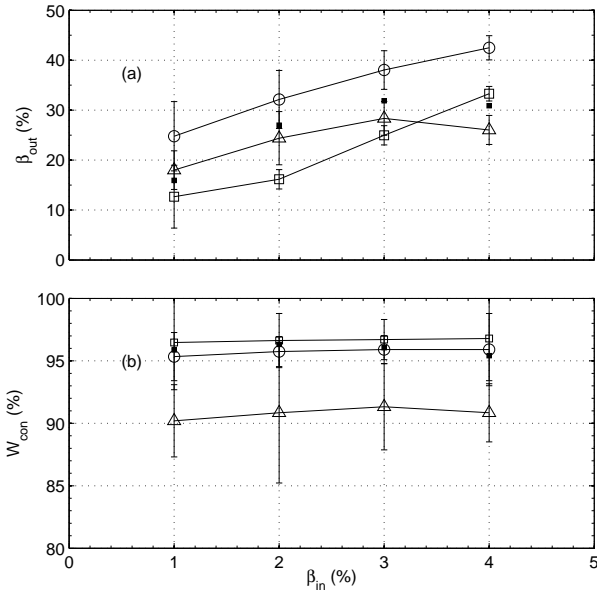


Figure 9: (a): Air volume quality β_{out} in the purge and (b): water conservation coefficient W_{con} as a function of the air volume quality β_{in} at a velocity of 2 m.s^{-1} and a deflector inclination angle $\beta = 45^\circ$ for three inlet pressures: \square : 1.17 bars, \circ : 1.24 bars and \triangle : 1.63 bars. Closed symbols stand for the numerical results.

data plotted in Fig. 7. A small increase in pressure to $P_{in} = 1.24$ bars (\circ) has a very strong effect on the efficiency: it is now 96% for $\beta_{in} = 1\%$. The shape of the curve is also completely different. The efficiency now decreases significantly with increasing the volume quality, down to 60% for $\beta_{in} = 4\%$.

Increasing further the pressure to $P_{in} = 1.63$ bars (\triangle) does not change the efficiency and seems to lead to equivalent performance as for $P_{in} = 1.24$ bars. The effect of inlet pressure is not related to a change of two-phase flow regime. The increase of inlet pressure may increase the mixture flow-rate through the purge (the pressure drop applied between the inlet and outlet in the purge branch is increased). The efficiency of the separator thus increases as a first order effect. The question is then to what extent the increase of inlet pressure modifies the mixture quality in the purge. The study of the water conservation coefficient will help to answer this question and to compare the results for $P_{in} = 1.24$ bars and $P_{in} = 1.63$ bars that have the same efficiencies.

The figure 9 presents the air volume quality β_{out} in the purge and the water conservation coefficient W_{con} at $J_w = 2 \text{ m.s}^{-1}$ for three inlet pressures.

A great difference between the pressure levels $P_{in} = 1.24$ bars (\square) and $P_{in} = 1.63$ bars (\triangle) can be seen. The mixture for $P_{in} = 1.24$ bars contains roughly twice more air than for $P_{in} = 1.17$ bars for the same water flow-rate which explains the efficiency doubling. On the contrary, for $P_{in} = 1.63$ bars, the volume quality in the purge is the same as for $P_{in} = 1.17$ bars and the efficiency doubling is due to a doubling of the liquid flow-rate in the purge. The

overall performance of the separator at $P_{in} = 1.24$ bars is thus much better than the performance at $P_{in} = 1.63$ bars since both the same volume of air and half water are extracted through the purge.

5. Conclusion

An experimental analysis of the performances of a separator with deflector is presented in this article. The effects of the tilt angle of the deflector and of the absolute inlet pressure are compared for various mixture velocities and air volumetric concentrations. It is demonstrated that the efficiency of the separator is tightly linked to the flow regime and to the inlet pressure and that there exists only one optimal tilt angle of the deflector for all flow-regimes. In addition to the experiments a numerical simulation has been performed to allow a better understanding of the flow patterns in the separator. The simulation is in relatively good agreement with their experiments, especially regarding the prediction of the separator performances. The sizes of the air bubbles are however overestimated. This overestimation is mainly due to the inlet boundary condition for the air volume fraction. The use of a “user defined function” (Fluent Inc., 2006) which enables to inject the air in terms of intermittent pockets should overcome this problem.

Finally the main contribution of this assessment analysis is to demonstrate that for this class of separators, two performance parameters are needed to fully characterize the separator: 1) the “classical” performance coefficient and 2) a coefficient that measures the purge water flow rate. Furthermore, this kind of separator presents only one design point where it is very efficient and is also very sensitive to very small variations in the vicinity of this design point. In the case of the automotive application, other technological solutions such as compact vortex separators may be more appropriate.

References

- Andreussi, P., Paglianti, A., Silva, F. S., 1999. Dispersed bubble flow in horizontal pipes. *Chemical engineering science* 54, 1101–1107.
- Azzopardi, B. J., Whalley, P. B., 1982. The effect of flow patterns on two-phase flow in a T junction. *International Journal of Multiphase Flow* 8, 491–507.
- Creutz, M., Mewes, D., 1999. A novel centrifugal gas-liquid separator for catching intermittent flows. *International journal of multiphase flow* 24, 1057–1078.
- Entress, J., Pridden, D., Baker, A., 1991. The current state of development of the VASPS subsea separation and pumping system. In: *Offshore Technology Conference*. pp. 627–635.
- Fluent Inc., 2006. FLUENT 6.3 Users Guide. <http://hpcce.iitm.ac.in/website/Manuals/Fluent6.3/fluent6.3/help>.
- Gregory, J., 1989. Vasps sends subsea separation on downward spiral to success. *Offshore Engineering* 24, 35–36.
- Hetsroni, G., 1982. *Handbook of multiphase systems*. McGraw-Hill Book Co., New York, NY.
- Hirt, C., Nichols, B., 1981. Volume of fluid (vof) method for the dynamics of free boundaries. *Journal of Computational Physics* 39 (1), 201–225.

- Honan, T. J., Lahey, R. T., 1981. The measurement of phase separation in wyes and tees. *Nuclear Engineering and Design* 64, 93–102.
- Hwang, S. T., Soliman, H. M., Lahey, R. T., 1988. Phase separation in dividing two-phase flows. *International journal of multiphase flow* 14, 439–458.
- Kolmogorov, A. M., 1949. Breakup of droplets in turbulent flow. In: *Dokl Acad Nauk USSR* (published in English by the Directorate of Scientific Information Services, DRB Canada, 1956). Vol. 66. pp. 825–828.
- Kouba, G. E., Shoham, O., Shirazi, S., 1995. Design and performance of gas-liquid cylindrical cyclone separators. In: *Proc. 7th Int. Conf. on Multiphase Production*. pp. 307–327.
- Movafaghian, S., Jaua-Marturet, J. A., Mohan, R. S., Shoham, O., Kouba, G. E., 2000. The effects of geometry, fluid properties and pressure on the hydrodynamics of gas-liquid cylindrical cyclone separators. *International Journal of Multiphase Flow* 26, 999–1018.
- Muschelknautz, S., Mayinger, F., 1990. Strömungsuntersuchungen in der austrittsrohrleitung und in einem zyklonabscheider bei druckentlastung= studies of flow in outlets and in a cyclone separator on pressure discharge. *Chemie Ingenieur Technik* 62, 576–577.
- Nebrensky, J. R., Morgan, G. E., Oswald, B. J., 1980. Cyclone for gas-liquid separation. *Offshore Services and Technology* 13, 12.
- Razzaque, M. M., Afacan, A., Liu, S., Nandakumar, K., Masliyah, J. H., Sanders, R. S., 2003. Bubble size in coalescence dominant regime of turbulent air-water flow through horizontal pipes. *International journal of multiphase flow* 29, 1451–1471.
- Rosa, E. S., França, F. A., Ribeiro, G. S., 2001. The cyclone gas-liquid separator: operation and mechanistic modeling. *Journal of Petroleum Science and Engineering* 32, 87–101.
- Saba, N., Lahey, R. T., 1983. The analysis of phase separation phenomena in branching conduits. *International journal of multiphase flow* 10, 1–20.
- Scardovelli, R., Zaleski, S., 1999. Direct numerical simulation of free-surface and interfacial flow. *Annual Review of Fluid Mechanics* 31, 567–603.
- Simmons, M. J. H., Azzopardi, B. J., 2001. Drop size distributions in dispersed liquid-liquid pipe flow. *International journal of multiphase flow* 27, 843–859.
- Taitel, Y., Dukler, A. E., 1976. A model for predicting flow regime transitions in horizontal and near horizontal gas-liquid flow. *AIChE J.* 22, 47–55.
- Thomas, R. M., 1981. Bubble coalescence in turbulent flows. *International Journal of Multiphase Flow* 7, 709–717.
- Youngs, D., 1982. Time-dependent multi-material flow with large uid distortion. K. Morton, M. Baines (Eds.), *Numerical Methods for Fluid Dynamics*, Academic Press, New York 31, 273–285.