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On the effect of the nozzle design on the performances of gas–liquid cylindrical cyclone separators

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ABSTRACT

This paper constitutes an experimental study of the separation performances of a gas–liquid cylindrical cyclone (GLCC) separator that interests the oil industry. The global hydrodynamics behavior in the GLCC is characterized by flow visualization under various inflow operating conditions. The effect of the inlet nozzle design on the performances of the separator is studied by using three different nozzles, and it proves to be a key parameter. With an insufficient nozzle restriction, low swirl intensity is imparted to the flow. Due to inadequate centrifugal effects, liquid is prematurely carried over by the gas as flooding occurs in the separator upper part. High amounts of gas are also carried under by the liquid stream. On the other hand, with a too severe nozzle convergence, the important drag applied by the gas leads to liquid “short circuiting” the cyclone toward the gas outlet. In addition to the nozzle design, the separator performances are influenced by phenomena such as liquid bridging or the occurrence of the slug flow regime at the cyclone inlet. This paper leads to a better understanding of the links between the hydrodynamics in the GLCC and its operational limits, which is necessary to enable reliable scaling up tools.

1. Introduction

The oil industry relies mainly on conventional gravity based vessel-type separators to process gas–liquid mixtures produced from oil/gas wells (see Arnold and Stewart, 2008 for a detailed statement on these separators). After several decades of use, their technology has reached an advanced degree of maturity (actual improvements in their design are minor, and are mainly about the vessels internals) and their design is well mastered. However, they are bulky, heavy and expensive to manufacture and operate.

The increasing number of offshore exploitations and the need to cut down equipment costs have motivated the petroleum industry to search for new and compact gas–liquid separators: on the platform, space is limited, and so the equipment size is of major concern. In addition, compact separators are beneficial from a “flow assurance” perspective, and are interesting for arctic, subsea and downhole operations. Following these researches, numerous alternatives to conventional separators have been proposed and developed. Many of these emerging separators follow the “reverse-flow cyclone” concept, as the VASPS,[1] the CS[2] (Rosa et al., 2001), and the GLCC©,[3] which will be addressed in this paper.

The GLCC (Fig. 1a) is a simple separator, which has neither moving parts nor internal devices. It consists of a vertical pipe with a downward inclined tangential inlet (that generally ends with a nozzle) located approximately at mid-height of the separator body, and two outlets respectively at the top and bottom of the pipe. The tangential inlet provides swirling motion to the incoming mixture. The phase separation process is enhanced by the resulting centrifugal forces (see Section 2). During regular operation, the gas exits from the top while the liquid is collected from the bottom outlet.

Most of the research on the GLCC has been conducted by the TUSTP[4] team of Tulsa University. Some applications of the GLCC as a pre-separator (enhancement of primary separators or slug-catchers) or as a partial separator have been reported (Shoham and Kouba, 1998; TUSTP, 2013). But the GLCC most common utilization nowadays is the control of gas/liquid ratio upstream of flow meters or other equipments as pumps or de-sanders (Fig. 1b) (Kouba and Shoham, 1996; Shoham and Kouba, 1998; Kouba et al., 2006; TUSTP, 2013): this improves the equipments accuracy and reduces their size and cost. For this last application, the outlet pipes can be recombined. The goal is to get a somewhat self-regulating flow loop, that maintains the liquid level around its optimum (i.e. slightly below the inlet) without an active control system (i.e. stand-alone configuration, Fig. 1b). Of course, this solution cannot be sufficient if the separator is mounted on lines whose flow rate varies a lot with time. In this case, the GLCC must be enslaved by controlled valves that are installed at the exits; such feedback control systems has been

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[1] For “Vertical Annular Separation and Pumping System”.

[2] For “Cyclone Separator”.

[3] For “Gas–Liquid Cylindrical Cyclone”, Copyright, The University of Tulsa, 1994.

[4] For “Tulsa University Separation Technology Projects”.

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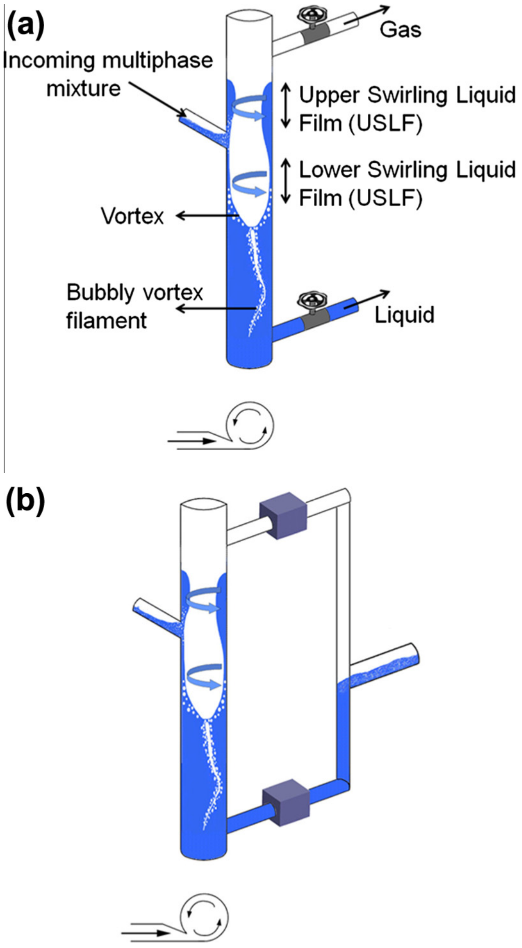

Fig. 1. Schematic representation of the GLCC and of the nozzle at its entrance pipe. (a) Full separator configuration. (b) Stand-alone configuration.

studied and developed by the TUSTP team (Wang et al., 1998; Wang, 2000).

Despite its simplicity and its numerous advantages, the GLCC has not known yet a widespread success. In fact, albeit its operating principle is simple, the complex multiphase hydrodynamics in the unit and the variability of the operating conditions render its performances prediction very difficult. This has been the largest obstacle to its broader use, especially as a full separator (Shoham and Kouba, 1998).

The vast majority of the studies relative to the separation efficiency in GLCCs deals with its stand-alone configuration (Kouba and Shoham, 1996; Movafaghian et al., 2000; Chirinos et al., 2000; Gomez, 2001). These results are not sufficient to characterize the GLCC efficiency as a full separator, because the liquid level shifts too much from its optimum for important variations in the inlet flow rates. Moreover, the influence of the inlet nozzle dimensions, which is a crucial parameter, has not been studied.

This paper tries to overcome these lacks through a detailed experimental investigation of the device performances. The hydrodynamics and the operating principle of the cyclone are outlined in Section 2. Our experimental facility and the flow patterns in the GLCC inlet channel are presented in Sections 3 and 4 respectively. Then, experimental results obtained on our laboratory pilot are presented and discussed in Sections 5 (liquid carry-over) and 6 (gas carry-under). The influence of the geometry (in particular the dimensions of the entrance nozzle) and of the physicochemical properties of the liquid on the performance of the separator are studied. The phenomena taking place when the GLCC operates below or beyond its limiting operational conditions are characterized by visualizations. These visual observations and the analysis of the experimental results allow us to identify key mechanisms that govern the operational limits of the system. This leads to a better understanding of the links between the hydrodynamics and the performance limits of the GLCC, which is crucial to enable accurate design and scaling up tools.

2. The flow hydrodynamics and the separation processes in the GLCC

In this section, we give a brief description of how the GLCC operates and of the main features and mechanisms taking place.

Because of gravity, a first rough separation step is achieved by expansion when the gas–liquid mixture enters the GLCC's main vessel: the liquid tends to move toward the cyclones lower part dragging down gas bubbles, while gas occupies the upper part. At this level, inherent fluctuations in the two phase inlet flow are damped, and after this point, the equipment operates more smoothly (Rosa et al., 2001). For a stand-alone system, the liquid vortex (to which we will refer simply by vortex) height will be determined by the pressure drop across the system. For an enslaved system, the vortex will be maintained at a small distance below the inlet nozzle level.

In the GLCC upper part, liquid droplets are pushed toward the walls by centrifugal force, and coalesce into a liquid film. As this liquid film is compact compared to individual droplets, the gas will have more difficulties to drive it up to the top outlet. The liquid from the wall film falls down by gravity into the liquid vortex thereafter. However, if the gas flow rate is increased beyond a certain threshold tolerable by the system, liquid is carried over with the gas stream in the GLCC upper outlet. This limiting phenomenon is called Liquid Carry-Over (LCO).

We can notice that even under regular operation, a certain amount of liquid in the shape of an annular film is encountered just above the entrance nozzle (Fig. 1. See also Video "Upper Swirling Liquid Film"). This annular liquid film results from the impact between the inlet jet and the wall, and it comes in addition to the liquid droplets pushed toward the wall by centrifugal forces. The amount of liquid present above the inlet and the thickness of this annular film generally increase with the liquid flow rate. We will refer to this Upper Swirling Liquid Film by USLF.

With a stand-alone system, for high liquid flow rates, the vortex level rises above the level of the inlet nozzle: the liquid attenuates or even destroys the vortex motion in the gaseous phase. The gas arriving from the inlet is forced through the liquid what leads to some liquid spraying, initiating an early LCO. For this reason, data obtained from experiments on stand-alone systems do not help us to understand and predict how the LCO is triggered in an enslaved GLCC.

To improve the separator performances, the inlet is inclined downward by an angle of about 27° with the horizontal as recommended by Kouba et al. (1995). This inclination reduces the LCO through two mechanisms. First, this angle of inclination promotes a stratified regime, which favors a phase separation at the inlet level. Second, it directs the liquid stream below the inlet, preventing it from standing in the way and blocking the gas moving toward the system upper part.

In the GLCC lower part, if the swirl intensity is high enough, the free gas–liquid interface gets carved out and the vortex can be observed. The liquid flows from the inlet nozzle to the vortex in a thin swirling film (Fig. 1), to which we will refer as Lower Swirling Liquid Film, LSLF. Large bubbles quickly move toward the free interface due to buoyancy. Smaller bubbles, while being dragged downward by the liquid, are pushed radially toward the vortex center. They form a bubbly filament which allows a nice visualiza-