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Hydrodynamics and velocity measurements in gas–liquid swirling flows in cylindrical cyclones☆

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ABSTRACT

The gas–liquid swirl flow in a gas–liquid cylindrical cyclone separator has been characterized first qualitatively by flow visualizations. The emerged findings were then confirmed quantitatively by Laser Doppler Velocimetry measurements. The vortex core presents a very complex hydrodynamics, characterized by an alternation between a laminar and a turbulent state. The laminar regime is associated with velocities pointing in the same direction as the mean flow, while the turbulent state induces velocities in the opposite direction, i.e. a flow reversal. These observations give a first understanding of the origin of the double flow reversal regime that is encountered in swirl flows. It is shown that this flow structure appears for high swirl intensities, and results from a frequent laminarization of the vortex core. Results show that, contrary to the commonly assumed hypothesis, this flow structure is associated with good separation performance of the cyclone. Accordingly, we propose the use of multiple tangential inlets to generate the swirl motion in the cyclone, which is supposed to favor the double flow reversal regime, and thus, improve the separation efficiency.

Keywords: Gas–liquid cyclone separator; Swirl flow; Vortex flow; Vortex core laminarization; Laser Doppler Velocimetry

1. Introduction

Swirl flows are generated by giving a tangential velocity component to an axial flow, which results in a helical winding of the streamlines. The research in the domain has been motivated by two somewhat antagonist reasons: on one hand, phase separation by centrifugation, and on the other hand, the improvement of mixing and transport phenomena. Swirl flows are nowadays used in a broad range of engineering applications, with various goals: phase separation in cyclone separators (Rosa et al., 2001; Tue-Nenu and Yoshida, 2009), mass transfer improvement (Yapici et al., 1997), heat transfer enhancement (Martemaniov and Okulov, 2004), reduction of localized wear in hydraulic or pneumatic transport (Fokeer et al., 2009), flame stabilization in burners (Wegner et al., 2004), etc.

☆ Dedicated to the memory of Pr. Noël Midoux who passed away during the revision of this publication.

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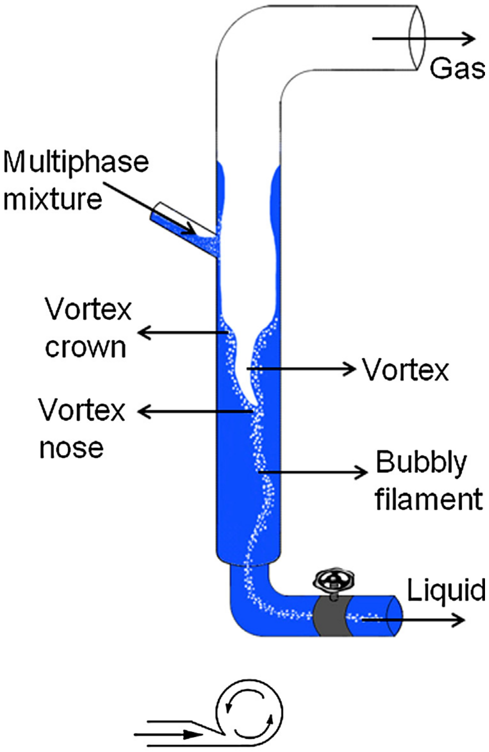

Fig. 1 – Schematic representation of the GLCC and of the nozzle at its entrance pipe.

This paper will focus on swirl flows in the context of the GLCC©,[1] a gas–liquid cyclone separator. The results concern swirl flows in a more general and broader context, however, it should be kept in mind that some characteristics of swirl flows depend on the method used to generate the swirl motion (Kitoh, 1991; Martemaniov and Okulov, 2004).

The GLCC (Fig. 1) is a gas–liquid separator of great interest for the oil industry, and that follows the "reverse-flow cyclone" technology. The GLCC is simple, compact, low-cost and low-weight compared to conventional separators, and contains no moving parts nor internal devices (so it requires only little maintenance). For these reasons, the use of the GLCC allows considerable saving in offshore, arctic, subsea and downhole operations.

The GLCC consists of a vertical pipe with a downward inclined tangential inlet located approximately at mid-height of the cyclone body, and two outlets, respectively, at the top and bottom of the pipe. The inlet generally ends with a nozzle: thus the mixture is injected into the cyclone body at a higher velocity, which increases the centrifugal effects in the flow and enhances the phase separation process. During regular operation, the gas exits from the top of the GLCC while the liquid is collected from the bottom outlet.

Once the mixture enters the GLCC, because of gravity, a first phase separation occurs: the liquid tends to move toward the cyclone lower part, while gas occupies the upper part. Liquid height in the GLCC is controlled through automated valves mounted at the exits (see Fig. 1) (Wang, 2000). Liquid height must not exceed the inlet level to avoid liquid getting sprayed by the gas stream and being carried over to the gas outlet, and must be high enough to ensure sufficient residence time to separate bubbles from liquid. Thus, liquid level control is crucial for optimal performance of the GLCC under variable operating conditions, and should enable the GLCC to better handle surging and slugging events (Shoham and Kouba, 1998).

In the GLCC upper part, liquid droplets contained in the gas stream are centrifuged toward the walls, and coalesce into a liquid film. As this 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, unless the liquid and gas flow rates couple exceeds the limit tolerated by the system. In this last situation, gas drags liquid from the film toward the GLCC upper outlet: this limiting phenomenon is called Liquid Carry-Over (LCO) (Hreiz et al., 2014). To improve the separator performance, it is recommended to incline the inlet downward by an angle of about 27° from the horizontal (Kouba et al., 1995). Compared to a horizontal inlet, this inclination directs the liquid stream below the inlet, preventing it from blocking the gas passage. It also promotes a stratified regime at the inlet (and thus phase segregation) and disadvantages the slug regime, prejudicial to the separation.

In the GLCC lower part, if the swirl intensity is high enough, the free gas–liquid interface gets carved out and the liquid vortex can be observed. The liquid vortex will be referred simply to as the vortex. The liquid flows from the inlet nozzle to the vortex in a thin swirling film, dragging down gas bubbles. In the vortex, large bubbles quickly move toward the free interface due to buoyancy and disengage. Smaller bubbles are dragged downward by the liquid, while getting pushed radially toward the vortex center due to centrifugal forces. They form a bubbly filament which allows a nice visualization of the vortex core. These bubbles are then supposed to rise up to the free interface and to disengage (see Section 2.2.2 for details). However, a fraction of the small gas bubbles passes along with the liquid underflow from the GLCC. This undesired phenomenon is called Gas Carry-Under (GCU) (see Hreiz et al. (2014) for details).

The GLCC is nowadays mainly used to control the gas/liquid ratio upstream of equipments such as pumps, flow meters or desander hydrocyclones: this enhances their performance, and reduces their size and cost (Shoham and Kouba, 1998). Other applications of the GLCC as portable well testing equipment, pre-separator or partial separator have been reported (Shoham and Kouba, 1998). However, despite its significant potential, the GLCC as a full gas–liquid separator has not reached yet a widespread deployment: industry is still suspicious about its design. In fact, albeit the simplicity of the unit, the hydrodynamics in the cyclone is very complex, and many of the phenomena taking place are still not fully understood. As a consequence, the GLCC design is still empirical, so scale up of the laboratory-scale model to real industrial prototypes does not rely on solid and reliable basis.

The aim of this paper is to better understand the swirl flow hydrodynamics in the GLCC lower part by means of experiments on a laboratory-scale model. Dispersed gas bubbles act as a tracer allowing visualization of the vortex core. Key phenomena governing the behavior of the vortex core are identified through flow visualization. These observations reveal a different flow behavior from that described in the literature. The emerging conclusions are supported quantitatively by Laser Doppler Velocimetry (LDV) measurements in the GLCC lower part. This data permit to fill partially the lack of reported velocity measurements in gas–liquid swirl flows.

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[1] For "Gas–Liquid Cylindrical Cyclone", Copyright, The University of Tulsa, 1994.

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