Effect of pressure and salinity on the performance of a gas-liquid separator-A preliminary study

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ABSTRACT
The separation of liquid from gas during the initial stages of separation process is very important to increase the well productivity. That’s why design of an efficient compact gas-liquid separator has received a lot of attention from academic researchers, as well as from field operators. All of them state the necessity of compact design to deploy separators offshore and potentially subsea in order to enhance the recovery of the gas wells. This current investigation describes an experimental and computational fluid dynamics (CFD) modelling of a laboratory scale compact gas-liquid separator designed by CSIRO. The separator consists of two concentric pipes with swirl tube in the annular space between the pipes. The gas-liquid mixture comes from the tangential side inlet and the system works with a combination of gravity and centrifugal forces to achieve a high-efficient gas-liquid separation. The effect of pressure and salinity on the performance of the gas-liquid CS-T (CSIRO’s Separation Technology) separator is investigated in this paper. The performance of the separator is visually established by observing the liquid carry over (LCO) regime in which liquid is carried out in the gas stream. The liquid and gas-flow rate at which the LCO is observed defines the upper operational range of the separator. Air-water mixture is used for both experimental and CFD investigations. The performance is evaluated at 1, 2, 5, 10 and 12 barg pressure. The upper operational range decreases with increases pressure. For higher pressure (10 and 12 barg) the LCO curve was nearly vertical which indicates no change in gas flow rate with the increase in water flow rate. The salinity does not affect the performance of the CS-T separator. The CFD results are used to visualize the constant LCO and to understand the physics and mechanism of LCO.

KEYWORDS: gas-liquid separator, modified Eulerian-Lagrangian multi-phase flow, LCO

INTRODUCTION

The challenge to separate the liquids from the gas stream at the initial state of the separation process brought a lot of attention to academic researchers and field operators (Powers, 1993; Talavera, 1990; Choi, 1990; Noui-Mehidi et al, 2007) to develop a compact gas-liquid separator suitable for off-shore application. The gas-liquid separation technology currently used by petroleum industry is not only large and heavy but also expensive to purchase and operate especially in the subsea. A separator has to be simple, reliable with low maintenance requirements, minimal footprint, low pressure loss and easy to install. The gas-liquid cylindrical cyclone separator (GLCC) and gas-liquid separator developed by CSIRO (CSIRO’s Separation Technology, CS-T) are excellent examples of compact gas-liquid separator. The design of these separators is based on swirl tube technology. GLCC has been implemented in a number of applications as reported by Kouba et al (2006). The details of experimental investigations and mechanistic model for developing GLCC separator have been reported by Kouba (2003), Kouba et al (1995), Movafaghian et al (2000) and Arpandi et al (1996). The laboratory scale experimental investigations for the CSIRO’s gas-liquid CS-T have been completed by Wong et al (2009). Sanchez-Soto et al (2010) introduced two preliminary mechanistic models to describe the performance of the gas-liquid CS-T based on Professor Edgar
Muschelknautz modelling approach (MM) and time of flight (TFM) approach of gas-solids cyclone separators which is described in the book by Hoffman and Stein (2008). Ahmed et al (2010) developed a model for pressure drop of the gas-liquid CS-T separator. However, more investigation is required to develop a comprehensive mechanistic model for the gas-liquid CS-T separator. Computational fluid dynamics (CFD) modelling for GLCC separator and for both single and two-phase flow are performed by Erdal (1996), Erdal et al (1996) and Motta et al (1997). The model assumes an axi-symmetric flow and three velocity components, applicable to steady-state and isothermal conditions. Ahmed et al (2009a, 2009b, 2010) presented the numerical modelling of the gas-liquid CS-T separator where they used Eulerian-Eulerian approach (2009a) and a modified Eulerian-Lagrangian approach (2009b, 2010) with specific sub model for wall film and droplets break-up/coalescence for modelling the complex behaviour of the multi-phase flow. The predicted pressure drop, flow field and volume fraction are reasonably matched when compared with experiments (Wong et al, 2009). It is important to have a sound knowledge of the effect of pressure and salinity on the performance of gas-liquid CS-T for the operation in the sub-sea level and that is the motivation of this present work.

The current investigation describes the effect of pressure and salinity on the performance of gas-liquid CS-T separator. Both experimental and CFD modelling of a laboratory scale gas-liquid CS-T separator are performed. The separator consists of two concentric pipes with helical swirl tube in the annular space between the pipes as shown in figure 1. The gas-liquid mixture enters from a tangential side inlet into the separator and passes through the annular swirl tube. While passing through the swirl tube the liquid separates from the gas due to the centrifugal action, strikes at the inner wall of the outer pipe, and creates a liquid film at the wall which ultimately goes down due to gravity. On the other hand the lighter gas goes up through the inner pipe and the separation occurs with a combination of centrifugal force and gravity. The unique feature of the gas-liquid CS-T separator is its simple design without any moving part. The designs and performance analysis of the separator are achieved in laboratory studies. The experimental investigations are performed in order to understand the effect of pressure and salinity on the performance of the gas liquid CS-T separator. The performance of the gas-liquid separator is visually established by observing the liquid carry over (LCO) regime in which liquid is carried out in the gas stream. The liquid and gas flow rates at which the LCO is observed defines the upper operational range of the separator. For the CFD modelling, two points are chosen; both are above the LCO curve for the 2 barg and 5 barg respectively (figure 2). CFD modelling is carried out to observe the continuous LCO, to gain further insights into the complexities of flow field and to understand the LCO phenomenon at the exit of the swirl tube. The air-water mixture is used for both experimental and numerical investigation.

EXPERIMENTAL PROCEDURE
Figure 1 shows the schematic diagram and dimensions of all the parameters. The details of the experimental set up are explained in Wong et al (2009). In conducting the experiments, initially the system is stabilized by fixing the liquid flow rate with a low gas flow rate. Then the gas flow rate is sequentially increased and adjusted repeatedly to locate the critical value of LCO. The accuracy of the critical air flow rate for LCO is estimated between 1% and 3% (Noui-Mehidi et al, 2007) depending on the range of the air flow rate. The experiments are performed for 1, 2, 5, 10 and 12 barg pressure. The results are shown in figure 2 and are discussed in the results and discussion section later. The water and air flow rates at which the LCO is observed define the upper operational range of the separator. Any point above the LCO curve will have constant LCO.

NUMERICAL MODELLING

Three-dimensional, transient, isothermal and incompressible multiphase flow fields are obtained by solving the continuity and Navier-Stokes equations. The standard k-ε turbulence model is used for turbulence closure. The modified Eulerian-Lagrangian multiphase model is used where gas flow was coupled with the spray and wall film models available in commercial software FIRE (2006). For the liquid phase, Discrete Droplet Method (DDM) is used which operates by solving ordinary differential equations for the trajectory, momentum, heat and mass transfer of single droplets, each being a member of a group of identical non-interacting droplets termed a ‘parcel’. Thus one member of the group represents the behaviour of the complete parcel. The droplet-gas momentum exchange, turbulent dispersion, secondary break-up, droplet collision and droplet-wall interaction are covered with a comprehensive set of models which allow the usage of the module very suitable for gas-liquid separation. The droplets are tracked in a Lagrangian way through the computational grid used for solving the gas phase partial differential equations. Full two-way coupling (interaction) between the gas and liquid phases is taken into account. In a gas-liquid separator, a significant amount of the liquid can be deposited on the walls as a thin liquid film due to wall collisions of liquid. Some amount of this liquid is sheared off and entrained back into the gas flow. The coupling between the liquid film phase and the air flow is accomplished in FIRE by setting up modified and refined boundary conditions at the interface. At high air velocity, the shear force at the film surface tears droplets entrained back into the air flow. The wall film entrainment model is simulated within the wall film module. The detailed mathematical description of the governing equations used for DDM spray model, Wall film model and all sub-models can be found in Ahmed et al (2010).

Boundary Conditions and Mesh

The inlet boundary condition is specified by introducing both air and water flow rate and volume fraction at the tangential side inlet. Mass flow boundary condition is applied at the air outlet. To be consistent with the experiments, gas-liquid CS-T separator is initialized with high pressure at the start of the simulation. The simulations are performed for 2barg and 5barg pressure. Experimental investigation (Wong et al, 2009) revealed that air in the form of bubbles are trapped with the downward flowing water which is known as gas carry under
It is assumed that 1% of the air is trapped and discharged with water as bubbles and this condition is imposed at the water outlet. The volume mesh consists of hexahedral elements. The solutions are grid independent when the total number of elements is 845,287. The interval step used for this simulation is 0.0025s which is chosen based on the Courant number, numerical stability and trial and error. Every simulation is started from a steady state results and is carried until long beyond the stability is reached which is observed after the 30 sec of transient run. For each interval the convergence criteria for the momentum equations and turbulent parameters are $10^{-4}$ and for the continuity equation is $10^{-3}$.

**RESULTS AND DISCUSSIONS**

Figure 2 shows the experimental results of LCO envelopes for the gas-liquid CS-T separator at high pressure. It is observed that the upper operational range of LCO moves to the left (the performance of the CS-T separator decreases) with increase of the operating pressure. This could be due to the increase of the lifting capacity of the gas due to higher density which allows the gas to carry out water droplets with larger diameters. Sanchez-Soto et al (2010) mention an inverse relationship between the water droplet diameter and the gas velocity in a pipe which suggests that the higher density of the gas can lift liquid droplets of larger diameter entering the CS-T at higher pressures. It is also worth noting that the LCO envelope for operating pressures above 10 Bar seems to become almost vertical which may indicate that at higher pressures the performance is limited by a critical gas flow rate (regardless of the liquid flow) due to the high carrying capacity of a much denser gas phase. Figure 3 depicts a comparison of the LCO envelopes for the saline (45ppK salt, NaCl) and tap water for the gas-liquid CS-T at different operating pressures. It is evident that the salt content does not affect the performance of the CS-T and the LCOs are similar for each operating pressure. It could be due to the strong g-force in the swirl section that does not allow the formation of foam as observed in the GLCC (Noui-Mehidi et al, 2007) which leads to a decrease of the GLCC performance. This could mean that experiments performed with tap water can be used when analysing real systems with high salinity production water. However, a verification of this trend should be carried out at larger scales.

The following section describes the results of the CFD modelling. The validation of the CFD model has been done somewhere else (Ahmed et al, 2009a, 2009b, 2010), this investigation is focused on to visualise the constant LCO, mechanism of formation of wall film thickness and LCO phenomenon at the exit of the swirl tube. As salinity does not affect the performance of the CS-T separator, only the properties of the tap water is used for CFD simulation. Two points, both above the LCO curve for 2barg (air flow=246.9 L/min, water flow=68 L/min, point 1) and 5barg (air flow=170 L/min, water flow=68 L/min, point 2) are selected (figure 2). Figure 4(a-b) shows the velocity near the wall regions for point 1 and 2 respectively. The air-water mixture enters the annular space through the tangential side inlet, strikes the outer pipe wall and immediately directed to the swirl tube. While passing through the swirl tube the flow accelerates and reaches the maximum velocity (15 m/s for point 1 and
10m/s for point 2) after making three turns. The maximum velocity for point 1 is higher because of increased air flow rate. Due to the centrifugal action the water gets separated inside the swirl tube and creates a wall film at the outer pipe (figure 6(a-b)). The wall film then travels down due to gravity and comes out through the water outlet. The lighter air rises, travel through the inner pipe and ultimately goes out through the air outlet. Figure 5(a-b) shows the wall film shear stress for the point 1 and 2. For both cases, the wall film shear stress is highest at the entrance of the swirl tube because of high velocity gradient there. The magnitude of the wall film shear stress is higher for point 1 (16 Pa) due to increased air flow rate.

The wall-film thickness shown in figure 6(a-b) describes the mechanism of wall-film formation. The air-water mixture enters the CS-T separator and strikes the wall of the outer pipe. Almost all of the water droplets are converted into wall film which moves downward into the swirl tube. The flow inside the swirl tube accelerates and reaches maximum after the third turn. Because of the high tangential velocity, the shear force at the film surface tears off the droplets from the wall-film, entraining them back into the air flow. As a result, the thickness of the wall film reduces at the exit of the swirl tube. After exiting from the swirl tube, the remaining amount of water in the wall film travels down along the wall to go out through the water outlet. A significant amount of water is carried out with air in the form of water droplets which goes out through the air outlet. This phenomenon can be explained more in detail with the help of figure 7(a-b). As mentioned before, the two points (figure 2) selected for CFD simulation are above the upper operational range of the LCO curve which indicates a continuous LCO. Due to the high shearing action between the wall film and the tangential air flow, substantial amount of water droplets are entrained back into the air stream near the exit end of the swirl tube. Air stream carries most of these water droplets into the inner pipe and the out through the air outlet. This is due to the higher drag force dominating over the gravity force and a constant LCO occurs (figure 7(a-b)). This phenomenon is well captured in the simulation and consistent with the experiments (Wong et al, 2009). It is noted that the size of the droplets is exaggerated in figure 7(a-b) for visual comfort. The actual size of the droplet can be obtained from the colour contour key.

**SUMMARY AND CONCLUSIONS**

This paper presents both experimental and numerical investigations of a laboratory scale gas-Liquid CS-T separator. Experiments are carried out to investigate the effect of pressure and salinity on the performance of the gas-liquid CS-T separator. The performance of the separator is visually established by observing the LCO in which liquid is carried out in the gas stream. The performance of the separator is decreased with increased pressure. For higher pressure (10 barg and above), the LCO curve is nearly vertical which implies that at high pressure the separator performance is limited to a critical gas flow rate irrespective of the liquid flow rate. Salinity doesn’t affect the performance of the gas-liquid CS-T separator. Numerical investigations are carried out for two points above the LCO curve at 2barg and 5 barg. The locations of the maximum swirl velocity and wall film shear stress are identified. The maximum swirl velocity occurred inside the swirl tube at the third turn. The location of the
maximum wall shear stress is identified at the entrance of the swirl tube where the velocity gradient is highest. The mechanism of wall film formation is described and the constant LCO phenomenon is captured which is consistent with the experiments. This experimental and numerical investigation can help to identify the entrainment of water droplets at the entrance of the inner pipe and LCO in determining the performance of a scale-up gas-liquid CS-T separator.

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CAPTIONS

Figure 1: Schematic diagram of CS-T gas-liquid separator. \( \text{DE}_{\text{inner}} = 52.5, \text{DI}_{\text{outer}} = 38.1, \text{DI}_{\text{inner}} = 32.1, \text{D}_{\text{inlet}} = 26.6, \text{L}_{\text{i}} = 5*\text{DI}_{\text{outer}}, \alpha = 20^\circ, S_0 = 38.1, H_{\text{chicane}} = 38.1 \) and \( H_{\text{bsw}} = 900 \) (all dimensions are in mm).

Figure 2: Effect of pressure on the performance of gas-liquid CS-T separator

Figure 3: Effect of Salinity on the performance of gas-liquid CS-T separator

Figure 4: Velocity in the near wall region for two points above the LCO curve. (a) 2barg, air=246.9 L/min, water=68 L/min, point 1 and (b) 5barg, air=170 L/min, water=68 L/min, point 2

Figure 5: The region of high wall film shear stress. (a) 2barg, air=246.9 L/min, water=68 L/min, point 1 and (b) 5barg, air=170 L/min, water=68 L/min, point 2

Figure 6: Formation of the wall film by the spray droplets impinging at the outer pipe wall for (a) 2barg, air=246.9 L/min, water=68 L/min, point 1 and (b) 5barg, air=170 L/min, water=68 L/min, point 2
Figure 7: Entrainment of the water droplets back into the air stream inside the swirl tube and at the entrance of the inner pipe which ultimately carried out by the air stream through the air outlet. Both points, (a) 2 barg, air=246.9 L/min, water=68 L/min, point 1 and (b) 5 barg, air=170 L/min, water=68 L/min, point 2, are above the upper range of the LCO curve and a constant LCO occurs.
Effect of pressure on performance of gas-liquid CS-T separator

Figure 1

Figure 2
Figure 3

Effect of salinity on performance of gas-liquid CS-T separator

Figure 4(a)  Figure 4(b)
Figure 7(a)          Figure 7(b)