DESIGN AND PERFORMANCE OF GAS LIQUID CYLINDRICAL CYCLONE SEPARATORS

by

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ABSTRACT

Current separation technology based on the conventional vessel-type separator is several decades old. The vessel-type separator is large, heavy and expensive to purchase and operate. Recently, the petroleum industry has shown interest in the development of innovative alternatives to the conventional separator that are compact and low weight, and have low capital and operational costs. One such alternative is the Gas Liquid Cylindrical Cyclone (GLCC) separator.

Very few studies are available on the optimum design and performance of GLCC's. Consequently, the sizing of GLCC's and estimation of the operational envelope are based on limited experience, without a high degree of confidence.

This paper presents new experimental laboratory data and limited number of field data on the flow behavior and performance of the GLCC separator. Also, initial mechanistic models that describe the flow behavior in the GLCC are presented and compared with the experimental data. These provide the state of the art for the design of GLCC's for the industry.
INTRODUCTION

The Petroleum Industry has relied heavily on the conventional vessel-type separation technology, which has not changed substantially over the last several decades. Conventional separators are bulky, heavy and expensive in capital and operating costs. These limitations are felt most severely in offshore operations where platform costs are escalating. The high costs associated with conventional separators have motivated the Petroleum Industry to explore the development and application of alternative technologies such as compact separator systems.

Fig. 1: ‘S’ Curve for Development Ranking of Separation Technology

Fig. 1 shows schematically the "S" curve for the developmental ranking of some of the various separation technologies. As shown in the figure, conventional vessel-type horizontal and vertical separators are very mature, with only minor improvements coming from new developments of internal devices and control systems. Hydrocyclones for cleanup of produced water are in the growth region. Although large diameter separators are relatively mature, recent developments have given rise to an emerging class of vertical separators known as Gas Liquid Cylindrical Cyclones (GLCC).

The GLCC, shown in Fig. 2, is a simple, compact, low-cost separator that can be used as an economically attractive alternative to the conventional separator. The wide variety of
applications of GLCC’s may have different performance requirements, varying from only partial separation to a complete phase separation. Potential applications include: control of GLR for multiphase flow meters and pumps, portable well test metering, steam quality metering, flare gas scrubbing, primary surface or subsea separation and pre-separation upstream of slug catchers or primary separators.

![Diagram of Gas Liquid Cylindrical Cyclone Configuration](image)

**Fig. 2: Gas Liquid Cylindrical Cyclone Configuration**

A representation of the available literature on cyclone separators and related physical phenomena is given in the bibliography section. A review of the literature reveals that very little information is available about the optimum design and performance of GLCC’s. Furthermore, existing mathematical models of cyclone separators have been limited to single phase flow with low concentration of a second dispersed phase. No reliable models are available for cyclones (conical or cylindrical) that are capable of simulating full range of multiphase flows entering and separating in a cyclone. Moreover, no models are available to account for the range of fluid properties that occur in the oil industry.
Despite the lack of performance information, GLCC’s are beginning to attract some interest for numerous applications. Several cases of successful application of gas/liquid cyclone separators were reported for multiphase separation, metering and pumping, as follows:

Two studies carried out for British Petroleum by Davies and Watson⁸ and Davies⁹ indicated size, cost and performance benefits (foam handling) of a modified cyclone over a conventional separator in offshore applications. This was confirmed by comparative tests conducted by Oranje²⁰.

In a different application, BHRG has developed a GLCC to control the gas liquid ratio to optimize efficiency of a multiphase pump¹⁹. Similarly, BHRG with AGIP are investigating using a GLCC in conjunction with multiphase meter for subsea metering applications. GLCC’s are also utilized for well testing meters (Paul Munroe Engineering; Spartan Controls) and for limited range of gas/liquid separation such as for wet gas (Gasunie; CE Natco; Porta-Test).

Arco¹⁴ has developed a GLCC with spiral vane internals. The GLCC was tested in Alaska and exhibited gas carryunder between 2% to 18%, depending on crude foaminess. Alternatives for level control were explored in lab tests by Kolpak¹⁴, including throttling floats and throttling diaphragm valves operated by the vessel hydrostatic head. Finally, sensitivity of the liquid level in the GLCC to the pressure drop in the liquid and gas legs was explored.

A gas liquid cylindrical cyclone was considered by the Naval Weapons Lab⁴,⁵ to remove gas from electrolyte used in large batteries. The GLCC used for this purpose had both tangential inlet and outlet. Bandopadhyay⁴ found that the stability of the vortex core is influenced by the rotational angle between the inlet and the outlet. Also, the optimum angle for the most stable core was found to be function of liquid flow rate and GLCC geometry.

The GLCC can also be very useful for small production or stripper well operations. One application is the measurement of fluids for production allocation and reservoir management. Typically, a battery of wells are cycled through a test separator where gas and liquids are measured before transport. A metering system based on a simple compact separator costs less and requires fewer control systems than a typical test separator. It is also expected to operate for long periods with little or no maintenance. Another impact of compact separators in this case is to reduce the cycle time between well tests, as smaller separators require less purge time. This translates into less down time for wells needing attention.
Chevron\textsuperscript{15} has successfully built and operated several GLCC's for use in a low GOR flow metering applications. In Chevron's configuration, gas and liquid streams are separated in a simple GLCC, metered by gas and liquid flow meters and recombined for transport. Kouba\textsuperscript{15} found that simple improvements to the GLCC resulted in greatly increased performance of the tested prototype. Figure 3 shows a field prototype GLCC operated successfully by Chevron in the Fox Deese Springer field in southern Oklahoma. The construction and installation cost for the field prototype have totaled about $2,500 apiece.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig3.png}
\caption{Gas Liquid Cylindrical Cyclone Field Prototype}
\end{figure}

The above examples demonstrate the applicability of the GLCC concept and the pronounced impact it can have in the Petroleum Industry. However, the GLCC's in these applications were utilized without a complete understanding of the hydrodynamic flow behavior. Additional research and development are needed to produce models capable of predicting the performance of GLCC's in different configurations and applications. The design tools resulting from these models will not only allow more predictable and reliable
implementation of GLCC's, but will also guide the way for additional design improvements. Realizing the potential of GLCC's and the need for more technology development in this area, the Tulsa University Separation Technology Projects (TUSTP) was formed. TUSTP focuses on collecting experimental laboratory and field data on the performance of the GLCC and developing mathematical models for the prediction of the hydrodynamic behavior of the flow in the GLCC.

![Fig. 4: Schematics of Chevron’s Multiphase Metering Loop](image)

**EXPERIMENTAL DATA**

One of the most enthusiastically explored applications of the GLCC is for gas separation in multiphase measurement system. Multiphase meters that measure the full stream flow without separation suffer from size and accuracy limitations in gas dominated flows. The size of the multiphase meter can be kept small and measurement accuracy improved by simply pre-separating most of the gas. It was recently observed\(^{21}\) that many, if not most, of the multiphase metering applications are, in fact, gas dominated and fall outside the
operational envelope for a typical full stream multiphase meter. Also, it was reported that the accuracy and range of application of such meters deteriorate for in-situ gas volume fraction greater than 70%. In low gas flow applications, complete gas separation in the GLCC allows use of conventional metering technology. Fig. 4 is a schematic of Chevron's multiphase metering loop, using a GLCC. A vortex shedding meter is used to measure the gas flow, while the oil and water are measured simultaneously with a Coriolis based net oil computer. The coriolis based net oil computer measures the total mass flow rate and the mixture density. These measurements combined with the knowledge of the oil and water densities allow the determination of the water cut and the water and oil mass or volume flow rates\(^\text{16}\). This configuration requires more space than a full stream multiphase meter, but is significantly cheaper and potentially more accurate. Another advantage of this configuration is that for a wide range of flow conditions no active liquid level control system is required. Initial testing have confirmed this concept and defined the operational envelope for adequate (99%) gas/liquid separation, under limited operating conditions.

Test data have been acquired on three laboratory metering loops, incorporating GLCC’s of 0.0254, 0.0508 and 0.0762 m I.D, respectively. The two smaller diameter GLCC’s were built and tested by Kouba\(^\text{15}\), and the larger 0.0762 m GLCC was built by TUSTP\(^\text{2,12}\). Fig. 5 shows the operational data obtained for three different 0.0508 m I.D. laboratory GLCC’s prototypes. The fluids used were air and water and the operating pressures were approximately 205, 308 and 446 kPa (absolute). The x and y axes represent the in-situ gas and liquid superficial velocities, respectively. The different data sets indicate the onset of liquid carryover in the gas stream. The data were obtained by establishing a liquid flow rate and increasing the gas flow rate until the onset of liquid carryover was observed. The mechanism for liquid carryover is generally churn flow, except for very high gas rates and low liquid rates, where the liquid is carried over by mist flow. Therefore, the appropriate operating region for a complete gas/liquid separation lies to the left of the data points for each lab prototype. The region to the right of each data set represents liquid carryover for the corresponding GLCC prototype.

The lower left data set was generated for a laboratory prototype GLCC with a tangential inlet oriented perpendicular to the axis of the separator. This configuration is typical for conventional vertical separators with a tangential inlet as commonly found in industry applications. The performance for this configuration suffers because the swirling liquid passes in front of the GLCC inlet, forcing gas to blow through and entrain liquid. The result is that liquid is carried over at relatively low gas flow rates.

The performance of the second single stage prototype is significantly improved by simply inclining the GLCC inlet downward. The downward inclined inlet promotes stratification and initial pre-separation of gas and liquid before entry into the GLCC. Kouba\(^\text{15}\) observed that the optimum inclination angle of the inlet is approximately -27°, which causes the
swirling liquid to pass below the inlet, allowing the gas unobstructed passage into the upper part of the GLCC. This resulted in more than a two-fold increase in the performance envelope, as shown in the figure.

![Graph showing operational envelope with data points and pressure levels](image)

**Fig. 5: Operational Envelope Defined by the Gas Capacity Limits to Avoid Liquid Carryover in a 0.0508 m I.D GLCC**

The third data set in Fig. 5 was obtained from a two stage configuration in which a second GLCC was placed in series with the first one. In this configuration the gas outlet of the first GLCC was connected to the inlet of the second GLCC. Liquid was carried over in a mist flow for the near vertical segment of the operational envelope. This is the onset to annular mist flow, which represents the theoretical limit to the performance of the GLCC. Data for the third set of runs were collected at 308 kPa (abs.). The effect of pressure on the performance of the GLCC was studied by lowering the pressure in the GLCC. The fourth set of data was taken at 205 kPa (abs.). Comparison between the third and fourth
sets of data reveals that increase in the GLCC pressure results in a decrease of the operational envelope. This indeed is the effect of pressure on the transition to annular mist flow, which is the mechanism for liquid carryover for high liquid loadings in the two-stage GLCC. The data for low liquid loadings seem to indicate little advantage of two stages over one stage under similar conditions.

The shaded region in the lower left corner of Fig. 5 indicates the region where Chevron's field prototypes have successfully operated. The boundaries for this region were based on average flow rates. Instantaneous flow rates, i.e., superficial velocities were generally more than double the average rates.

A critical parameter for the prediction of liquid carryover is the maximum allowable liquid holdup in the GLCC above the inlet, as a function of the gas velocity. Measurements of this liquid holdup were made for zero net liquid flow conditions in the upper region of the GLCC. The GLCC was first filled with water and the liquid exit blocked. A low gas flow rate was then established, which initially removed part of the liquid from the upper region of the GLCC. This resulted in a special two phase flow above the inlet, where the gas flows through the liquid, but no liquid is carried over, i.e., zero net liquid flow conditions.

The experiments were repeated for increasing gas flow rates. Each gas flow rate resulted in a unique maximum allowable liquid holdup which decreased as the gas flow rate increased, as shown in Fig. 6. The liquid holdup above the GLCC inlet is calculated as the ratio of the liquid volume above the inlet to the volume of the GLCC from the inlet to the highest point reached by the liquid. At the gas capacity limit prior to liquid carryover, the highest point that the liquid reaches is the GLCC gas exit. Gas flowing conditions are under the capacity limit when the highest excursion point of the liquid falls below the gas exit.

Two different methods were used to measure the volume of the liquid above the inlet. The liquid volume was measured statically in the first method by simultaneously stopping the gas flow and trapping the liquid in the GLCC. This method ignores the small amount of gas entrained below the inlet. In the second method the differential pressure across the GLCC was measured under flowing conditions and attributed entirely to the hydrostatic head across the GLCC.

The differential pressure was converted to an equivalent fluid column height, and the liquid holdup in the upper part of the GLCC was calculated based on the amount of liquid above the inlet. As can be seen from Fig. 6, the two sets of data fall close together, which implies that the assumptions made in the two methods are valid. These are: neglecting entrained...
gas below the inlet in the first method, and neglecting frictional pressure drop in the second method.

![Graph showing liquid holdup vs. superficial gas velocity](image)

**Fig. 6: Liquid Holdup Above GLCC Inlet vs. Superficial Gas Velocity**

The fourth set of data was obtained under flowing conditions for both gas and liquid. The liquid holdup was measured by the second method. The close agreement between the data sets indicate that the method is a reasonable means to obtain liquid holdup in the upper part of the GLCC.

**MECHANISTIC MODELING**

The models presented in this section represent initial mechanistic models developed for the prediction of the hydrodynamic flow behavior in the GLCC. The models enable the prediction of the equilibrium liquid level, bubble trajectory and onset of annular mist flow...
in the GLCC. The equilibrium liquid level and the onset of annular mist flow are needed for the prediction of liquid carryover. The bubble trajectory will enable the prediction of gas carryunder. The mechanistic models are necessary to properly scale the results from the laboratory experiments to field conditions. In particular the occurrence of slug flow which can be handled easily in the laboratory, might be a potential problem under field conditions, where long slugs may occur in large diameter flowlines.

**Equilibrium Liquid Level**

For proper operation of a GLCC the liquid level should be maintained below the inlet, in order to avoid gas blowing through the liquid phase and carrying liquid in the gas stream. Under static no-flow conditions, the liquid phase will have the same level in the GLCC and in the recombination section. As the liquid flow increases, the liquid level in the GLCC will rise up due to hydrostatic head gain needed to compensate for frictional losses in the liquid section. For two phase flow the liquid level in the GLCC may be above or under the
inlet, depending on the operational conditions. Thus, it is essential to be able to predict the liquid level in the GLCC.

The proposed model determines the liquid level from a simple pressure balance between the inlet and outlet of the GLCC. This simple model neglects any hydrodynamic interactions between the gas and the liquid phases. Refer to Fig. 7 for the geometrical parameters.

The pressure drops in the liquid and gas sections are given, respectively, by

\[ \Delta P_l = \rho_l g (L_{ni} - L_{ni}) + \rho_g g (L_{in} - L_{ni}) - \left( \Phi_l + \frac{f_{hi} L_{ni} \rho_l v_{hi}^2}{D_l} \right) \]  
\[ \Delta P_g = \rho_g g (L_{gi} - L_{in}) - \Phi_g \]  

where \( \Phi_l \) and \( \Phi_g \) are the frictional pressure losses in the liquid and gas sections, respectively, as given by

\[ \Phi_l = \frac{\rho_l}{2} \left( \sum f_i L_i v_i^2 \frac{1}{D_i} + \sum K_i v_i^2 \right) \]  
\[ \Phi_g = \frac{\rho_g}{2} \left( \sum f_i L_i v_i^2 \frac{1}{D_i} + \sum K_i v_i^2 \right) \]  

The first terms in the parentheses of Eqs. (3) and (4) represent the frictional losses in the different pipe segments of the loop. Note that consistent with Eq. (1), the first term in Eq. (3) does not include the frictional losses in the GLCC itself. The second terms in the parentheses represent the resistive losses such as through reductions and elbows.

Equating the pressure drop in the liquid and gas sections, one can solve for the liquid level in the GLCC, as follows

\[ L_{ni} = \frac{\Phi_l - \Phi_g + \rho_l g L_{ni} - \rho_g g (L_{in} + L_{gi} - L_{in})}{g(\rho_l - \rho_g) - \left( \frac{\rho_l v_{hi}^2 f_{hi}}{2 D_l} \right)} \]  

318
The prediction of Eq. (5) for the liquid level in the 0.0508 m lab GLCC prototype as a function of the operational conditions is presented in Fig. 8. As will be discussed later, the equilibrium liquid level can be used for the prediction of liquid carryover in the GLCC.
Bubble Trajectory
The swirl created below the GLCC inlet causes a radial separation of the gas and the liquid phases due to the buoyant and centrifugal forces acting on them. The liquid phase moves towards the GLCC wall and the gas bubbles towards the centerline. Prediction of the bubble trajectory can be used to determine the "fate" of the bubbles, i.e., whether the bubbles are carried under with the liquid or caught in the updraft with the gas core. Some of the bubbles will move radially inward sufficiently to merge with the gas core, and will be carried upwards in the gas stream. Other bubbles will not merge with the gas core but will be carried by the liquid stream out of the GLCC.

The radial motion of a gas bubble can be determined from a force balance on the bubble. In this simple model the forces acting on a bubble in the radial direction are the centrifugal, buoyant and drag forces. Equating these forces yields the radial velocity distribution of a gas bubble, as follows
where the mixture density distribution $\rho_m(r)$ and the circumferential velocity distribution $v_t(r)$ are approximated, respectively, by

$$\rho_m(r) = \rho_g + \left(\rho_l - \rho_g\right) \left(\frac{r}{R_s}\right)^m \quad (7)$$

$$v_t(r) = v_{ts} \left(\frac{r}{R_s}\right)^n \quad (8)$$

In Eqs. (7) and (8) $r/R_s$ is the ratio of the radial location to the GLCC radius, and the value used for both the exponents $m$ and $n$ is 0.9.

The drag coefficient proposed by Turton and Levenspiel\textsuperscript{10} is used in this study, as follows

$$Cd(r) = \frac{24}{\text{Re}(r)} \left[1 + 0.173 \ \text{Re}(r)^{0.657}\right] + \frac{0.413}{1 + 16,300 \ \text{Re}(r)^{-1.09}} \quad (9)$$

where the Reynolds number is determined from

$$\text{Re}(r) = \frac{\rho_m(r) v_t(r) D_b}{\mu_l} \quad (10)$$

For a short time increment $dt$, the differential distance traveled by the gas bubble in the axial direction is

$$dz = \frac{dr}{v_t(r)} v_z \quad (11)$$

where $v_z$ is the axial liquid velocity in the GLCC. Thus, Eqs. (11) and (6) enable the determination of the bubble trajectory, i.e. $z(r)$. The total axial distance traveled by the gas bubble in the GLCC is determined from the integration of Eq. (11), yielding


\[ Z_t = \int \frac{v_r}{v_r(r)} \, dr \]  \hspace{1cm} (12)

Figure 9 shows the prediction of a 0.5 mm bubble trajectory in the 0.0508 m laboratory GLCC operating with air and water. For these conditions, the GLCC length below the inlet should be at least 0.4 m long in order to avoid gas carryunder.

**Onset of Annular Mist Flow**

The onset to annular mist flow represents the theoretical gas capacity limit to the performance of the GLCC. Under these gas flow rates conditions the first fine droplets of liquid are atomized and carried over in the gas stream. The criterion for this transition is similar to the one suggested by Taitel et al.\textsuperscript{23} for the transition boundary between slug or annular flow in vertical pipes, as follows

\[ v_{a-m} = 2.3351 \left( \frac{\sigma}{We} \frac{\rho_l - \rho_g}{\rho_g^2} \right)^{0.25} \]  \hspace{1cm} (13)

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Fig. 9: Bubble Trajectory for Air-Water Flow in a 0.0508 m I.D GLCC
Taitel et al.\textsuperscript{23} used a value of $We=20$ for large droplets encountered in the transition boundary between slug to annular flow. In this study a value of $We=7$ is used to represent the fine droplets occurring in annular mist flow. As shown in Fig. 5, an excellent agreement is obtained between the prediction of Eq. (13) and the experimental data for the high liquid loading region for the two sets of data.

**FUTURE WORK**

The models presented in this study provide qualitative guidance for GLCC design. However, enhancements of these models are underway that will enable prediction of the GLCC performance. For example, the proposed equilibrium liquid level model can predict the operational envelope (Fig. 5) for liquid carryover, if provided with the following: the actual liquid holdup in the region above the GLCC inlet, and the maximum allowable liquid holdup prior to liquid carryover. The actual liquid holdup will be determined from the prediction of the shape of the gas liquid interface, applying free vortex theory. The maximum allowable liquid holdup will be predicted from zero net liquid flow analysis for the gas region above the inlet. This is shown empirically in Fig. 6. The bubble trajectory model will be improved to account for bubble swarm and turbulent diffusivity effects.

Additional work being planned for this project include:

1. Field testing of GLCC prototypes.
2. Collection of laboratory and field data into a data bank.
3. Investigate passive and active controls for the GLCC.
4. Analyze response of the GLCC to severely fluctuating flows.
5. Development of a dedicated multiphase multidimensional CFD simulator for the GLCC.

**CONCLUSIONS**

GLCC's are finding a broad range of applications in the Petroleum Industry. Successful applications have been reported despite of lack of understanding of the optimum design and performance of the GLCC. Potential applications abound but are dependent upon a more complete understanding of the hydrodynamic behavior of the flow in the GLCC.

New data and rudimentary models have been presented which are the building blocks for the design tools that will allow better performance prediction and application of the GLCC. The operational envelope developed in the laboratory prototype was found to be exclusively governed by the liquid carryover in the gas stream. The operational envelop was found to be significantly enhanced by using an inclined inlet. Furthermore, using two
GLCC’s in series reached the theoretical performance limit due to the onset of annular mist flow. Mechanistic models were proposed for the prediction of the equilibrium liquid level, bubble trajectory and onset of annular mist flow in the GLCC. Further enhancements of these model were discussed that will enable the prediction of the GLCC operational envelope.

NOMENCLATURE

\begin{align*}
C_d &= \text{drag coefficient} \\
D &= \text{diameter} \\
f &= \text{friction factor} \\
g &= \text{acceleration of gravity} \\
K &= \text{resistance coefficient for elbow or tee} \\
L &= \text{length} \\
m &= \text{mixture density exponent, } m = 0.9 \\
n &= \text{tangential velocity exponent, } n = 0.9 \\
q &= \text{volumetric flow rate} \\
r &= \text{radial coordinate} \\
Re &= \text{Reynolds Number} \\
R_s &= \text{radius of GLCC} \\
T &= \text{temperature} \\
v &= \text{velocity} \\
z &= \text{axial coordinate} \\
Z_t &= \text{axial distance} \\
We &= \text{Weber Number, } W_e = 7 \\
\Delta P &= \text{pressure drop} \\
\Phi &= \text{frictional losses} \\
\mu_l &= \text{liquid viscosity} \\
\rho &= \text{density} \\
\sigma &= \text{surface tension}
\end{align*}

Subscripts

\begin{align*}
b &= \text{bubble} \\
c &= \text{core} \\
g &= \text{gas}
\end{align*}
l = liquid
m = mixture
r = radial
s = slot
t = tangential
z = axial

REFERENCES


