A REVIEW OF GAS-LIQUID CYLINDRICAL CYCLONE (GLCC) TECHNOLOGY

by

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ABSTRACT

Economic pressures continue to force the petroleum industry to seek less expensive alternatives to conventional gravity based separation. The gas-liquid cylindrical cyclone (GLCC) is a simple, compact, low-cost separator that can provide an economically attractive alternative to conventional separators over a wide range of applications. Although cyclones have long been used for liquid/liquid, solid/liquid, and gas/solid separation, they have experienced only limited use in full range gas/liquid separation applications. The biggest impediment to the wide spread use of GLCCs has been the lack of reliable performance prediction tools in order to know where they can and cannot be successfully applied.

This paper presents the status of the development of the GLCC, the state-of-the-art with respect to modeling the GLCC, and discusses current installations and potential applications.

INTRODUCTION

The GLCC is a simple, compact, low-weight and low-cost separator that is rapidly gaining popularity as an alternative to conventional gravity based separators. Shown in Fig 1 is a simple GLCC consisting of a vertical pipe with a tangential inlet and outlets for gas and liquid. The tangential flow from the inlet to the body of the GLCC causes the flow to swirl with sufficient tangential velocity to produce centripetal forces on the entrained gas which are an order of magnitude higher than the force of gravity. The combination of gravitational and centrifugal forces pushes the liquid radially outward and downward toward the liquid exit, while the gas is driven inward and upward toward the gas exit.

The performance of a GLCC is characterized by it's operational envelope which is bounded by lines of constant liquid carry-over in the gas stream and constant gas carry-under in the liquid stream. The onset to liquid carry-over is identified by the smallest flow of liquid observed in the gas stream. Similarly, the first observable bubbles in the liquid underflow mark the onset of gas carry-under.

Despite the long history of cyclone technology and the seemingly simple design and operation of the GLCC, these cyclones have not been widely used for full-range gas-liquid separation. Part of the reluctance to use GLCCs must be attributed to the uncertainty in predicting performance of the GLCC over a full range of gas-liquid flows. The difficulty in developing accurate performance predictions is largely due to the variety of complex flow patterns that can occur in the GLCC. The flow patterns above the inlet can include bubble, slug, churn, mist and liquid ribbon. Below the inlet the flow generally consists of a liquid vortex with a gas core. At lower liquid levels, a region of annular swirl flow may exist between the inlet and the vortex. Further refinements of flow pattern definition below the inlet have not been made.

This difficulty in predicting the hydrodynamic performance of the GLCC has been the single largest obstruction to broader usage of the GLCC. Even without tried and tested performance predictions, several successful applications of GLCCs have been reported. The development of reliable performance prediction tools will govern the speed and extent to which the GLCC technology can spread in existing and new applications.

APPLICATIONS

The GLCC has a distinct advantage over conventional gravity based separators when compactness, weight, and cost are the overriding considerations for separator selection. There are a variety of applications where requirements may vary from partial to complete gas-liquid separation. Below are some of the current installations and potential applications for the GLCC.

Multiphase Measurement Loop: Figure 2 shows a GLCC in a multiphase metering loop configuration. This type of measurement loop configuration affords several advantages over either conventional separation and single phase measurement or nonseparating multiphase meters. The loop configuration is somewhat self- regulating which can reduce or even eliminate the need for active level control. The compactness of the GLCC allows the measurement loop to weigh less, occupy less space, and maintain less hydrocarbon inventory than a conventional test separator. Furthermore, complete or even partial gas-liquid separation can improve the accuracy of each phase rate measurement in a multiphase metering system.

When complete gas-liquid separation is achieved in the GLCC, several liquid metering options are available, e.g., bulk liquid metering and proportional sampling. Chevron has several multiphase metering loops in operation that use this standard liquid metering approach on the liquid leg of a GLCC. This is a very low cost option for multiphase measurement although sampling can be labor intensive.

Two-phase liquid-liquid meters are also available for the liquid leg. Liu and Kouba[16] have shown that Coriolis meters with the net oil computer (NOC) option can simultaneously measure oil and water flow rates with excellent accuracy for production allocation applications, such as well testing, provided there is no gas present in the meter. Chevron has deployed several multiphase metering loops with Coriolis NOCs on the liquid leg as shown in Fig.3. One of the main limitations of the Coriolis NOC in the measurement loop is the sensitivity of the Coriolis NOC to small amounts of gas that may carry-under with the liquid. The Accuflow multiphase measurement system, shown in Fig. 4, utilizes a second stage horizontal pipe separator between the GLCC and the Coriolis meter to prevent gas carry-under from reaching the Coriolis meter[17].

When gas carry-under cannot be prevented, a three-phase metering system is required on the liquid leg. In general, the accuracy of a multiphase meter on the liquid leg will benefit significantly from removing some of the gas. Most multiphase meters have an upper limit on the gas volume fraction allowed through the meter in order to maintain their accuracy specifications. Beyond improved accuracy, partial gas separation provides the additional benefit of utilizing a smaller, less expensive, multiphase meter. For some multiphase meters whose price scales directly with size, the cost savings of using a smaller meter was over 4 times the cost of the GLCC.

The effect of partial gas separation on multiphase metering can be so pronounced that several multiphase meter manufacturers are configuring their meters in multiphase measurement loops utilizing compact gas-liquid separation. At least two manufacturers are supporting further research on GLCCs.

Preseparation: A compact GLCC is often very appropriate for applications where only partial separation of gas from liquid is required. One such application is the partial separation of raw gas from high pressure wells to use for gas lift of low pressure wells. Weingarten et al.[23] developed a gas-liquid cyclone separator with an auger internal for downhole and surface separation of raw gas. They showed that the auger cyclone could successfully separate up to 80% of the gas without significant liquid carry-over into raw lift gas stream. The cost of the auger separator was reported to be about 2% of a conventional separator. The real savings in this sort of application comes from reducing or eliminating gas compression facilities.

Separating a significant portion of the gas will reduce fluctuations in the liquid flow and may result in improved performance of other downstream separation devices. Krebs Petroleum Technologies[28] is investigating the use of a GLCC in series with other compact separation devices such as a wellhead desanding hydrocyclone and a free water knockout hydrocyclone. Chevron is investigating the series combination of a GLCC with a free-water knockout hydrocyclone and a deoiling hydrocyclone in an effort to improve discharge water quality, as shown in Fig. 5.

Arato and Barnes[1] investigated the use of GLCC to control GLR to a multiphase pump to improve pumping efficiency. Sarshar et al[22] showed several combinations of GLCC and jet pumps that could be used to extract energy from high pressure multiphase wells to enhance production from low pressure wells.

Production Separation: Vertical separators with tangential inlets are fairly common in the oil field. These predecessors of the GLCC are often big and bulky with low velocity perpendicular tangential pipe inlets. The tangential velocities are usually so low that gravitational and centrifugal forces contribute roughly equally to separation. Technological developments (discussed in later sections) in both GLCC hardware and software should reduce the size and improve the performance of vertical separators. One challenge in optimizing the size of a GLCC for production separation is designing a system that can respond quickly to surges without serious upsets.

Cyclone separation has already proven useful in internal separation devices for large horizontal separators. The GLCC may also provide a useful external preseparation device to enhance performance of existing horizontal separators, as in Fig. 6. By separating part of the gas, the separator level might be raised to increase residence time without encountering the mist flow regime in the vessel.

The biggest impact to the petroleum industry from GLCC technology may be in subsea separation applications. Baker and Entress[4] have concluded that "wellhead separation and pumping is the most thermodynamically efficient method for wellstream transfer over long distances, particularly from deep water". No doubt, the development of marginal offshore fields will depend upon developing efficient and profit effective technologies. Subsea applications demand a high degree of confidence in separator design and performance while demanding that the equipment be simple, compact, robust and economical. Here again the virtues of the GLCC should place it in good standing among competing technologies.

DEVELOPMENTS

Few systematic studies of design configurations of different GLCC physical features have been conducted. Laboratory observations and computer simulation indicate that some modifications to the GLCC can have a profound effect on the GLCC performance.

Inlet Designs

The GLCC performance is dependent upon the tangential velocities of the swirling fluids, especially that of the liquid. The inlet is the single most redesigned component of the GLCC because of the inlet's influence on tangential velocity.

Inclined Inlet: At moderate to high gas velocities, the inclined inlet, Fig. 1 & 2, reduces liquid carry-over in the gas stream through two mechanisms. First, the downward inclination of the inlet promotes stratification and provides preliminary separation in the inlet nozzle to the GLCC. Second, while the tangential inlet causes the fluids to flow circumferentially, the downward inclination causes the liquid stream to spiral below the inlet after one revolution, preventing the liquid from blocking the flow of gas in the upper part of the inlet. Inclining the inlet approximately 27° downward retards the onset of liquid carry-over significantly compared to a perpendicular inlet in a low pressure air-water system[15]. This has yet to be confirmed either quantitatively or qualitatively under different fluids and flow conditions.

Slotted Wall Nozzle: The slotted nozzle produces a thin tangential wall jet of rectangular cross-section. The advantage of the rectangular jet over the circular jet is that the angular momentum generated by the incoming fluid is concentrated closer to the wall which should aid separation. We know of no systematic evaluations of the effect of nozzle geometry on GLCC performance.

Variable Inlet: A variable area inlet should serve to maintain an optimum tangential velocity for separation. Davies[10] reported the use of a variable inlet, but did not indicate to what extent controlling the tangential velocity improved the separator performance. Marti et al[18] used CFD simulations to predict gas carry-under parameters as a function of the ratio of tangential to axial velocities, and employed mechanistic modeling to predict the gas-liquid vortex height as a function of inlet tangential velocity. From this work we conclude that an optimum tangential velocity must exist. The challenge is to predict the optimum tangential velocity for different fluids and flow conditions.

Dual Inlet: There are several different configurations for dual inlets. Diametrically opposed inlets can be used to help stabilize the gas core if the geometry and flow rates are well matched. While this arrangement has been successfully used for liquid-liquid hydrocyclones, we are not aware of any tests of this configuration on GLCCs.

Dual inclined inlets at different axial locations are being investigated by Chevron and TUSTP. The idea behind this configuration is to reduce the sensitivity to liquid level in the GLCC by preseparating the mixture into liquid rich and gas rich streams in the lower and upper inlets, respectively. Preliminary testing at the Tulsa University Separation Technology Projects (TUSTP) of the dual inlet GLCC indicates a significant improvement in liquid carry-over performance at low to moderate gas rates with no discernible improvement at high gas rates.

Body Configuration

Despite the simple design of the GLCC, there are several possible modifications to the body configuration that can influence performance.

Optimum Aspect Ratio: The dimensions of the GLCC will influence performance and cost. The aspect ratio is the ratio of GLCC's length to diameter. The residence time of fluid in the GLCC is directly proportional to length and the square of diameter, while the centrifugal and centripetal forces are inversely proportional to diameter. Frictional damping of the tangential velocity can dramatically reduce the centripetal forces at large distances away from the inlet indicating diminishing improvements in performance for increases of length. Although there are several factors to consider in sizing a GLCC for a specific application, a fundamental set of criteria to determine the optimum aspect ratio has not yet been determined.

Cyclone Body Taper: Millington and Thew[19] investigated diverging, converging and cylindrical cyclones and found cylindrical walls to be slightly superior to either converging or diverging walls for gas-liquid separation.

Gas Outlet: The coaxial gas outlet penetrating into the GLCC is sometimes referred to as a "vortex finder". Laboratory tests at Chevron could not find any combination of outlet diameter and protrusion length into the GLCC that performed measurably better than a constant GLCC diameter outlet at low to moderate gas rates. At high gas rates, we expect that the conservation of angular momentum in the outlet will produce a combined forced and free vortex in the gas region of the GLCC and improve liquid carry-over performance.

Liquid Outlet: A tangential exit for the liquid flow out the GLCC would seem to pull liquid from the near wall region and reduce gas carry-under and may even help to stabilize the gas core. Although several GLCC prototypes have been tested with tangential exits, we are not aware of any systematic efforts to test the effect of the tangential exit on GLCC performance.

Optimum Liquid Level: Most testing to date indicates that the optimum liquid level in the single GLCC is just below the inlet down to approximately 3L/D below the inlet. The incoming tangential liquid stream makes about one revolution around the inside circumference of the GLCC over this distance and maintains a high angular momentum. Farther below the inlet than 3L/D, friction causes significant decay in the tangential velocity. If the liquid level is above the inlet, gas must blow through the swirling liquid sheet and is more likely to carry-over liquid.

System Considerations

The GLCC is typically part of a larger system of pipes and separation equipment. Because of the GLCC's small size and short fluid residence time, it is not as forgiving as a large vessel in responding to severe flow rate surges. Consequently, care must be taken in the system integration of the GLCC.

Two-Stage GLCC: Theoretical work by Kouba et al.[15] successfully predicted that a second stage GLCC on the gas leg would push the liquid carry-over performance of the two-stage GLCC to the onset of mist flow boundary which was anticipated as the theoretical performance limit. It was found that at very low liquid loadings, the centripetal forces on the liquid would allow the operational envelope to push well beyond the normal annular mist flow boundary.

The Accuflow measurement system uses a second stage horizontal pipe separator to remove any small gas bubbles that may have passed through with the liquid underflow from the GLCC. This has enabled Accuflow to extend the operating range of their system beyond the "normal" operating range of the GLCC for complete gas-liquid separation.

Liquid Level Controls: The liquid level in a GLCC is somewhat ill-defined because of the shape of the gas-liquid interface. This presents a dilemma to most liquid level control schemes, for what we would like to know is the height of the crown of the liquid vortex. Unfortunately, what we typically measure is the equilibrium liquid level, i.e., sight gage level. Efforts to relate crown height to equilibrium liquid level height are discussed elsewhere in the section on simulation. Suffice it to say, liquid level control usually begins with measurement of the equilibrium liquid level. Other issues in level control also include: type of control system, response time, power requirements, robustness and cost.

The Accuflow multiphase measurement system has successfully used conventional control equipment to maintain a tight control on liquid level by controlling the gas flow rate out the GLCC[17]. Kolpak[14] explored low power alternatives to conventional level controls that exploited hydrostatic head difference in the GLCC to operate the controls. Chevron has used inexpensive internal floating ball check valves to prevent liquid flooding in the GLCCs used in well test systems[15].

SIMULATION EFFORTS

The Tulsa University Separation Technology Projects (TUSTP) was organized specifically to develop reliable performance prediction tools for the GLCC. We believe that the inability to accurately predict GLCC performance under different operational scenarios is the single biggest impediment to wider spread usage of the GLCC technology. For many years, correlations based on limited laboratory and field data have been the primary tools for designing and predicting some performance aspects of cyclone separators. Correlations are typically limited to the test conditions used to obtain the data on which the correlation is based. Interpolation can be risky and extrapolating to completely different conditions requires a leap of faith for the designer relying solely on correlations. Consequently, users could not have great confidence in applying the technology to applications outside their range of experience.

The state-of-the-art in predicting detailed hydrodynamic flow behavior within cyclone separators has in the past revolved solely around computational fluid dynamics (CFD). These simulators can predict the flow field and track the trajectories of discreet particles of the dispersed phase. While well suited for local modeling of single phase and dispersed two-phase flows, present CFD models are unable to handle some of the complex flow regimes observed in the GLCC, in particular, slug and churn flows. Only recently have some of the CFD simulators accomplished true two-phase modeling of dispersed flows and modeling of a free surface between two single phase flows. To our knowledge, no CFD program can yet simultaneously model both the dispersed and free surface in rotating flows that occur in a GLCC. Furthermore, CFD models of large piping systems that include the GLCC are typically too unwieldy to be practical for design purposes.

Mechanistic modeling offers a practical approach to GLCC design and performance prediction that can be an alternative or complementary to CFD simulation. Mechanistic models use simplifying assumptions but, ideally, still capture enough of the fundamental physics of the problem to allow interpolation and extrapolation to different fluid flow conditions. Because the mechanistic models are greatly simplified, they are not as detailed, rigorous, or accurate as the CFD models. Still, there are many advantages of mechanistic modeling: speed of setup and computation, ability to model entire system, and suitability for PC operation. Consequently, these models are more accessible to engineers as a design tool than CFD models. Our approach is to develop fundamental mechanistic models, then verify and refine them with experimental data and CFD predictions.

Mechanistic Modeling

The discussion here is limited to the status of ongoing work at TUSTP as we are unaware of any other major efforts in this area. Most of this work has been presented in references [2, 3, 13, 15, and 18].

The ultimate aim of this modeling work is to predict the operating envelope for the GLCC with respect to liquid carry-over in the gas stream and gas carry-under in the liquid stream. Each fluid flow path has its own particular set of calculations. The starting point for either calculation path is the global distribution of gas and liquid in the GLCC.

The equilibrium liquid level in the GLCC is determined by the pressure drop between the gas and liquid outlets by using a differential pressure cell or sight gauge. Because the frictional losses in the GLCC are low, the equilibrium liquid level is a reasonable indication of the amount of liquid in the GLCC. The details of this model were given by Kouba[15] and Arpandi [2,3]. Arpandi also presented a model to determine the shape and location of the gas-liquid interface when coupled with the calculation for equilibrium liquid level. This model of the global distribution of gas and liquid provides the groundwork for the performance models.

Liquid Carry-Over in Gas Stream: Liquid carry-over with the gas stream is largely dependent upon the flow pattern in the upper (gas) part of the GLCC. Flooding may occur in the GLCC at high liquid levels and low gas rates producing a bubbly flow. The unstable liquid oscillations, characteristic of churn flow at moderate gas rates, may splash liquid into the gas outlet. Liquid can be carried out in droplets at the onset to annular mist flow at high gas rates. At very high gas rates, the centrifugal force of the swirling gas pushes the liquid to the wall of the pipe where it may form an upward spiraling continuous ribbon of liquid.

At present, we can predict the onset of liquid carry-over from low to moderately high gas rates. The key to onset of liquid carry-over has been to accurately predict the maximum liquid holdup (volume fraction) at zero-net liquid flow conditions in the upper region of the GLCC and the pressure balance between the gas and liquid legs. Figure 7 compares our predictions against experimental results in plots of the maximum liquid holdup in the upper GLCC against the superficial gas velocity in the GLCC. Once the maximum liquid holdup allowed in the upper part of the GLCC is known for a given gas rate, then the pressure balance calculation is used to determine the liquid rate required to achieve this holdup.

The operational envelope with respect to liquid carry-over is formed by stepping through the range of gas rates and calculating the corresponding liquid rates. Figure 8 compares the experimental and predicted operational envelopes for TUSTP's 3" laboratory GLCC in a loop configuration operated with air and water at low pressures. The agreement of model predictions with data is very good; however, the model is incomplete as it does not handle gas velocities beyond the onset to annular mist flow.

Future improvements to liquid carry-over modeling will include verifications for different fluid properties and operational conditions, ability to simulate high gas rate conditions, and predictions of dynamic responses to flow rate surges.

Gas Carry-Under in Liquid Stream: Three mechanisms have been identified as possible contributors to gas carry-under: 1) shallow bubble trajectories prevent small bubbles from escaping to the gas core, 2) rotational flow instability results in helical whipping and breaking of the gas core filament near the liquid exit, 3) liquid rate surges can produce a concentrated cloud of bubbles that hinders bubble migration to gas core. At present attempts to predict gas carry-under have focused only on the first mechanism.

Recent work by Marti et al[18] used bubble trajectory analysis to predict the onset to gas carry-under and separation efficiency for different size bubbles. Marti predicted the d_{100} bubble diameter, i.e. the minimum bubble size that always migrated from GLCC wall to gas core, and investigated the effects of tangential to axial velocity ratio and tangential velocity decay on d_{100} size, Figs. 9 and 10, respectively. Releasing bubbles at radial locations less than the GLCC wall radius resulted in bubbles smaller than d_{100} that could just be captured before reaching the axial location of the liquid exit. The bubble capture efficiency was calculated from the ratio of squares of release radius to GLCC radius. Figure 11 shows how the bubble capture efficiency varies with bubble diameter and tangential velocity decay rate.

The region of interest in the bubble trajectory analysis[18] was assumed to extend from the bottom of the gas-liquid vortex to the liquid exit. The vortex height is a strong function of inlet velocity and bubble trajectory length diminishes with vortex height. From this it can be inferred from that an optimum inlet velocity must exist that will minimize gas carry-under. An inlet velocity that is too low produces insufficient centripetal forces, whereas, if the inlet velocity is too high then the available length for bubble trajectory is too short.

Although a procedure for determining overall separation efficiency was not reported by Marti, this work combined with the approach of Wolbert et al.[22] for liquid-liquid hydrocyclones establishes the foundation for calculation of overall gas separation efficiency.

Computational Fluid Dynamic (CFD) Simulation

Verifying the mechanistic models with real data is not always practical or possible. CFD simulation is used to support our mechanistic modeling effort by investigating the detailed hydrodynamics of the flow in the GLCC to see if our simplified models capture enough of the physics to be valid for the intended purpose.

Single Phase Dispersed Flow: The simplest and most widely used approximation for modeling two-phase flows with a CFD simulator is to consider single phase populated with particles (bubbles) that neither interact with each other or influence the flow. Marti et al[18] compared single phase CFD simulations from a commercial package to the experimental data of Farchi[11] which investigated tangential velocity profiles in a GLCC. Both data and CFD models demonstrated the rapid radial decay of tangential velocity near the inlet that quickly adjusted to a typical forced vortex flow away from the inlet region. The CFD simulations were also used to verify the mechanistic modeling of the axial decay of tangential velocity.

These simulations[18] also predicted the existence of a central upward recirculating region that established a bubble capture radius much larger than the capture radius defined by the gas core filament. The bubble capture radius was defined as the radial location where the axial velocity component becomes zero. At smaller radial locations than the capture radius, the local liquid velocity is upward even though the net liquid flow is downward. The capture radius was further investigated as a function of the tangential to axial velocity ratio and axial location, Fig. 12. The results indicated a rapid decline of capture radius as the velocity ratio decreased below 10. As yet there is no comparable mechanistic model to predict bubble capture radius.

Two-Phase Flow: True two-phase CFD simulation is still in its infancy. Such simulations should predict the influence of the dispersed phase on the flow of the continuous phase and the interface between the two phases. True two-phase CFD simulation work at TUSTP is proceeding on two fronts. First, we are investigating the two-phase simulations of flow in a GLCC using a commercial CFD package (CFX). Second, TUSTP is also developing a dedicated CFD code for GLCC flow predictions.

CONCLUSIONS

The gas-liquid cylindrical cyclone is a compact, low-cost separator suitable for a wide range of applications. New applications and improved designs are rapidly being explored. The single biggest impediment to the wide-spread implementation of the GLCC is the lack of proven performance prediction tools which are valid over a wide range of conditions. These tools are essential to the reliable deployment of GLCC technology.

Performance prediction tools based on empirical formulations are limited in ability to interpolate or extrapolate to new conditions. CFD simulations can capture much detail of local hydrodynamics but are too computationally intensive, time consuming and complicated to apply to large systems. While CFD modeling is essential to improve our understanding of the hydrodynamics of flow in a GLCC, it is impractical and therefore insufficient as a general design tool.

Mechanistic modeling is a reasonable compromise between the simplicity of empirical formulations and the complexity of CFD. Mechanistic modeling can be validated with CFD simulations to capture the fundamental physics of the flow without excessive detail. The combination of CFD and mechanistic modeling provide a realistic approach to obtaining useful tools for design and performance predictions for the GLCC.

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REFERENCES

1. Arato, E.G., Barnes, N.D., "In-line Free Vortex Separator Used for Gas/Liquid Separation within a Novel Two-Phase Pumping System", Hydrocyclones - analysis and application. Editors: L. Svarovsky, M. T. Thew. Brookfield, VT: Kluwer-Academic (1992), pp. 377-396.

2. Arpandi, I., "A Mechanistic Model for the Prediction of the Hydrodynamic Behavior of Two-Phase Flow in the Gas-Liquid Cylindrical Cyclone Separator", M.S. Thesis, The University of Tulsa (1995).

3. Arpandi, I., Joshi, A.R., Shoham, O., Shirazi, S., Kouba, G.E.: “Hydrodynamics of Two-Phase Flow in Gas-Liquid Cylindrical Cyclone Separators”, SPE 30683, Proceedings of the SPE Annual Technical Conference, Dallas, USA, October 22-26, 1995, pp. 429-440.

4. Baker, A.C., Entress, J.H., "VASPS (Vertical Annular Separation Pumping System) Subsea Separation and Pumping System", Trans I Chem E., v. 70, Part A (Jan. 1992), p. 9-16. Paper presented at the Institution of Chemical Engineers Conference "Subsea Separation and Transport III", London, (23-24 May, 1991).

5. Bandopadhyay, P. R. , Pacifico, G.C and Gad-el-Hak, M., “Sensitivity of a Gas-Core Vortex in a Cyclone-Type Gas-Liquid Separator”, Advanced Technology and Prototyping Division, Naval Undersea Warfare Center Division, Newport, Rhode Island (1994).

6. Bandopadhyay, P.R., Pacifico, G.C., Weapons Technology and undersea Systems Department; Gad-el-Hak, M. University of Notre Dame, “Gas Core Configurations in a Cyclone-Type Gas-Liquid Separator”, NUWC-NPT Technical Report 10, 308, 3 (January 1994).

7. Boyson, F. Ayers, W.H., Swithenbank, J., : "A Fundamental Mathematical Modelling Approach to Cyclone Design", Trans. IChemE., v. 60, No. 4 (July 1982), pp. 222-230.

8. Cowie, D., "Vertical Caisson Slugcatcher Performance", Trans. IChemE, v. 70, part A (Jan. 1992), p. 25-31. Paper presented at the Institution of Chemical Engineers Conference "Subsea Separation and Transport III" held in London, (23-24 May, 1991).

9. Davies, E. E., Watson, P., "Miniaturised Separators for Offshore Platforms." 1st New Technology for Exploration and Exploitation of Oil and Gas Reserves Symposium. Luxembourg, Apr. 1979. London, Eng.,BP Research Centre, (1979), pp. 75-85.

10. Davies, E.E., "Compact Separators for Offshore Production", 2nd, New Technology for the Exploration & Exploitation of Oil and Gas Resources Symposium. Luxembourg, 5 Dec. 1984. London, Eng.,BP Research Centre, (1985), Proceedings, v. 1, pp. 621-629.

11. Farchi, D.: "A Study of Mixers and Separators for Two-Phase Flow in M.H.D. Energy Conversion Systems", M.S. thesis (in Hebrew), Ben-Gurion University, Israel, 1990.

12. Forsyth, Ray A., "Cyclone Separation in Natural Gas Transmission Systems - the Design and Performance of Cyclones to Take the Debris out of Natural Gas", Chemical Engineer, (London) (June 1984), pp. 37-41.

13. Joshi, A., "Two-Phase Flow in Gas-Liquid Cylindrical Cyclone Separators - Experiments and Modeling", M.S. Thesis, The University of Tulsa (1995).

14. Kolpak, M., : "GLCC Level-Pressure Sensitivity, Level Control and Turbulent Diffusion" Internal Report, ARCO, (1994).

15. Kouba, G.E., Shoham, O., Shirazi, S.: "Design and Performance of Gas-Liquid Cylindrical Cyclone Separators", Proceedings of the BHR Group 7th International Conference on Multiphase Flow, Cannes, France, June 7-9, 1995, pp. 307-327.

16. Liu, K. T. and Kouba G. E., : "Coriolis Based Net Oil Computers Gain Acceptance at the Wellhead" Oil & Gas J., vol. 92, No. 26 (June 27, 1994).

17. Liu, K.T.: private communications

18. Marti, S.K., Erdal, F.M., Shoham, O., Shirazi, S.A., Kouba, G.E.: "Analysis of Gas Carry-Under in Gas-Liquid Cyclones", International Conference on Hydrocyclones, Cambridge, UK, April 2-4, 1996.

19. Millington, B.C., Thew, M. T., "LDA Study of Component Velocities in Air-Water Models of Steam-Water Cyclone Separators", 3rd International Conference on Multiphase Flow. The Hague, Neth., (18 May 1987). Cranfield, Bedford, Eng.: BHRA Fluid Engineering Centre, (1987), pp. 115-125.

20. Nebrensky, N.T., Morgan, G.E., Oswald, B. J., "Cyclone for Gas/Oil Separation", International Conference on Hydrocyclones, paper no. 12, held at Churchill College, Cambridge, Eng., (1980). Organized by BHRA Fluid Engineering Centre.

21. Oranje, I. L., "Cyclone-Type Separators Score High in Comparative Tests", Oil & Gas Journal v. 88., no. 4, (22 Jan. 1990), pp. 54-57.

22. Sarshar, M.M., Loh, W.L.: " Applications of Wellcom Systems to Enhance Production", Proceedings of the BHR Group 7th International Conference on Multiphase Flow, Cannes, France, June 7-9, 1995, pp. 147-169.

23. Weingarten, J.S., Kolpak, M.M., Mattison, S.A., Williamson, M.J.: "New Design for Compact Liquid-Gas Partial Separation: Downhole and Surface Installations for Artificial Lift Applications", SPE 30637, Proceedings of the SPE Annual Technical Conference, Dallas, USA, October 22-26, 1995, pp. 73-82.

24. Zhikarev, A.S., Kutepov, A.M., Solov'ev, V., "Design of a Cyclone Separator for the Separation of Gas-Liquid Mixtures", Chemical and Petroleum Engineering v. 21., no. 3/4 (Mar. 1985), pp. 196-198.

25. "Study of the Action of a Cyclones Classifier for Separating Gas-Liquid Mixtures", Journal of Applied Chemistry of the USSR v. 58, no. 1 (1985): pp. 169-172. Translated from: Moscow Institute of Chemical Engineering. Zhurnal Prikladnoi Khimli, (January 1985), pp. 180-183.

26. "Cyclone for Gas/Liquid Separators - Platform Equipment", Offshore Services & Technology (Nov. 1980), pp. 12-17. Paper presented at the International Conference on Hydrocyclones, Churchill College, Cambridge, Eng., (1980).

27. "Well Testing Service Uses New Mini-Separator - Platform Equipment", Offshore Service & Technology (Jan. 1981), pp. 16-17.

28. "How Good Are Gas-Liquid Separators?", 8th International Conference on Offshore Mechanics & Arctic Engineering., The Hague, Neth., (Mar. 1989), The Hague, Neth., OMPEC (Offshore Mechanics & Polar Engineering Council), (1989), pp. 297-403.

29. Private communications with Krebs Petroleum Technologies.

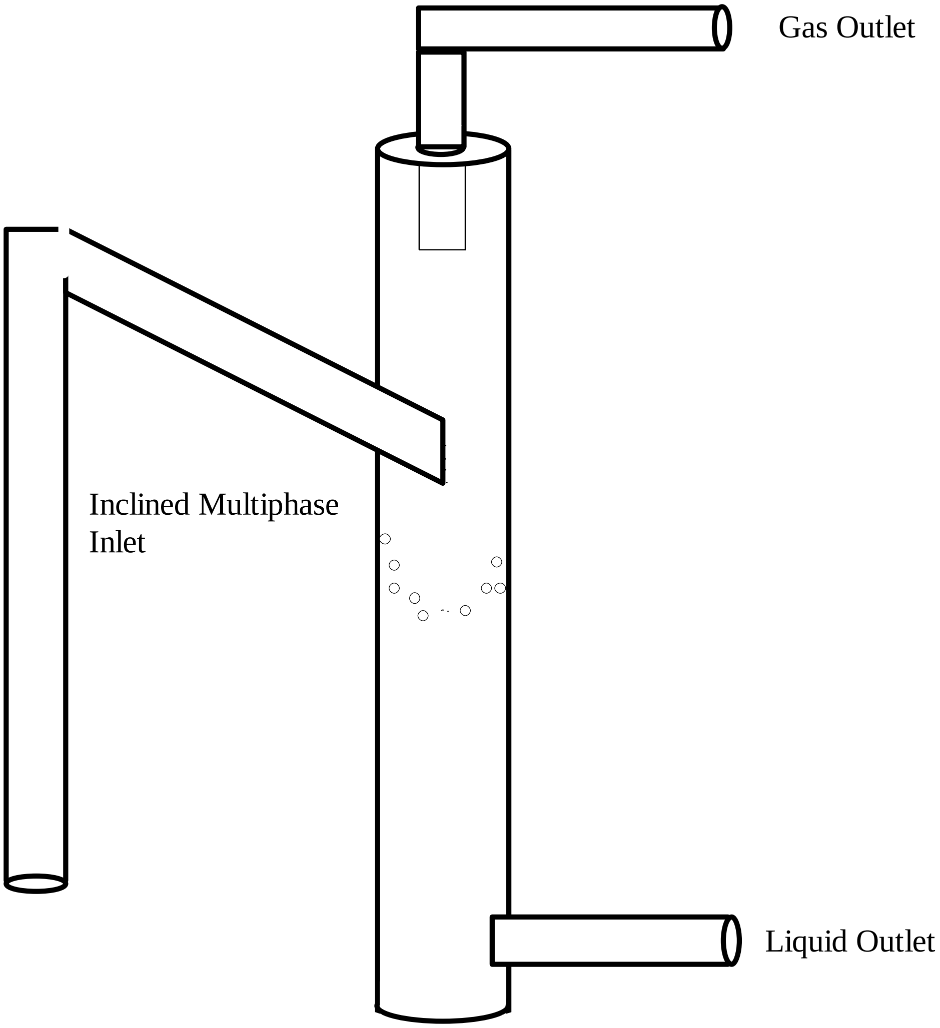

Fig. 1 - The Gas-Liquid Cylindrical Cyclone

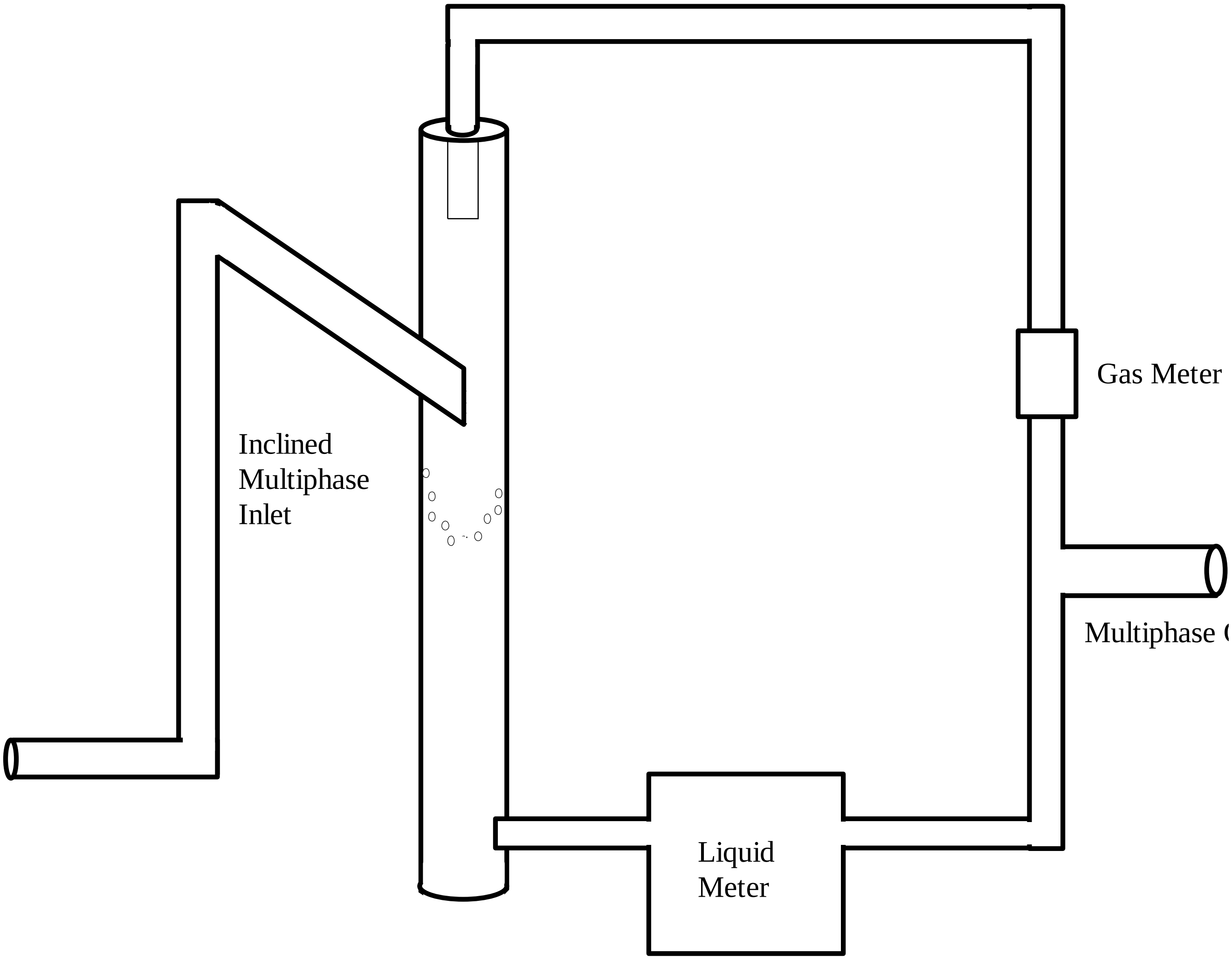

Fig. 2 - GLCC in a Multiphase Metering Loop Configuration

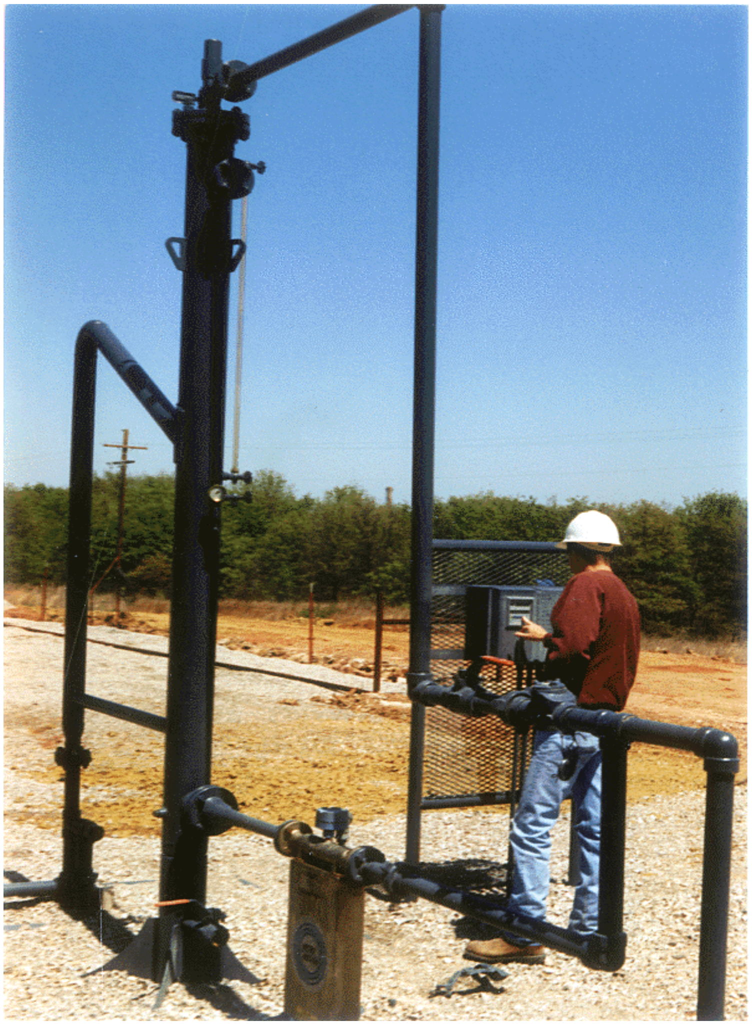

Fig. 3 – A GLCC in Chevron’s Multiphase Metering Loop in Low GLR Applicatior

Fig. 4 – Accuflow’s Multiphase Metering System Uses a Horizontal Pipe for Second Stage Separation Do

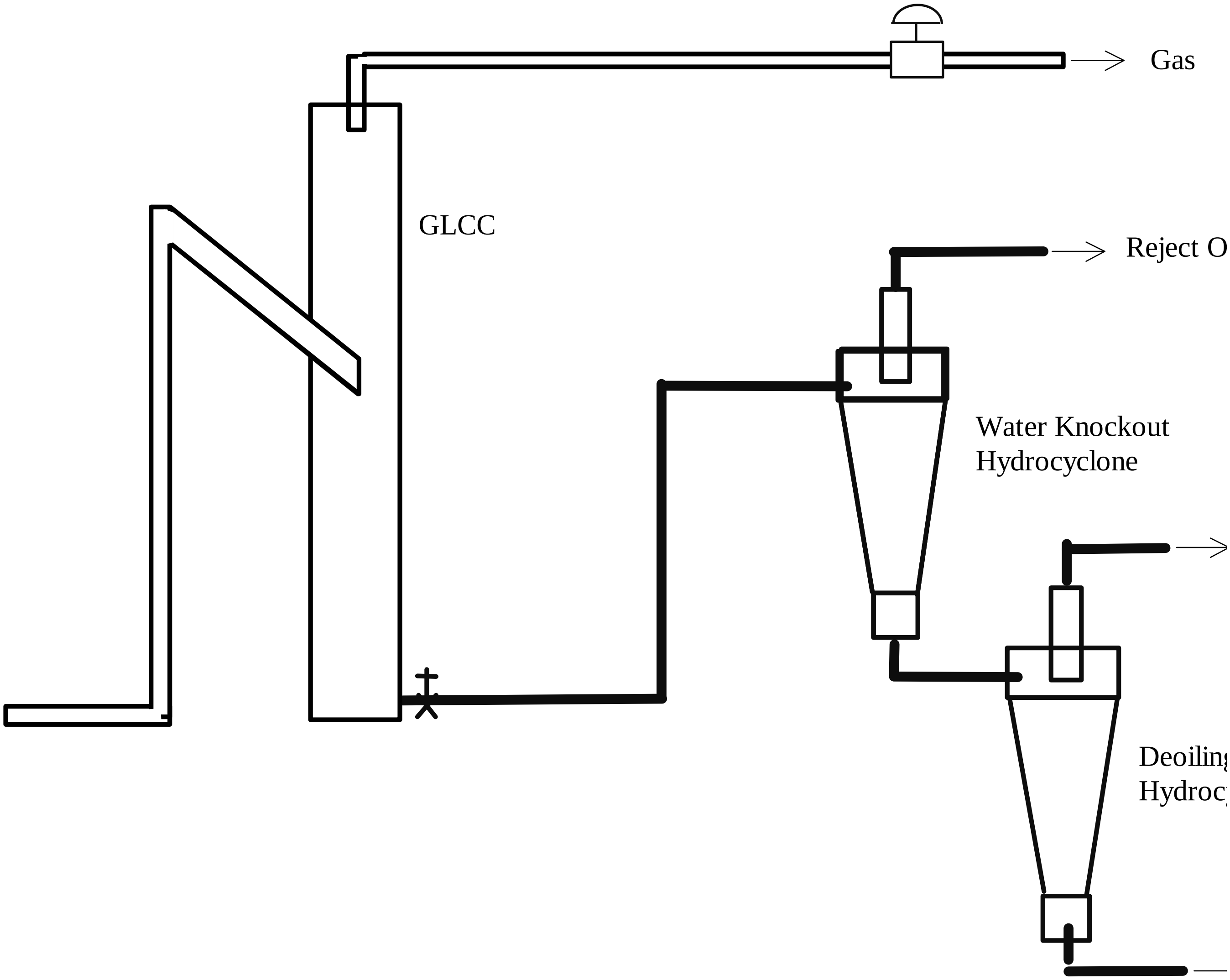

Fig. 5 - GLCC in Series with Water Knockout and Deoiling Hydrocyclones.

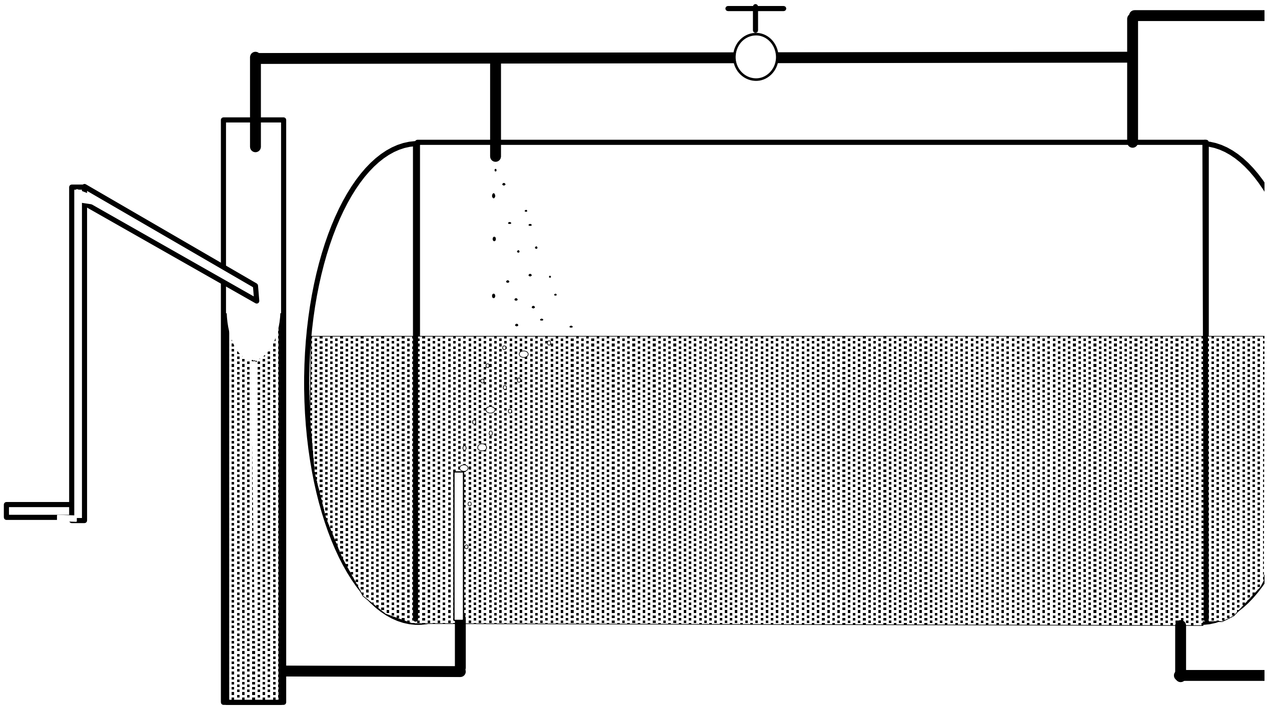

Fig. 6 - The GLCC as an External Preseparator to an Existing Separator.

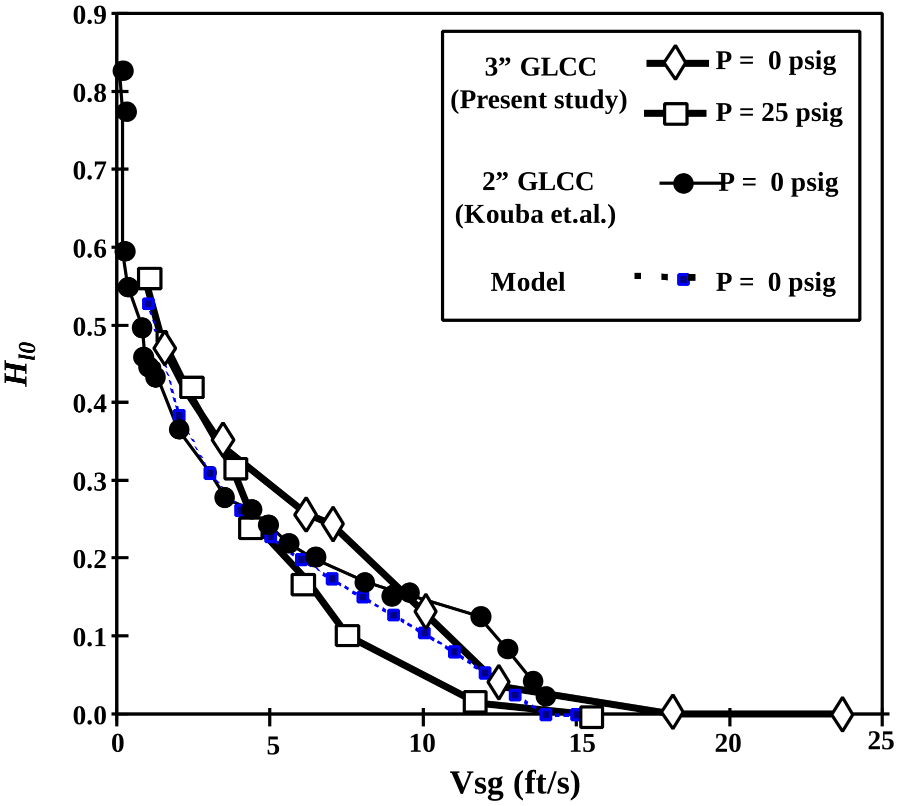

Fig. 7 - Zero-Net Liquid Holdup in Air-Water Systems

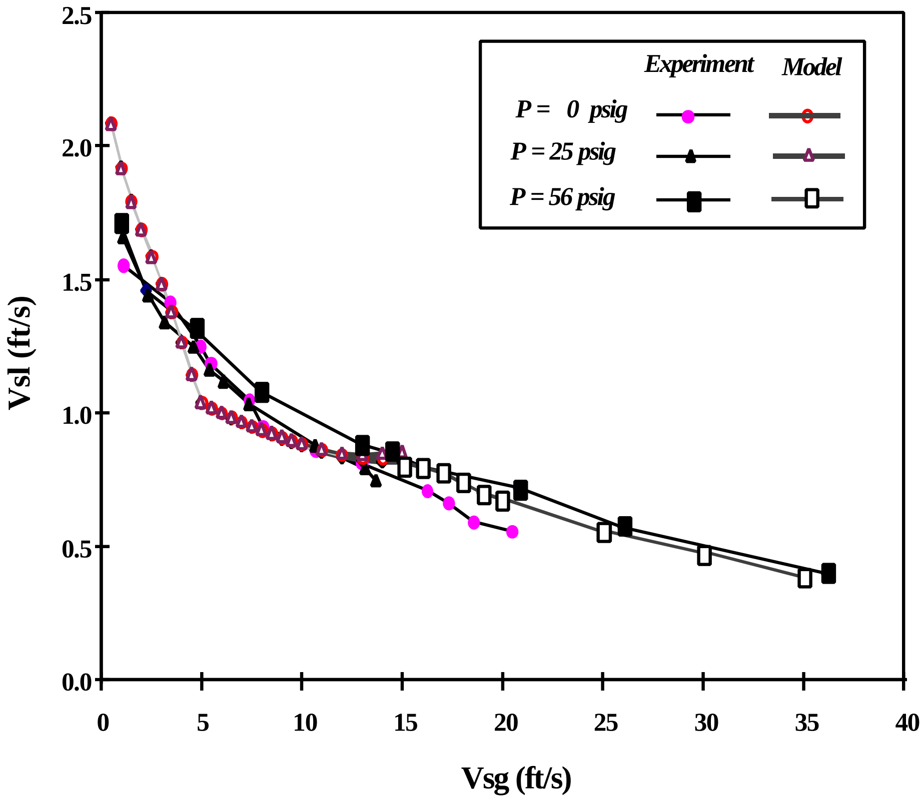

Fig. 8 - Operational Envelope for Liquid Carry-Over with Gas Stream from GL

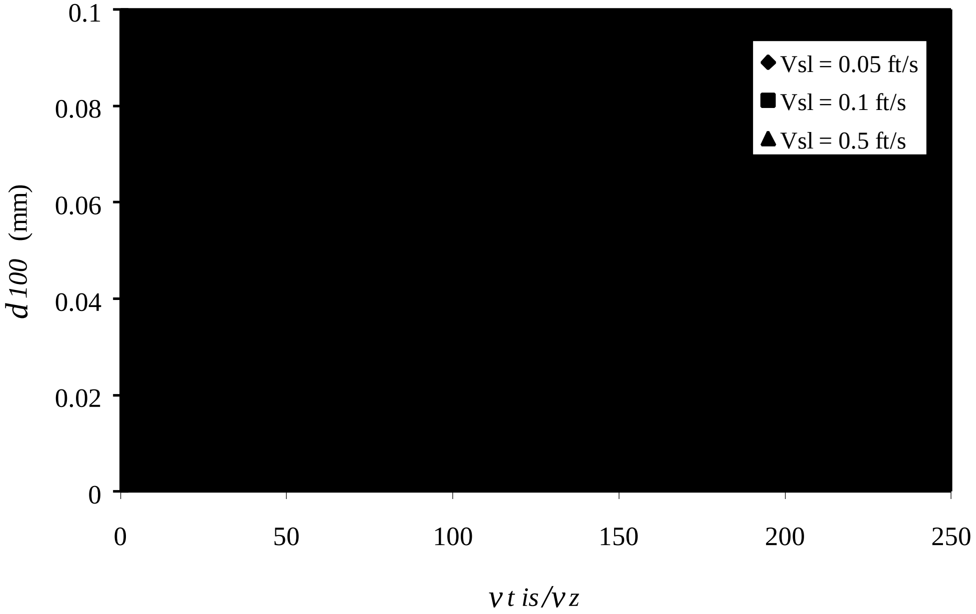

Fig 9 - Effect of the Ratio of Tangential Velocity to Axial Velocity on d_{100} for a 3” GLCC Operated with Air-Water at Atmospheric Conditions

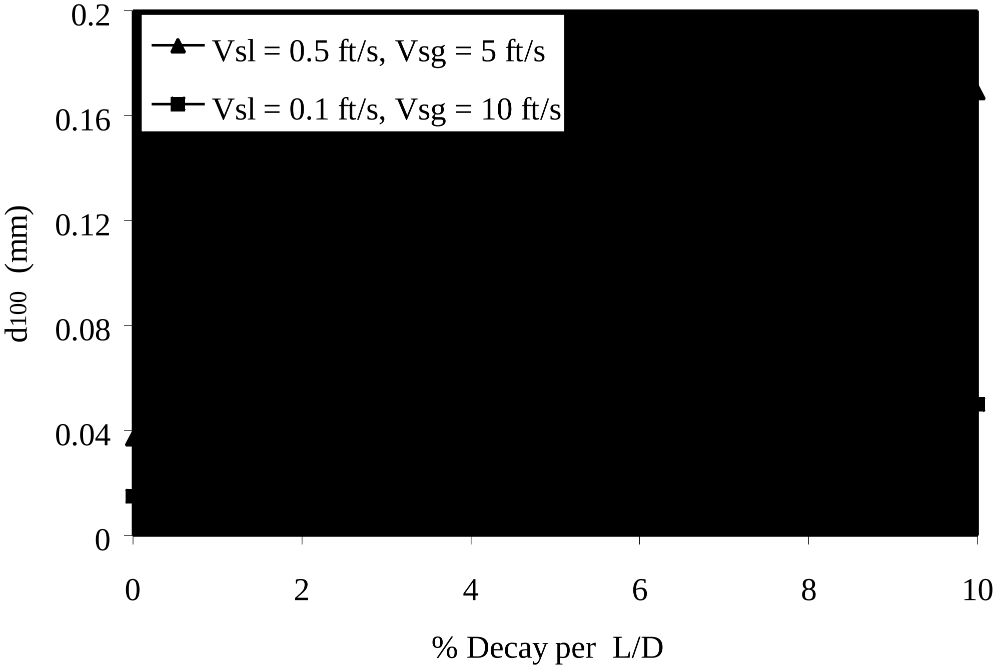

Fig 10- Effect of Decay on d_{100} for a 3” GLCC Operated with Air-Water at Atmospheric Conditions

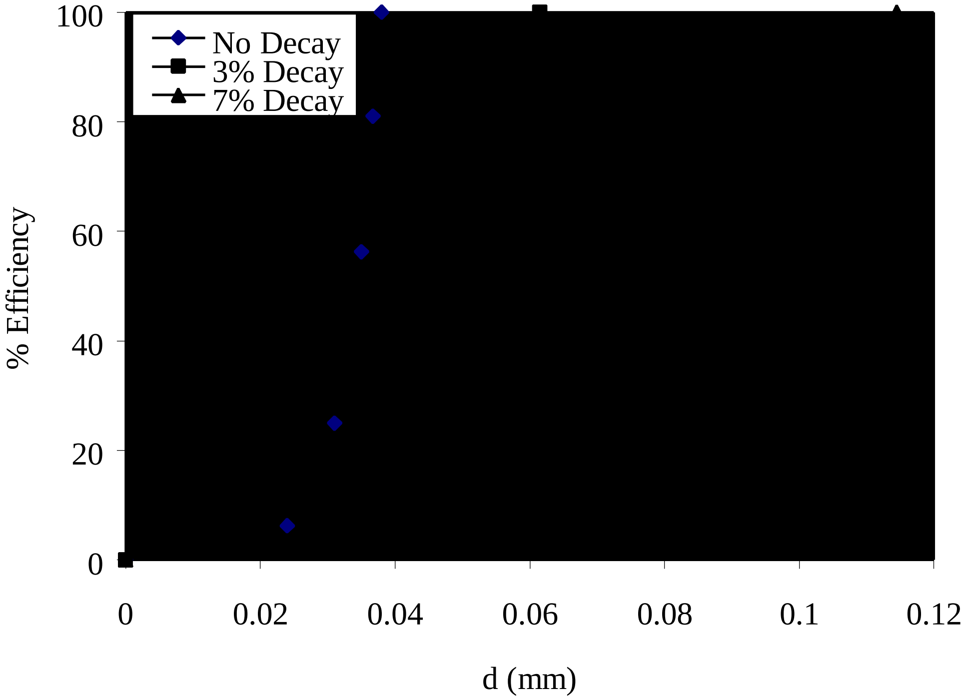

Fig 11 - Bubble Capture Efficiency for Various Decay Factors for a 3” GLCC Operated with Air-Water at Atmospheric Conditions

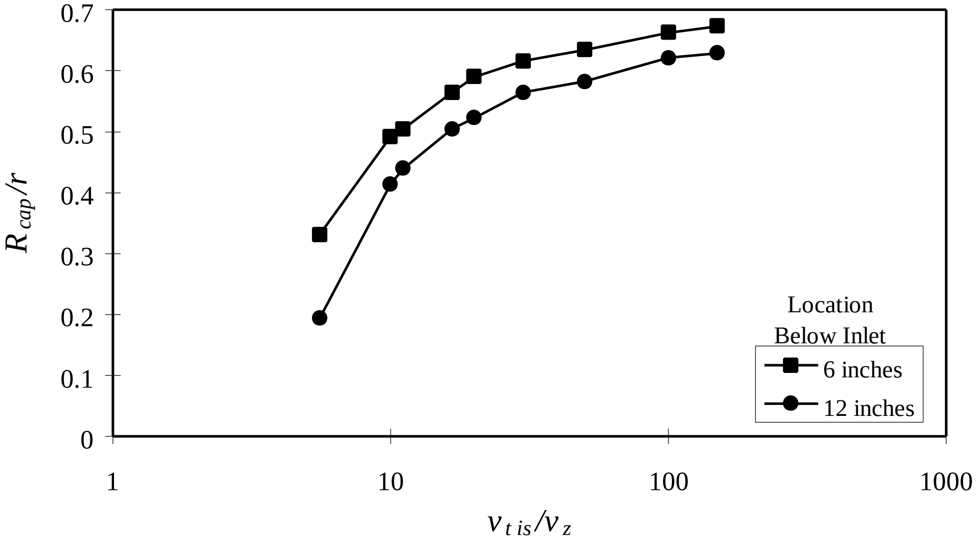

Fig 12 - Variation of Capture Radius with the Ratio of Tangential to Axial Velc