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Design and Development of Gas-Liquid Cylindrical Cyclone Compact Separators for Three-Phase Flow

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THE UNIVERSITY of TULSA

Tulsa University Separation Technology Projects (TUSTP)

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2. Abstract

The U.S. Department of Energy (DOE) has awarded a five-year (1997-2002) grant (Mohan and Shoham, DE-FG26-97BC15024, 1997) to The University of Tulsa, to develop compact multiphase separation components for 3-phase flow. The research activities of this project have been conducted through cost sharing by the member companies of the Tulsa University Separation Technology Projects (TUSTP) research consortium and the Oklahoma Center for the Advancement of Science and Technology (OCAST). As part of this project, several individual compact separation components have been developed for onshore and offshore applications. These include gas-liquid cylindrical cyclones (GLCC©[1]), liquid-liquid cylindrical cyclones (LLCC©[2]), and the gas-liquid-liquid cylindrical cyclones (GLLCC©[3]). A detailed study has also been completed for the liquid-liquid hydrocyclones (LLHC). Appropriate control strategies have been developed for proper operation of the GLCC© and LLCC©. Testing of GLCC© at high pressure and real crude conditions for field applications is also completed. Limited studies have been conducted on flow conditioning devices to be used upstream of the compact separators for performance improvement.

[1] GLCC© - Gas-Liquid Cylindrical Cyclone - copyright, The University of Tulsa, 1994.
[2] LLCC© - Liquid-Liquid Cylindrical Cyclone - copyright, The University of Tulsa, 1998.
[3] GLLCC© - Gas-Liquid-Liquid Cylindrical Cyclone - copyright, The University of Tulsa, 2000.

This report presents a brief overview of the activities and tasks accomplished during the 5-year project period, October 1, 1997 – March 31, 2003 (including the no-cost extended period of 6 months). An executive summary is presented initially followed by the tasks of the 5-year budget periods. Then, detailed description of the experimental and modeling investigations are presented. Subsequently, the technical and scientific results of the activities of this project period are presented with some discussions. The findings of this investigation are summarized in the "Conclusions" section, followed by relevant references. The publications resulting from this study in the form of MS Theses, Ph.D. Dissertation, Journal Papers and Conference Presentations are provided at the end of this report.

3. Table of Contents

	Page No.
1. Disclaimer	1
2. Abstract	1
3. Table of Contents	3
4. Executive Summary	4
5. Tasks of the 5-year Budget Period	5
6. Experimental and Modeling Investigations	6
7. Results and Discussion	11
8. Conclusions	37
9. References	40
10. Publications resulting from this Research	42

4. Executive Summary

The objective of this five-year project (October, 1997 – September, 2002) is to expand the current research activities of Tulsa University Separation Technology Projects (TUSTP) to multiphase oil/water/gas separation. The aim of this project is to investigate the feasibility of three-phase GLCC© as a bulk separator. Is it possible to utilize the 3-phase GLCC© for bulk separation of the oil-water liquid phase for free-water knock out? If proven successful, this will significantly simplify the separation facilities downstream.

This project is executed in two phases. Phase I (1997 - 2000) focused on the investigations of the complex multiphase hydrodynamic flow behavior in a three-phase Gas-Liquid Cylindrical Cyclone (GLCC©) separator. The activities of this phase included development of a mechanistic model, a computational fluid dynamics (CFD) simulator, and detailed experimentation on the three-phase GLCC©. The experimental and CFD simulation results are suitably integrated with the mechanistic model.

The goal of Phase II (Project years 4 and 5 - 2000 to 2002) is to conduct field-scale testing of GLCC© technology at high pressure and with real crudes. This is crucial for validating the GLCC© design for field applications and facilitating easy and rapid technology deployment. Tasks include design, fabrication and testing of a high pressure GLCC© test facility. Design criteria for industrial applications have been developed based on these results and have been incorporated into the mechanistic model by TUSTP.

This report presents a brief overview of the activities and tasks accomplished during the 5-year project period, October 1, 1997 – March 31, 2003 (including the extended period of 6 months). An executive summary is presented initially followed by the tasks of the 5-year budget periods. Then, detailed description of the experimental and modeling investigations are presented. Subsequently, the technical and scientific results of the activities of this project period are presented with some discussions. The findings of this investigation are summarized in the "Conclusions" section followed by relevant references. The list of publications resulting from this study in the form of MS Theses, Ph.D. Dissertation, Journal Papers and Conference Presentations are provided at the end of this report.

5. Tasks of the 5-year Budget Periods (Oct. 1, 1997 – Sept. 30, 2002)

Tasks of the First Year Project Activities: (Oct. 1, 1997 – Sept. 31, 1998):

Objective: Initial Modeling and Data Acquisition.

a. Initial development of the mechanistic model for three-phase separation.
b. Design and expansion of two-phase test facility for three-phase loop.
c. Preliminary experimental data acquisition of global separation efficiency.
d. Preliminary simulation of three-phase flow using computational fluid dynamic (CFD) code.
e. Interim reports preparation.

Tasks of the Second Year Project Activities: (Oct. 1, 1998 - Sept. 31, 1999):

Objective: Gas Carry-under and Model Refinement.

a. Measurement of the operational envelope of the GLCC for gas carry-under.
b. Detailed measurement of gas carry-under beyond the operational envelope.
c. Development of constitutive models for CFD code for simulation of gas carry-under.
d. Refinement of mechanistic model for gas carry-under.
e. Investigation of three-phase separator configurations and verification with experimental results.
f. Interim reports preparation.

Tasks of the Third Year Project Activities: (Oct. 1, 1999 – Sept. 31, 2000):

Objective: Liquid Carry-over and Model Refinement.

a. Measurement of the operational envelope of the GLCC© for liquid carry-over.
b. Detailed measurement of liquid carry-over beyond the operational envelope.
c. Development of constitutive models for CFD code for simulation of liquid carry-over.
d. Completion of CFD simulations and refinement of mechanistic model for liquid carry-over.
e. Combining gas-carry under and liquid-carry over mechanistic models into a comprehensive model.
f. Interim reports preparation.

Tasks of the Fourth Year Project Activities: (Oct. 1, 2000 – Sept. 30, 2001):

Objective: High Pressure Field Pilot Plant GLCC© Design and Experimentation.

a. Design and Fabrication of High Pressure 3-phase GLCC©.
b. Installation of high-pressure 3-phase GLCC© & modification of high-pressure loop.
c. Instrumentation and Data Acquisition for Operational Envelope.
d. Data Analysis and Evaluation of High Pressure GLCC© performance.
e. Mechanistic Model Improvement for high pressure conditions for two-phase and three-phase applications.
f. Interim reports preparation.

Tasks of the Fifth Year Project Activities: (Oct. 1, 2001 – Sept. 30, 2002):

Objective: High Pressure Data Acquisition and Field Design and guidelines.

a. Design, fabrication and installation of second generation High Pressure 3-phase GLCC©.
b. Detailed experimental data for liquid carry-over.
c. Detailed experimental data for gas carry-under.
d. Incorporation of high pressure GLCC results into mechanistic model.
e. Development of design guidelines for GLCC field application for the industry.
f. Interim reports and final technical report preparation.

6. Experimental and Modeling Investigations

The project activities are divided into three main parts, which are carried out in parallel. The first part is the experimental program that includes a study of the oil/water two-phase behavior at low and high pressures and control system development for the GLCC© and two-phase LLCC©. This investigation is eventually extended for three-phase flow. The second part consists of the development of a mechanistic model for three-phase GLCC© incorporating the experimental results and behavior of dispersion of oil in water and water in oil. This provides an insight into the hydrodynamic flow behavior and serves as the design tool for the industry. Although useful for sizing GLCC©s for proven applications, the mechanistic model will not provide detailed and local hydrodynamic flow behavior

information needed to screen new geometric variations or to study the effect of fluid property variations. Hence it is validated with a more rigorous approach of computational fluid dynamics simulation. Multidimensional multiphase flow simulation at high pressures and for real crude conditions will provide much greater depth into the understanding of the physical phenomena and the mathematical analysis of three-phase GLCC© design and performance. In the third part, design guidelines for three-phase GLCC© field applications by the industry have been developed. These design guidelines form the basis for high-pressure real crude conditions. Following is a more detailed description of the experimental and modeling activities.

6.1. Oil-Water-Gas State-of-the Art Flow Loop

A new 3-phase experimental flow loop has been constructed in the College of Engineering and Natural Sciences Research Building located in The University of Tulsa (North Campus), near the existing outdoor two-phase facility. This indoor facility enables year around data acquisition and simultaneous testing of different compact separation equipment.

The oil/water/gas three-phase indoor flow facility is a fully instrumented state-of-the-art two-inch flow loop, enabling testing of single separation equipment or combined separation systems. The three-phase flow loop consists of a metering and storage section and a modular test section. Following is a brief description of both sections.

Metering and Storage Section: As shown in Figure 1, air is supplied from a compressor and is stored in a high-pressure gas tank. The air flows through a one-inch metering section consisting of Micromotion® mass flow meter, pressure regulator and control valve. The liquid phases (water and oil) are pumped from the respective storage tanks (400 gallons each), and are metered with two sets of Micromotion® mass flow meters, pressure regulators and control valves, before being mixed. The pumping station consists of a set of two pumps (10 HP and 25 HP) for each liquid phase and each set has an automatic re-circulating system to avoid build-up of high pressures. Several mixing points have been designed to evaluate and control the oil-water mixing characteristics at the inlet. The liquid and gas phases are then mixed at a tee junction and sent to the test section. State-of-the-art Micromotion® net

oil computers (NOC) are used to quantify the watercut, gas-oil ratio (GOR), and mixture density. Downstream of the test sections, the multiphase mixture flows through a 3-phase conventional horizontal separator (36” x 10’), where the air is vented to the atmosphere and the separated oil and water phases flow to their respective storage tanks. A technical grade white mineral oil type Tufflo® 6016 with a specific gravity of 0.857 is used as the experimental fluid along with tap water.

Figure 1. Tanks, Pumping Station and Metering Section

Figure 2. Test Section

Modular Test Section: The metered 3-phase mixture coming from the metering section can flow into 4 test stations, as shown in Figure 2. This flexibility enables the testing of single separation equipment, such as a Gas-Liquid Cylindrical Cyclone (GLCC©), Gas-Liquid-Liquid Cylindrical Cyclone (GLLCC©), Liquid-Liquid Cylindrical Cyclone (LLCC©), Liquid-Liquid Hydrocyclones (LLHC), conventional separators or any combination of these equipment, in parallel or series, forming a compact separation system. Two 10' x 15' x 8' frames were installed in the test section in order to support the equipment.

Figure 3. Three-phase Flow Loop

Instrumentation, Control and Data Acquisition System: Control valves placed along the flow loop control the flow into and out of the test sections. The flow loop is also equipped with several temperature sensors and pressure transducers for measurement of the in-situ temperature and pressure conditions. All output signals from the sensors, transducers, and metering devices are collected at a central panel. A state-of-the art data acquisition system,

built using LabView®, is used to both control the loop and acquire data from analog signals transmitted from the instrumentation. The program provides variable sampling rates. A regular calibration procedure, employing a high-precision pressure pump, is performed on each pressure transducer on a regular schedule to guarantee the precision of measurements. The temperature transducers consist of a Resistive Temperature Detector (RTD) sensor, and an electronic transmitter module.

The photograph of the completed 3-phase flow loop is shown in Figure 3. It can be noted that the initial loop built as part of the DOE project has been leveraged with TUSTP member companies and the loop has been considerably augmented to enable experimentation and testing of several different test equipment.

6.2. Mechanistic Modeling Investigations

The missing link in compact separation technology is a sound understanding of the complex hydrodynamic flow behavior of the swirling two-phase flow and the associated separation processes in the cyclones. TUSTP's research and development focuses on the understanding of the physical phenomena of the flow, as it will result in better models and simulators and better design tools. This is achieved by pursuing several avenues in parallel, namely, experimental data acquisition, CFD simulations (Erdal, 2001) and mechanistic modeling. The ultimate goal is the development of mechanistic models for the compact separators, to be used as design tools by the industry.

A mechanistic model is developed for the prediction of the hydrodynamic flow behavior and performance of the single stage as well as two-stage, three-phase GLCC© separator.

The input parameters to the model include the following:

- Operational parameters: range of oil-water-gas flow rates, pressure and temperature;
- Physical properties: oil, gas and water densities, viscosities and surface tensions;
- Geometrical parameters: complete geometric description of the GLCC: GLCC configurations, inlet pipe I.D, inclination angle and roughness, outlet piping I.D, length and roughness,

- Performance characteristics of active liquid level control.

The mechanistic model enables determination of the performance characteristics of the GLCC, namely:

- plot of the operational envelopes for both liquid carry-over and gas carry-under;
- percent liquid carry-over and gas carry-under beyond the operational envelopes;
- oil in water and water in oil fractions;
- pressure drop across the GLCC;
- liquid level in the separator;
- sensitivity to flow rate fluctuations (with no active control).
- sensitivity to flow rate fluctuations (with active control).

The mechanistic model enables insight into the hydrodynamic flow behavior in the three-phase GLCC. It also allows the user to optimize the GLCC design accounting for tradeoffs in the I.D., height and inlet slot size of the GLCC. The model also provides the trends of the effect of fluid physical properties and the information required to determine when active controls will be needed.

7. Results and Discussion

The following gives a summary of the important technical and scientific activities that have been completed, towards the tasks identified for this project.

7.1. GLCC Development

Previous studies of GLCC (Movafaghian, 2000) have focused on design and applications at relatively lower gas velocities (below the minimum velocity for onset of liquid carry-over in the form of annular mist flow). In this study, modifications of GLCCs were carried out to expand the GLCC capabilities for wet gas and high gas oil ratio (GOR) applications, characterized by higher gas velocities, to knock out the liquid droplets from the gas core.

7.1.1. Modified GLCC for High GOR Applications:

A novel design of GLCC capable of separating liquid droplets from a wet gas stream has been developed. Experimental investigations have been carried out to evaluate the GLCC performance improvement in terms of operational envelope for liquid carry-over and, measure the liquid extraction from the gas stream. Specific design guidelines for wet gas GLCC have also been formulated based on the experimental studies. This investigation provides new capabilities for compact separators for wet gas and high GOR (exceeding 90%) applications (Wang et al., 2001).

A schematic of the modified GLCC for high GOR applications is shown in Figure 4. As can be seen, the main modification is the installation of an Annular Film Extractor (AFE) section in the GLCC body above the inlet. The AFE consists of a gap in the GLCC body, through which the liquid film generated from the droplets due to the high gas velocities is extracted into an annulus, and sent to the liquid leg through a return pipe.

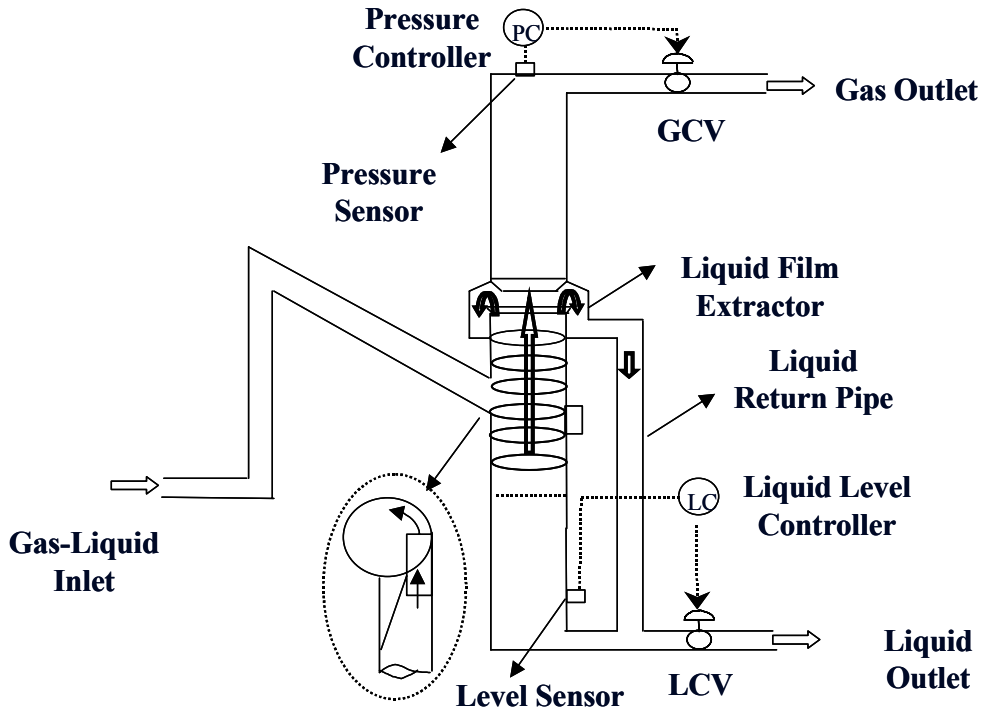

Figure 4. Modified GLCC for High GOR Applications

The experimental results and comparison between the performance of the new GLCC design with the AFE and the performance of the original GLCC is shown in Figure 5. It includes the operational envelopes for liquid carry-over, as follows

- Operational envelope for the original GLCC without liquid level control.
- Operational envelope for the original GLCC with liquid level control.
- Operational envelope for the modified GLCC for wet gas applications with level control.

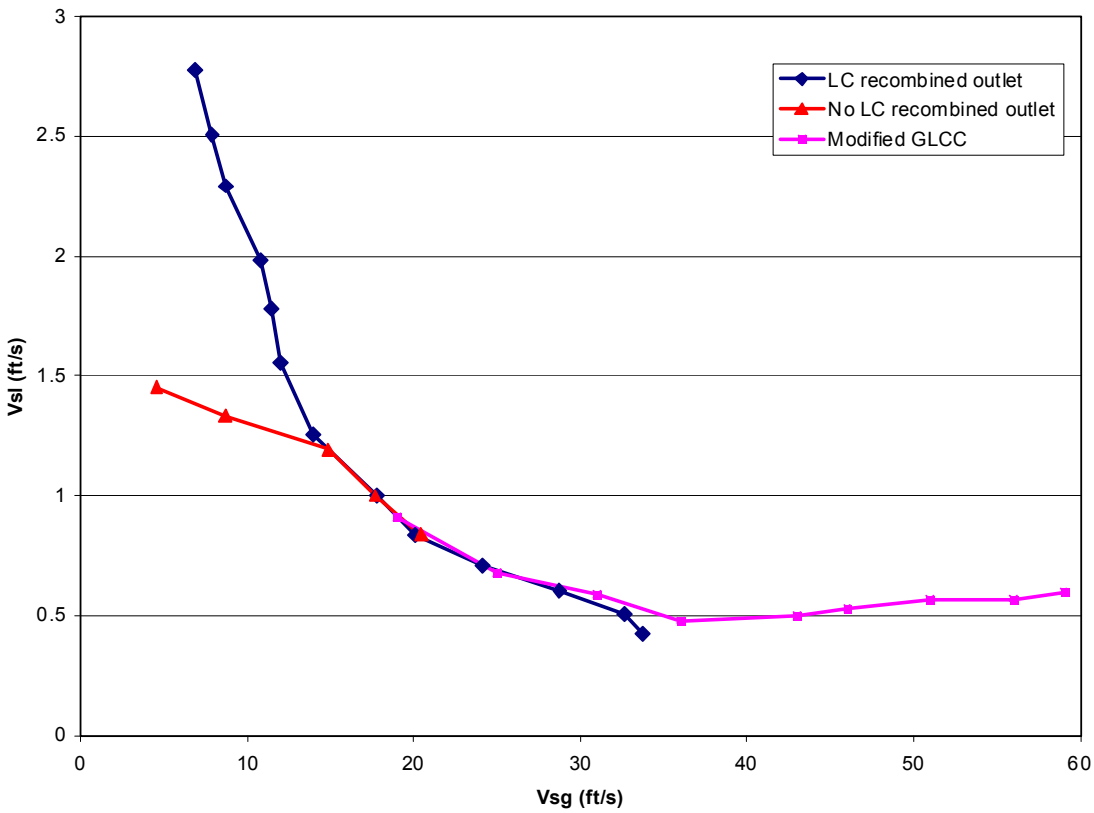

Figure 5. Comparison of Operational Envelopes for Different GLCC Configurations (Modified GLCC indicates GLCC for wet gas applications)

As can be seen from Figure 5, the operational envelope for the original GLCC terminates at a superficial gas velocity of 20 ft/s. Beyond this gas velocity, the gas will blow out through the liquid leg because of the low liquid level in the GLCC. The liquid level control extends the operational envelope both in the high liquid velocity and high gas velocity regions. But the operational envelope terminates at superficial gas velocity of 33 ft/s,

which is the critical gas velocity for the onset of mist flow. Beyond this gas velocity, mist flow occurs at the upper part of the GLCC and liquid is carried-over either by fine droplets or by liquid film along the pipe wall. With the modified GLCC, high velocity of the gas core through the tangential nozzle pushes the liquid droplets in the gas core towards the pipe wall forming an upward swirling liquid film. The annular film extractor (AFE) removes all the upward flowing liquid film before the liquid gets re-entrained into the gas core. Therefore, the modified GLCC can operate at very high gas velocities (beyond $v_{ann} = 33$ ft/s) and still can tolerate superficial liquid velocities up to 0.5 ft/s. The operational envelope for the modified GLCC terminates at superficial gas velocity of 58 ft/s because of the capacity limitation of the compressor. The operational envelope can extend further in the higher gas velocity region until the axial gas velocity is high enough to re-entrain the liquid into the gas core. The new design GLCC for high GOR applications was tested at high pressures, up to 1000 psia. The results are given in the section "High Pressure Testing" below.

7.2. LLCC Development

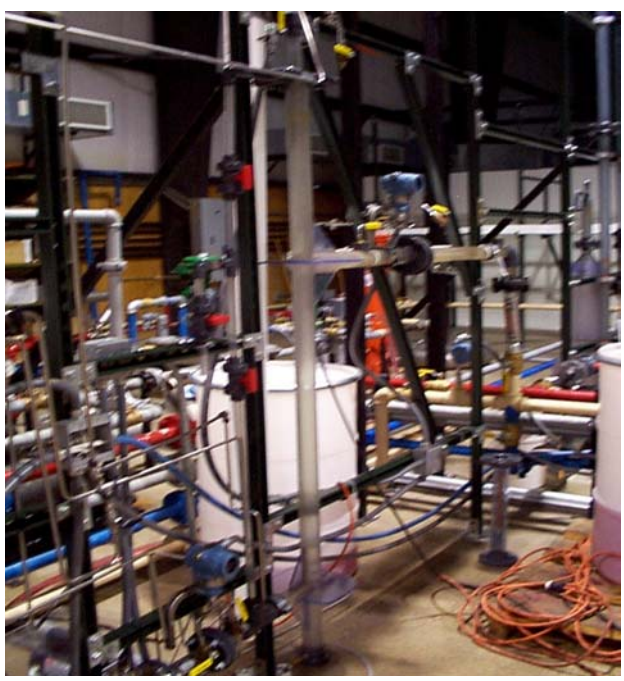

Figure 6. LLCC Test Section

The primary objective of this study is experimental investigations to determine the performance of LLCC© for bulk separation (free water knockout) of oil-water mixtures. A picture of the LLCC test section is shown in Figure 6. The LLCC is a 2-inch ID pipe mounted vertically with a total height of 80 inches. It is fabricated utilizing transparent R-4000 clear PVC pipe, schedule 80. The mixture flows into the LLCC through a horizontal inlet of 2-inch ID, located 40 inches below the top of the LLCC. The oil-water mixture is separated due to centrifugal and gravity forces. The mixture is split into two streams, the overflow stream that is rich in oil and the underflow stream that is rich in water. At downstream of the LLCC, each of the two streams flows through the downstream metering section, located upstream of the three-phase separator, where flow rate, density and watercut are measured for each stream, using Micromotion mass flow meter and Starcut watercut meter. Control valves, mounted downstream of the meters control the flow rate in each stream.

Experiments were conducted for the entire water-continuous and oil-continuous range, i.e. from 95% watercut at the inlet to 10% watercut. For each inlet water concentration, three different mixture velocities were taken into account and for each mixture velocity, split ratio (overflow rate / total inflow rate) was varied so as to obtain 100% pure water in the underflow. Based on the results (Mathiravedu, 2001, Mathiravedu et al., 2002), following conclusions can be drawn:

- LLCC can be successfully used for free water knockout bulk separation of oil and water mixtures for both water continuous (inlet water concentration ranging from 50% to 95%) and oil continuous flow (inlet water concentration ranging from 40% to 50%).
- The free water knockout process can be optimized between increasing underflow rates and acceptable watercut in the underflow stream.
- For the LLCC, at low split ratios, the effluent in the underflow is clean water. Above a specific split ratio the oil phase starts flowing into the underflow. There always exists an optimal split ratio, as shown in Figure 7, where the water flow rate is maximum with 100% watercut. The value of the optimal (maximum) split ratio for 100% watercut in the underflow varies, depending upon the existing flow pattern; for the Stratified and Oil-in-Water Dispersion - Water Layer flow patterns this maximum split ratio is about 60%. For the Double Oil-in-Water Dispersion and Oil-in-Water Dispersion flow patterns, the

maximum split ratio ranges from 50% to 20%, decreasing with the increase of oil content at the inlet.

- Underflow watercut is measured using two different watercut meters (Micromotion mass flow meter & Starcut watercut meter) operating by different principles, namely, Coriolis principle and microwave attenuation principle, respectively. Both the watercut meter readings showed very good agreement for most of the cases. However, for low inlet mixture velocities, the microwave meter (Starcut) showed a more accurate reading compared to the Coriolis watercut meter (Micromotion). This performance difference could be due to oil entrapment in the underflow meter and oversized Coriolis meter for low mixture velocities. Need for having a sample strip stream is an important issue to be considered for a Starcut configuration.

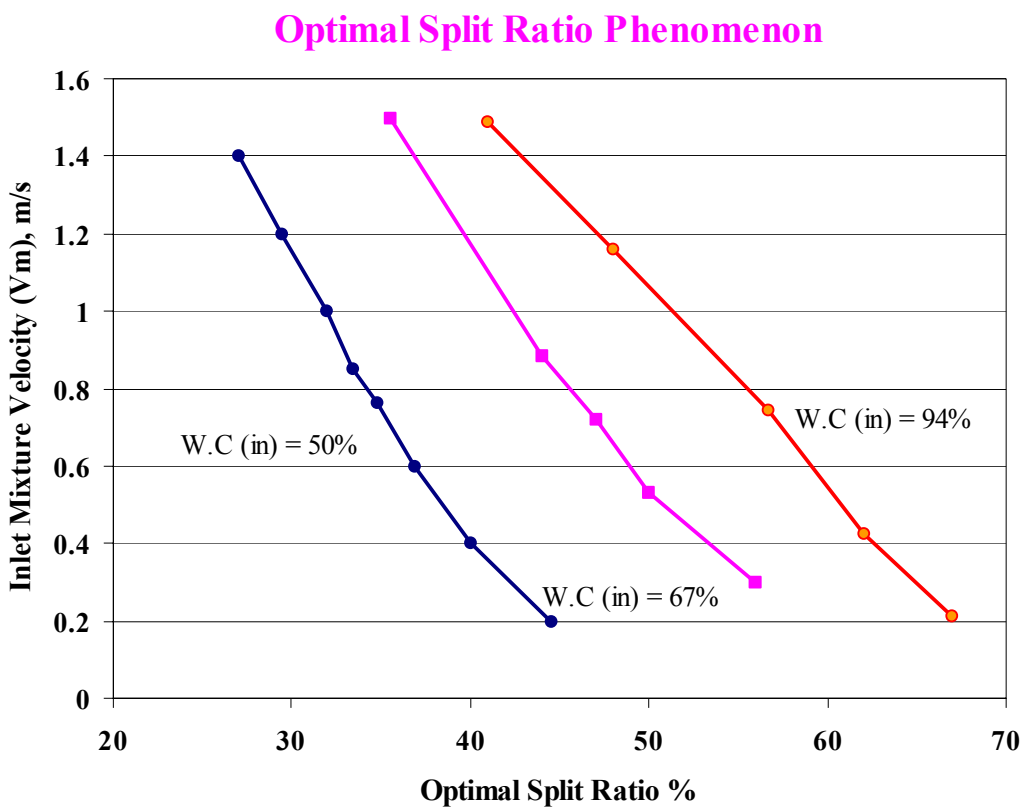

Figure 7 – Optimal Split Ratio Phenomenon. (Relative uncertainty for each data point is ±0.2%. Each data point averaged over 350 measurements)

A mechanistic model has been developed (Oropeza-Vazquez 2001) for the LLCC separator. Figure 8 shows a comparison between the model predictions and the experimental data. Excellent agreement is observed between the data and the model predictions.

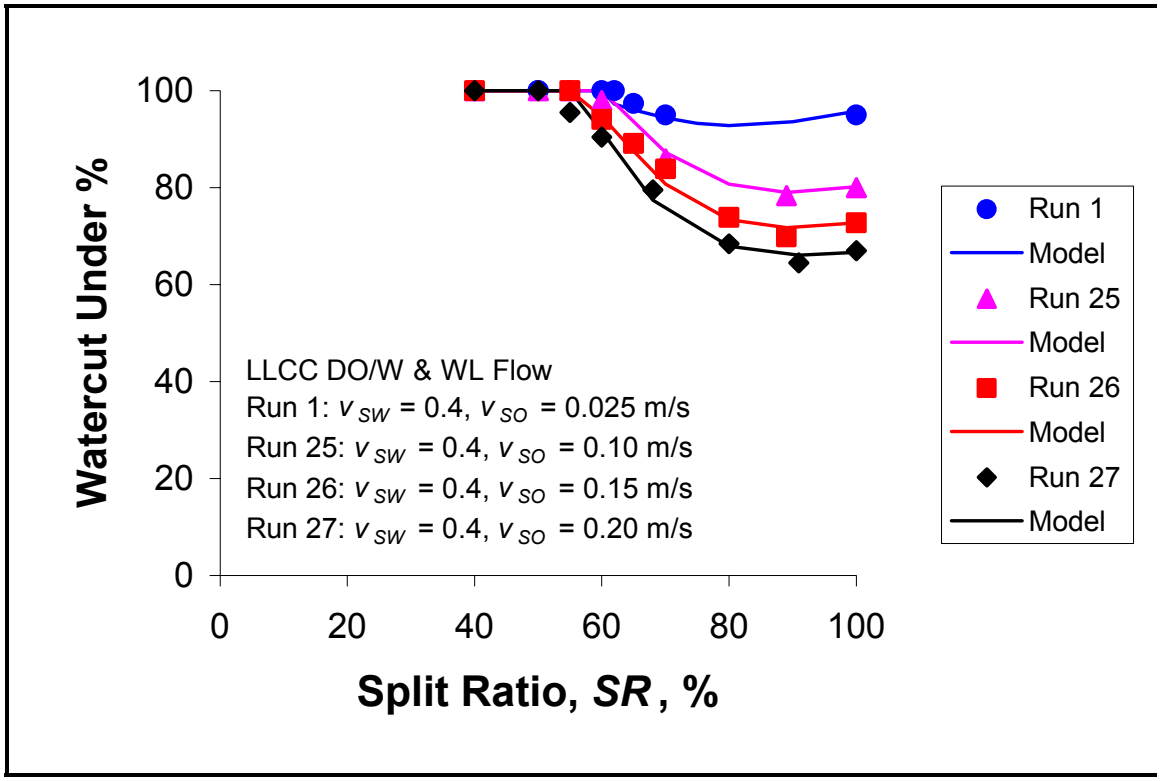

Figure 8 – LLCC Model-Data Comparison (DO/W & W Layer Flow Pattern)

A unique control strategy has been developed (Mathiravedu 2001) for the LLCC, which can provide superior performance as it involves the direct measurement of a control parameter of immediate concern, namely, the watercut in the underflow. This strategy is capable of maintaining clear water in the underflow and simultaneously maximizing the flow rate in the underflow stream. The controller design and dynamic simulation of the proposed control strategy are also provided. The developed control system is capable of controlling the underflow watercut over a range of flow conditions (inlet water concentrations ranging from 40% to 95%) namely, stratified flow, dispersion of oil in water with a water layer at the bottom, double dispersion of oil in water and dispersion of water in oil. The time responses

of the underflow watercut and the control valve show that the system can be restored to the set point very fast.

Figure 9 – Single-stage GLLCC in Operation

7.3. GLLCC© Development

The GLLCC, shown in Figure 9, is a single-stage three-phase flow compact separator. It can knock out simultaneously the gas phase and free water. It consists of a 7 feet, 3-inch ID vertical pipe, with a 5 feet, 3-inch ID, 27 degrees inclined inlet. The inlet slot area is 25% of the inlet full bore cross sectional area and is connected tangentially to the vertical pipe. The inlet is located 3 feet below the top of the vertical section. The 2-inch ID gas outlet is located radially at the top of the vertical pipe. The water 2-inch ID outlet is located tangentially at the bottom of the vertical pipe. The oil finder is a movable, 3 feet, 1.5-inch ID

pipe that enters the lower end of the vertical pipe through a special seal arrangement. Four pins at the top of the oil finder keep it concentric to the vertical pipe, allowing its up and down movement. The oil finder is attached to an electromechanical lift device. Traps are provided to remove any entrained liquid in the gas outlet and the entrained gas in both liquid outlets. The gas being carried under by the liquid is separated inside the trap by reducing the velocity and swirling the liquid, and it goes to the top of the trap.

In the GLLCC, the gas-liquid separation occurs as in a regular GLCC. However, in the liquid section, due to centrifugal forces, the oil is segregated from the water forming an oil core at the center of the pipe. The oil finder captures this oil core, which is an oil-rich stream. Moreover, clean water flows downward through the annulus formed between the oil finder and the pipe wall and exits through the water outlet.

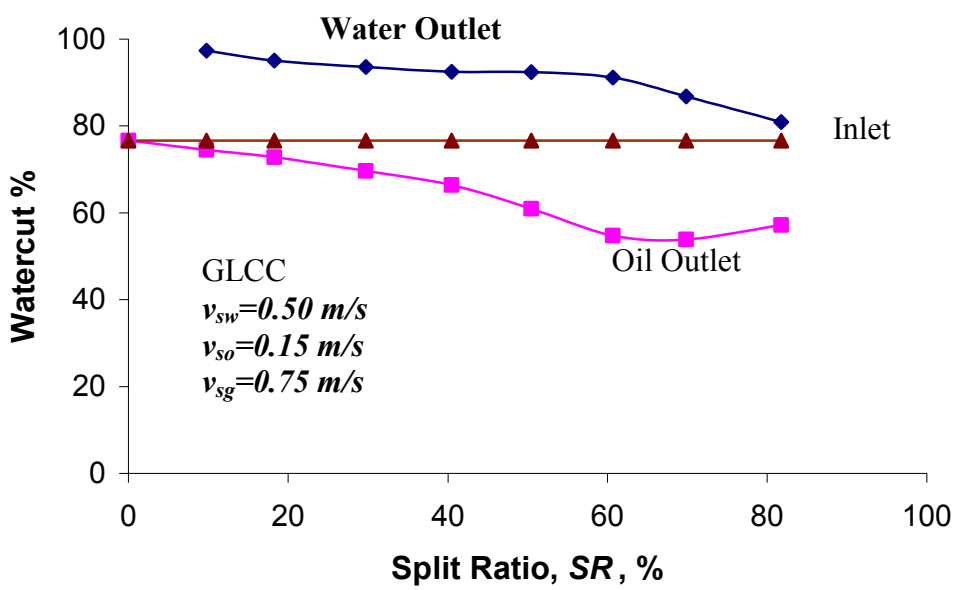

Figure 10. GLLCC Separation Efficiency Results (Set 3)

Figure 10 presents typical experimental results for the GLLCC, showing the measured watercuts in both liquid outlets of the GLLCC as functions of the split ratio for superficial water and oil velocities of 0.5 m/s and 0.15 m/s, respectively. The horizontal line indicates the watercut in the inlet, which is kept constant during these experiments. The upper line is the watercut in the water outlet stream. As can be seen, this line is always

located above the inlet watercut line, indicating the decrease of the oil fraction in this liquid stream. On the other hand, the lower line, corresponding to the watercut in the oil outlet, is always below the inlet watercut line, indicating the increase in oil content in the oil stream outlet. A similar behavior was observed in all the experiments.

A mechanistic model has been developed for the GLLCC. It is a combination of the GLCC and LLCC models developed previously. Comparison between the model predictions and the experimental data are given below. The comparison for the first set of data, taken with the oil finder located at 30 inches below the inlet, is presented in Figure 11. The watercut in the water outlet is plotted in the Y-axis, as a function of the superficial water velocity in the X-axis, for different oil superficial velocities. The scattered points represent the experimental data and the continuous lines represent the predictions of the GLLCC mechanistic model. Similarly, the comparison for data set 2, for which the oil finder is located at 36 inches below the inlet, is given in Figure 12. For these 2 sets of data, the split ratio is constant, namely, SR = 40%. Also, the superficial gas velocity is maintained constant around 0.75 m/s. Very good agreement between the model predictions and the data is observed, both with respect to the trend and the absolute values. The model predicts well the decreasing separation efficiency with increasing oil superficial velocity, and also the increasing separation efficiency with increasing water superficial velocity.

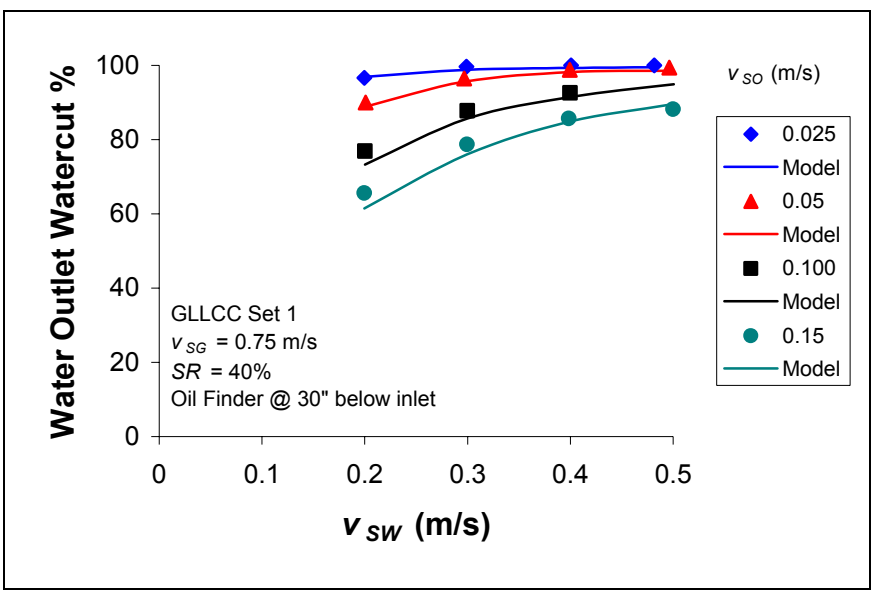

Figure 11. GLLCC Comparison Study for Data Set 1

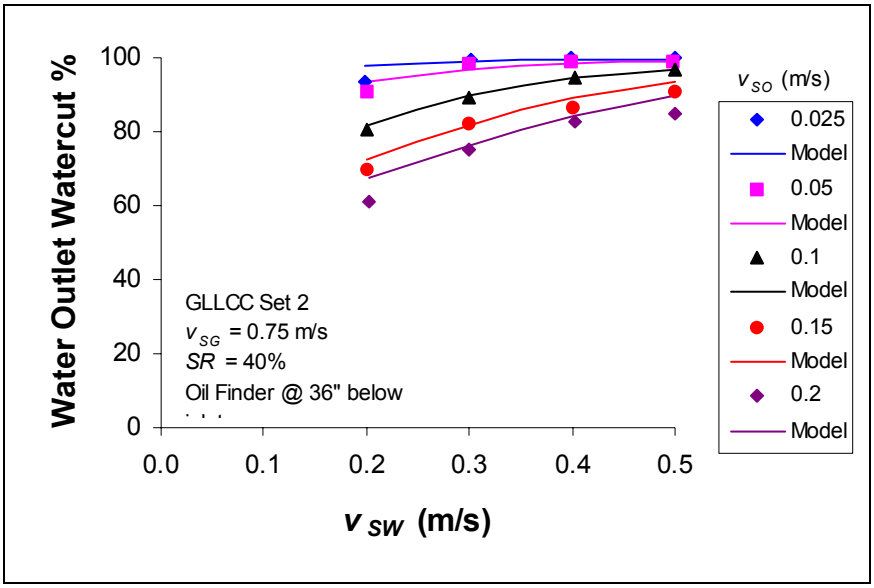

Figure 12. GLLCC Comparison Study for Data Set 2

7.4. LLHC Study

The liquid-liquid Hydrocyclone (LLHC) has been widely used by the Petroleum Industry for the past several decades. A large quantity of information on the LLHC available in the literature includes experimental data, computational fluid dynamic simulations and field applications. The design of LLHCs has been based in the past mainly on empirical experience/data. However, no simple and overall design mechanistic model has been developed to date for the LLHC. The objective of this study is to develop a mechanistic model for the de-oiling LLHCs, and test it against available and new experimental data. This model will enable the prediction of the hydrodynamic flow behavior in the LLHC, providing a design tool for LLHC field applications.

A simple mechanistic model is developed for the LLHC. The required input for the model is: LLHC geometry, fluid properties, inlet droplet size distribution and operational conditions. The model is capable of predicting the LLHC hydrodynamic flow field, namely, the axial, tangential and radial velocity distributions of the continuous-phase. The separation efficiency and migration probability are determined based on swirl intensity prediction and droplet trajectory analysis. The flow capacity, namely, the inlet-to-underflow pressure drop is predicted using an energy balance analysis.

An extensive experimental program has been conducted during this study, using a 2" MQ Hydroswirl hydrocyclone. A photograph of the test section with the LLHC in place and a schematic are shown in Figures 13 and 14, respectively. A total of 124 runs were conducted in this study. The data is analyzed and presented, so as to demonstrate the effect of the flow variables on the separation efficiency. The inlet flow conditions are: total flow rates between 18 to 27 gpm, oil-cut up to 10%, median droplet size distributions from 50 to 500 μm, and inlet pressures between 60 to 90 psia. The acquired data include the flow rate, oil-cut and droplet size distribution in the inlet and in the underflow, the reject flow rate and oil concentration in the overflow and the separation efficiency. Additional data for velocity profiles were taken from the literature, especially from the Colman and Thew (1980) study.

Figure 13: Photograph of LLHC Test Section

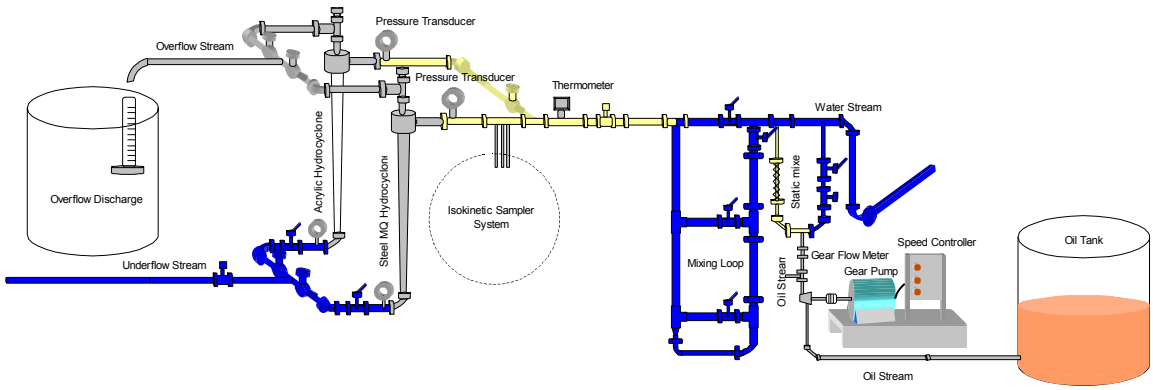

Figure 14: Schematic of LLHC Test Section

The experimental results, consisting of comparisons between the LLHC model prediction and the experimental data, are given below:

Migration Probability: A comparison between the model predictions of the migration probability curve and experimental data of Colman and Thew (1980) is given in Figure 15. Fair agreement is observed with the data.

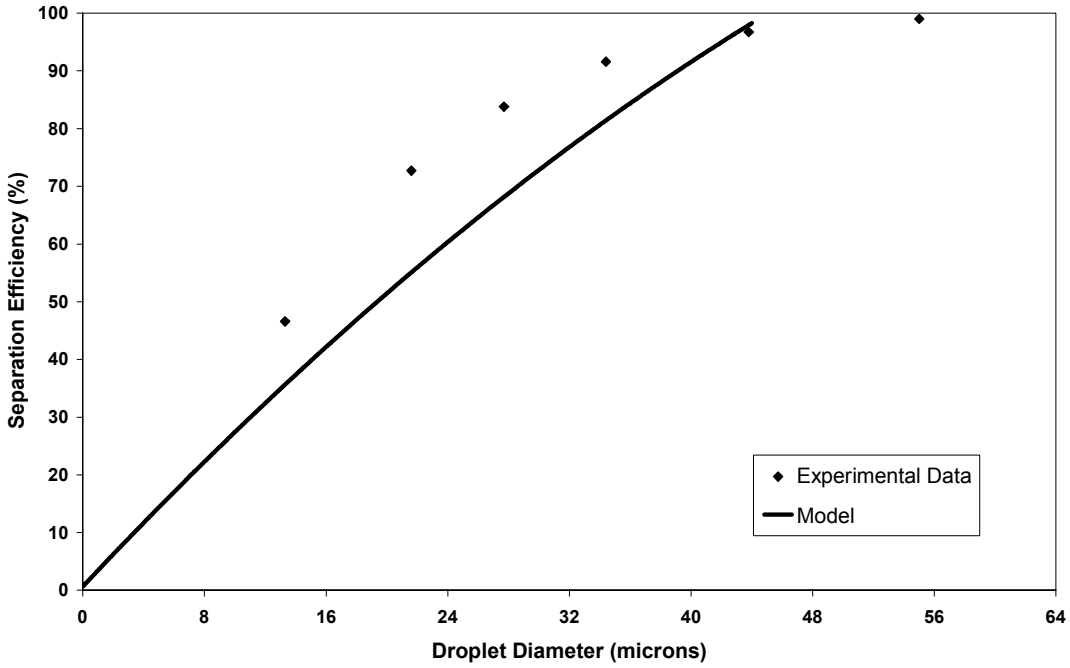

Figure 15: Migration Probability Comparison, Colman and Thew (1980) Data

Pressure Drop: A comparison between the predicted pressure drop and experimental data from Young et al. (1990) is shown in Figure 16. Very good agreement is observed in both cases, with an average relative error of 1.6%.

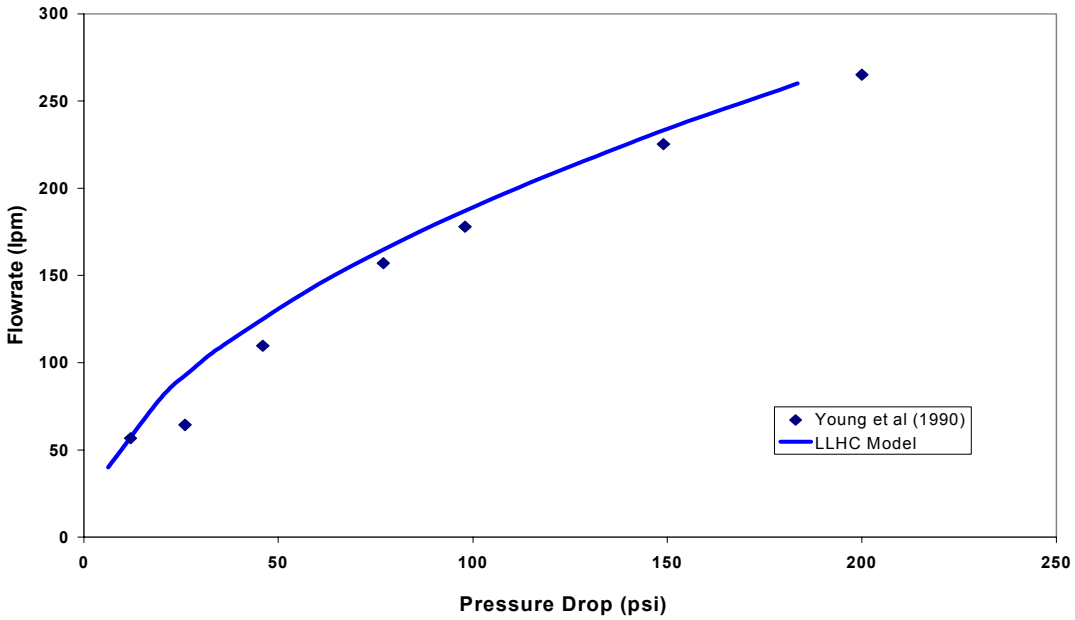

Figure 16: Comparison of Pressure Drop vs. Flow Rate (Young et al., 1990, Data)

Droplet Size Distribution: Figure 17 shows a comparison between the model predictions and experimental data of the droplet size distribution for runs 101. As shown in the figure, good agreement is observed with experimental results. The model prediction curves for the underflow droplet size distribution are shifted to the right, which means that the model predicts efficiency smaller than the experimental one. Also there is a discontinuity in the model curve because the model doesn't consider either breakup or coalescence. This means that the smallest droplet that enters the LLHC is also the smallest one that is found in the underflow stream. On the other hand, the largest droplet in the underflow stream is the largest droplet with a calculated efficiency below 100%.

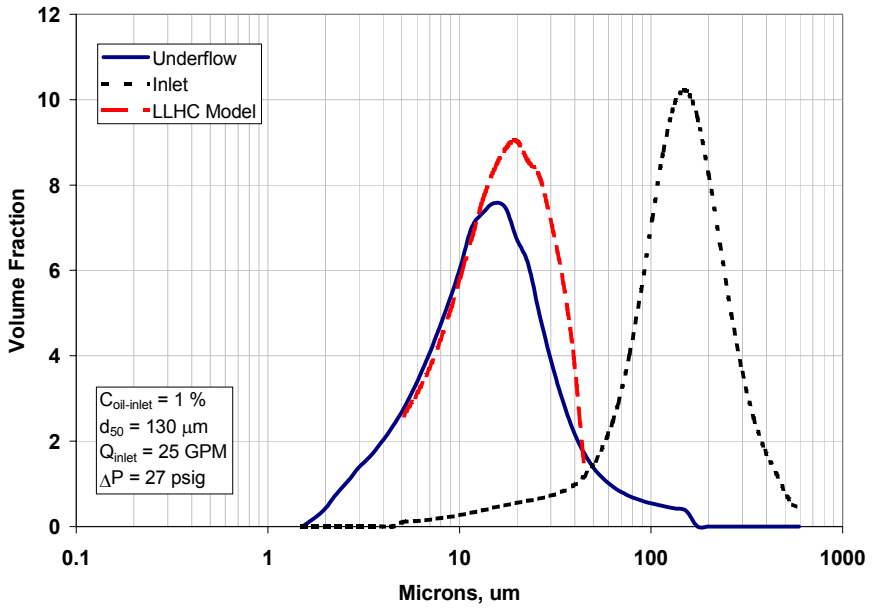

Figure 17: Comparison of Droplet Size Distribution Results for Test 101

Global Separation Efficiency: Figure 18 presents a comparison between the model prediction and the experimental data taken currently, while Figure 19 shows a similar comparison with the Colman et al. (1980) data. As can be seen, excellent agreement is observed between the model prediction and the experimental data with respect to both separation efficiency (average relative error of 3%) and pressure drop (average relative error of 1.6%).

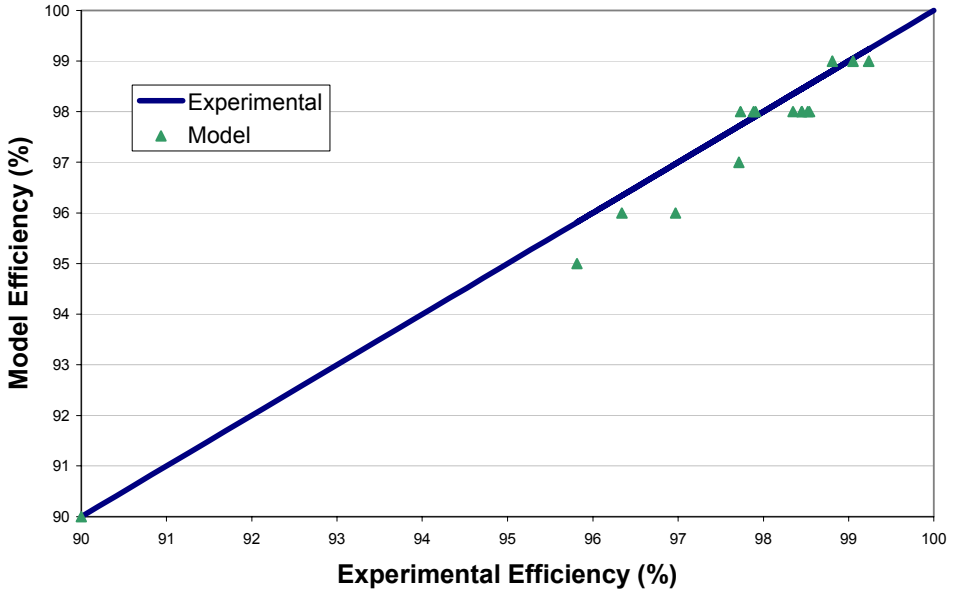

Figure 18: Comparison of Model Efficiency with Present Study Experimental Data

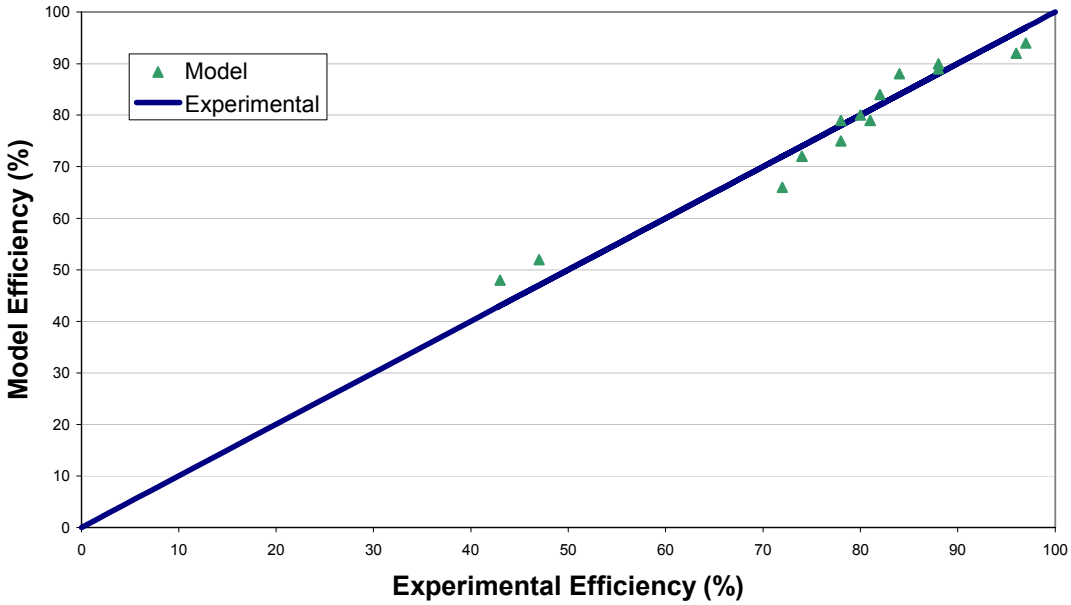

Figure 19: Comparison of Model Efficiency with Literature Experimental Data.

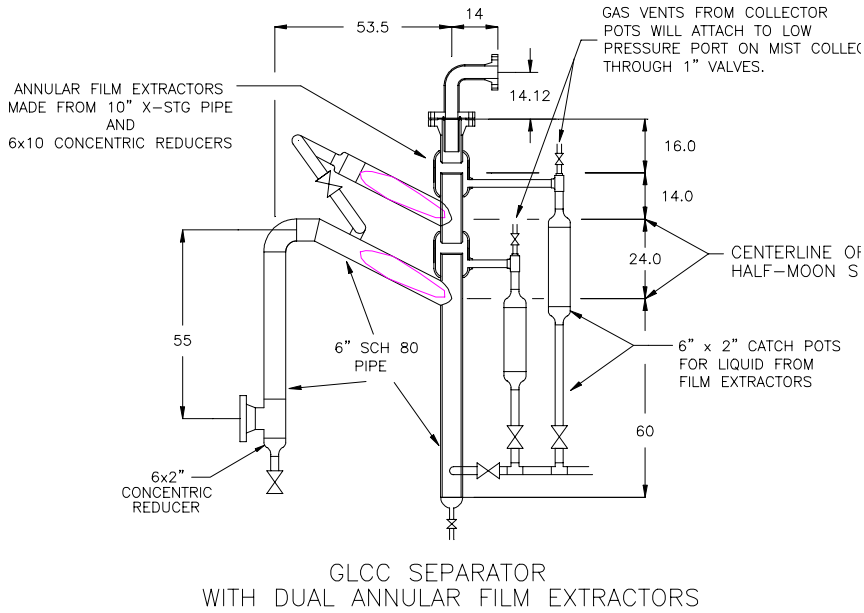

Figure 20: High Pressure GLCC Test Facility Schematic

7.5. High Pressure Testing

High GOR GLCC: Figure 20 shows the GLCC test section with dual annular film extractor for high GOR applications at high pressures. It is a 6" GLCC with a 6" inclined inlet pipe and a tangential inlet nozzle with an opening area of 25% percent of the inlet pipe cross section area. The liquid film extractor is located just above both the inlets. A liquid control valve in the liquid leg is used to control the liquid level using the level signal provided by the liquid level sensor, and a gas control valve in the gas leg is used to control the operating pressure using the pressure signal provided by the pressure transducer. The photograph of this GLCC designed for high GOR applications and tested at high-pressure conditions in CEESI (Colorado Engineering Experiment Station) is shown in Figure 21. The modular design of the GLCC© will allow easy modification of the inlet, outlet and piping configurations.

Figure 21 – High Pressure GLCC Test Facility at CEESI
(Colorado Engineering Experiment Station)

a) <u>High Pressure GLCC Test Results</u>

This project calls for high pressure, high gas volume fraction (GVF) testing at the CEESI facility in Colorado. In pursuit of this task, a GLCC has been fabricated and investigations have been conducted to evaluate the separation efficiency of the GLCC for pressures as high as 1000 psi. A suitable test matrix has been developed for testing that complement the work already done by Chevron at this facility. High-pressure GLCC test results on the separation efficiency are plotted in Figure 22. The results indicate that the liquid separation efficiency is around 100% if the superficial gas velocity is about 1.2 to 1.6 times the annular mist velocity of the gas. As the superficial gas velocity increases the separation efficiency drops down drastically (to as low as 30%) at lower pressures and higher liquid velocities due to the liquid carry-over in the form of annular mist. However, at higher pressures the separation efficiency is much higher (above 60%). It is interesting to note that this difference is much less pronounced at lower liquid superficial velocities. The efficiency curves for 200 psi, 500 psi and 1000 psi overlap each other at lower liquid velocities.

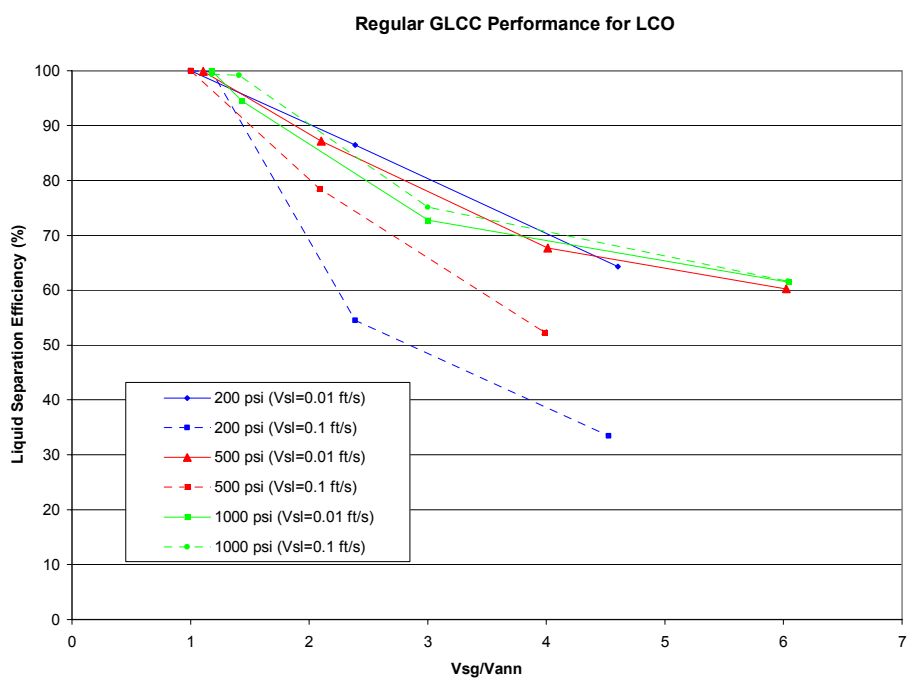

Figure 22 – Performance of High Pressure GLCC for Liquid Carry-over

7.6. Control Strategies Development

7.6.1. Predictive Control of GLCC© Using Slug Detection

Field applications of Gas Liquid Cylindrical Cyclone (GLCC©) separators strongly depend on the implementation of control systems, due to its compactness, less residence time and possible inlet large flow variations. Current design and performance of the GLCC© are dependent on the prediction of the upstream inlet flow conditions based on available models. It is expected that early detection of terrain slugging (slug length, slug velocity and holdup) and controlling the liquid level in the GLCC© using feed-forward mechanism can improve the operational range of GLCC©, by decreasing the liquid carry over and gas carry under, and thereby decreasing the control valve dynamics. The conventional feedback control loops can seldom achieve perfect control considering the impact of huge slugs that is keeping the output of the process continuously away from desired set point value. A feedback controller reacts only after it has detected a deviation in the value of the level from the set point. Whereas, a feed forward control configuration measures the disturbance directly and takes control action to negate the effect of the disturbance on the liquid level in the GLCC©. Therefore, feed forward control system has the theoretical potential for perfect control.

A model has been developed for predictive control system integrating feedback and feed forward control systems (Earni et al., 2003). This strategy for GLCC© predictive control incorporates the slug characteristics in terms of holdup, length and velocity, and calculation of the volumetric liquid flow rate. The predictive control system is designed to operate only when large slugs are encountered. Based on the design, a predictive control model has been simulated in MATLAB-Simulink integrating feedback and feed forward control systems, as shown in Figure 23. Detailed theoretical and experimental studies were carried out to evaluate control system dynamics under different control configurations. Comparison of simulation and experimental results shows that the predictive control system is capable of handling huge slugs by reducing the liquid level percentage overshoot and liquid level settling time considerably. Significant reduction in control valve dynamics is also achieved. This can be considered as a viable approach to handle large slugs, which can cause considerable damage to the operational efficiency of GLCC©.

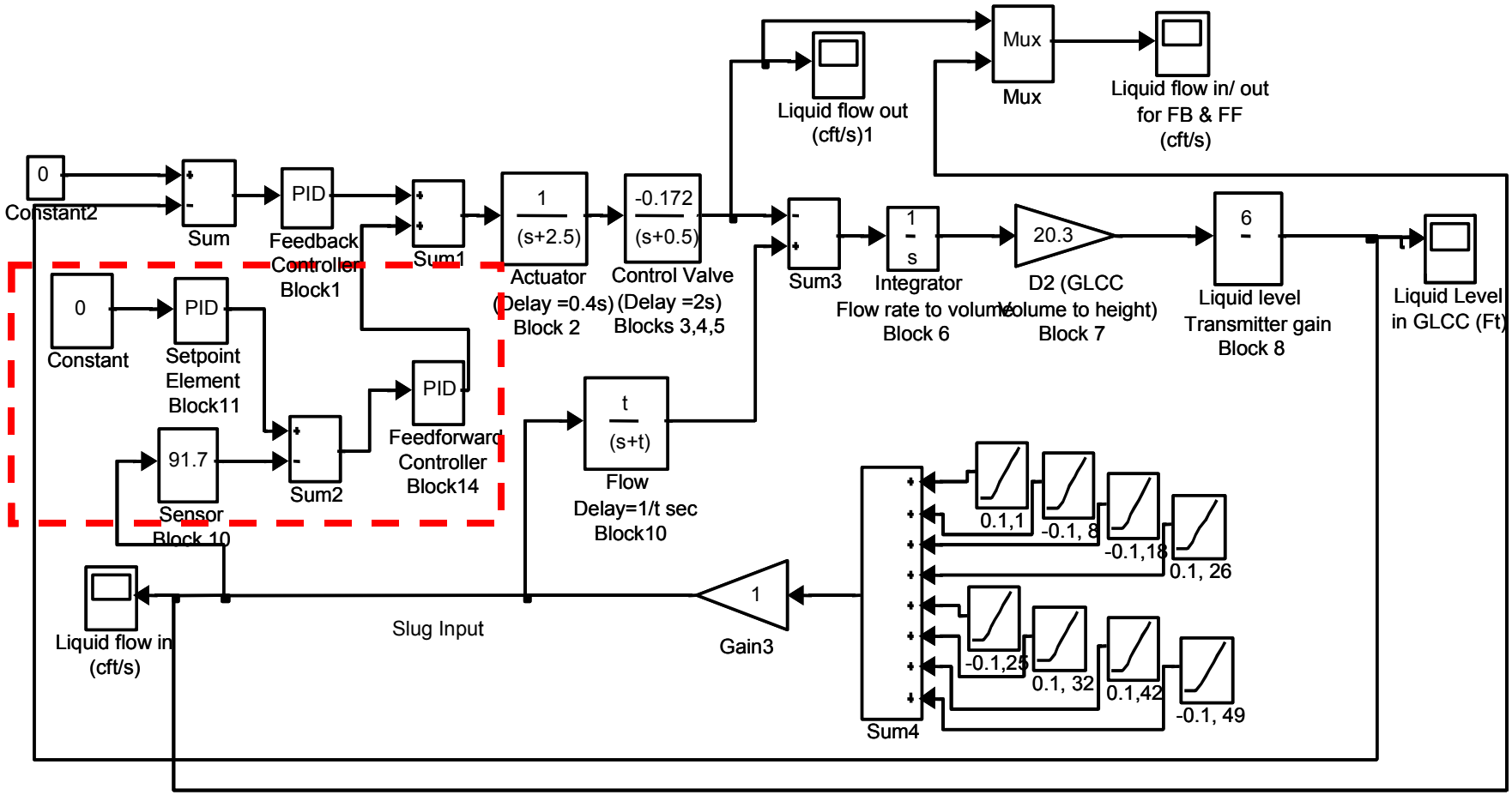

Figure 23. GLCC Predictive control System Simulator

7.6.2. GLCC© Control Strategies: Based on the inflow conditions, appropriate control strategies were developed for GLCC© control. For liquid dominated system (bubbly flow), a gas control valve (GCV) is desirable and for a gas-dominated system (annular flow), a liquid control valve (LCV) is desirable. For intermediate gas and liquid flow conditions (slug flow), both LCV and GCV are needed for level and/or pressure control. The optimal control strategy uses LCV to control the liquid level and uses GCV to maintain the optimal LCV equilibrium position (set point) by adjust the GLCC© pressure based on the inlet flow conditions. This strategy is capable of operating at any flow conditions with minimum pressure drop across the GLCC© and is capable of adapting the inflow conditions to maintain the desired performance without modifying the controller settings.

Development of Control Simulators and Dynamic Simulations: A dedicated control simulator for the GLCC optimal control strategy was built in MATLAB/SIMULINK® to evaluate the optimal control system performance for different inlet conditions, namely, liquid step input, gas step input, liquid slug, and gas pocket. A slug generator was built using the simulator to investigate the behavior of the GLCC© control system to slug unit input. The dynamic behavior of liquid level, pressure, LCV and GCV, liquid outflow and gas outflow were monitored in terms of the transient response.

Experimental Studies: A new GLCC© with state-of-the art gas and liquid control valves has been fabricated and installed and is now in operation in the TUSTP outdoor flow loop. A computer-based dedicated data acquisition system with control capability was also built using LabView® software. This facility was utilized to test the optimal control strategy being developed and simulated by TUSTP. Detailed experiments were conducted using this facility to investigate the system dynamics in terms of liquid level, pressure, and control valves at a wide range of inflow conditions. The results include the control strategy evaluations for different flow conditions, controller gain sensitivity, dynamics of liquid level, pressure, LCV and GCV. The optimization of set point and controller settings were also studied.

Conclusions: Based on the detailed theoretical and experimental investigations (Wang, 2000), the following conclusions can be drawn:

1. A unique optimal control strategy is developed. This strategy is capable of self-adapting and minimizing the operating pressure, providing unique valve positions for a given flow condition. The controller design and dynamic simulation of the optimal control strategy are also provided. This yields a robust control strategy, which can be applied for any flow conditions without modifying the controller settings.
2. A dedicated simulator is built using Matlab/Simulink® software to evaluate the performance of the optimal control strategy for different input conditions.
3. Detailed experimental studies demonstrate that:
   - The developed optimal control system is capable of controlling the liquid level over a wide range of flow conditions, namely, slug flow, churn flow and annular flow. The time responses of the liquid level and the pressure show that more flow disturbance will cause more dynamics of the system.
   - The liquid level can be well controlled at the expense of larger LCV dynamics, which will reduce the lifetime of the control valve. If liquid level fluctuation can be tolerated over a wider range, the controller gain can be suitably designed causing lesser control valve dynamics.
4. The simulation studies and experimental investigations demonstrate that the optimal control strategy has the advantages of handling large flow variations with the minimum pressure drop across the GLCC©. That makes the optimal control strategy the best strategy available for the field.

7.7. Mechanistic Models and Design Procedures for GLCC, LLCC, GLLCC and LLHC

Mechanistic models have been developed for the GLCC, LLCC, GLLCC and LLHC. The mechanistic models are based on the physical phenomena and incorporate the flow mechanisms. The developed models have been tested against TUSTP experimental data and in the case of the GLCC also under high-pressure conditions. Since the models incorporate the important flow variables such as diameter, length, pressure, temperature, flow rates and PVT, they can be scaled up with more confidence. The developed mechanistic models are

probably the main contribution to TUSTP's success in the deployment of the developed technology.

GLCC Model: The enhancement of the GLCC mechanistic model is an ongoing activity for TUSTP (Gomez, 2001). New studies on the GLCC are always incorporated in the model. Based on experimental and theoretical studies, a preliminary mechanistic model was developed by Arpandi et al. (1996). This mechanistic model was capable of predicting the general hydrodynamic flow behavior in a GLCC, including simple velocity distributions, gas-liquid interface shape, equilibrium liquid level, total pressure drop, and operational envelope for liquid carry-over. Recently, the existing mechanistic model has been enhanced by incorporating the following features (Gomez et al., 2000):

- Identification of inlet flow patterns;
- Inlet and Nozzle analysis for prediction of the inlet tangential velocities;
- An analytical model for prediction of the vortex characteristics;
- A unified particle trajectory model for bubble and droplet trajectory analysis;
- A novel approach for determination of the tangential velocity decay of the swirling flow along the GLCC; and
- Quantification of the limiting in-situ erosion velocity.

Dedicated design procedures have been developed for design and fabrication of GLCC separators. These procedures are documented in detail in Gomez et al., 2000.

LLCC Model: A novel mechanistic model has been developed by Oropeza-Vasquez (2001) for prediction of the complex flow behavior in the LLCC and its separation performance. The model consists of several sub-models as follows. The first sub-model predicts the inlet flow pattern. Separate models for the prediction of the spatial distribution and velocities of the oil and water phases in the inlet are provided for each of the flow patterns. The nozzle analysis predicts the oil and water distribution and velocities at the LLCC inlet slot. Models to predict the droplet size distribution based on inlet flow conditions are also provided. The centrifugal separation in the LLCC lower vertical pipe section (the water leg) is analyzed by means of droplet trajectories in swirling flow, resulting in the global separation efficiency of the LLCC. Comparison between the experimental data and the LLCC model predictions shows

an excellent agreement. The model is capable of predicting both the trend of the experimental data as well as the absolute measured values.

The design procedure and design guidelines for the LLCC separators have been developed recently and are documented in the M.S. thesis of Contreras (2002).

GLLCC Model: Oropeza-Vasquez (2001) also developed a novel mechanistic model for the prediction of oil-water separation performance of the GLLCC. The model consists of several sub-models as follows. The inclined inlet is analyzed with the two-fluid model for gas-liquid flow, in order to predict the spatial configuration and velocities of both gas and liquid phases. The oil and water phases are treated as a pseudo-single (homogenous) phase with average properties. A model is provided to analyze the nozzle effect on the flow, predicting the spatial configuration and velocities of the gas and liquid phases at the inlet slot. The droplet size distribution model is based on inlet flow conditions. The centrifugal oil-water separation in the GLLCC liquid leg is predicted based on droplet trajectory analysis from the inlet slot to the top of the oil finder. Mass balances between the oil and water flow rates in the water outlet and the oil outlet yield the purity of the liquid in the water outlet as a function of the split ratio. The developed model shows excellent agreement when tested against the experimental data.

The design procedure and design guidelines for the GLLCC separators are documented in the Ph.D. dissertation of Oropeza-Vazquez (2001).

LLHC Model: A simple mechanistic was developed for the LLHC (Caldentey, 2000 and Gomez et al., 2001). The model is capable of predicting the hydrodynamic flow field of the continuous phase within the LLHC. The separation efficiency is determined based on droplet trajectories, and the inlet-underflow pressure drop is predicted using an energy balance analysis. The predictions of the proposed model are compared with elaborate published experimental data sets. Good agreement is obtained between the model predictions and the experimental data with respect to both separation efficiency and pressure drop.

A summary of the LLHC mechanistic model features is given below:

- A set of correlations is developed to predict the hydrodynamic flow behavior of the continuous phase in the LLHC, based on the swirl intensity concept.

- The droplet trajectory analysis is developed assuming local momentum equilibrium. The only forces acting on the droplet are the centripetal and drag forces in the radial direction. For simplification it is assumed that the droplet moves at the fluid velocity in the axial and tangential directions.
- Based on the droplet trajectory the separation efficiency of the LLHC is determined, and the underflow purity can be computed for a given feed droplet size distribution. Comparison with experimental data reveals that the model predicts the underflow purity with an average relative absolute error of 4%.
- Utilizing the energy balance equation, the pressure drop can be predicted by the model, with an average relative absolute error of 11.1% and an average relative error equal to –7.9%.

7.8. Technology Transfer and Resulted Field Applications

Technology transfer and helping member companies implement the newly developed compact separation technology are important aspects of the TUSTP joint industry project. TUSTP and the supporting member companies aim at rapid deployment of GLCC systems in the field. Over 400 GLCC's that have already been installed and put to use in the field have successfully demonstrated the pronounced impact compact separators are bound to have on the petroleum industry. Table 1, given below shows a rough distribution of these GLCC separators. Most of the applications are in single phase and multiphase metering loops and as bulk separators. To accomplish the final goal of complete separation of all the phases, delivering clean streams of gas, oil and water, a compact separation system needs to be developed, integrating the individual compact separation components into a system.

Currently, compact separators find their potential applications as pre-separators and as gas knockout and free water knockout systems upstream of production equipment. Through control of the gas-liquid ratio or oil-water ratio, compact separators enhance the performance of multiphase meters, multiphase flow pumps, and de-sanders. Other applications are portable well testing equipment; flare gas scrubbers, and slug catchers and primary onshore and offshore surface separation. The popularity of compact separators is due to the fact that they are an order of magnitude smaller, cheaper, and most often clearly superior to conventional separation alternatives. Also, the sizing and performance predictions

are at a level unsurpassed by any other available separation technology. The results of a size comparison study is described below:

Table 1. GLCC Field Installations (as of September 30, 2002)

Quantity Installed	Location	Installer and/or Operator
50 ~ 60	Southern Oklahoma	Chevron
Approx 220	California	Systems Measurement Services
Approx 25	California	Chevron, Texaco
27	Colorado	Premier Instruments (Mining Application)
5	North Texas (1), Midland (2), Portable (2)	Chevron, Emerson Process, Texaco
2 ~ 5	Venezuela	PDVSA
3 ~ 5	Mexico	PEMEX
6 ~ 8	Gulf of Thailand	Unocal and Chevron
5 ~ 7	Nigeria	Chevron
4	Angola (1), Humble (3)	Texaco
3 ~ 5	Eugene Island	Texaco
2	Gulf of Mexico	Chevron
16	Chad, Africa	Premier Instruments/ExxonMobil
20 (4 + 16)	Indonesia (Minas and Duri)	CPI / ChevronTexaco
4	Brazil	Petrobras

Size Comparison of GLCC and Conventional Vessel Type Separators. The compact dimensions, smaller footprints and lower weight of compact separators have a significant potential for cost savings to the industry. This is especially true for deep-water, offshore platforms for which production separators are usually the largest and heaviest equipment. For this application, platform space and weight-carrying capacity are very crucial. Thus, the reduction in size and weight of the compact separators is highly advantageous and can lead to considerable cost savings. A size comparison study has been conducted to aid in the decision making process of selecting an appropriate separator for a field application. The results of comparison study between the required size of the GLCC and conventional horizontal and vertical 1-g separators for a field operated by Chevron are given below. The average expected flow rates in this field are qg = 71,000 Mscf/d and ql = 200,000 bbl/d at an operating pressure of 170 psig, and temperature of 360 F (light oil steam flooded). The size

comparison between conventional vessel-type horizontal and vertical separators with a GLCC separator for the above mentioned field operations reveals a significant reduction in size when a GLCC is used. The GLCC design was based on the developed simulator, while the dimensions of both conventional vessel type separators are determined by a widely available commercial code. For this case, the required GLCC I.D. and height/length (5 x 20 ft) are about half of the corresponding dimensions of the required conventional vertical separator (9 x 35 ft), and about a quarter of those of a conventional horizontal separator (19 x 75 ft). Translating this dimension to weight of half-loaded separators, the GLCC weight is 1/8 and 1/64 of the weights of the conventional vertical and horizontal separators.

8. Conclusions

Based on the investigations of this project and the resulting deliverables, we can arrive at the following specific conclusions:

- Fundamental knowledge of compact multiphase separation technology has been developed which will pave the foundation for the development of other compact separators. State-of-the art technology of three-phase GLCC separator for bulk oil/water separation has been developed.
- Novel mechanistic models have been developed for the prediction of the complex flow behavior and the separation efficiency in the GLCC, LLCC and GLLCC. The models consist of several sub-models, including inlet analysis, nozzle analysis, droplet size distribution model, and separation model based on droplet trajectories in swirling flow. Comparison between the experimental data and the LLCC and GLLCC model predictions shows excellent agreement. The developed models can be utilized for the design and performance analysis of the LLCC and GLLCC. This model provides an insight into the hydrodynamic flow behavior and serves as the design tool for the industry.
- A model has been developed for GLCC predictive control system integrating feedback and feed forward control systems. This strategy incorporates the slug characteristics in terms of holdup, length and velocity, and calculation of the volumetric liquid flow rate. Comparison of simulation and experimental results shows that the predictive control

system is capable of handling huge slugs by reducing the liquid level percentage overshoot and liquid level settling time considerably.

- A unique optimal control strategy is developed for compact separator control. This strategy is capable of self-adapting and minimizing the operating pressure, providing unique valve positions for a given set of flow conditions. Detailed experimental studies demonstrate that the developed optimal control system is capable of controlling the liquid level over a wide range of flow conditions, namely, slug flow, churn flow and annular flow.
- The feasibility of using Liquid-Liquid Cylindrical Cyclone (LLCC) as a free water knockout device for bulk separation of oil-water mixtures is proved. A unique "direct" control strategy is developed and implemented, capable of obtaining clear water in the underflow line and maintaining maximum underflow rate. Dedicated control system simulations are conducted using Matlab/Simulink software to simulate the real system dynamic behavior. Detailed experimental investigations demonstrate that the proposed control system is capable of controlling the underflow watercut around its set point by obtaining maximum free-water knockout for a wide range of flow conditions (inlet water concentration of > 40% and an inlet mixture velocity of < 1.5 m/s).
- Data bank, including laboratory and field data on GLCC performance has been prepared and published in literature. This data bank will be maintained and updated on an ongoing basis for continuous improvement of the mechanistic models.
- Refined constitutive models for CFD (computational fluid dynamic) code (CFX) for turbulence anisotropy in rotating flows, oil-water interaction and gas/liquid dispersion has been developed. A multidimensional multiphase CFD model, based on CFX, for detailed prediction of the GLCC flow behavior, is developed. The CFD model is generic in nature and could be utilized for analyzing different compact separation devices and other complex multiphase systems.
- A modified GLCC for wet gas applications, which can withstand pressures as high as 1500 psi, has been developed and tested. The low pressure (<30psia) experimental results show that the operational envelope for liquid carry-over expands in the high gas velocity region (up to 60 ft/s) and the liquid film extractor has 100% efficiency at low liquid rates

(Vsl<0.5 ft/s). The liquid carry-over for a regular GLCC is in the range of 1-3% of the inlet liquid. The high-pressure (upto 1000 psi) tests show that the onset of liquid carry-over occurs at the velocity ratio of 1.3. The wet gas GLCC has very high liquid separation efficiency (>90%) compared to the original GLCC for Vsg/Vann<3. The separation efficiency increases by about 5% by adding the second AFE.

- The GLCC for the high pressure, real crude experimental investigation has been tested at Colorado Engineering Experiment Station Inc. (CEESI), so as to withstand pressures as high as 1500 psi. This device is equipped with several temperature and pressure transducers to enable evaluation of the hydrodynamic flow phenomena. Detailed testing of the GLCC separators upto 1000 psi have been completed.
- Design guidelines for high-pressure GLCC separators for field applications have been developed to enable the commercial fabrication of the GLCC©. Design guidelines for LLCC© separators have also been developed.

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10. Publications resulting from this Research

Theses (3) and Dissertation (8):

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