<u>Project Title:</u>

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

UNIVERSITY of TULSA

Tulsa University Separation Technology Projects (TUSTP)

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1. Disclaimer

2. Abstract

This report presents a brief overview of the activities and tasks accomplished during the second half year (April 1, 2001 – September 30, 2001) of the fourth project year budget period (October 1, 2000 – September 30, 2001). An executive summary is presented initially followed by the tasks of the current budget period. 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 fourth project year activities are divided into three main parts, which are carried out in parallel.   The first part is continuation of the experimental program that includes a study of the oil/water two-phase behavior at high pressures and control system development for the three-phase GLCC$^{©}$. This investigation will be eventually extended for three-phase flow. The second part consists of the development of a simplified mechanistic model incorporating the experimental results and behavior of dispersion of oil in water and water in oil. This will provide an insight into the hydrodynamic flow behavior and serve as the design tool for the industry.   Although useful for sizing GLCC$^{©}$s for proven applications, the

mechanistic model will not provide detailed hydrodynamic flow behavior information needed to screen new geometric variations or to study the effect of fluid property variations. Therefore, in the third part, the more rigorous approach of computational fluid dynamics (CFD) will be utilized. 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.

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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.   This project is executed in two phases. Phase I (1997 - 2000) focuses on the investigations of the complex multiphase hydrodynamic flow behavior in a three-phase Gas-Liquid Cylindrical Cyclone (GLCC[©1]) Separator.   The activities of this phase include the 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.   In Phase II (2000 - 2002), the developed GLCC[©] separator is tested under high pressure and real crudes conditions. This is crucial for validating the GLCC[©] design for field applications and facilitating easy and rapid technology deployment.   Design criteria for industrial applications will be developed based on these results and will be incorporated into the mechanistic model by TUSTP.

This report presents a brief overview of the activities and tasks accomplished during the second half year (April 1, 2001 – September 30, 2001) of the budget period (October 1, 2000 – September 30, 2001). The total tasks of the budget period are given initially, followed by the technical and scientific results achieved to date from the experimental and modeling investigations. The report concludes with a summary and a list of references.

5. Tasks of the Current Budget Period (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[©] and modification of the high-pressure loop.
   c. Instrumentation and Data Acquisition for Operational Envelope.
   d. Data Analysis and Evaluation of High Pressure GLCC[©] performance.

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[1] GLCC[©] - Gas Liquid Cylindrical Cyclone – copyright, The University of Tulsa, 1994.

e. Mechanistic Model Improvement for high pressure conditions for two-phase and three-phase applications.

f. Interim reports preparation.

6. Experimental and Modeling Investigations

The ultimate testing of a new development such as a three-phase GLCC$^{©}$ is at high pressures and with real crudes, similar to the conditions in the field. The goal of Phase II (Project years 4 and 5) is to conduct field-scale testing of GLCC$^{©}$ technology at high pressure and with real crudes. Tasks will include design, fabrication and testing of a high pressure GLCC$^{©}$ facility. The results of this testing will be incorporated by The University of Tulsa (TU) personnel into the TUSTP mechanistic model and be used by TUSTP to develop design criteria to assist industry with implementation of GLCC$^{©}$ systems in field operations.

As a sub-contractor to TU, Texas A&M University will provide field-scale testing of GLCC$^{©}$ compact separator in support of this project for year 4. Texas A&M work will be performed in the Multiphase Field Laboratory at the Harold Vance Department of Petroleum Engineering. This existing facility has installed equipment to conduct these tests at high rates and pressures (10,000 bbl per day @ 200-250 psig). Benchmark two-phase tests will be conducted using air/water and air/gelled water.

As a complimentary effort to Texas A&M University activities, plans are underway to conduct detailed testing of the GLCC$^{©}$ separators at field locations and other large-scale facilities such as the Colorado Engineering Experiment Station Inc. (CEESI). The GLCC$^{©}$ prototype has been built at CEESI in collaboration with TUSTP member companies (Chevron). Initial experimentation has been performed at CEESI and data analysis is in progress. Hardware modifications are currently underway to enhance the applicability of the GLCC$^{©}$ for high GOR (gas-oil ratio) conditions.

The phase II project research activities are similar to the phase I project activity, only difference being that the emphasis is on high-pressure, real crude conditions. The mechanistic modeling of liquid carry-over and gas carry-under are continued in the fourth year for integration with the respective constitutive models.

Two types of GLCC$^{©}$ configurations are being considered namely single stage GLCC$^{©}$ and dual stage GLCC$^{©}$. Feasibility of these two configurations have been established in the Phase I investigations at The University of Tulsa. The high-pressure flow loop at Texas A&M University can be used for both configurations. The GLCC$^{©}$ for this experimental investigation has been built at CEESI using steel pipes so as to withstand high pressures, and is equipped with several temperature and pressure transducers to enable evaluation of the hydrodynamic flow phenomena. A schematic of the modified GLCC for high GOR applications is shown in Figure 1. The photograph of this GLCC designed for high GOR applications and tested at high pressures conditions in CEESI is shown in Figure 2. The modular design of the GLCC$^{©}$ will allow easy modification of the inlet, outlet and piping configurations.
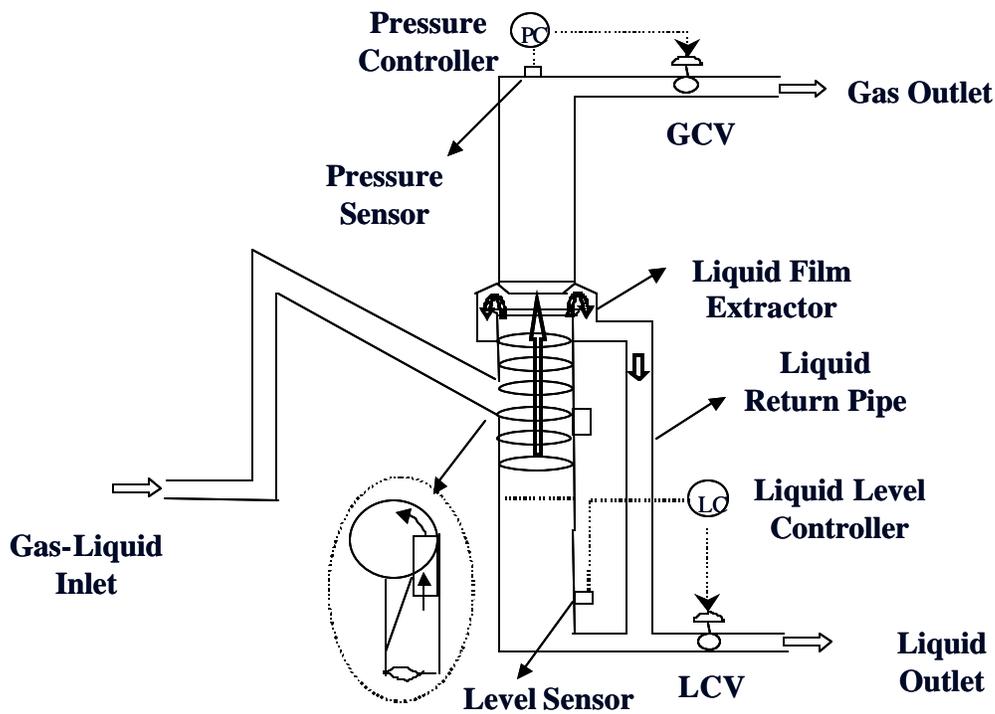

Figure 1 – Modified GLCC for High GOR Applications

In addition to the inlet flow rates of the three-phases, the following measurements will be acquired for each experimental run:

1. Absolute pressure, temperature and pressure drop in the GLCC$^{©}$;
2. Equilibrium liquid level using differential pressure transducers;
3. Zero net liquid flow hold-up at high pressures and comparison with low pressures.

Figure 2 – High Pressure GLCC Test Facility at CEESI

4. Churn region and droplet region lengths (in the upper part of the GLCC$^{©}$) as limiting conditions;
5. Global separation efficiency namely oil fraction in the water outlet, water fraction in the oil outlet;
6. Bulk measurement of liquid carry-over in the gas leg.

The mechanistic model development initiated in the first phase of the project will be continued during the second phase, which will lead to an integrated model. A mechanistic

model for operational envelope of liquid carry-over and gas carry-under will be developed for the prediction of the hydrodynamic flow behavior and performance of the three-phase GLCC$^©$ separator.

The input parameters to the model would 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$^©$ such as, GLCC$^©$ configurations, inlet pipe I.D, inclination angle and roughness, outlet piping I.D, length and roughness;

The mechanistic model will enable determination of the performance characteristics of the GLCC$^©$, namely:

- plot of the operational envelopes for both liquid carry-over and gas carry-under at high pressures;
- 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;

The simplified integrated mechanistic model will enable insight into the hydrodynamic flow behavior in the three-phase GLCC$^©$. It will allow the user to optimize the GLCC$^©$ design accounting for tradeoffs in the I.D, height and inlet slot size of the GLCC$^©$. The model will also provide the trends of the effect of fluid physical properties and the information required for determining when active controls will be needed.

The purpose of the computational fluid dynamics (CFD) modeling is to provide both macroscopic and microscopic scale information on multidimensional multiphase flow hydrodynamic behavior for real crude conditions. The CFD model will be general so that it can be utilized for the analysis of GLCC$^©$ and other complicated multiphase flow systems. Thus, the numerical simulator will provide a powerful analytical tool, which will also reduce

experimental costs associated with testing of a variety of different operating conditions. Constitutive models for the CFD code (CFX) will be developed and will be added to the simulator to capture the important physics of three-phase separation at high pressures.

The experimental data acquired at high pressures on the GLCC© and other available data from complex three-phase systems, such as flow splitting at tee junctions, will be used to test and refine the numerical code. For the current project, the CFD model will be used for initial parametric studies of possible design modifications to the GLCC©. Moreover, the model will provide detailed performance prediction for untried applications for which no data are available, such as high-pressure, sub-sea separation.

7. Results and Discussion

As a part of the tasks identified for the current budget period, the following specific activities have been completed:

A) Oil/Water Separation in LLCC©2 Separators

Objective: The primary objective of this study is experimental investigations to determine the performance of LLCC© for bulk separation of oil-water mixtures.

The picture of the LLCC test section is shown in Figure 3. 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.

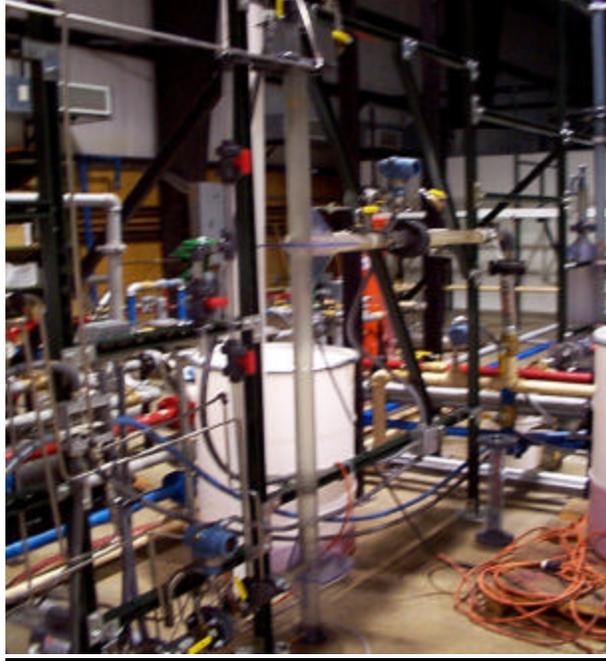[2] LLCC© - Liquid-Liquid Cylindrical Cyclone – copyright, The University of Tulsa, 1999.

Figure 3 - LLCC Test Section

Experimental Investigations:

The feasibility of the Liquid-Liquid Cylindrical Cyclone for free water knockout bulk separation of oil-water mixtures has been studied experimentally and theoretically. This study promotes a better understanding of liquid-liquid flow characteristics necessary for the development of the LLCC as a free water knock out device.

LLCC inlet design is modified from inclined inlet to horizontal inlet. Other appropriate design change such as the vortex finder is added to the LLCC, and a modified LLCC is obtained. This modified LLCC is capable of separating free water from high inlet mixture velocities. Figure 4 demonstrates the performance improvement of the modified LLCC.

Test Matrix: Experiments were conducted for the entire water-continuous and oil-continuous range, i.e. from 95% Water-Cut at the inlet to 10% Water-Cut. For each inlet water concentration, three different mixture velocities were taken into account and for each

LLCC with Inclined Inlet   LLCC with Horizontal Inlet   Modified LLCC

Figure 4 (a) - O.S.R = 43%   Figure 4 (b) - O.S.R = 43%   Figure 4 (c) - O.S.R = 49%
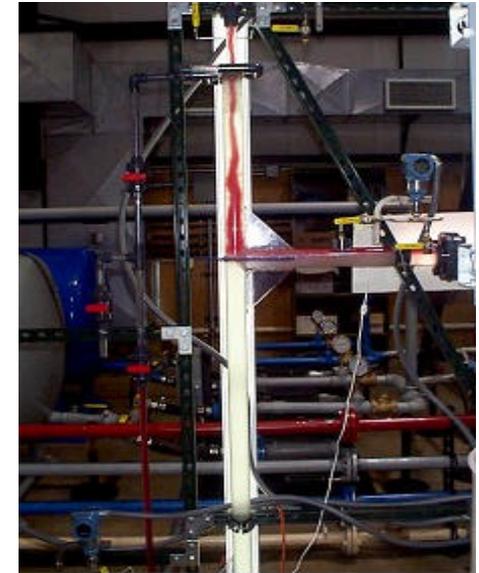Underflow W.C = 96.9%   Underflow W.C = 100%   Underflow W.C = 100%

Figure 4 – Performance Improvement of Modified LLCC

mixture velocity, split ratio (Overflow rate / Total Inflow rate) was varied so as to obtain 100% pure water in the underflow.

Results: Based on the results, 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.
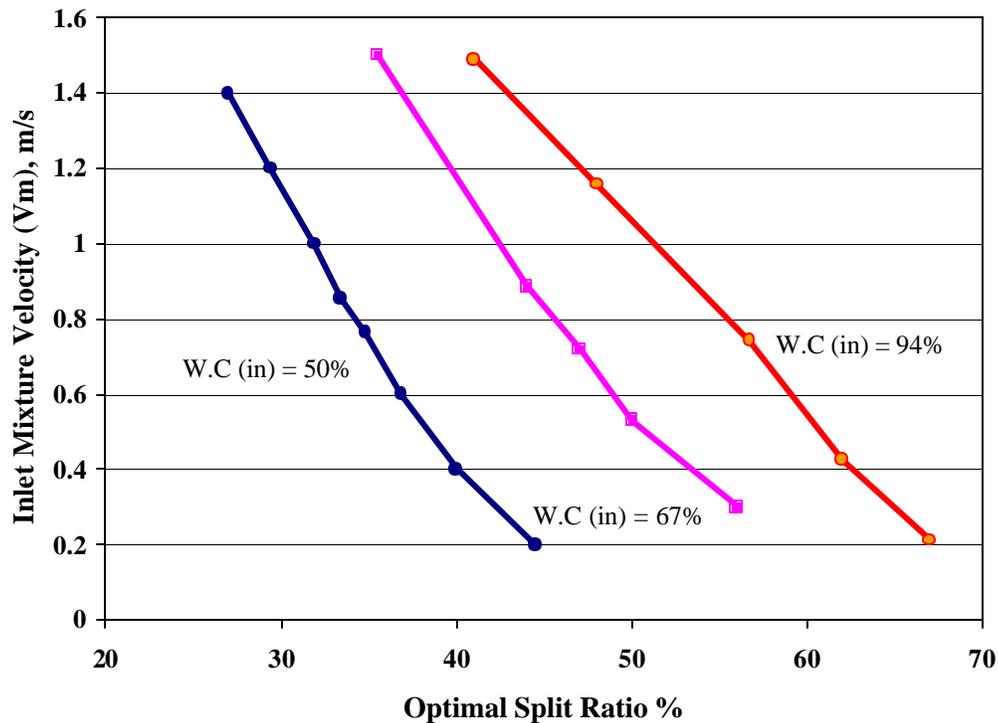
Optimal Split Ratio Phenomenon

Figure 5 – Optimal Split Ratio Phenomenon in an LLCC Test Section

- 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 5, where the water flow rate is

maximum with 100% water-cut. The value of the optimal (maximum) split ratio for 100% water-cut 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 an 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. Sampling is an important issue to be considered for a Starcut configuration.

B) Oil/Water LLCC© Control

- A linear model is developed for LLCC with underflow watercut as the control parameter. This model provides the framework for control system design and dynamic simulation. Controller design has been conducted for the proposed control strategy using Root Locus Techniques. From the root locus design, the feedback controller settings are obtained. It can be noted that the controller settings depend upon the inlet watercut and the inlet mixture velocity. Different settings have to be provided for different inlet flow conditions for perfect feedback control. However, the controller settings designed for one particular flow condition can be useful for a range of flow conditions achieving satisfactory performance.

- A unique control strategy is developed, which can provide a much superior performance as it involves the direct measurement of a control parameter of immediate concern. This strategy is capable of maintaining clear water in the underflow and simultaneously maximizing the flow rate in the underflow stream. It

tries to maintain the optimal split ratio that depends upon the inlet water concentration and inlet mixture velocity. The controller design and dynamic simulation of the proposed control strategy are also provided.

- Control system simulator is developed as shown in Figure 6, using Matlab/Simulink® software. Detailed dynamic simulations show that: LLCC control system can handle different combinations of the inlet water and oil flow disturbances. The system can be brought back to the desired set point very fast. However, the optimal split ratio may not be the same for all flow conditions. The control valve dynamics are much less. As the life of the control valve is limited, creating a lot of control valve dynamics can wear out the control valve early.
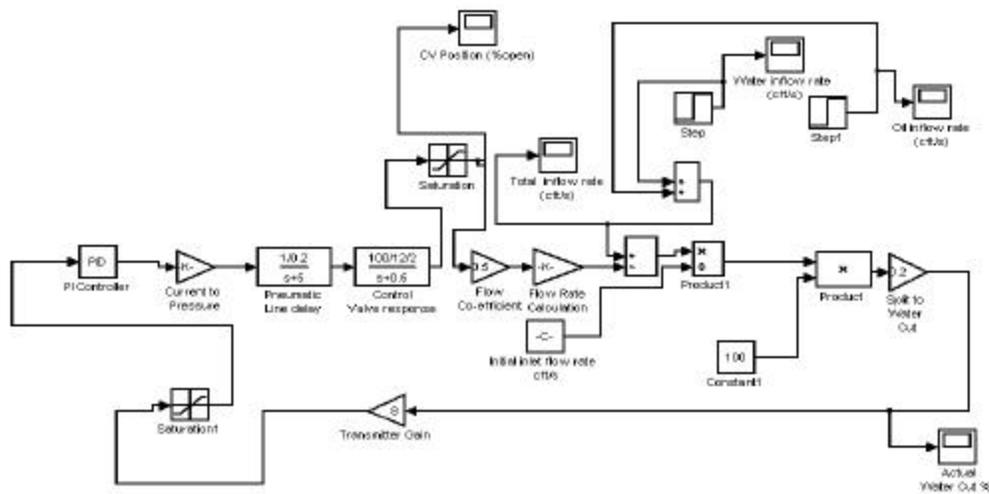

Figure 6 – LLCC Control System Simulator

- 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. It may also be noted that, as the disturbance increases, the dynamics of the system will also increase.

C) <u>Oil/Water/Gas Separation in Three-Phase GLLCC$^{©}$</u>

        The objective of this study 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.

        A new experimental flow loop has been constructed in the College of Engineering and Natural Sciences Research Building located in the North Campus of TU. This indoor facility enables year around data acquisition and simultaneous testing of different compact separation equipment. The oil/water/air 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.

        The experimental data acquisition for the 3-phase GLLCC, shown in Figure 7, has been completed. Extensive data set was acquired for a fixed gas superficial velocity and fixed oil finder position. The water and oil superficial velocity ranges were 0.1 to 0.5 m/s and 0.025 to 0.5 m/s, respectively. The split ratio (the ratio of total flow rate in the overflow and the total flow rate at the inlet) was varied from 10 to 100% for each oil and water velocities combination. The results indicate that for low oil concentrations and high water superficial velocities the watercut in the water stream increases. Typical experimental results in a GLLCC separator to demonstrate the purity of watercut in water line for different inlet concentrations is shown in Figure 8. The experimental results from the single stage GLLCC demonstrate that it is a very good bulk separator but not a fine separator.

        The initial modeling effort of this project focuses on the LLCC. A preliminary modeling for the LLCC$^{©}$ has been developed. It includes the prediction of the existing flow patterns at the horizontal inlet, and the analysis for moderate input oil concentration and low input oil concentration. The LLCC model has been completed, and will be extended to the GLLCC in the next few months. Schematic of the observed inlet flow patterns in an LLCC and the inlet flow pattern map are shown respectively in Figures 9 and 10. Models for maximum and minimum oil droplet size distribution for different inlet flow pattern are shown in Figure 11.

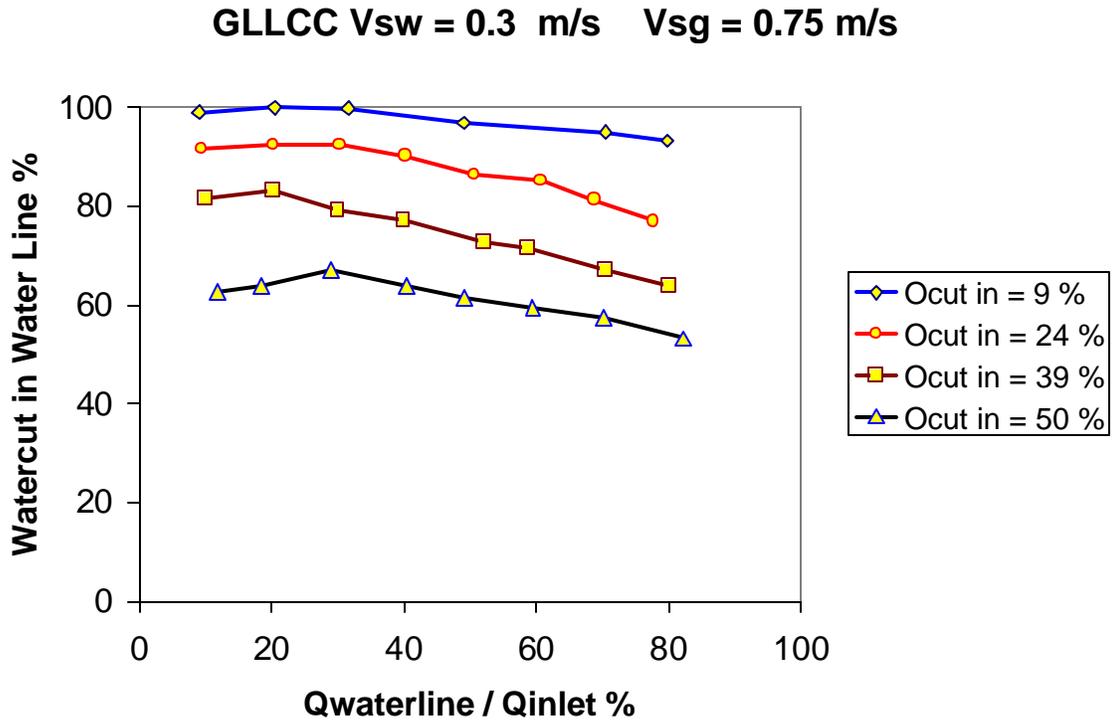# Fig. 7 - Single-Stage GLLCC© in Operation

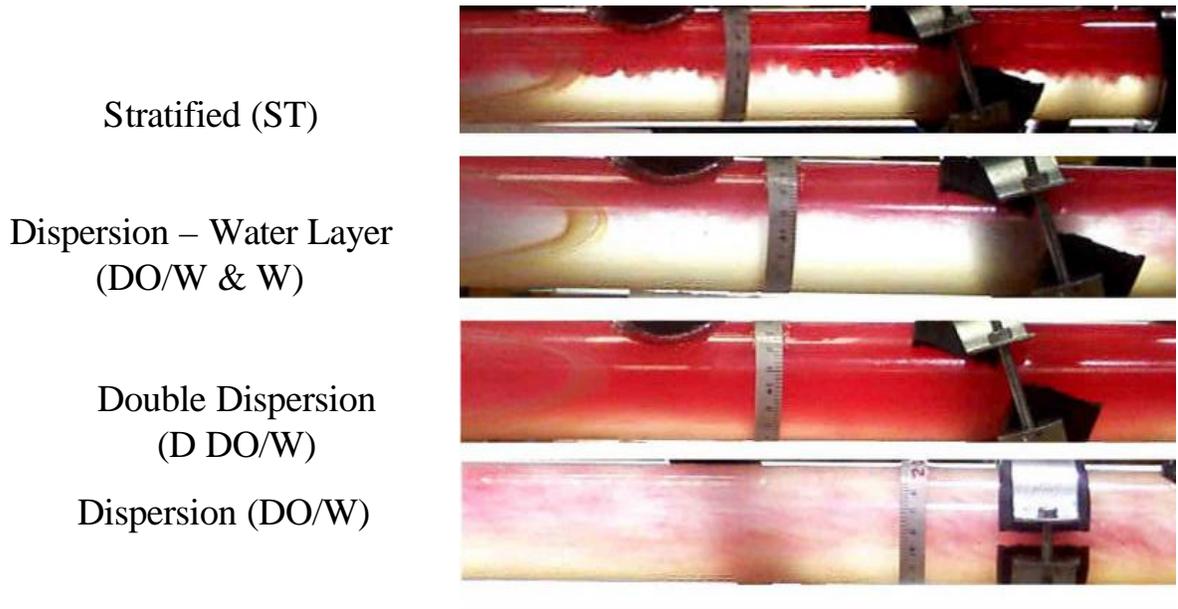Figure 8. Typical Experimental Results of GLLCC Separator.

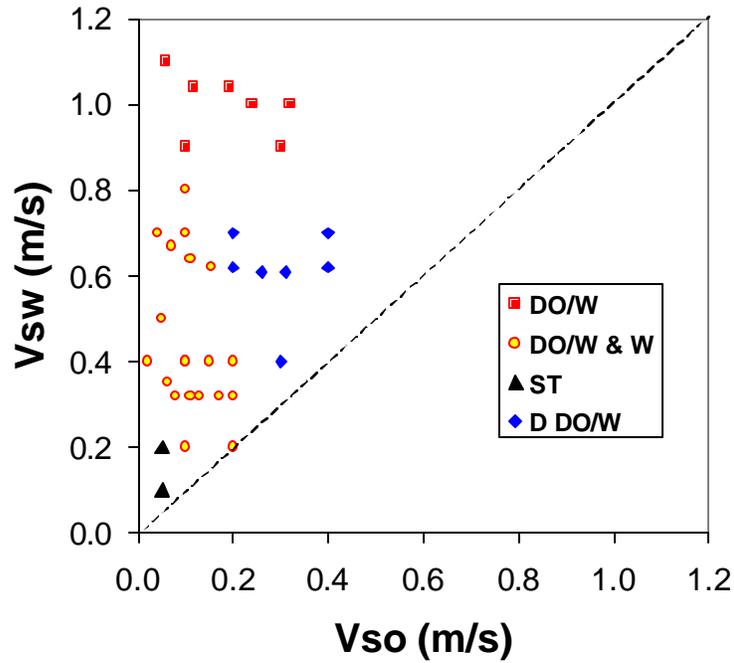Figure 9. Observed Inlet Flow Patterns in an LLCC Separator.

Figure 10. Inlet Flow Pattern Map

❖ **DO/W & W and Stratified**

Modified Hinze

$$d_{od,max} = \left[\frac{l_{w,in}^{0.5}}{1.9}\right] 0.725 \left(\frac{s_{ow}}{r_d}\right)^{0.6} \left(\frac{2 f_d v_d^3}{d_d}\right)^{-0.4}$$

Modified Levich

$$d_{od,min} = \left[\frac{l_{w,in}^{0.5}}{2.5}\right] 2 \left(\frac{s_{ow} m_d}{25 r_d^2 v_d^3 (0.5 f_d)^{1.5}}\right)^{\frac{1}{2}}$$

❖ **DO/W and D DO/W**

Modified Hinze

$$d_{o\,max} = \left[\frac{1}{2.14}\right] 0.725 \left(\frac{s_{ow}}{r_m}\right)^{0.6} \left(\frac{2 f_m v_m^3}{d_{in}}\right)^{-0.4}$$

Modified Levich

$$d_{o\,min} = \left[\frac{1}{1.43}\right] 2 \left(\frac{s_{ow} m_m}{25 r_m^2 v_m^3 (0.5 f_m)^{1.5}}\right)^{\frac{1}{2}}$$

Figure 11. Models for Maximum and Minimum Oil Droplet Size Distribution

D) Predictive Control of GLCC$^©$ Using Slug Detection

Field applications of Gas Liquid Cylindrical Cyclone (GLCC$^©$) separators strongly depends 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. 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 (schematic shown in Fig. 12) is designed to operate only when huge slugs are encountered. Based upon the design, a predictive control model has been simulated in MATLAB-Simulink integrating feedback and feed forward control systems, as shown in Fig. 13. Detailed theoretical and experimental studies were carried out to estimate 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 huge slugs, which can cause considerable damage to the operational efficiency of GLCC$^©$.
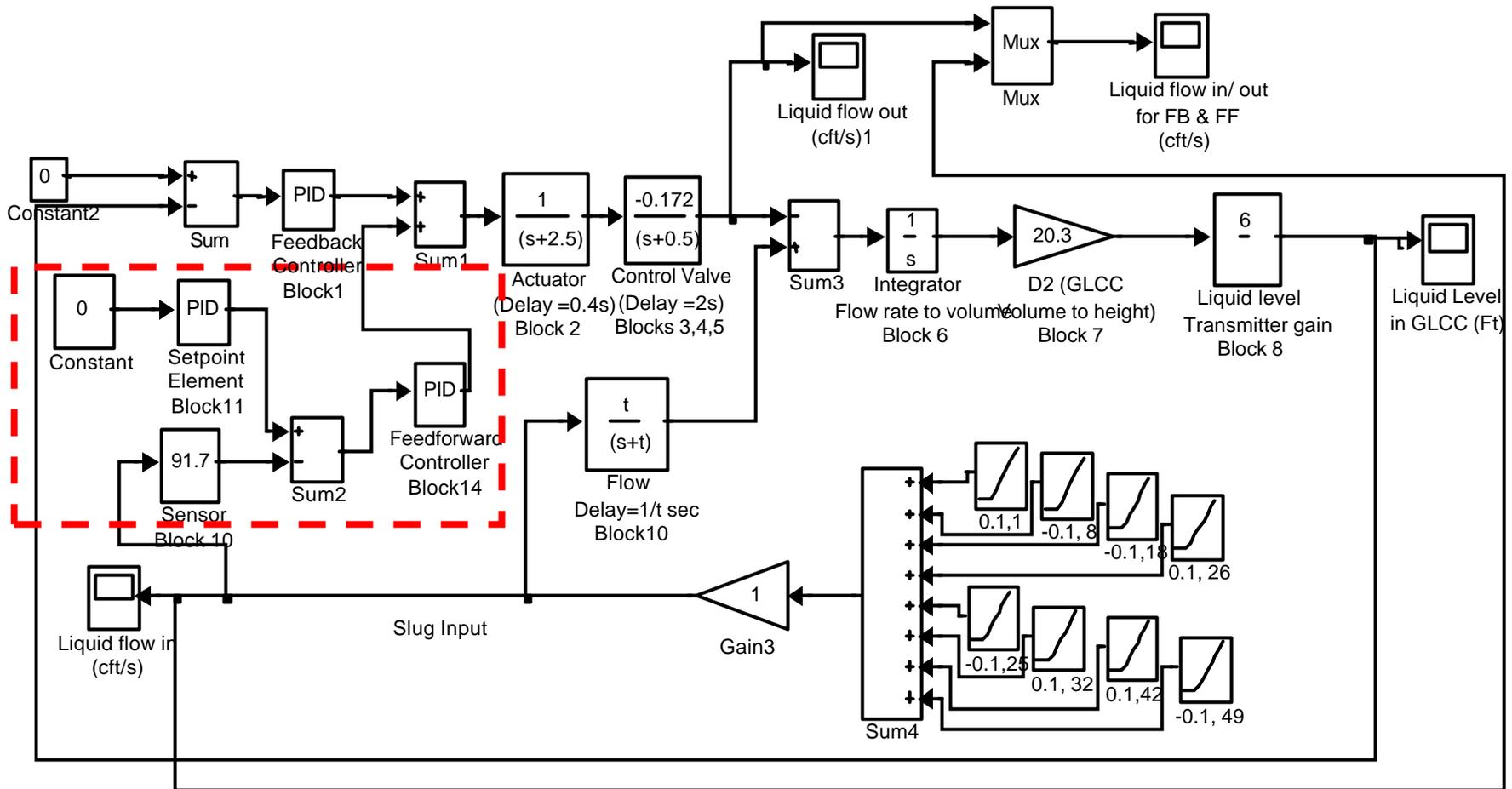
Fig. 12 - Schematics of Integrated Level Control Loop
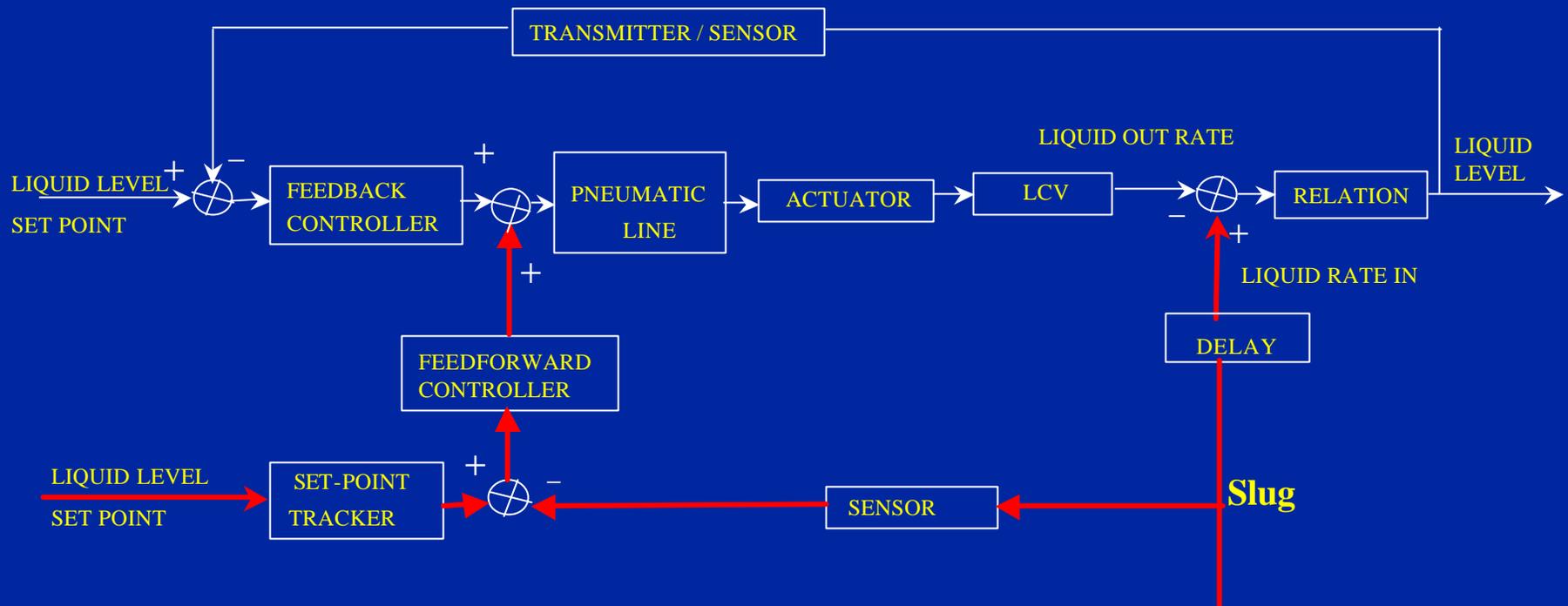
Fig. 13 - Level Control Simulator with FF and FB Controller (LCV)

E) GLCC Separators for Wet Gas Applications

Objectives: Present studies of GLCC focus on design and applications at relatively lower gas velocities (below the minimum velocity for onset of liquid carry-over in the form of mist flow). With appropriate modifications GLCCs can be used 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. As part of this study, a novel design of GLCC capable of separating liquid from a wet gas stream has been developed. Experimental investigations are in progress 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 are also being formulated based on the experimental studies. This investigation provides new capabilities for compact separators for wet gas and high GOR (exceeding 90%) applications.

Figure 14 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 liquid 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.

Experimental Results: The experimental results include the operational envelopes for liquid carry-over and measurement of liquid extraction by the liquid film extractor.

Operational Envelope. The experimental results of the operational envelops for different GLCC configurations include

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

Fig. 14 - High Pressure GLCC Test Facility
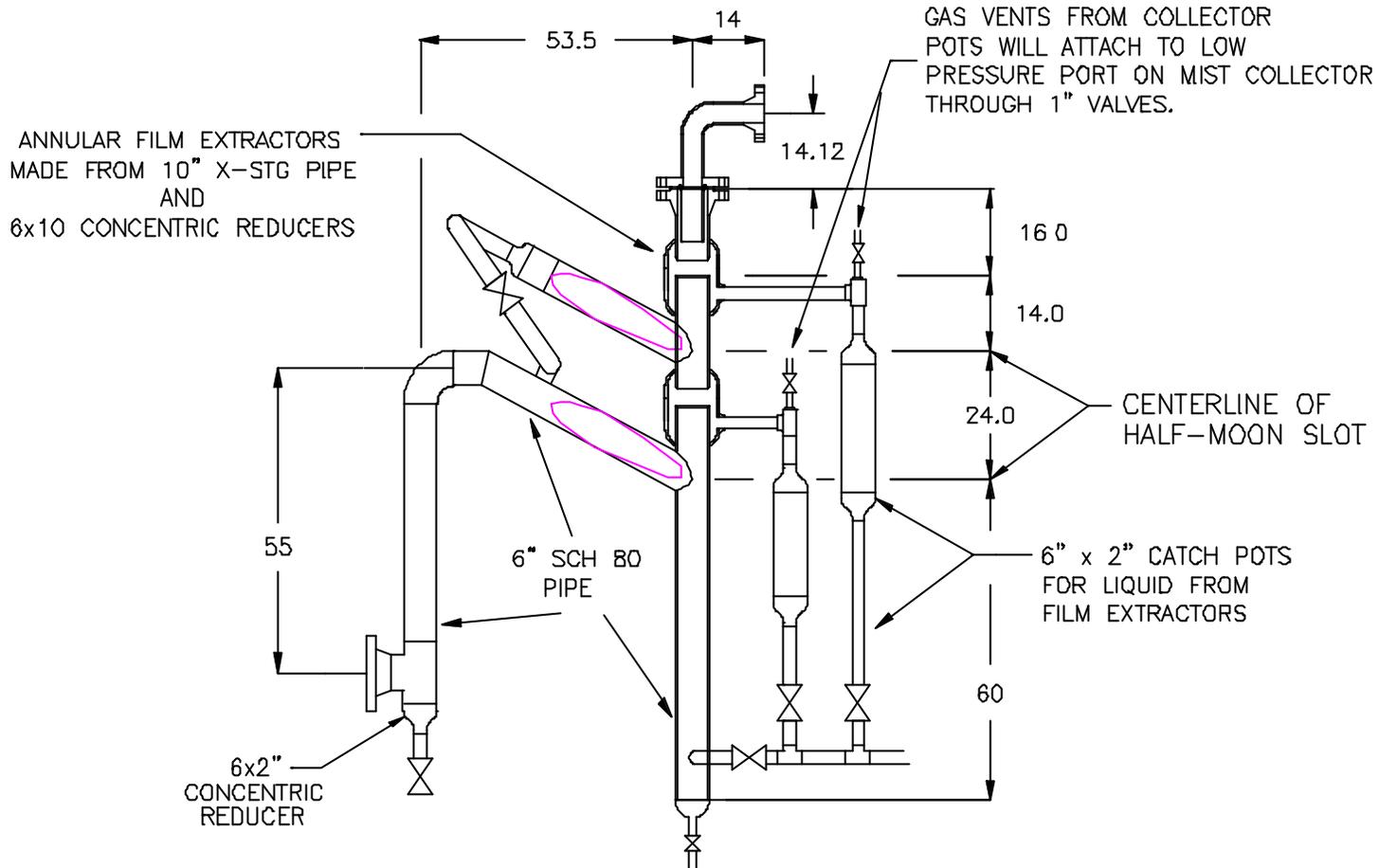
GLCC SEPARATOR
WITH DUAL ANNULAR FILM EXTRACTORS

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 gas critical 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 liquid film extractor 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 $n_{crit} = 33$ ft/s) and still can tolerate superficial liquid velocities up to 0.5 ft/s. The operational envelope for the modified GLCC (shown in Fig. 15) 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. Specific design guidelines have been formulated for high GOR GLCCs and are given in Figure 16.

F) High Pressure GLCC Test Results

In addition to the Texas A&M experimental work, 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 preliminary 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 Fig. 17. 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 (always above 60%). It is interesting to note that this difference is much less pronounced at

Fig. 15 - Oper. Env. for Liquid Carry-Over of High GOR GLCC
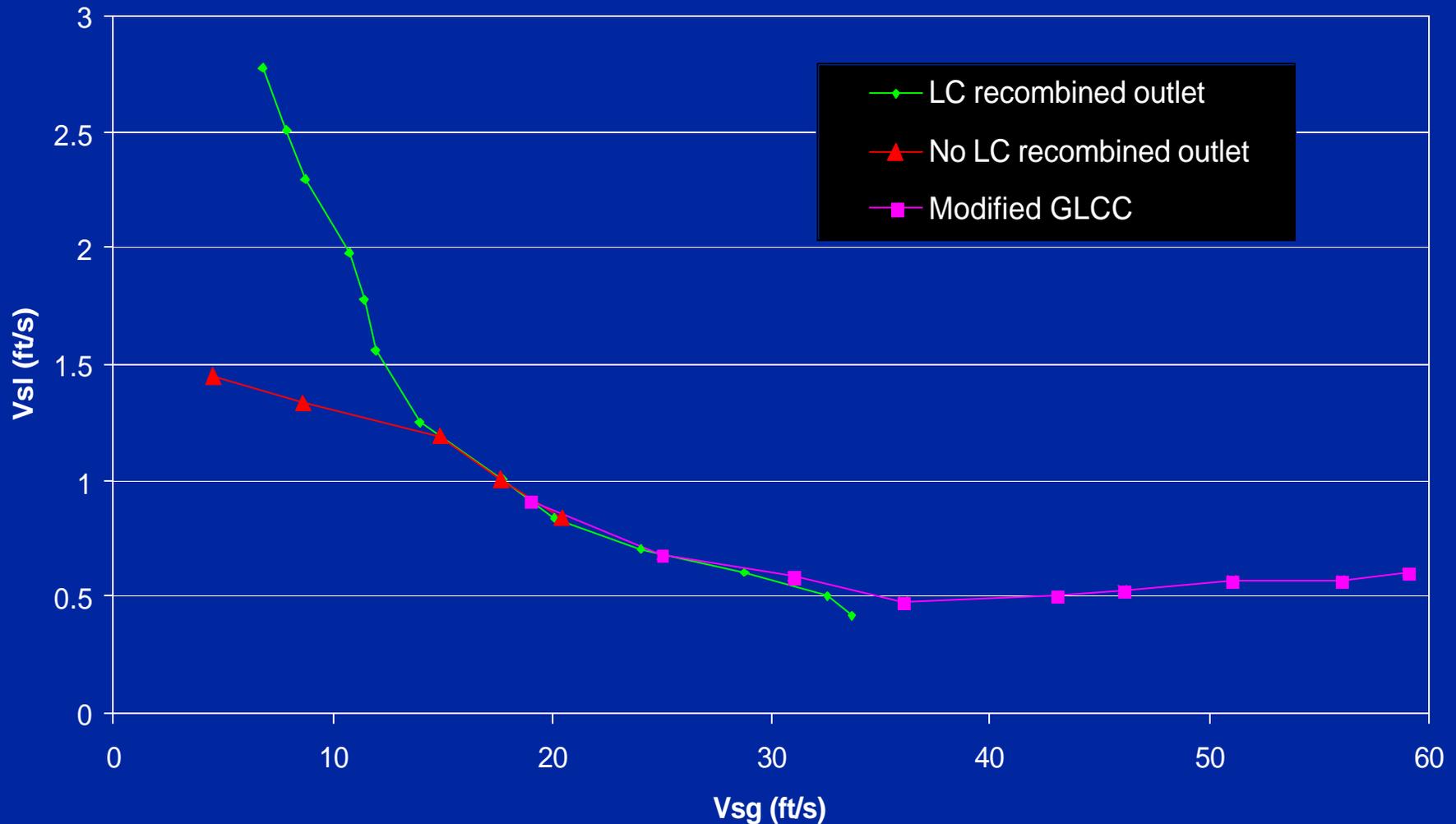
Fig. 16 - Design Guidelines: High GOR GLCC Dimensions

❖ **GLCC diameter**

  ❑ **Vsg/Vann = 2-3 for efficiency above 90%**
  ❑ **Vsl<0.5 ft/s**

❖ **Inlet dimensions**

  ❑ **Diameter: <=Dglcc**
  ❑ **Inclination angle: -20 to –30 degree**
  ❑ **Length: 5-10 Dglcc**
  ❑ **Nozzle: 20-25% of A_{GLCC}**

Multiphase Flow

Gas Phase

Liquid Phase

❖ **GLCC height**

  ❑ **Upper section (above inlet): depends on AFE**
  ❑ **Lower section (below inlet): depends on retention time for GCU**
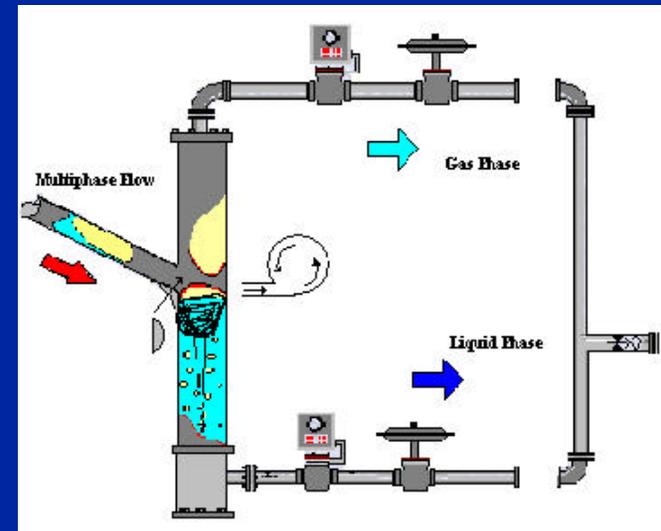
Fig. 17 - High Pressure GLCC Test Results: Separation Efficiency

Regular GLCC Performance for LCO

Legend:
- 200 psi (Vsl=0.01 ft/s)
- 200 psi (Vsl=0.1 ft/s)
- 500 psi (Vsl=0.01 ft/s)
- 500 psi (Vsl=0.1 ft/s)
- 1000 psi (Vsl=0.01 ft/s)
- 1000 psi (Vsl=0.1 ft/s)

X-axis: Vsg/Vann

Y-axis: Liquid Separation Efficiency (%)
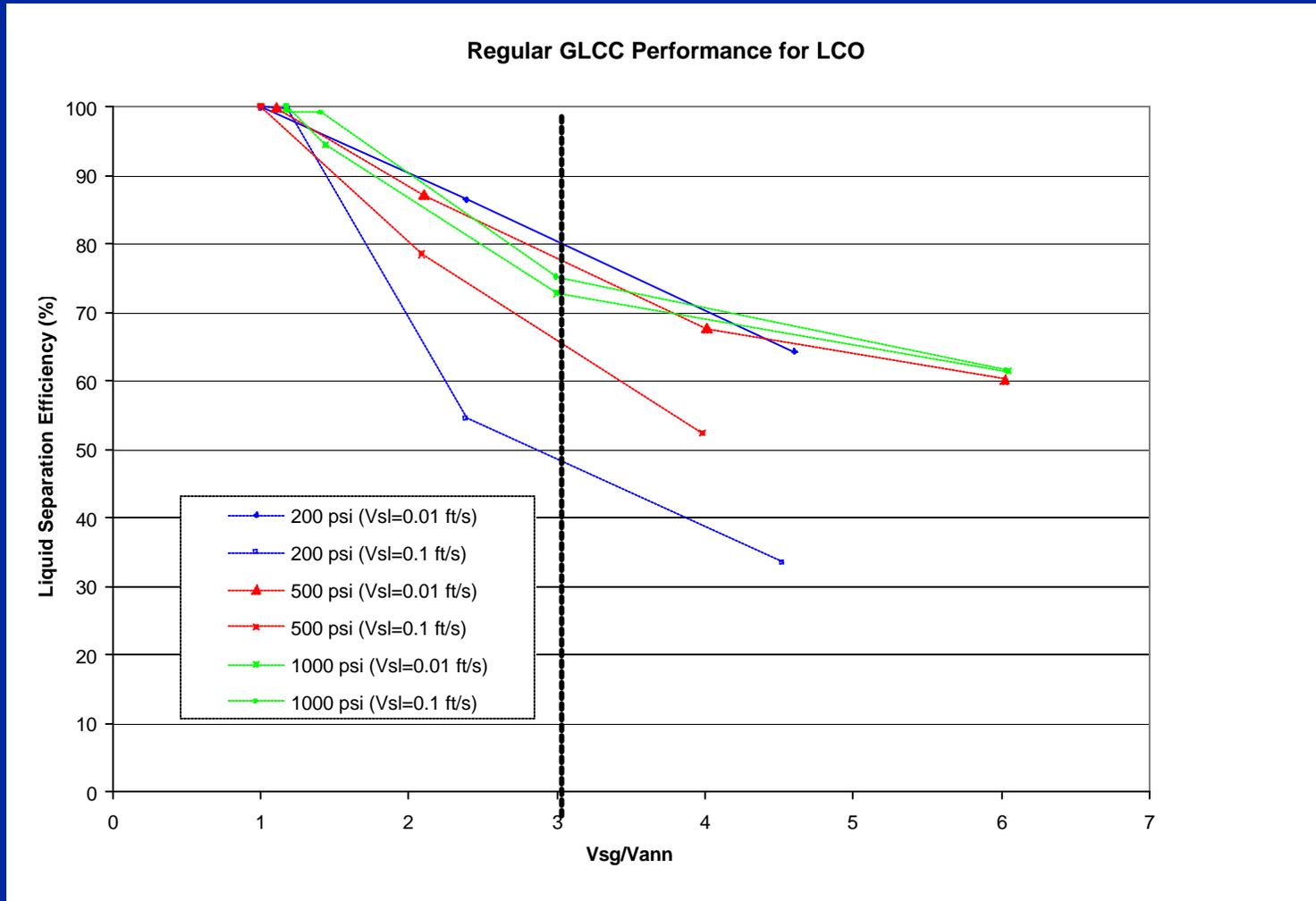
lower liquid superficial velocities. The efficiency curves for 200 psi, 500 psi and 1000 psi overlap each other at lower liquid velocities.

G) Gas Carry-under in GLCC© Separators

The objective of this study is twofold: to study experimentally the hydrodynamics of dispersed two-phase swirling flow in the lower part of the GLCC; and, to develop a mechanistic model for the prediction of this complex flow behavior, to enable the prediction of the gas carry-under in the GLCC.

The developed mechanistic model is composed of several sub-models as follows:

- *Gas entrainment in the inlet region*
- *Continuous-phase swirling flow field*
- *Dispersed-phase particle (bubbles) motion*.
- *Diffusion of dispersed-phase*

Integration of the above sub-models yields the amount of gas being carried-under, and the separation efficiency of the GLCC. Two solution schemes are proposed, namely, the Eulerian-Lagrangian Diffusion model (using finite volume method) and Lagrangian-Bubble Tracking model. Also simplified mechanistic models for these two approaches have been developed.

Large amount of local measurement of swirling flow have been processed and analyzed to develop correlations for the swirling flow field and the associated turbulent quantities. These correlations are used in the proposed models. Also, experimental data on gas-carry under were acquired for air-water flow.

The results include the performance of the developed correlations for the swirling flow field and its turbulent quantities. Also presented are the results for both solution schemes and the performance of the mechanistic model. The results of this study demonstrate the potential of the proposed approach for predicting the void fraction distribution in dispersed two-phase swirling flow and the associated gas carry-under in GLCC separators.

8. Conclusions

LLCC inlet design is modified from inclined inlet to horizontal inlet. Other appropriate design change such as the vortex finder is added to the LLCC, and a modified LLCC is obtained. This modified LLCC can be successfully used for free water knockout bulk separation of oil and water mixtures for both water continuous and oil continuous flow. The free water knockout process can be optimized between increasing underflow rates and acceptable watercut in the underflow stream. There always exists an optimal split ratio, where the water flow rate is maximum with 100% water-cut.

A linear model has been developed for the first time for LLCC separators equipped with underflow watercut control. A unique control strategy is developed and implemented, capable of obtaining clear water in the underflow line and maintaining maximum underflow. Comparison of simulation and experimental results shows that the control system simulator is capable of representing the real physical system. The results of experimental studies prove that the LLCC equipped with control system can be readily applied in the field, for inlet water concentration ranging between 40% and 98%.

The experimental data acquisition for the 3-phase GLLCC has been completed. Extensive data set was acquired for a fixed gas superficial velocity and fixed oil finder position. The watercut in the water output stream was plotted as a function of the split ratio. The results indicate that for low oil concentrations and high water superficial velocities the watercut in the water stream increases.

A preliminary model for the LLCC$^{©}$ has been developed. It includes the prediction of the existing flow patterns at the horizontal inlet, and the analysis for moderate input oil concentration and low input oil concentration.

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 novel design of GLCC capable of separating liquid from a wet gas stream has been developed. Experimental investigations are in progress to evaluate the GLCC performance

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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 are also being formulated based on the experimental studies. This investigation provides new capabilities for compact separators for wet gas and high GOR (exceeding 90%) applications.

The high-pressure (upto 1000 psi) GLCC test 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 (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%). This difference is much less pronounced at lower liquid superficial velocities.

Mechanistic model has been developed incorporating gas entrainment in the inlet region, continuous-phase swirling flow field, dispersed-phase particle (bubbles) motion and diffusion of dispersed-phase. Integration of the above sub-models yields the amount of gas being carried-under, and the separation efficiency of the GLCC.

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