Project Title:

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

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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 first half year (October 1, 2000 – March 31, 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 will be tested under high pressure and real crudes conditions. This is crucial for validating the GLCC© design for field application 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 first half year (October 1, 2000 – March 31, 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. Texas A&M work will be performed in the Multiphase Field Laboratory of Dr. Stuart Scott, a professor 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). This facility also has equipment to conduct tests at higher rates and pressures (15,000 bbl per day @ 500 psig), which are to be installed for use by this project. Benchmark two-phase tests will be conducted using air/water and air/gelled water. Three-phase tests will be performed subsequently during the final year of the project.

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 is 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 will be built using steel pipes so as to withstand high pressures, and will be equipped with several temperature and pressure transducers to enable evaluation of the hydrodynamic flow phenomena. The modular design of the GLCC© will allow easy modification of the inlet, outlet and piping configurations.

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..
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 gas carry-under in liquid streams.
7. 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 the 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 CFD activity initiated during the first phase will be continued through the upcoming project period (October 2000 to September 2001).

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 technical and scientific 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.

Re-Design of LLCC©: LLCC© was designed and experimental investigations were conducted by E. Afanador for her Master's Thesis. The design was similar to that of GLCC©. It is a vertically installed pipe, mounted with a downward inclined tangential inlet, through which the oil-water mixture is introduced. Due to centrifugal and gravity forces, the mixture separates into two streams. LLCC© has two exits, the upper outlet, which is oil rich, and the lower outlet, which is water rich. Experimental results revealed that LLCC© can be termed as an effective alternative for oil-water separation in the form of a free water knockout device.

a) Inlet Modification:

Detailed study of various literatures revealed that at high mixture velocities, LLCC© with inclined inlet tends to mix rather than to separate. Based upon various flow prediction maps, it was decided to replace the inclined inlet with horizontal inlet. Experiments were conducted to compare the effect of horizontal inlet versus the inclined inlet. The results revealed that performance of LLCC© was improved considerably and LLCC© was able to separate high mixture velocities too. These results ensured that horizontal inlet is the appropriate inlet for LLCC© . Further studies led to modify the existing design of LLCC© in

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

order to improve its performance. Two additional parts were added to the existing design. Figure-1 refers to the LLCC© with all the modified parts .

b) Vortex Finder:

Description: It is an annular 1” pipe mounted in the upper portion of the 2” existing LLCC© pipe.

Significance: The two liquids of the incoming mixture are separated due to centrifugal and gravity forces. The heavier water is forced radially towards the wall of the cylinder and is collected at the bottom, while the lighter oil moves to the center of the cyclone and is taken out through the vortex finder.

c) Water Extractor:

Description: It is a ½” pipe mounted to the side of LLCC© ,just below the vortex finder.

Significance: Water gets blocked in the top portion of the 2” pipe due to the intrusion of the vortex finder. Water extractor removes the accumulated water in that portion.

Experimental Investigations:

Test Matrix: Experiments were conducted for the entire water-continuous range, i.e. from 95% Water-Cut at the inlet to 50% Water-Cut. 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.

Results: Based on the results, following conclusions can be drawn:

- Water-Cut (underflow) is a function of inlet conditions (inlet water concentration and mixture velocities) and the Split Ratio.
- There is trade off between the flow rate and the concentration of oil in the underflow of the LLCC©. Thus there is an Optimal Split Ratio that gives 100% Water-Cut in the underflow and maximum underflow can also be obtained.

B. Oil/Water LLCC© Control

Three different control strategies are identified and discussed as given below. Logic Controller with Downstream is likely to be implemented in the near future.

- **Upstream Metering**: Inlet metering should be provided in order to determine the Optimal Split Ratio. Using the Split Ratio, control valve position can be manipulated to obtain pure water in the underflow.
- **Logic Controller with Downstream Metering:** A logic controller is provided in the underflow stream. Based upon the logic fed to the controller, it is possible to obtain pure water with an Optimal Split Ratio by manipulating the control valve. The advantage of this strategy is that it doesn't need inlet metering.

- **PID Controller with Downstream Metering:** A PID controller is provided in the underflow stream. Further studies need to be done to implement this strategy.

As a future work the experimental investigations will be extended to oil-continuous range. This will be followed by experiments to evaluate the complete control system.

C. Three-Phase GLCC© Separators

The objective of this project is to investigate the feasibility of GLLCC© as a bulk separator. Is it possible to utilize the GLLCC© for bulk separation of the oil-water liquid phase for free water knock out? If proved successful, this will significantly simplify the separation facilities downstream.

Experimental Facility. The new experimental flow loop has been constructed in the College of Engineering and Natural Sciences Research Building located in the North Campus of TU, near our existing outdoor GLCC© facility. 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. Following is a brief description of both sections.

Metering and Storage Section: 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.

Modular Test Section: The metered 3-phase mixture coming from the metering section can flow into 4 test stations. This flexibility enables the testing of single separation equipment, such as a Gas-Liquid-Liquid Cylindrical Cyclone (GLLCC$^{©}$), Liquid-Liquid Cylindrical Cyclone (LLCC$^{©}$), Liquid Hydrocyclones (LHC), 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.

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 pressure and temperature 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. The sampling rate was set for 2 Hz for a 2 minutes sampling period. The final measured quantity results from an arithmetic averaging of 240 readings, when steady-state condition is established.

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.

GLCC$^{©}$ Configurations: Two three-phase flow separation configurations are studied. The first one is a single-stage GLLCC$^{©}$ (Fig. 2) where the gas is removed from the top, the oil from the middle/center of the GLLCC$^{©}$, and the water tangentially from the bottom of the GLLCC$^{©}$. The second configuration is a two-stage system, whereby the gas is separated from the liquid phase in the first GLCC$^{©}$ stage, and the oil is separated from water in the second LLCC$^{©}$ stage.

Project Status. The analysis of Oil/water flow patterns indicated the convenience of replacing the inclined inlet for a horizontal one. The change was done and the Oil/water runs utilizing the Liquid–Liquid Cylindrical Cyclone (LLCC) were repeated. The performance of this device was dramatically improved. On the other hand, the design, construction and installation of the single-stage three-phase GLLCC$^{©}$ were completed. It consists of a regular GLCC$^{©}$ body but with a concentric movable inner pipe to collect the oil from the oil core at the center of the system. Extensive data on the single-stage three-phase GLLCC$^{©}$ for a fixed gas superficial velocity and fixed oil finder position, varying the water superficial velocity from 0.1 to 0.5 m/s and varying the oil superficial velocity from 0.025 to 0.5 m/s, and the split ratio from 10 to 100% for each oil and water velocities combination, were acquired (Figs. 3 and 4). The separation efficiency is plotted as a function of the ratio between the oil flow rate in the overflow and the oil flow rate at the inlet (split ratio). The results indicated that for low oil concentrations and high water superficial velocities the watercut in the water stream increases.

Preliminary modeling of the GLLCC© flow pattern is conducted as shown in Fig. 5. Also, preliminary mechanistic models are developed for moderate oil content to predict the inlet droplet trajectory, radial droplet velocity, axial droplet velocity and drag coefficient (Figs. 6, 7). For the case of low oil content also, equations for the main velocities and droplet trajectories are developed, as shown in Figs. 8, 9 and 10.

D. Predictive Control of GLCC© Using Slug Detection

A strategy for GLCC© predictive control has been developed which incorporates the slug characteristics in terms of holdup, length and velocity, and calculation of the volumetric liquid flow rate. This predictive control system (schematic shown in Fig. 11) 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. 12. The results obtained from the simulations and experimental investigations demonstrate that the proposed strategy is a viable approach for GLCC© predictive control.

E. GLCC Separators for Wet Gas Applications

Objectives: As more and more GLCCs are deployed in the field, the need for high GOR and wet gas applications becomes critical for oil and gas industry to handle high gas rates above the critical velocity. The GLCC design is not optimized for these applications due to liquid carry-over in the form of droplets and annular liquid film. The objectives of this study are to design a novel GLCC capable of separating liquid from a wet gas stream; conduct experimental investigations to evaluate the GLCC performance improvement in terms of operational envelope for liquid carry-over; and, measure the liquid extraction from the gas stream.

Figure 13 shows the GLCC test section, which is a 3” GLCC with a 3” 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 the inlet. 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. The liquid film extractor just above the inlet consists of a 4” trap annular, a 1” spacing between the vortex tube and the vortex finder and a 1.5” liquid return pipe to the liquid leg. The upper end of the vortex tube is machined inside the pipe wall and forms a small pipe extension with a sharp edge. The lower end of the vortex finder is machined outside and forms a cone with a sharp edge.

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.

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 liquid film swirling flow. The liquid film extractor removes all the upward 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. 14) 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.

E. Design and Fabrication of High Pressure GLCC

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 for testing at CEESI with a tentative date set for summer 2001. The photograph of this facility is shown in Fig. 15. Future plans call for development of a test matrix that complements the work already done by Chevron at this facility.

GLCC Construction at Texas A&M - As shown in the Figure 16, the high pressure GLCC has been designed to be 6-inches in diameter with a 12-foot height. This size was selected after review by Tulsa University Researchers. Construction of the spool pieces that comprise the GLCC body have begun. Purchase orders have also been provided to construct the GLCC inlet, skid mounting, oil finder bottom flange and associated inlet/outlet piping. These pieces are expected to be completed in April and assembled in May, 2001.

F. Construction of DOE Separation Test PAD and Facilities

To support this project, a new area is being developed at the Texas A&M Multiphase Field Lab. A 20x20 ft concrete pad was poured in March to support the planned GLCC test skid and instrumentation. Future plans call for installation of electricity, data acquisition cables and shop air to this pad and installation of a tin roof. Also, crushed limestone will be placed around the pad to facilitate better access by heavy equipment. All these tasks are expected to be completed during April.

Instrumentation - Specialized sensors are needed to conduct high pressure testing. A meeting was held with the President of Phase Dynamics in March to discuss their water-cut meters. They have agree to replace their old model meters (received in the ARCO donation) with their latest technology. Two new 2-inch meters will be received by April 12th: one 0-100% water cut range and one 0-20% water cut range. Future plans call for upgrading existing 1 1/2-inch MicroMotion coriolis meters (donated to Texas A&M by ARCO) to newer models of sensors and/or transmitters.

Facilities Modification - Some modifications to the existing multiphase flowloop are necessary to achieve the high pressure and also the highest possible flow rates. Plans have been prepared to re-pipe a section of the loop from the metering pad to the Bornemann Multiphase Pump, installing 6-inch pipe to replace the 2-inch pipe. This reduces suction pressures for the Bornemann pump allows maximum pressure while still obtaining high flow rates. This section of pipe is expected to be delivered in April and installed in May. Halliburton has donated a large amount of multiphase equipment to Texas A&M and this was moved to the Multiphase Field Lab. Several large tanks and compressors will be installed and connected in April/May to support this project. In addition a 15 horsepower motor is to be install on an existing large centrifugal pump to provide higher pressure capability at the separator. This motor is expected to arrive in April and be installed in May.

8. Conclusions

Detailed experimental investigations of the Liquid-Liquid Cylindrical Cyclone (LLCC©) revealed that the performance of the modified LLCC© with horizontal inlet was improved considerably and it was able to separate high mixture velocities also. These results lead us to define a new term, Split Ratio (Total Overflow Rate / Total In-Flow Rate). There is an Optimal Split Ratio that gives pure water in the underflow maintaining maximum underflow, which formed the basis for Control system studies. Three different strategies, namely, Upstream Metering, Logic Controller with Downstream Metering and PID Controller with Downstream Metering are identified.

Extensive data on the single-stage three-phase GLLCC© for a fixed gas superficial velocity and fixed oil finder position, varying the water superficial velocity from 0.1 to 0.5 m/s and varying the oil superficial velocity from 0.025 to 0.5 m/s, and the split ratio from 10 to 100% for each oil and water velocities combination, are acquired. The results indicated that for low oil concentrations and high water superficial velocities the watercut in the water stream increases. Preliminary modeling of the GLLCC$^{©}$ flow pattern is conducted. Also, preliminary mechanistic models are being developed for moderate oil content and low oil content stream.

A model has been developed for predictive control system integrating feedback and feed forward control systems. The feedback controller has been designed in frequency domain approach and the feed forward controller has been designed using an analytical approach. Based upon the design, the predictive control model has been simulated in MATLAB-Simulink and the results obtained demonstrated that the proposed strategy is a viable approach for GLCC$^{©}$ predictive control.

A modified GLCC for wet gas applications has been developed and tested. The liquid film extractor and the liquid return pipe enable the GLCC to be operated at high gas velocities (beyond the critical velocity) without liquid carry-over in the gas stream. The 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 highest liquid velocity that can be tolerated is about 0.5 ft/s.

A high-pressure, real crude GLCC has been fabricated and installed for testing at CEESI facility. Currently it is undergoing testing at high gas volume fraction conditions. Construction of test pad and facilities including a GLCC is in progress at Texas A&M University for investigation at low GVF conditions.

Fig. 1 - Modified LLCC© in Operation

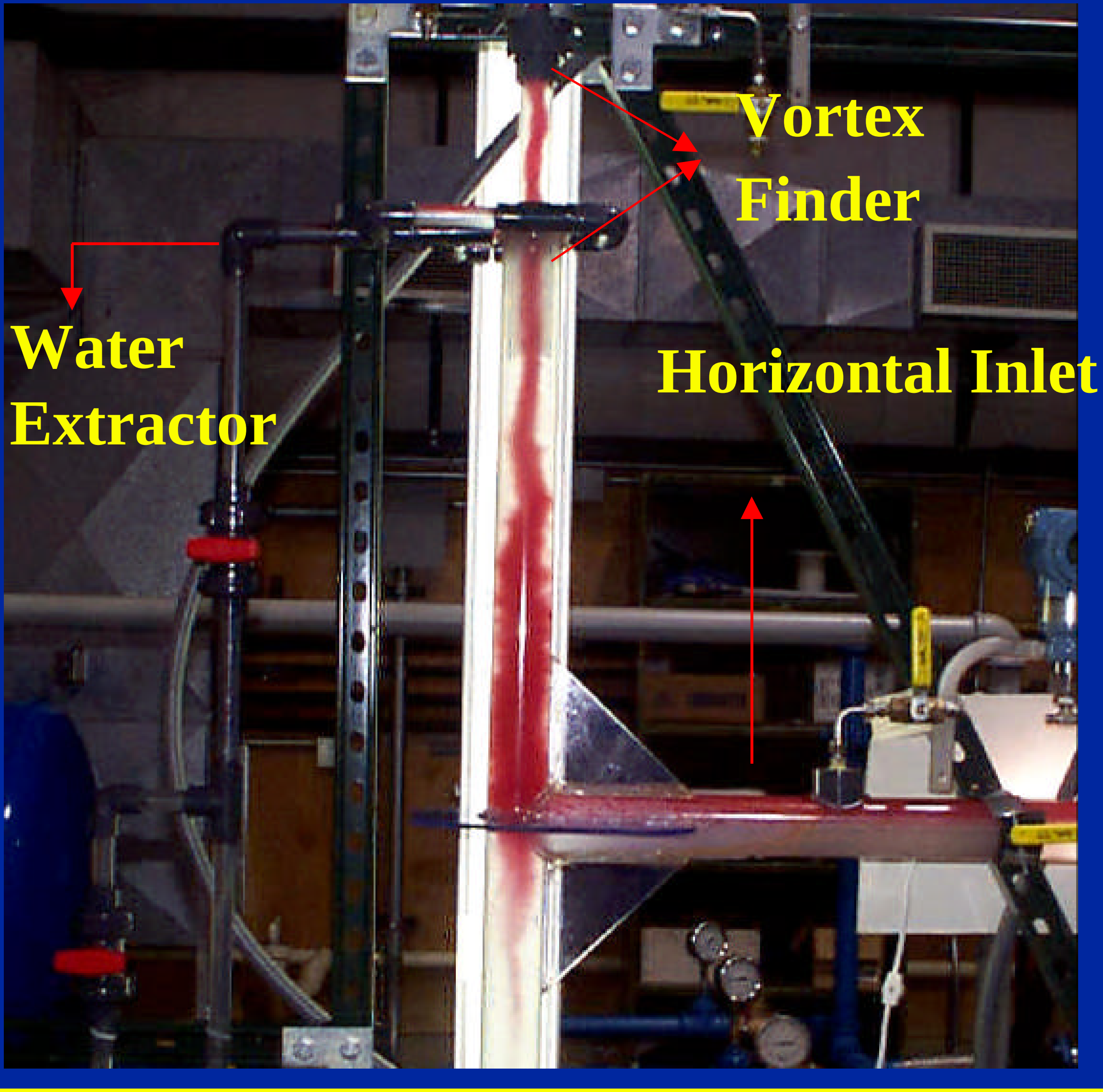


Fig. 2 - Single-Stage GLLCC© in Operation

Fig. 3 - Oil-Water Interface

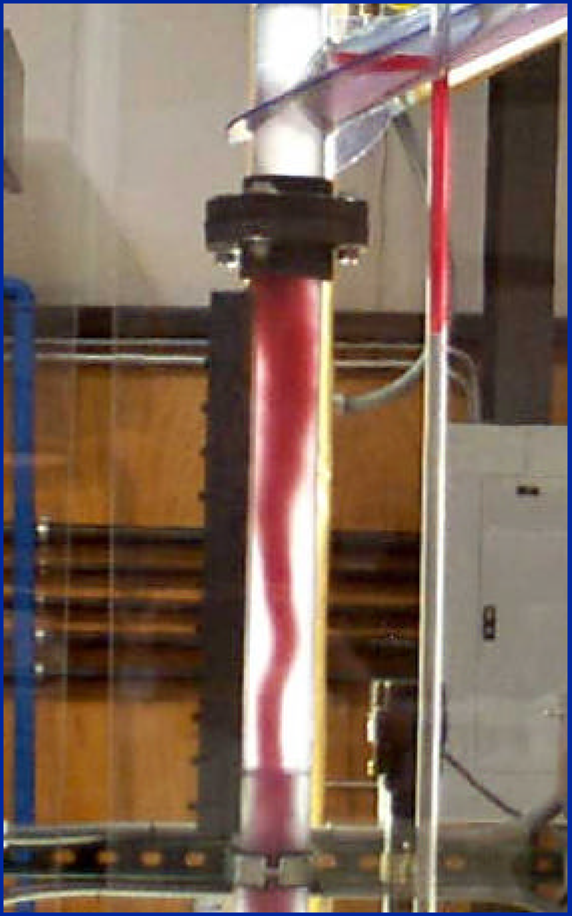


Fig. 4 - GLLCC© Experimental Results

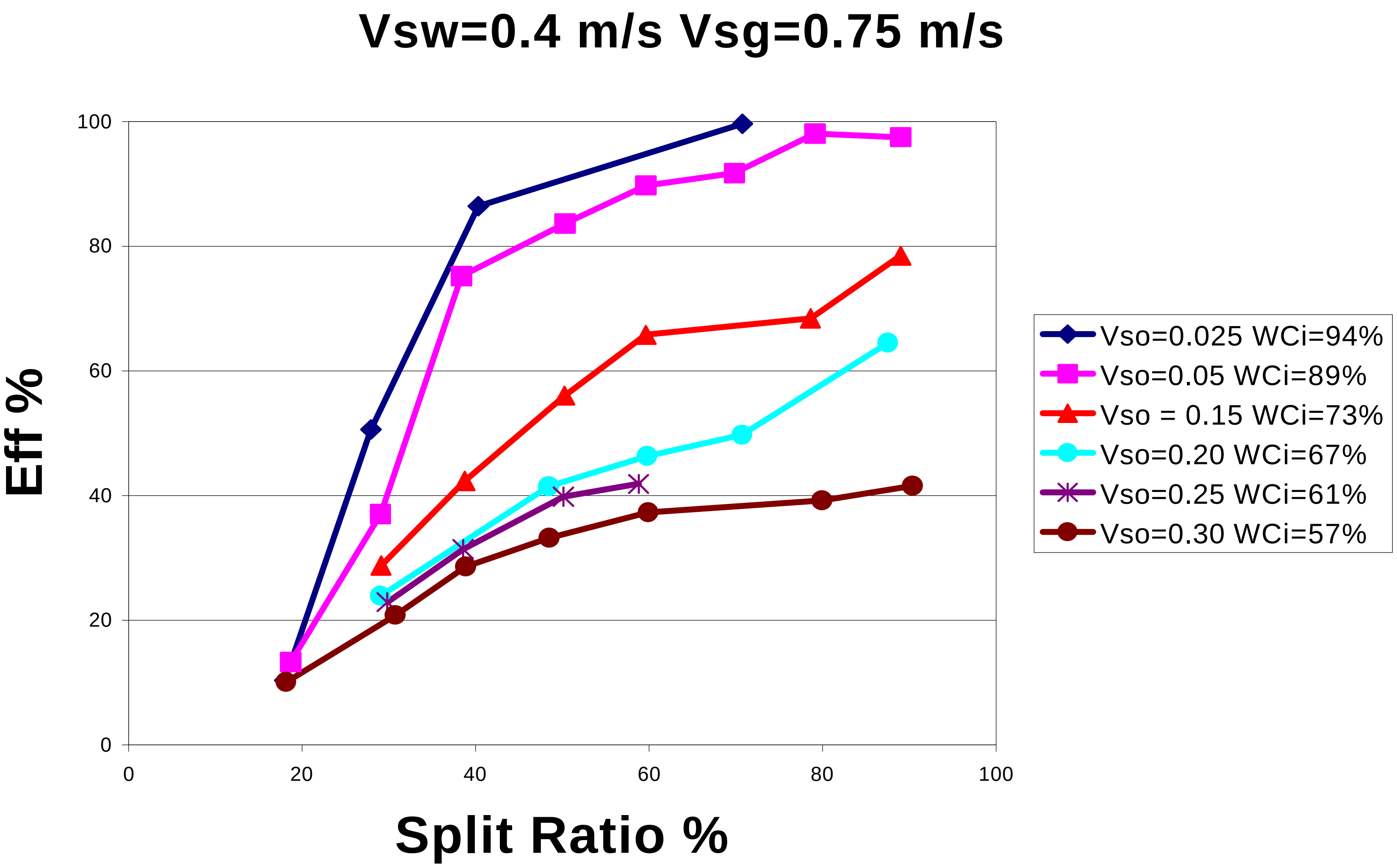


Fig. 4 - GLLCC© Experimental Results (Contd.)

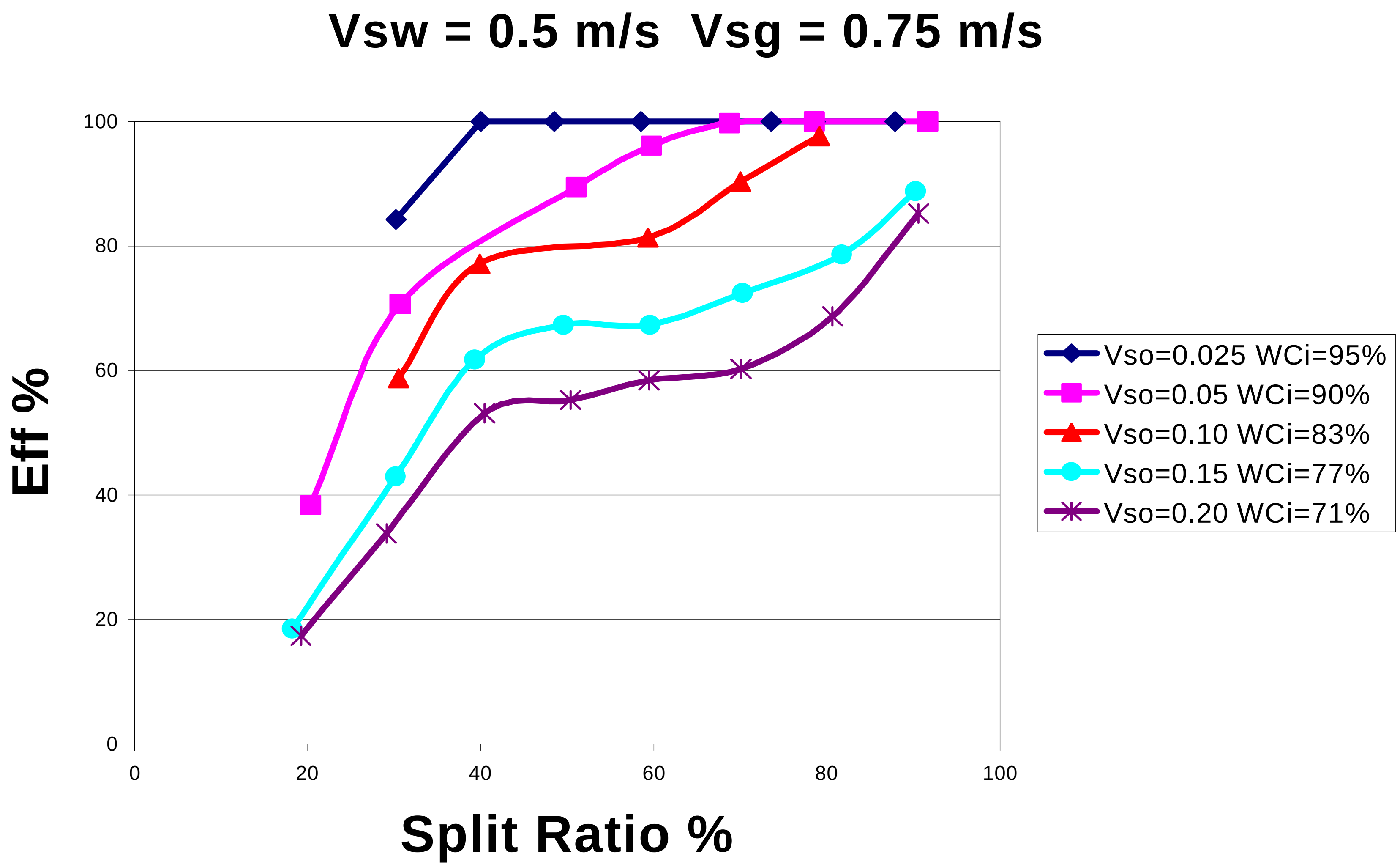


Fig. 5 - Preliminary GLLCC© Modeling

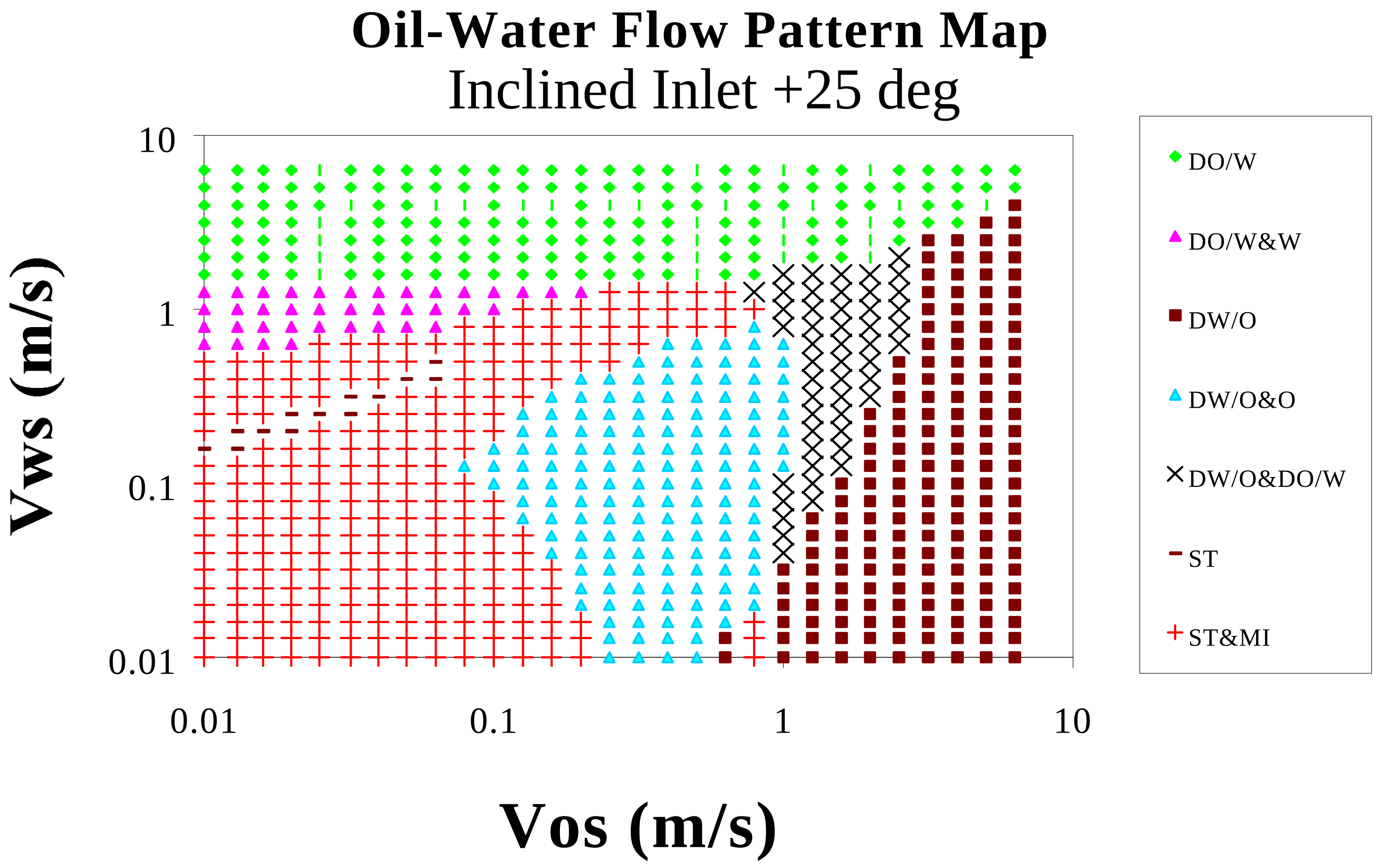
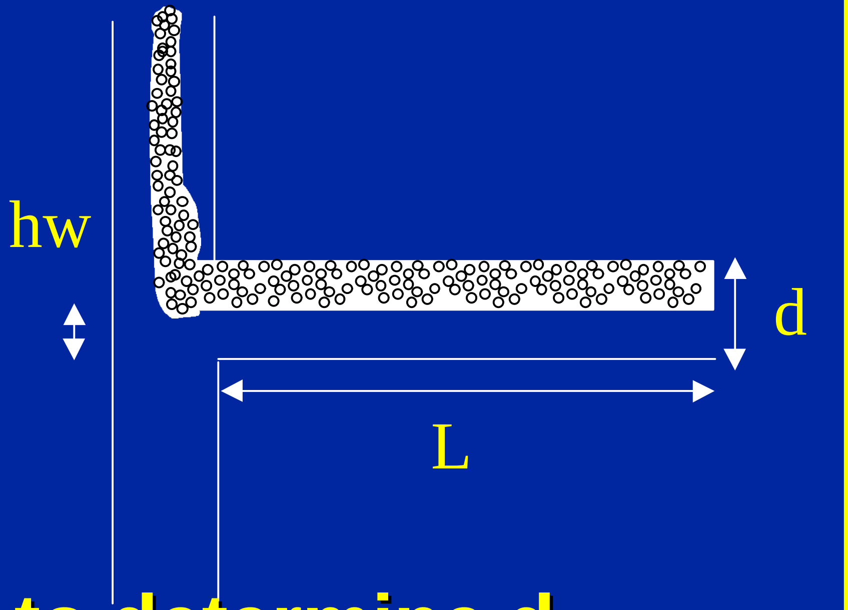


Fig. 6 - Moderate Oil Content



- **Allow Stratification**
  - **Low Velocity**
  - **Low Centrifugal Force**
- **Modeling**
  - **Flow Pattern Prediction to determine d**
  - **Two Fluid Model to Determine hw**
  - **Droplet Trajectory to Determine L**
  - **Maximum Split Ratio determined by Geometrical Relationship**

Fig. 7 - Modeling of Moderate Oil Content

Inlet Droplet Trajectory

$$z(h) = \int_0^{hw} \left(\frac{V_z(r)}{V_r(r)} \right) dh \quad ; \quad r = \left| R - h \right|$$

Radial Droplet Velocity

$$V_r = \sqrt{\frac{4(r_w - r_o) g d_d}{3 C_D r_w}}$$

Axial Droplet Velocity (no-slip)

Laminar

$$V_z = 2\overline{V_z}\left(1 - \left(\frac{r}{R}\right)^2\right)$$

Turbulent

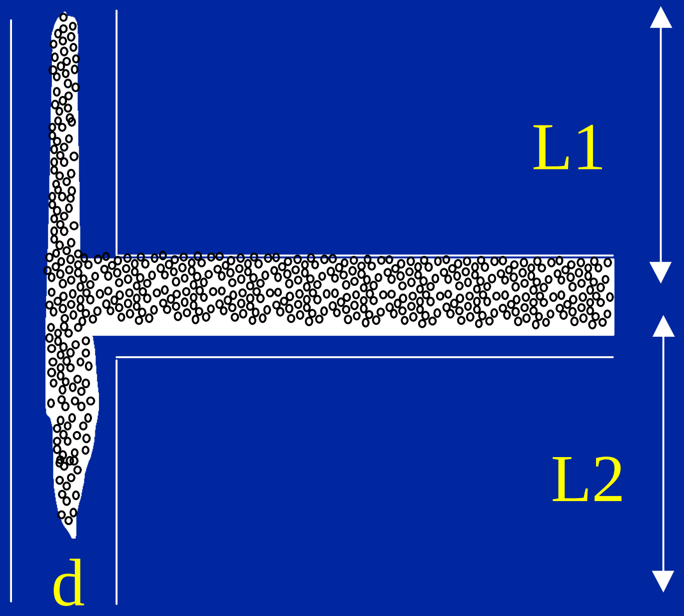
$$V_z = \frac{(n+1)(2n+1)}{2n^2}\overline{V_z}\left(1 - \frac{r}{R}\right)^{\frac{1}{n}} \quad ; \quad n = C_1 + C_2 Log(\mathrm{Re})$$

Drag Coefficient

$$C_D = \frac{16}{\mathrm{Re}_d}\left[1 + \left(\frac{8}{\mathrm{Re}_d} + \frac{1}{2}\left(1 + \frac{3.315}{\mathrm{Re}_d}\right)\right)^{-1}\right] \quad ; \quad \mathrm{Re}_d = \frac{r_w V_w d_d}{m_w}$$

Fig. 8 - Low Oil Content

- Poor Stratification (Mixing)
  - High Velocity
  - High Centrifugal Force



- Modeling
  - Optimum Tangential Velocity for d
  - Droplet Trajectory for L1 and L2 and Split Ratio

Fig. 9 - Main Velocities

Swirl Intensity

$$\Omega = 1.48\left(\frac{Vtis}{\overline{Vz}} I^{2}\right)^{0.93} \exp\left[-0.5\left(\frac{Vtis}{\overline{Vz}} I^{4}\right)^{0.35} \mathrm{Re}^{-0.16}\left(\frac{z}{d}-2\right)^{0.7}\right] \quad ; \quad I = 1-\exp\left(-\frac{n}{2}\right)$$

Tangential Velocity

$$V_t = \frac{1.1433\overline{V_z} R\Omega^{1.3188}}{r}\left\{1-\exp\left[-1.85\left(\frac{r}{R}\right)^{2}\right]\Big]\right\}$$

Axial Velocity

$$V_z = \overline{V_z}\left[\frac{2}{C}\left(\frac{r}{R}\right)^{3} - \frac{3}{C}\left(\frac{r}{R}\right)^{2} + \frac{0.7}{C} + 1\right]$$

$$C = \left[\left(\frac{r_{rev}}{R}\right)^{2}\left(3-2\left(\frac{r_{rev}}{R}\right)\right)\right]^{-0.7} \quad ; \quad r_{rev} = 0.174 R\Omega^{0.63}$$

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Fig. 10 - Droplet Trajectory

Droplet position

$$z(r) = \int_R^r \left(\frac{V_z - V_{zd}}{V_{rd}} \right) dr$$

Droplet Slip Velocity

$$V_d = \sqrt{B} \left[g^2 + \left(\frac{V_t}{r} \right)^2 \right]^{\frac{1}{4}} \quad ; \quad B = \frac{4(r_w - r_o) d_d}{3 r_w C_D}$$

Droplet Axial and Radial Slip Velocities

$$V_{zd} = \frac{Bg}{V_d} \quad ; \quad V_{rd} = \frac{BV_t^2}{rV_d}$$

$$C_D = \frac{16}{\mathrm{Re}_d} \left[1 + \left(\frac{8}{\mathrm{Re}_d} + \frac{1}{2} \left(1 + \frac{3.315}{\mathrm{Re}_d} \right) \right)^{-1} \right] \quad ; \quad \mathrm{Re}_d = \frac{r_w V_b d_d}{m_w}$$

Fig. 11 - Schematics of Integrated Level Control Loop

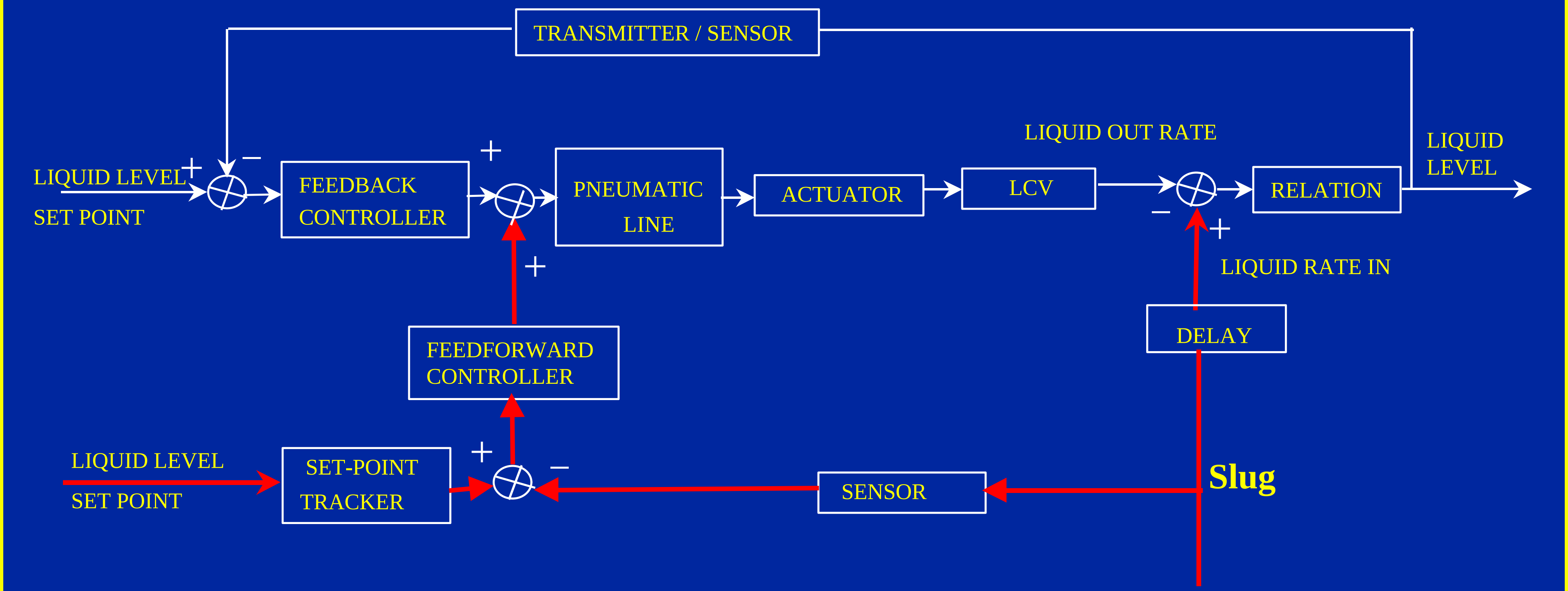


Fig. 12 - Level Control Simulator with FF and FB Controller (LCV)

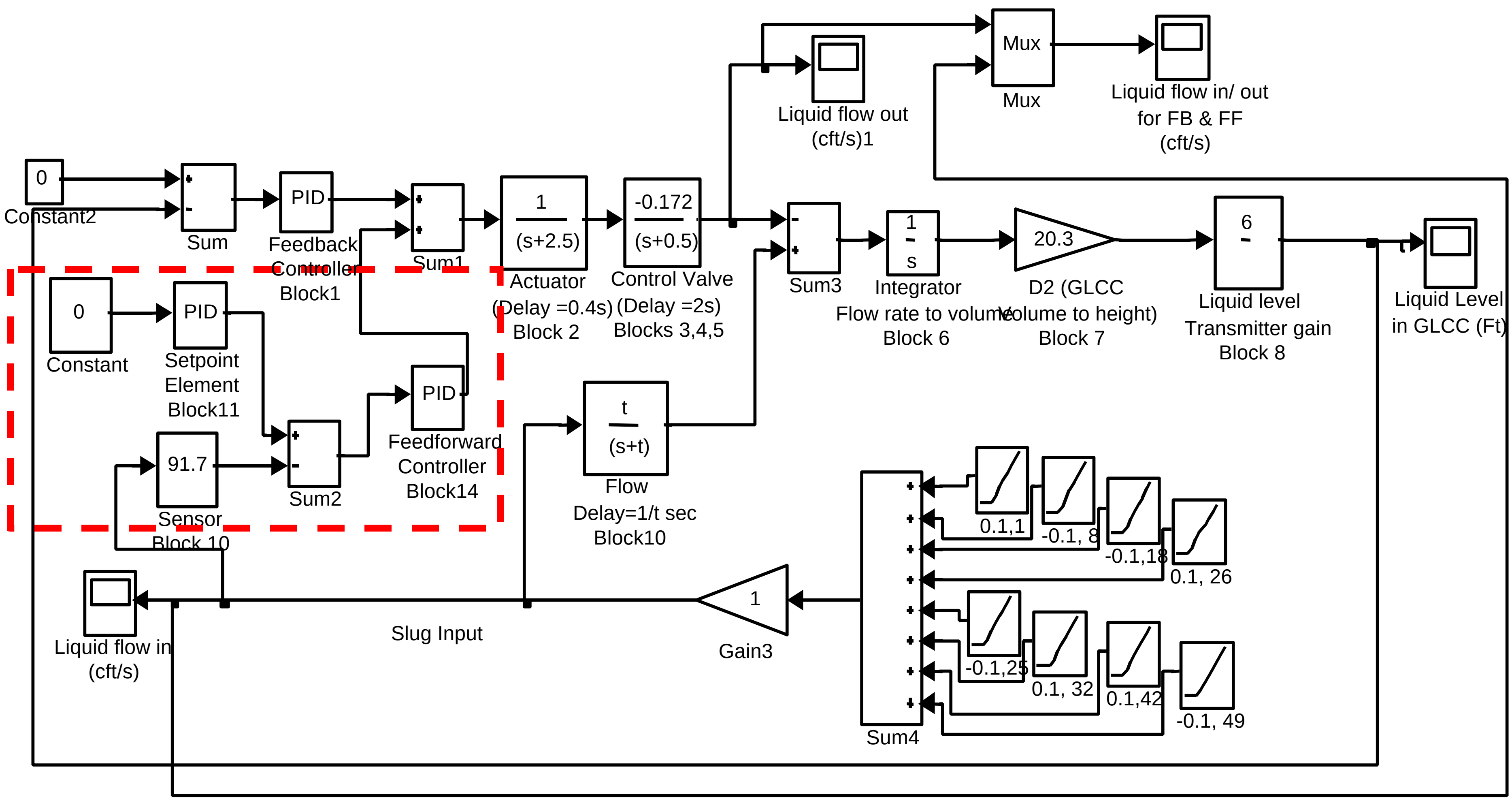
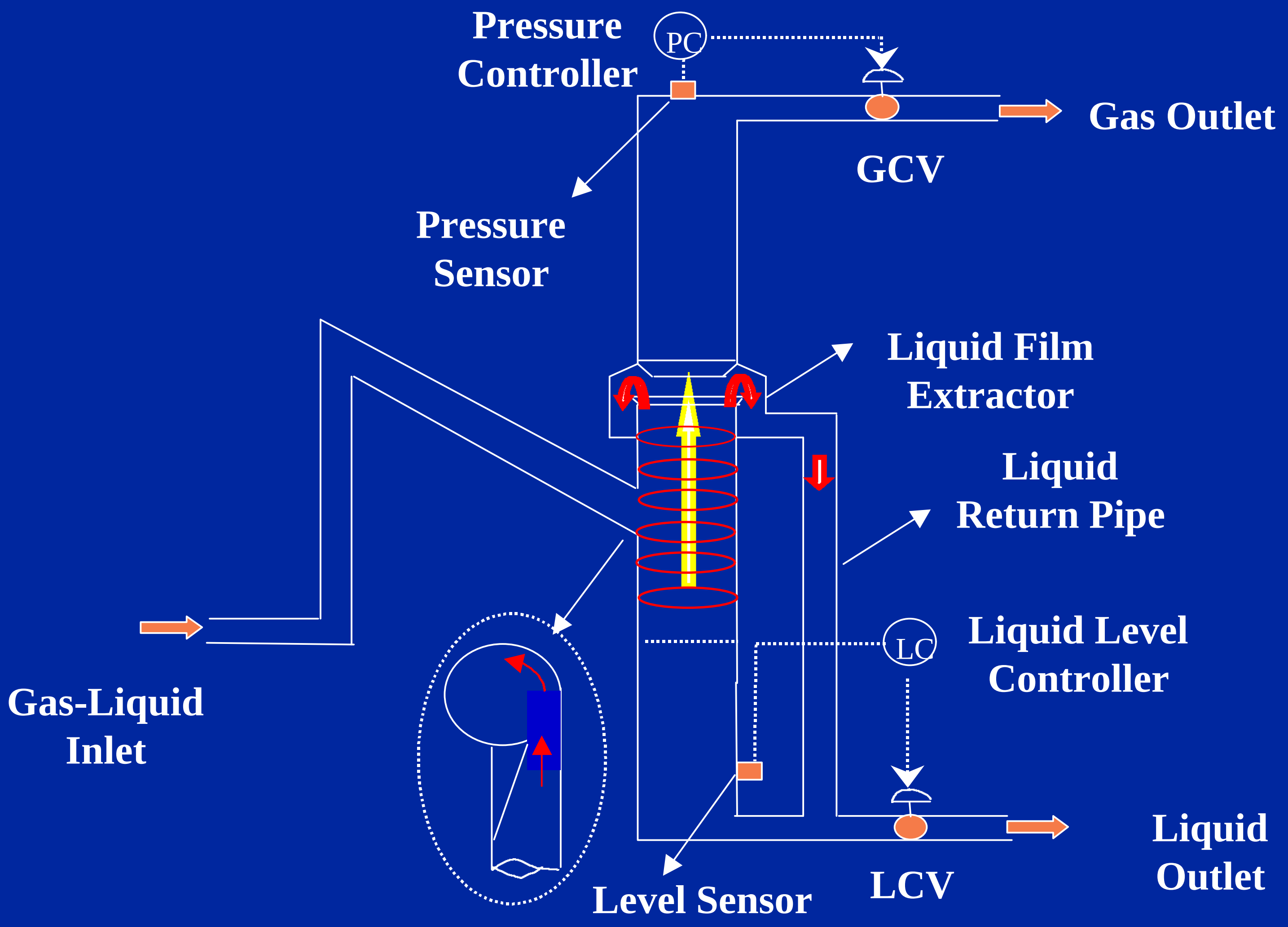


Fig. 13 - Schematic of GLCC© for High GOR Applications



Pressure Controller

Gas Outlet

GCV

Pressure Sensor

Liquid Film Extractor

Liquid Return Pipe

Liquid Level Controller

Gas-Liquid Inlet

Liquid Outlet

Level Sensor

LCV

Fig. 14 - Oper. Env. for Liquid Carry-Over of High GOR GLCC

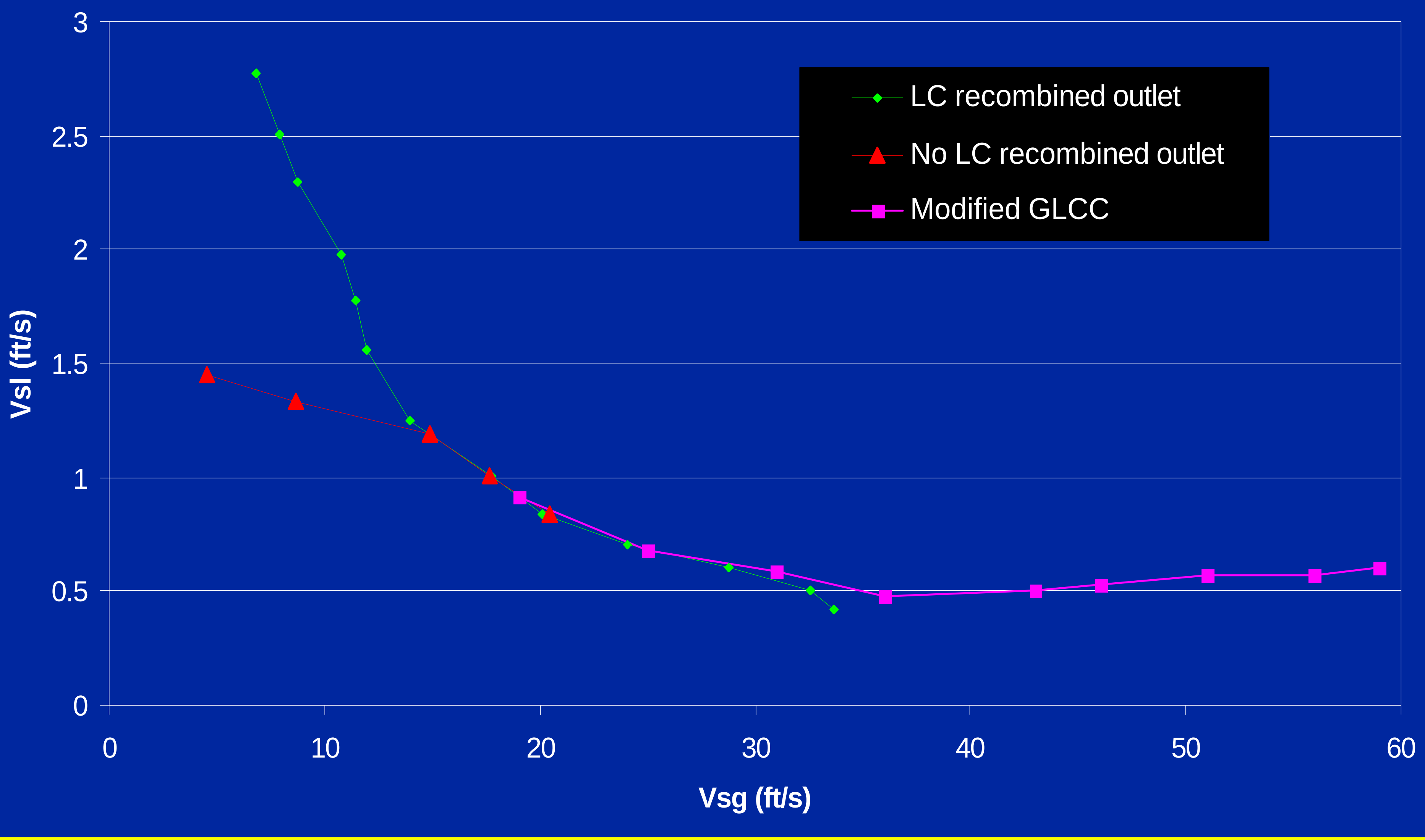
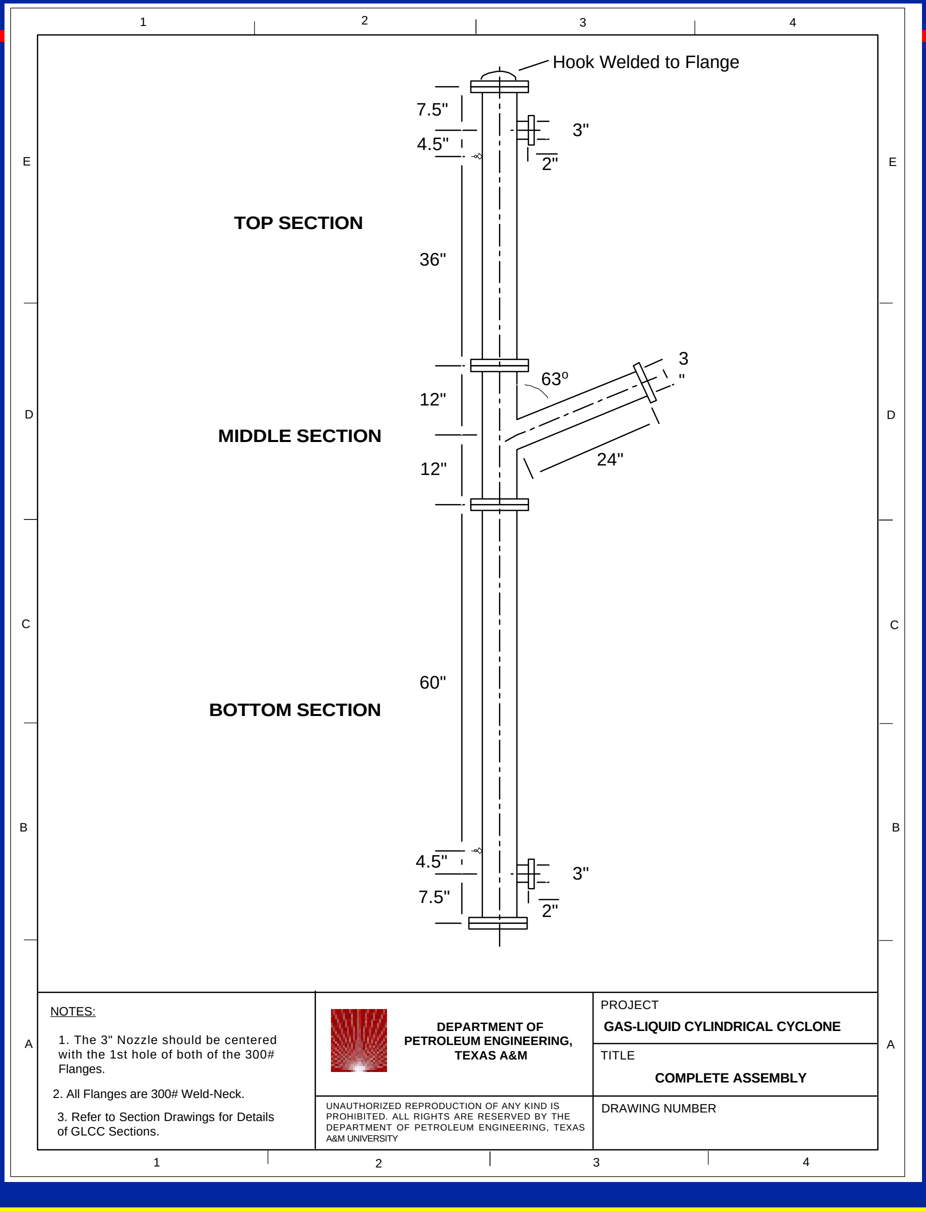


Fig. 15 - High Pressure GLCC© at CEESI

Fig. 16 -Schematic of High Pressure GLCC© to be installed at Texas A&M



NOTES:

1. The 3" Nozzle should be centered with the 1st hole of both of the 300# Flanges.

2. All Flanges are 300# Weld-Neck.

3. Refer to Section Drawings for Details of GLCC Sections.

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PROJECT

GAS-LIQUID CYLINDRICAL CYCLONE

TITLE

COMPLETE ASSEMBLY

DRAWING NUMBER

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