

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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## **2. 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 will be executed in two phases. Phase I (1997 - 2000) will focus on the investigations of the complex multiphase hydrodynamic flow behavior in a three-phase Gas-Liquid Cylindrical Cyclone (GLCC<sup>®</sup>) Separator. The activities of this phase will include the development of a mechanistic model, a computational fluid dynamics (CFD) simulator, and detailed experimentation on the three -phase GLCC<sup>®</sup>. The experimental and CFD simulation results will be suitably integrated with the mechanistic model. In Phase II (2000 - 2002), the developed GLCC<sup>®</sup> separator will be tested under high pressure and real crudes conditions. This is crucial for validating the GLCC<sup>®</sup> 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, 1999 – March 31, 2000) of the budget period (October 1, 1999 – September 30, 2000). The total tasks of the budget period are given initially, followed by the technical and scientific results achieved till date. The report concludes with a detailed description of the plans for the conduct of the project for the second half year (April 1, 2000 – September 30, 2000) of the current budget period.

## **3. Tasks of the Current Budget Period (Oct. 1, 1999 – Sept. 31, 2000)**

Objective: Liquid Carry-over and Model Refinement:

- a. Measurement of the operational envelope of the GLCC<sup>®</sup> 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 CFX 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.

## **4. Technical and Scientific Results Achieved in the Reporting Period**

**(October 1, 1999 – March 31, 2000)**

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

### **1. Control System Design and Experimental Results**

Several GLCC<sup>®</sup> control strategies have been developed based on the liquid level control by controlling the liquid leg valve, pressure control by controlling the gas leg valve, integrated level and pressure control, and integrated liquid level control by controlling both the liquid and gas leg valves. Schematic of two strategies is given in Figures 1 and 2. Mathematical models have been developed for these strategies and computer-based dedicated simulators have been built. Simulation studies indicated that the integrated control strategies are more suitable for slug flow due to faster response. The set point pressure control is crucial for integrated liquid level and pressure control. The experimental investigations are being conducted in our outdoor experimental facility using a dedicated GLCC<sup>®</sup> capable of withstanding higher pressures. Preliminary investigations indicate that (see Fig. 3) there is considerable improvement (more than three-fold) in the operational envelope of a 2-phase GLCC<sup>®</sup> equipped with a control system. However, the mechanisms responsible for liquid carry-over in a GLCC<sup>®</sup> with control system are different from those responsible in the case of a GLCC<sup>®</sup> without control systems. For example, churn flow is responsible for liquid carry-over in a GLCC<sup>®</sup> with control systems even for relatively large liquid flow rates, whereas in the case of a GLCC<sup>®</sup> without control system, it is primarily caused by annular flow conditions. Current focus on the experimental investigations is on detailed measurement of gas carry-under beyond the operational envelope. Towards this objective, characterization of gas carry-under and quantification of amount of entrained gas in the liquid leg are in progress. Detailed experimental investigations are in progress to evaluate the sensitivity of the control parameters on the GLCC<sup>®</sup> performance and optimization of control strategies.

### **2. Predictive Control of GLCC<sup>®</sup> Using Slug Detection**

A strategy for GLCC<sup>®</sup> 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 is designed to operate only when huge slugs are encountered. Based upon the design, a predictive control model is being developed for control system simulation integrating feedback and feed forward control systems. Experimental investigations are in progress to verify and implement the strategy.

### **3. Three-Phase GLCC<sup>®</sup> Separators**

Construction of the experimental facility for three-phase flow loop is completed and is shown in Figure 4. Air is supplied from a compressor and is stored in a high-pressure gas tank. The air flows through a metering section consisting of Micro-Motion<sup>®</sup> mass flow meter and control valve. The liquid phases (water and oil) are pumped from the respective storage tanks and are metered with two sets of Micro-Motion<sup>®</sup> mass flow meters and control valves, before being mixed. Several mixing sections 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 Micro-Motion<sup>®</sup> net oil computers (NOC) are being used to

quantify the watercut, Gas -Oil ratio (GOR), and mixture density. The test section consists of 2 dual stage GLCC<sup>®</sup>s. Initially the test section will be equipped with one dual stage GLCC<sup>®</sup> and later it will be upgraded to 2 dual stage GLCC<sup>®</sup>s. The three -phases from the GLCC<sup>®</sup> outlets will also metered using micro -motion mass flow meters. The test section construction is modular so that in place of GLCC<sup>®</sup> any other separators such as hydro -cyclones could be used in series to form compact separation systems. 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. Installation of the data acquisition system and electrical schematics, and calibration of the flow meters, pressure transducers, temperature transducers and net oil computers have also been completed.

Design and fabrication of the three -phase GLCC<sup>®</sup> is completed and has been installed in the flow loop. A schematic of the single stage 3 -phase GLCC<sup>®</sup> is shown in Figure 5 . Preliminary experimental investigations are in progress to evaluate the performance of the first generation three-phase GLCC<sup>®</sup> laboratory prototype. The results of preliminary feasibility testing of 3 -phase GLCC<sup>®</sup> separator are shown in Figures 6 and 7. These tests demonstrate that it is feasible to separate an oil -water-gas flow in a single stage 3 -phase GLCC<sup>®</sup>. A schematic of the oil -water interface and the gas -liquid interface is shown in Figure 8. Detailed experimental testing of the 3 -phase GLCC<sup>®</sup> will be conducted in the next half year of this project period to evaluate the operating performance. The data will help in the development of a mechanistic model for the GLCC<sup>®</sup>. The model will be computer coded which could be used for design of 3 -phase GLCC<sup>®</sup> units.

#### 4. Oil/Water Separation in LLCC<sup>®</sup> Separators

Installation of the support structure for the experimental facility, a 3 -inch oil-water test Liquid-Liquid Cylindrical Cyclone (LLCC<sup>®</sup>) separator and downstream metering section has been completed. The LLCC<sup>®</sup> installed in the flow loop is shown in Figure 9. The preliminary phase of this project is completed. Several literature have been identified to provide more information into the nature of the oil -water interface for cyclonic separators of low G -forces such as the GLCC<sup>®</sup>s and formulation of appropriate separation strategies for the GLCC<sup>®</sup>. Inlet flow patterns in the LLCC<sup>®</sup> separator are given in Figure 10. The feasibility of utilization of the Liquid -Liquid Cylindrical Cyclone (LLCC<sup>®</sup>) compact separator for free water knockout bulk separation of oil -water mixtures has been established by experimental testing of the lab LLCC<sup>®</sup> prototype, with measured efficiencies greater than 90% for some flow conditions. The typical flow pattern in an LLCC<sup>®</sup> is a combination of free vortex and forced vortex. The schematic of the axial and tangential velocity profile is given in Figure 11. A mechanistic model for the LLCC<sup>®</sup> has been developed to predict the tangential and axial velocity profiles. The developed correlations are given in Figures 12 and 13. The mechanistic model will be used to design LLCC<sup>®</sup> field applications and comparison with experimental data.

#### 5. Mechanistic Model and Experimental Investigation of Hydrocyclones

Two dedicated graduate students are investigating strategies to identify techniques for integration of GLCC<sup>®</sup>s with hydrocyclones for building three -phase compact separation systems. As a part of the detailed study of compact separation systems, investigations are in progress to develop mechanistic model for liquid hydrocyclones (LHC). During the second half

of the current project period, a velocity field correlation will be completed for the LHC. The velocity field will be incorporated into a mechanistic model for prediction of separation efficiencies in the LHC. Modular Production Equipment (MPE), a TUSTP member company has provided us with two 2 -inch LHCs, one of them fabricated from transparent plastic and the other from steel. The modular construction of the TUSTP 3 -phase flow loop will be capitalized to enable easy installation of both LHCs. Subsequently, data acquisition on separation efficiency of oil/water flow in the LHC will be conducted. The data will be used to test and refine the mechanistic model for the LHC.

## **5. Descriptions of Project Work Planned for the next Reporting Period**

**(April 1, 2000 - September 30, 2000)**

The next reporting project research activity will be similar to the second year project activity, only difference being that the emphasis will be on liquid carry -over. The mechanistic modeling of gas carry-under will be continued in the third year also and will be completed so that it can be integrated with the constitutive model for liquid carry -over. The third project year activities are divided into three main parts, which will be carried out in parallel. The first part is continuation of the experimental program that includes a study of the oil/water two -phase behavior and control system development for the three -phase GLCC<sup>®</sup>. The second part consists of the development of a simplified mechanistic model incorporating the control strategies 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<sup>®</sup>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 will provide much greater depth into the understanding of the physical phenomena and the mathematical analysis of three -phase GLCC<sup>®</sup> design and performance. Further investigations will be carried out, as part of this study, to enhance the potential of a commercial CFD code called CFX to three -phase applications. Following is a more detailed description of the three parts of the upcoming year activities.

### **A. Experimental Program:**

The experimental program will be conducted in two facilities, indoor and outdoor. A dedicated GLCC<sup>®</sup> is built outdoors, which is capable of withstanding higher pressures, for conducting detailed controls experiments. Control strategy developed in the outdoor facility, will be an essential part of the indoor, three -phase GLCC<sup>®</sup>. This experimental investigation will provide necessary and vital information about the control system design for the three -phase flow loop. The indoor experimental facility for three -phase flow, which has been constructed as a part of the second year activity, will be used for the experimentation.

Two types of GLCC<sup>®</sup> configurations will be considered namely single stage GLCC<sup>®</sup> and dual stage GLCC<sup>®</sup>, as described previously. The above flow loop can be used for both configurations. The GLCC<sup>®</sup> for the indoor facility is being built using transparent PVC pipes so as to enable visual observations of the hydrodynamic flow phenomena, which is essential for the

modeling. The modular design of the GLCC<sup>®</sup> will allow easy modification of the inlet, outlet and piping configurations. Finally, the effect of fluid properties can be investigated through use of viscosity and surface tension modifiers to water.

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<sup>®</sup>;
2. Equilibrium liquid level;
3. Interface shape and location;
4. Gas core filament shape and dynamics;
5. Churn region and droplet region lengths (in the upper part of the GLCC<sup>®</sup>);
6. Global separation efficiency namely oil fraction in the water outlet, water fraction in the oil outlet;
7. Total gas carry-under in liquid streams.
8. Observation of oil/water interface,
9. Observation of bubble size distribution;
10. Response of three-phase GLCC<sup>®</sup> to liquid level control.

## **B. Mechanistic Model:**

The mechanistic model development initiated in the second year of project activity will be continued during the third year 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<sup>®</sup> 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<sup>®</sup> such as, GLCC<sup>®</sup> configurations, inlet pipe I.D, inclination angle and roughness, outlet piping I.D, length and roughness;
- Performance characteristics of liquid level control.

The mechanistic model will enable determination of the performance characteristics of the GLCC<sup>®</sup>, 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<sup>®</sup>;
- liquid level in the separator;
- sensitivity to flow rate fluctuations (with and without active control).

The simplified integrated mechanistic model will enable insight into the hydrodynamic flow behavior in the three-phase GLCC<sup>®</sup>. It will also allow the user to optimize the GLCC<sup>®</sup> design accounting for tradeoffs in the I.D, height and inlet slot size of the GLCC<sup>®</sup>. 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.

### **C. Computational Fluid Dynamics (CFD) Simulator:**

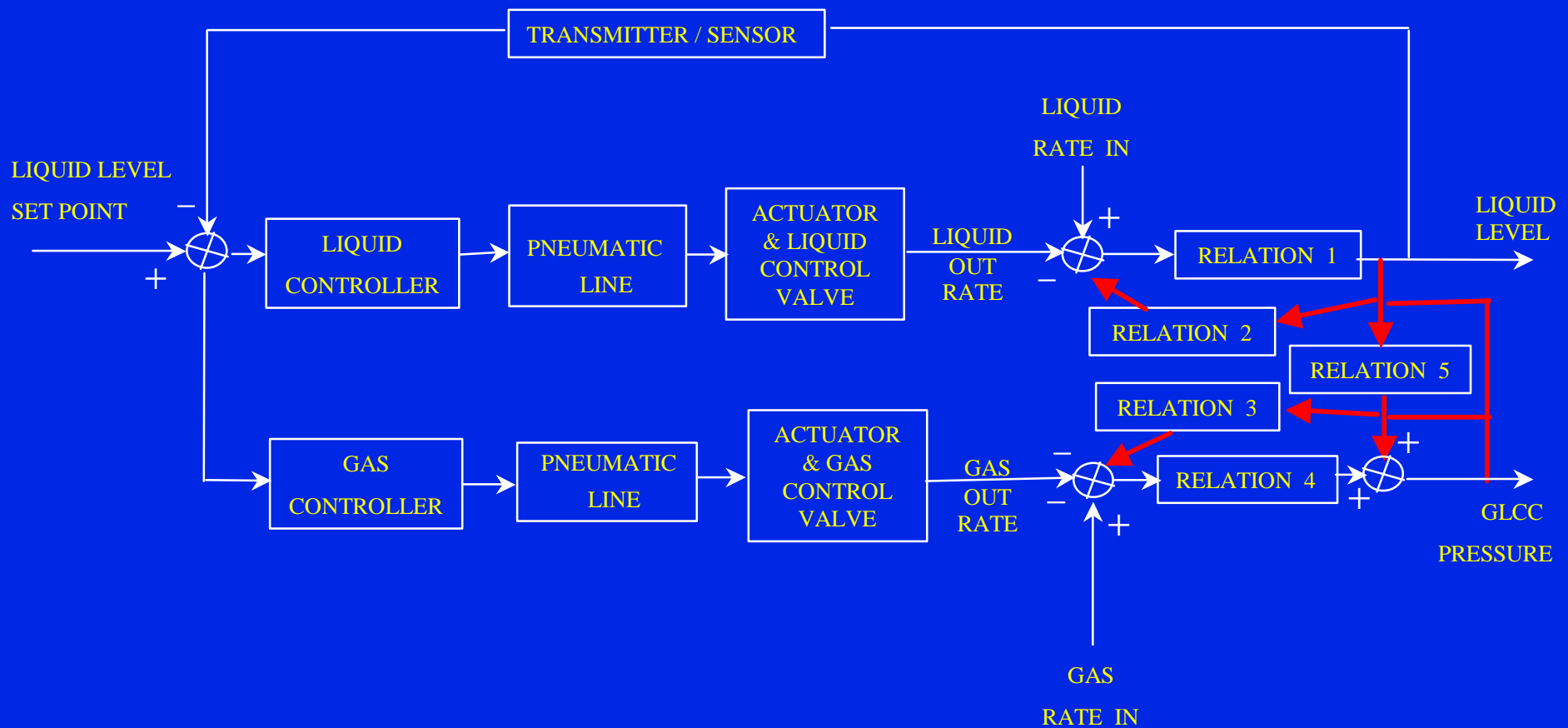
The purpose of the computational fluid dynamics (CFD) modeling is to provide both macroscopic and microscopic scale information on multidimensional multiphase flow hydrodynamic behavior. The CFD model will be general so that it can be utilized for the analysis of the GLCC<sup>®</sup> and other complicated 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. The CFD activity initiated during 1998 -1999 will be continued through the current project (October 1999 to September 2000).

A general numerical solution procedure for simulating three-dimensional three-phase flow in complex pipe geometries will be developed based on CFX. The numerical model will employ the three-fluid model. A turbulent flow model is also required for specifying the constitutive relations in the momentum equations. The eddy viscosity concept will be used to define an effective viscosity for the mixture. Both Prandtl mixing-length model and a more sophisticated  $k-\epsilon$  model will be used for modeling this complex flow geometry.

The experimental data acquired on the GLCC<sup>®</sup> 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<sup>®</sup>. Moreover, the model will provide detailed performance prediction for untried applications for which no data are available, such as high-pressure subsea separation.



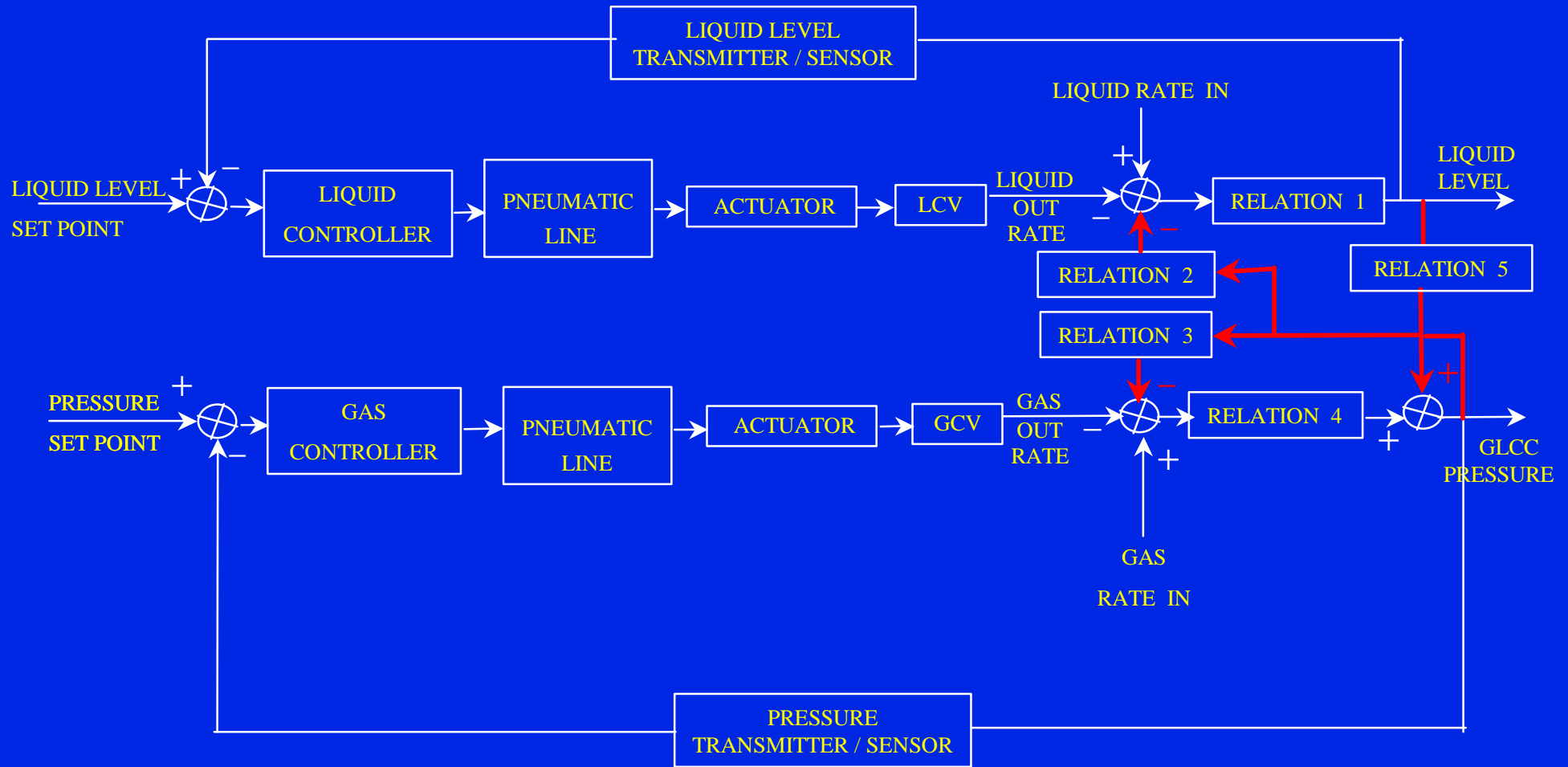
# Figure 1. 2-Phase GLCC<sup>®</sup> Integrated Level Control Strategy





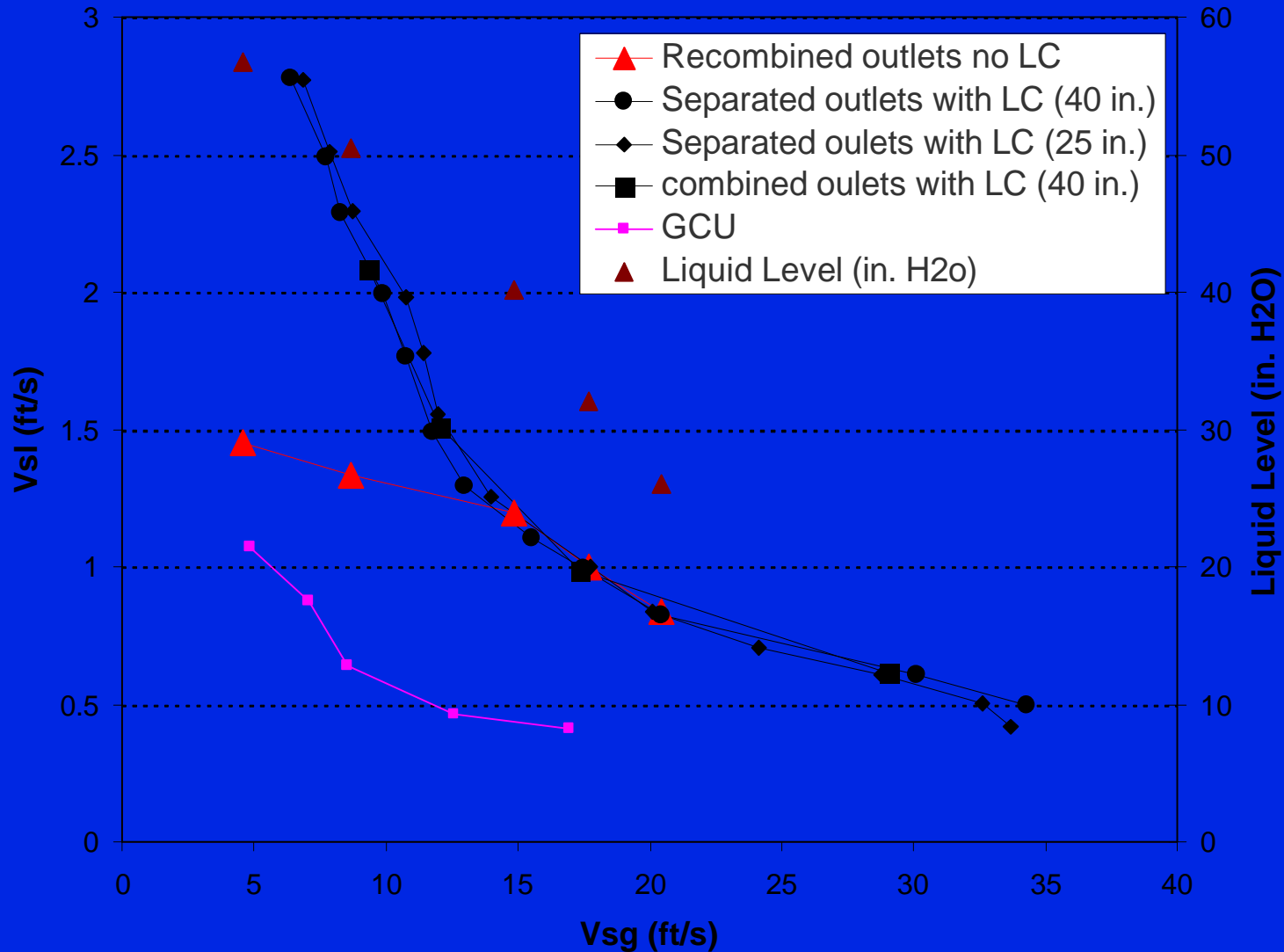


# Figure 2. 2-Phase GLCC<sup>®</sup> Integrated Level and Pressure Control Strategy





**Figure 3. Experimental Results: Operational Envelope for Liquid Carry-over (LCO) & Gas Carry-under (GCU)**





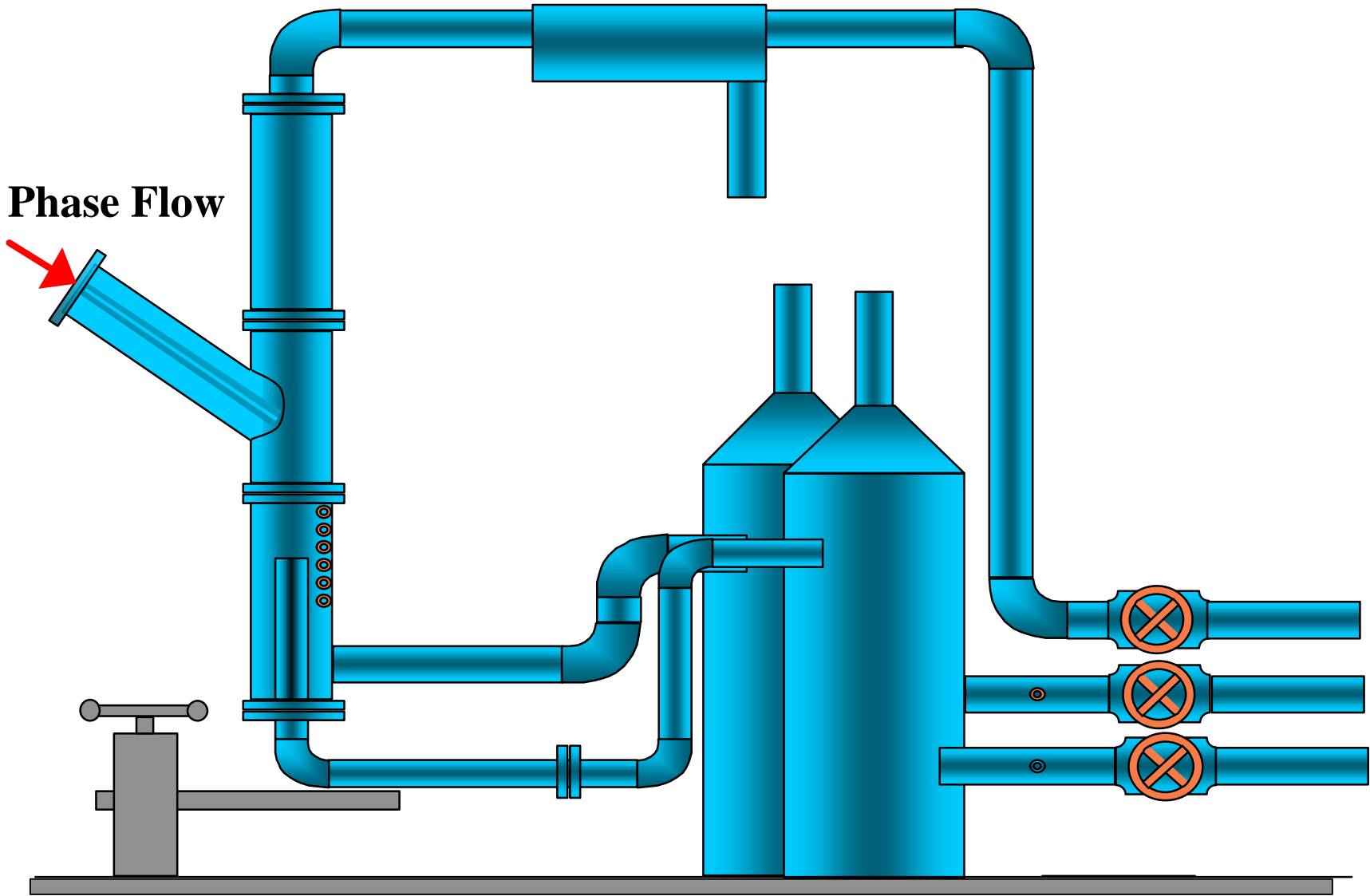
## *Figure 4. Experimental Facility for 3-Phase Flow Loop*





# Figure 5. Schematic of Single Stage 3-Phase GLCC<sup>®</sup> Design

3 - Phase Flow





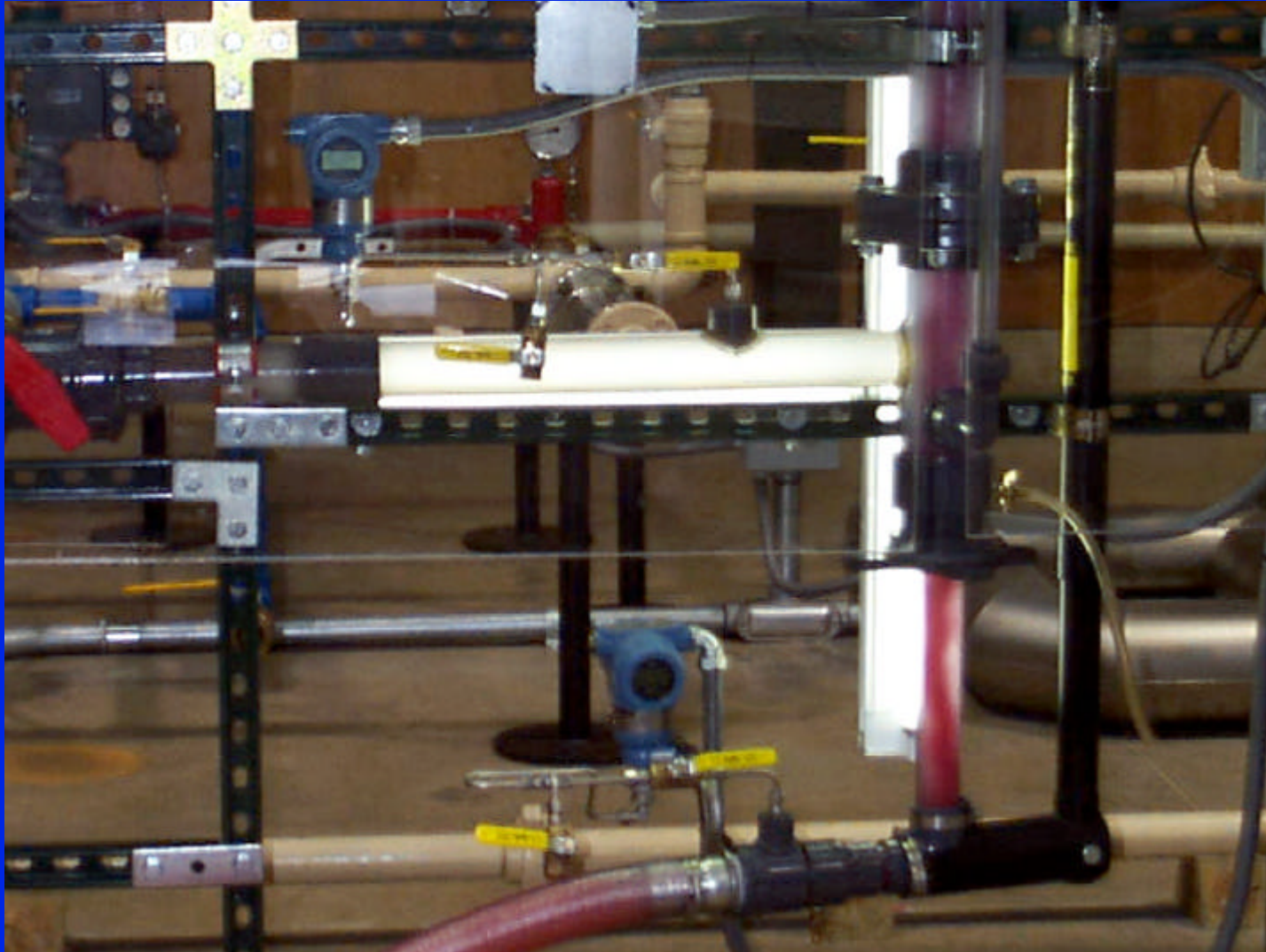


# *Figure 6. Operation of 3-phase GLCC<sup>©</sup> - Experimental Visualization*



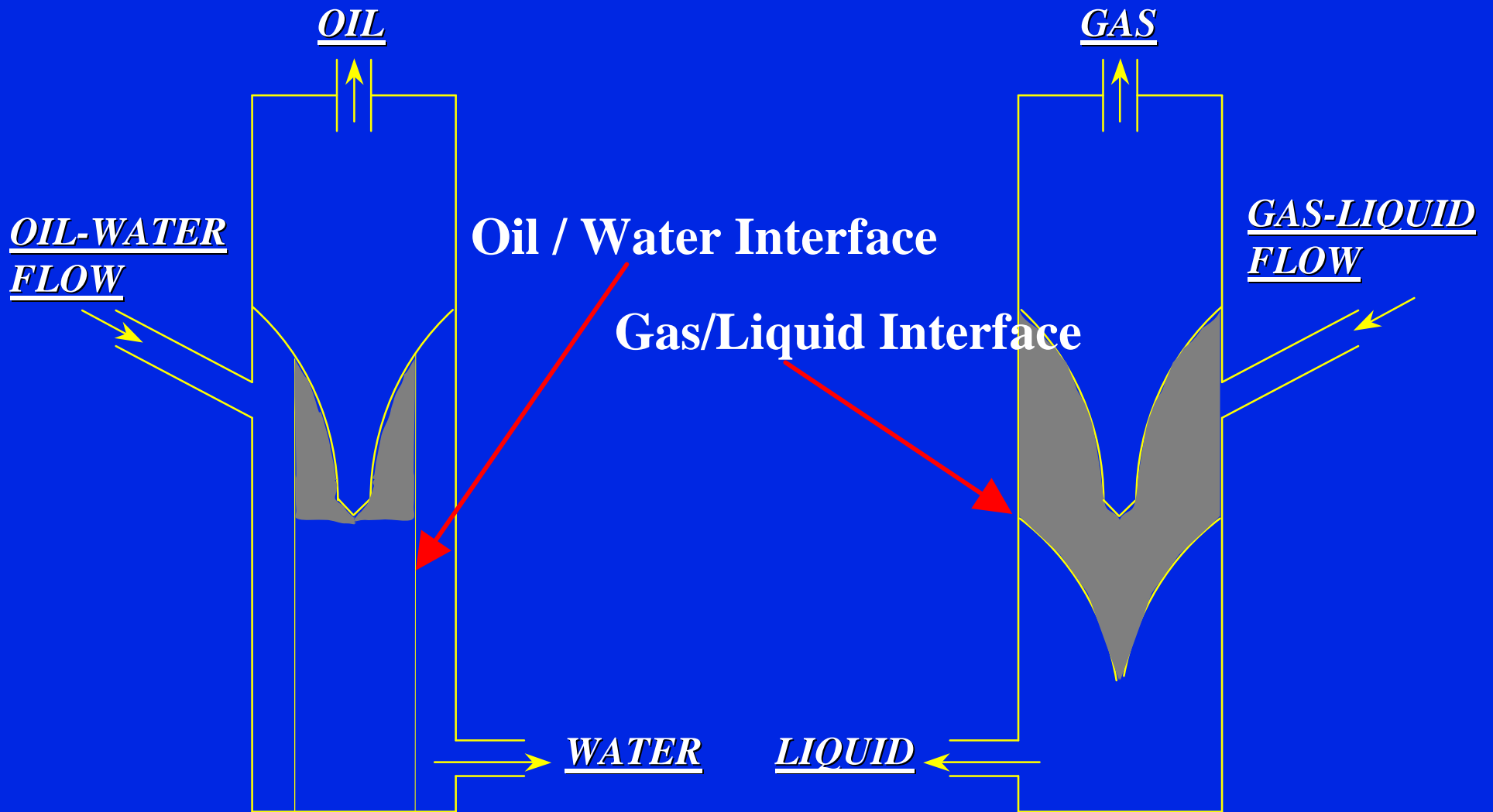


## *Figure 7. Operation of 3-phase GLCC<sup>©</sup> - Oil and Water Legs*





# Figure 8. Schematics of Oil - Water and Gas-Liquid Interfaces







## *Figure 9. LLCC<sup>©</sup> Installed in the 3-Phase Flow Loop*

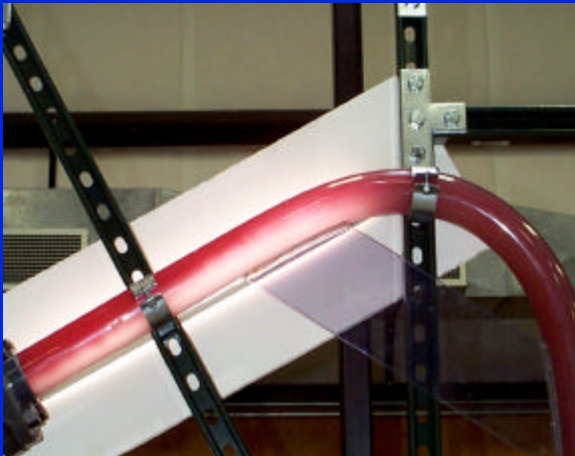




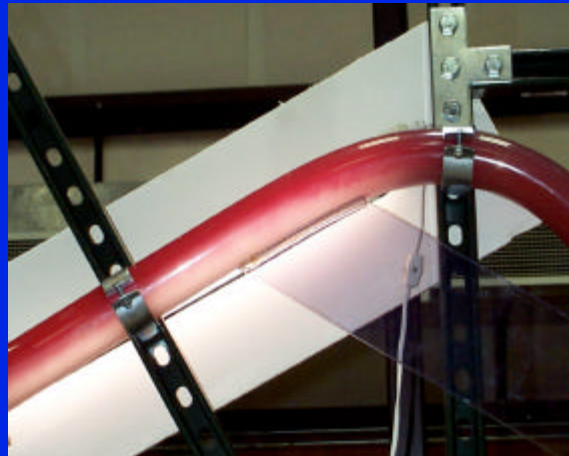


# Figure 10. Inlet flow Patterns in the LLCC<sup>©</sup>

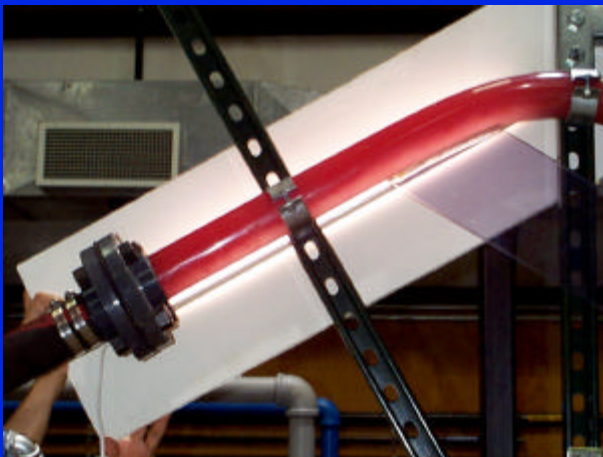
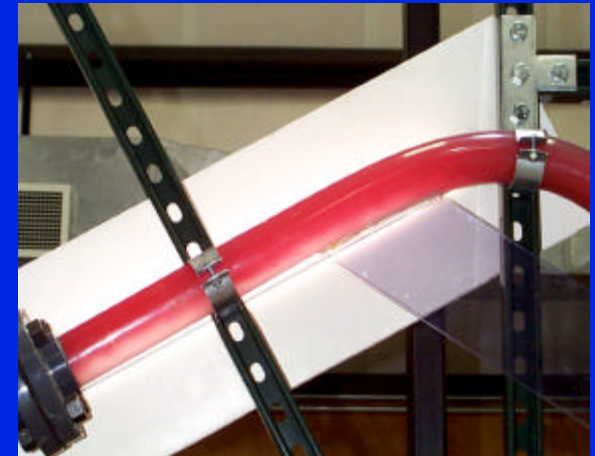
$V_{sw} = 0.4 \text{ m/s}$   
 $V_{so} = 0.08 \text{ m/s}$   
*Stratified + O/W*



$V_{sw} = 0.4 \text{ m/s}$   
 $V_{so} = 0.1 \text{ m/s}$   
*Stratified + O/W*

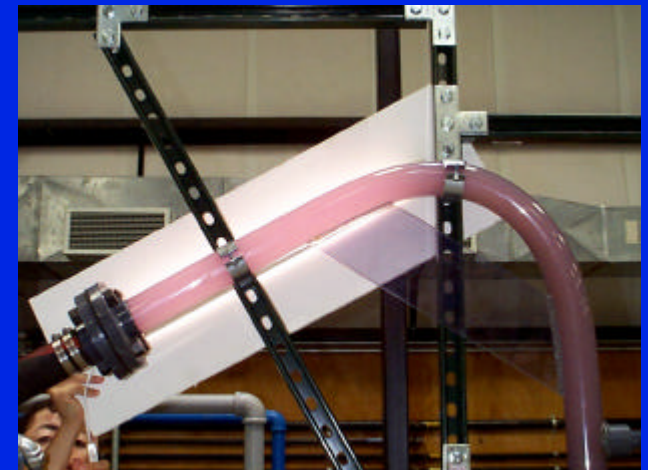


$V_{sw} = 0.4 \text{ m/s}$   
 $V_{so} = 0.2 \text{ m/s}$   
*Stratified + O/W*



$V_{sw} = 0.2 \text{ m/s}$   
 $V_{so} = 0.3 \text{ m/s}$   
*Dispersed W/O*

$V_{sw} = 1.5 \text{ m/s}$   
 $V_{so} = 0.05 \text{ m/s}$   
*Dispersed O/W*



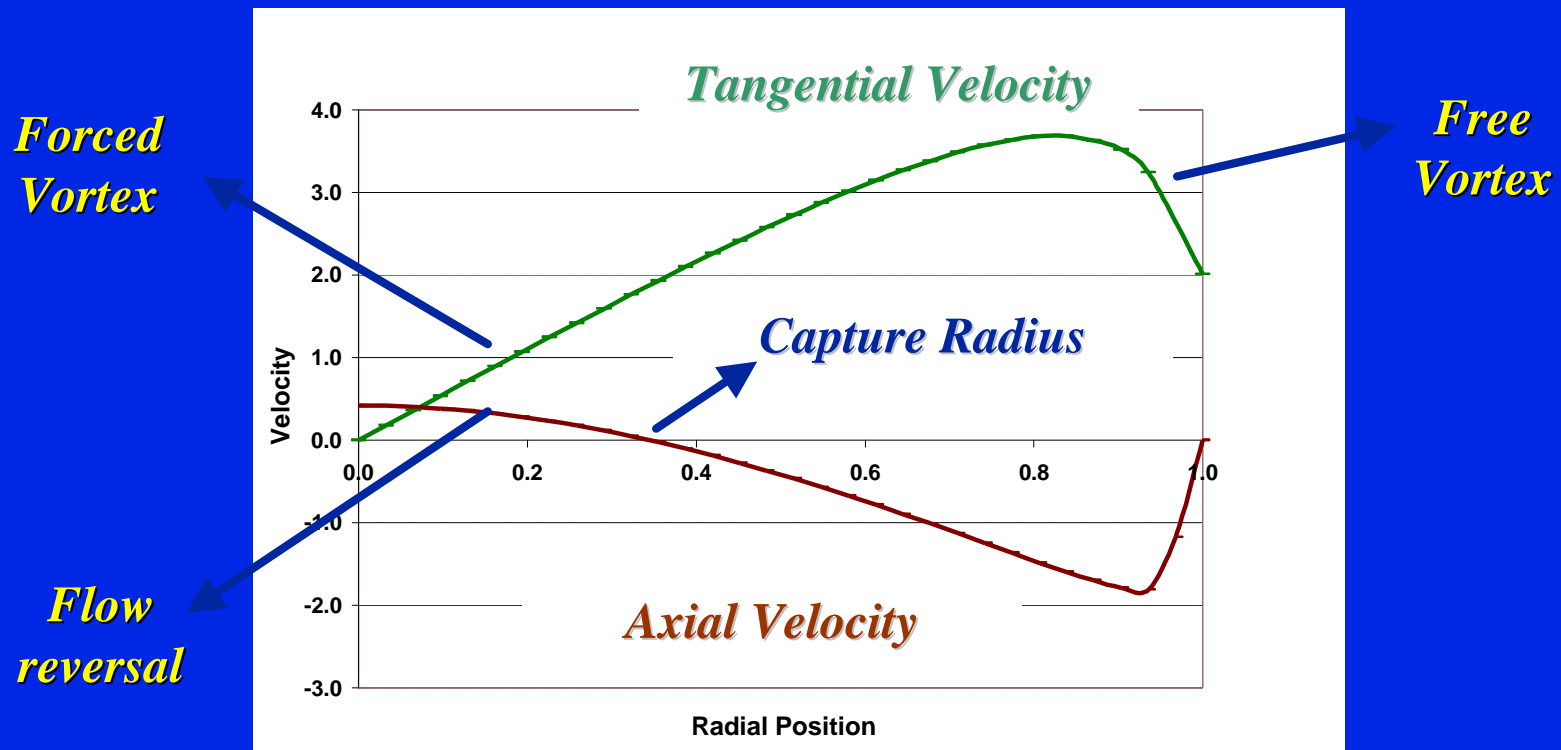


# Figure 11. Velocity Distribution in the LLCC<sup>©</sup>

❖ *From Experimental Data, CFD and Observations*

❖ *Tangential Profile: Forced and Free Vortex*

❖ *Axial Profile: Reverse Flow Region*





# Figure 12. LLC<sup>©</sup> Axial Velocity Correlations

## ❖ Axial Velocity - Lower Part

$$\frac{U}{U_{av}} = \frac{2}{C} \left( \frac{r}{R} \right)^3 - \frac{3}{C} \left( \frac{r}{R} \right)^2 + \frac{0.7}{C} + 1$$

$$C = \frac{1}{C} \left( \frac{r_{rev}}{R} \right)^2 \frac{1}{C} 3 - 2 \frac{1}{C} \left( \frac{r_{rev}}{R} \right) \frac{1}{C} - 0.7 \frac{1}{C}$$

$$\frac{r_{rev}}{R} = 0.174 W^{0.63}$$

## ❖ Axial Velocity - Upper Part

$$\frac{U}{U_{av}} = \left( 1 - \frac{3 * \text{EXP}^{-1.5\Omega}}{U_{av}} \right) \left[ 2.86 \left( \frac{r}{R} \right)^3 + 4.26 \left( \frac{r}{R} \right)^2 \right] + \frac{3 * \text{EXP}^{-1.5\Omega}}{U_{av}}$$

$\Omega = \text{Swirl} - \text{Intensity}$



# Figure 13. LLCC<sup>©</sup> Tangential Velocity Correlation

## ❖ Tangential Velocity

$$\frac{W}{U_{av}} = \frac{T_m}{\rho r \omega} \exp\left(-1.85 \frac{\rho r \omega^2}{\rho R \omega}\right)$$

$$T_m = 1.1433 W^{1.3056} \quad \text{Lower Part of the LLCC}^{\tilde{a}}$$

$$T_m = 0.7152 W^{1.3056} \quad \text{Upper Part of the LLCC}^{\tilde{a}}$$

*T<sub>m</sub> is Related to Maximum Momentum of Tangential Velocity*