DOE/BC/15024-2
(OSTI ID: 773002)

DESIGN AND DEVELOPMENT OF GAS-LIQUID CYLINDRICAL
CYCLONE COMPACT SEPARATORS FOR THREE-PHASE FLOW

Semi-Annual Report
April 1, 2000-September 30, 2000

By
Dr. Ram S. Mohan
Dr. Ovadia Shoham

Date Published: January 2001

Work Performed Under Contract No. DE-FG26-97BC15024

The University of Tulsa
Tulsa, Oklahoma

National Petroleum Technology Office
U.S. DEPARTMENT OF ENERGY
Tulsa, Oklahoma

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, expressed or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government.

This report has been reproduced directly from the best available copy.

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

By
Dr. Ram S. Mohan
Dr. Ovadia Shoham

January 2001

DE-FG26-97BC15024

Prepared for
U.S. Department of Energy
Assistant Secretary for Fossil Energy

Jim Barnes, Project Manager
National Petroleum Technology Office
P.O. Box 3628
Tulsa, OK 74101

Prepared by
The University of Tulsa
L169 Keplinger Hall
600 South College Avenue
Tulsa, OK 74104-3189

Table of Contents

1. Disclaimer.....	1
2. Executive Summary.....	1
3. Tasks of the Current Budget Period (Oct. 1, 1999-Sept. 31, 2000).....	2
4. Technical and Scientific Results Achieved in the Reporting Period (October 1, 1999-September 30, 2000).....	2
A. Control System Design and Experiment Results.....	2
B. Predictive Control of GLCC ® Using Slug Detection.....	4
C. Three-Phase GLCC ® Separators.....	5
D. Oil/Water Separation in LLCC ^{®2} Separators.....	6
E. Oil/Water LLCC ^{®2} Control.....	6
F. Mechanistic Model and Experimental Investigation of Hydrocarbons	8
5. Description of Plans for Conduct of Project During the Project Year 4 (October 1, 2000-September 30, 2001).....	9
6. Tasks 6 of the Fourth Project Year Activities: High Pressure Field Pilot Plant GLCC ® Design and Experimentation. (Oct. 1, 2000-Sep. 31, 2001)	13
Figures 1-12	14-25

1. Disclaimer

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

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 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 second half year (April 1, 2000 – September 30, 2000) of the budget period (October 1,

---

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

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 upcoming budget year (October 1, 2000 – September 30, 2001).

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® 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 – September 30, 2000)

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

A. Control System Design and Experimental Results

Several GLCC® 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. Mathematical models have been developed for these strategies and computer-based dedicated simulators have been built. Schematics of the simulators for two strategies are given in Figures 1 and 2. Simulation studies indicated that for gas-dominated systems, characterized by high gas superficial velocities and low liquid superficial velocities, liquid level control can be achieved only by a liquid control valve on the liquid discharge line. For liquid dominated systems, characterized by low gas superficial velocities

and high liquid superficial velocities, only a gas control valve on the gas discharge line can achieve liquid level control. For intermediate liquid and gas flow conditions characterized by slug flow, the integrated liquid level and/ or pressure control strategies are needed. For integrated liquid level and pressure control strategy the level control loop compliments the operation of the pressure control loop and vice versa. This strategy is ideal for reducing the pressure fluctuations in the GLCC®. The integrated liquid level control strategy is preferable for severe slug flow conditions due to faster response.

The experimental investigations are being conducted in out-door experimental facility using a dedicated GLCC® capable of withstanding higher pressures. Detailed experimental studies demonstrate that:

- By using the control systems, the GLCC® operational envelope for liquid carry-over can be increased by two folds in the high liquid flow and gas flow regions (see Fig. 3). The liquid leg and gas leg configurations will not affect the operational envelope for liquid carry-over if the liquid level is controlled below the inlet. The operational envelope for liquid carry-over is unique for a GLCC® with specified diameter and height. The mechanisms responsible for liquid carry-over in a GLCC® with control system are different from those responsible in the case of a GLCC® without control systems. For example, churn flow is responsible for liquid carry-over in a GLCC® with control systems even for relatively large liquid flow rates, whereas in the case of a GLCC® without control system, it is primarily caused by annular flow conditions.
- The developed control systems are capable of controlling the liquid level and GLCC® pressure over a wide range of flow conditions – slug flow, churn flow and annular flow. The time responses of the liquid level and the pressure show that more flow disturbance will cause more dynamics of the system.
- The liquid level can be well controlled at the expense of larger LCV dynamics, which will reduce the lifetime of the control valve. If liquid level fluctuation can be tolerated over a wider range, the controller gain can be suitably designed causing lesser control valve dynamics.

B. Predictive Control of GLCC® Using Slug Detection

Current design and performance of the GLCC® is 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 GLCC® using feed-forward mechanism can improve the operational range of GLCC®, by decreasing the gas carry under and liquid carry over, 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. The reason is simple: A feedback controller reacts only after it has detected a deviation in the value of the level from the set point. Unlike the feedback systems, a feed forward control configuration measures the disturbance directly and takes control action to negate the effect of the disturbance on liquid level in the GLCC®. Therefore, feed forward control system has the theoretical potential for perfect control.

A strategy for GLCC® predictive control strategy, integrating feedback and feed forward control system, has been proposed, modeled and simulated. A feed forward controller has also been designed using an analytical approach. From our design we found that the controller design is a function of the velocity of the slug. So from our proposed predictive control system we consider the slug detection as a crucial factor in determining the effectiveness of our control system.

A predictive control algorithm has been developed and is being tested to validate the simulation. The highlights are as follows:

- Determining the presence of the slug flowing and determining the liquid volume flow rate. A slug detection algorithm for characterizing the slug on-line developed and tested. The step of detecting the presence of the slug in the flow line is done by using a pair of conductance probe sensors, and an ultrasonic sensor is used to measure the hold up of the slug.
- Predictive control system operates only when huge slugs are encountered. So the length of the slug is a parameter to trigger this control system.
- Determining the available volume in the GLCC® for receiving the liquid slug.

- Comparing the volume of said slug to said available volume and throttling the downstream control valve to accommodate the flow rate after a time delay, the time taken for the slug to travel from slug detector to GLCC®.
- Integrating the feedback and feed-forward to compensate for error due to slug characterization.

C. Three-Phase GLCC® 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® 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® 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® 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®s. Initially the test section will be equipped with one dual stage GLCC® and later it will be upgraded to 2 dual stage GLCC®s. The three-phases from the GLCC® outlets will also be metered using Micro-Motion® mass flow meters. The test section construction is modular so that in place of GLCC® 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® is completed and has been installed in the flow loop. A photograph of the single stage 3-phase GLCC® is shown in Figure 5. Preliminary experimental investigations are in progress to evaluate the performance of the first generation three-phase GLCC® laboratory prototype. The results of preliminary

feasibility testing of 3-phase GLCC® separator are shown in Figures 6 and 7 for the case of an oil-finder at 36-inch below the inlet. These tests demonstrate that it is feasible to separate an oil-water-gas flow in a single stage 3-phase GLCC® at relatively high efficiencies. Detailed experimental testing of the 3-phase GLCC® is in progress to evaluate the operating performance. The data will help in the development of a mechanistic model for the GLCC®.

D. Oil/Water Separation in LLCC^{®2} Separators

Installation of the support structure for the experimental facility, a 3-inch oil-water test Liquid-Liquid Cylindrical Cyclone (LLCC®) separator and downstream metering section has been completed. The LLCC® installed in the flow loop is shown in Figure 8. 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®s and formulation of appropriate separation strategies for the GLCC®. Inlet flow patterns in the LLCC® separator are given in Figure 9. The feasibility of utilization of the Liquid-Liquid Cylindrical Cyclone (LLCC®) compact separator for free water knockout bulk separation of oil-water mixtures has been established by experimental testing of the lab LLCC® prototype, with measured efficiencies greater than 90% for some flow conditions. The typical flow pattern in an LLCC® is a combination of free vortex and forced vortex. The schematic of the axial and tangential velocity profile is given in Figure 10. A mechanistic model for the LLCC® has been developed to predict the tangential and axial velocity profiles. The developed correlations are given in Figures 11 and 12. The mechanistic model will be used to design LLCC® field applications and for comparison with experimental data.

E. Oil/Water LLCC® Control

Objective: The primary objective of the research study is to design and develop a control system strategy for Liquid-Liquid Cylindrical Cyclone (LLCC®) separators. However in future, this design may be extended to Three-Phase GLLCC® control as well.

---

² LLCC® - Liquid- Liquid Cylindrical Cyclone – copyright, The University of Tulsa, 1999.

Necessity of a Different Strategy: Existing Control System Strategies for GLCC® separators are based on liquid level. By controlling the liquid level, the operational efficiency (quality) of the GLCC® is enhanced. This is possible because of the free gas-liquid interface visible in GLCC®. But in LLCC®, there is no such free oil-water interface. The oil-water interface does not seem to be as distinct as in GLCC®. Hence liquid level would not be the controlling variable for LLCC®. All these factors lead to search for a new strategy for LLCC® control.

Parameter to be Controlled: Split Ratio in LLCC® is defined as the ratio of the overflow rate to the inlet flow rate. Experiments conducted previously indicate that as the split ratio is increased, oil-cut in the underflow decreases. But the underflow rate decreases. There is a trade off between the flow rate and the concentration of oil in the underflow of the LLCC®. So an optimized split ratio should be determined. Since split ratio has an effect on efficiency, it is the parameter to be controlled.

Different Control System Approaches: Split ratio can be controlled using two different approaches:

Approach 1, uses Water Cut meter, which measures the amount of water in respective liquid legs. Two-phase mixture (oil and water) enters the LLCC® through the inclined inlet. After separation occurs, oil passes through the upper leg while water passes through the lower leg. The water cut meter acts as a sensor and passes the information to oil and water control valves provided in the respective liquid legs. The valves open and close in such a way that the set point split ratio is always maintained constant.

Approach 2, uses Mass Flow meter, which measures the density of water/oil in respective liquid legs. However the principle remains the same as in Approach 1. Here the mass flow meter acts as a sensor and provides information to oil and water control valves. Again the valves are operated in such a way that the split ratio is maintained constant.

Tasks to be accomplished: Schedule for the next project year is as follows:

- a) Conduct experiments using two approaches
- b) Compare the data obtained and develop a model in SIMULINK

c) Develop LLCC® with complete control system.

F. Mechanistic Model and Experimental Investigation of Hydrocyclones

Two dedicated graduate students are investigating strategies to identify techniques for integration of GLCC®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 a mechanistic model for liquid hydrocyclones (LHC). Determination of a velocity field correlation for the LHC also is in progress. The velocity field will be incorporated into a mechanistic model for prediction of separation efficiencies in the LHC. NATCO (former 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.

The objective of this project is to develop an overall mechanistic model for the LHC to predict the separation efficiency and flow capacity (pressure drop–flow rate relationship). A crucial element of the mechanistic model is the velocity profile in the LHC. Wolbert et al. (1995) used an empirical approach that applies for a unique geometry and conditions. Bloor and Ingham's model (1973) is based on mathematical solutions of the fluid flow mechanics equations for solid-liquid hydrocyclones. The present model estimates the velocity field of the continuous fluid based on the prediction of the swirl intensity for given operational conditions and the LHC geometry. The swirl intensity is defined as the ratio of tangential momentum flux to axial momentum flux.

The knowledge of the velocity distributions enables the calculation of droplet trajectories, which is the basis for determination of the separation efficiency. Assuming local equilibrium for each droplet, the force balances in the axial and radial direction define the position of the droplet within the velocity field. Mainly the forces acting in the droplets are: centripetal, drag and buoyancy.

In the model, Bernoulli Equation is used to calculate the pressure drop from the inlet to the underflow outlet of the LHC. This energy balance considers the frictional losses and the centrifugal force due to the swirling motion.

Good agreement is observed between the model and several experimental data acquired by other researchers. Together with these experimental data, some CFD simulation will be carried-out to improve and evaluate the mechanistic model.

The project schedule is as follows. The experimental facility will be finalized in by end of next quarter (December 2000) and data acquisition will be completed in the next project period. Subsequently, efforts will be focused to conduct the data analysis and the mechanistic model improvement.

5. Description of Plans for Conduct of Project During the Project Year 4

(October 1, 2000 - September 30, 2001)

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®'s 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 during the final year of the project. The P.I and the Co-P.I.s will also work to coordinate testing at

field locations or another large-scale facility if a suitable site can be identified such that the work can be performed at no cost to the project.

The phase II project research activities will be similar to the phase I project activity, only difference being that the emphasis will be on high-pressure, real crude conditions. The mechanistic modeling of liquid carry-over will be continued in the fourth year also for integration with the constitutive model for liquid carry-over. The fourth 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 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. 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.

Two types of GLCC® configurations will be considered namely single stage GLCC® and dual stage GLCC®. Feasibility of these two configurations have been established in the Phase I investigations at TU. 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 LD, 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 the 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.

6. Tasks of the Fourth Project Year Activities: High Pressure Field Pilot Plant GLCC® Design and Experimentation. (Oct. 1, 2000 - Sep. 31, 2001):

- 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.
- e. Mechanistic Model Improvement for high pressure conditions for two-phase and three-phase applications.
- f. Interim reports preparation.

Figure 1. Simulator for 2-Phase GLCC® Integrated Liquid Level Control System

**Figure 2. Simulator for 2-Phase GLCC®
Integrated Level and Pressure Control**

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. Single Stage 3-Phase GLCC© in Place

*Figure 6. Oil Finder at 36”
Below Inlet*

Figure 7. Experimental Results for Oil Finder @ 36'' Below Inlet

Figure 8. LLCC® Installed in the 3-Phase Flow Loop

Figure 9. Inlet flow Patterns in the LLCC©

$V_{sw} = 0.4 \text{ m/s}$
 $V_{so} = 0.08 \text{ m/s}$
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 10. Velocity Distribution in the LLCC®

❖ *From Experimental Data, CFD and Observations*

❖ *Tangential Profile: Forced and Free Vortex*

❖ *Axial Profile: Reverse Flow Region*

Figure 11. LLCC© Axial Velocity Correlations

❖ Axial Velocity - Lower Part

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

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

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

❖ Axial Velocity - Upper Part

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

Ω = Swirl – Intensity

Figure 12. LLCC© Tangential Velocity Correlation

❖ Tangential Velocity

$$\frac{W}{U_{av}} = \frac{T_m}{\left(\frac{r}{R}\right)} \left[1 - \exp \left(-1.85 \left(\frac{r}{R} \right)^2 \right) \right]$$

$$T_m = 1.1433 \Omega^{1.3056} \quad \text{Lower Part of the LLCC©}$$

$$T_m = 0.7152 \Omega^{1.3056} \quad \text{Upper Part of the LLCC©}$$

T_m is Related to Maximum Momentum of Tangential Velocity