Project Title:

Design and Development of Integrated Compact Multiphase Separation System (CMSS)

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Tulsa University Separation Technology Projects (TUSTP)

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2. Disclaimer

3. Abstract

The petroleum industry has relied in the past mainly on conventional vessel-type separators, which are bulky, heavy and expensive, to process wellhead production of oil-water-gas flow. Economic and operational pressures continue to force the petroleum industry to seek less expensive and more efficient separation alternatives in the form of compact separators. The compact dimensions, smaller footprint and lower weight of compact separators have a potential for cost savings to the industry, especially in offshore and subsea applications. Also, compact separators reduce the inventory of hydrocarbons significantly, which is critical for environmental and safety considerations.

This report presents a brief overview of the activities and tasks accomplished during the Budget Period II (October 09, 2004 – April 30, 2006) of the DOE project titled "Design and Development of Integrated Compact Multiphase Separation System (CMSS©[1])". 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 discussions. The findings of this investigation are summarized in the "Conclusions" section followed by relevant references.

In this investigation, the concept of CMSS© has been developed and is proven through simulation studies and validated by experimental data. As part of the second phase of the project (Budget Period II – 10/09/2004 – 04/30/2006) experimental investigation of the integrated CMSS© for different configurations has been conducted in order to evaluate the performance of the individual separation components, and determine how they will affect the performance of each other when integrated in the CMSS©. An intelligent control system is also developed to improve the total system efficiency of Compact Multiphase Separation System (CMSS©).

In mature oil fields, water handling poses a huge problem. Thus water knock out at the earliest stage helps in significant cost savings during handling, separation and transportation of oil. One of the objectives of the CMSS© configuration is to knock out free water from the upstream fluids. The results from theoretical and experimental studies show that Free Water Knock Out (FWKO) CMSS© system can be readily deployed in the field using the control system strategies designed, implemented and tested in this study.

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[1] CMSS© - Compact Multiphase Separation Systems - Copyright, The University of Tulsa, 2002

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5. Executive Summary

The goal of this three-year (July 09, 2003 – April 30, 2006) DOE sponsored project is to make compact separators and compact separation systems predictable, reliable and a viable economic alternative to conventional separation technology. There are two overall objectives of this cooperative agreement. The first objective is development of Compact Multiphase Separation Systems (CMSS©) for onshore and offshore applications by integrating the already developed and to be developed individual components. The second objective is to evaluate the performance of the developed compact separation system for field applications. At the completion of this project The University of Tulsa is releasing to the public domain this final report describing the findings and recommendations. This technology is intended for use by oil and gas production companies and production equipment manufacturers.

The initial phase of the project (Budget Period I – 07/09/2003 to 10/08/2004) focused on the development of additional individual compact separation components, such as the horizontal pipe separator (HPS©[2]), for obtaining clean oil stream from oil-water mixture, flow conditioning components, such as the helical pipe (HP) and slug damper (SD©[3]), for dissipating slugs upstream of the compact separators. The design and testing of an upstream slug train generator (SG) was also conducted as part of the activities.

As part of the second phase of the project (Budget Period II – 10/09/2004 – 04/30/2006) experimental investigation of the integrated CMSS© for different configurations has been conducted in order to evaluate the performance of the individual separation components, integrated in the CMSS©. The experimental results are used to evaluate how the individual components will affect the performance of each other, and the total system efficiency.

In this investigation, an intelligent control system has been developed for Compact Multiphase Separation System (CMSS©) which consists of integrated configurations of three compact separators, namely, Gas-Liquid Cylindrical Cyclone (GLCC©[4]), Liquid-Liquid Cylindrical Cyclone (LLCC©[5]) and Liquid-Liquid Hydrocyclone (LLHC). In mature oil fields, water handling poses a huge problem. Thus water knock out at the earliest stage helps in significant cost savings during handling, separation and transportation of oil. The specific objective of this CMSS© configuration is to knock out free water from the upstream fluids. The results from theoretical and experimental studies show that Free Water Knock Out (FWKO) CMSS© system can be readily deployed in the field using the control system strategies designed, implemented and tested in this study.

Reliability analysis for FWKO CMSS© system has also been conducted in this study. System reliability has been calculated from reliability of components and performance reliability of the system. A new protocol has been introduced to calculate performance reliability based on performance failure of the system from simulation data. This protocol has been proven to predict performance reliability of a new system which does not have prior historical information on failure of components or devices.

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[2] HPS© - Horizontal Pipe Separator - Copyright, The University of Tulsa, 2000
[3] SD© - Slug Damper - Copyright, The University of Tulsa, 2001
[4] GLCC© - Gas-Liquid Cylindrical Cyclone - Copyright, The University of Tulsa, 1994
[5] LLCC© - Liquid-Liquid Cylindrical Cyclone - Copyright, The University of Tulsa, 1998

This report presents a brief overview of the activities and tasks accomplished during the Budget Period II (October 09, 2004 – April 30, 2006), of the DOE project titled "Design and Development of Integrated Compact Multiphase Separation System (CMSS©)". An executive summary is presented initially followed by the tasks of the current budget period. Then, detailed description of the experimental investigations is 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.

6. Tasks of the Current Budget Period - (Oct. 9, 2004 - April 30, 2006):

Task Four: Experimental Investigations

a. Completion of Experimental Investigations of CMSS© components such as horizontal pipe separator, and dual inlet GLCC.
b. Development of CMSS© configurations and control strategies, and experimental evaluation.
c. Develop mechanistic models of compact separation components (LLCC©, HPS© and LLHC).
d. Presentations in Advisory Board Meetings and report preparation.

7. Experimental Investigations

As part of the second phase of the project (Budget Period II – 10/09/2004 – 04/30/2006) experimental investigation of the integrated CMSS© for different configurations has been conducted in order to evaluate the performance of the individual separation components, integrated in the CMSS©. The experimental results are used to evaluate how the individual components will affect the performance of each other, and the total system efficiency.

7.1. Experimental Flow Loop

Experimental flow loop located in the Special Projects building of The University of Tulsa has been used for testing the compact separators and FWKO CMSS©. This indoor facility enables year around data acquisition and simultaneous testing of different compact separation equipment. Figure 1 shows an overview of the flow loop and Figure 2 shows a schematic of the test facility. This oil-water-air, three-phase flow facility is a fully instrumented, state-of-the-art, two-inch flow loop, enabling testing of single compact separation device like GLCC©/LLCC©/Hydrocyclone or combined separation systems such as FWKO CMSS©. 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 (shown in figure as red line). 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. The pumping station consists of a set of two pumps (10 HP and 25 HP equipped with motor speed controllers) for each liquid phase. Each set of pumps has an automatic re-circulating system to avoid high pressures. The liquid and gas phases are then mixed at a tee junction and sent to the test section. After separation from the test section, the multiphase fluid travels in three different pipelines. The gas, oil-rich and water-rich streams flow through three Micromotion® net oil computers to measure the outlet gas flow rate, and total flow rate and water-cut of the two liquid streams. The three streams then flow into a three-phase conventional horizontal separator (36-

inch diameter and 10 feet long), where the air is vented to the atmosphere and the separated oil and water flow back to their respective storage tanks. A technical grade white mineral oil type Tulco Tech® 80 with a specific gravity of 0.84 and a viscosity of 11.91 cp (@40 °C) is used as the experimental fluid along with tap water.

Figure 1- Overview of Experimental Flow Loop

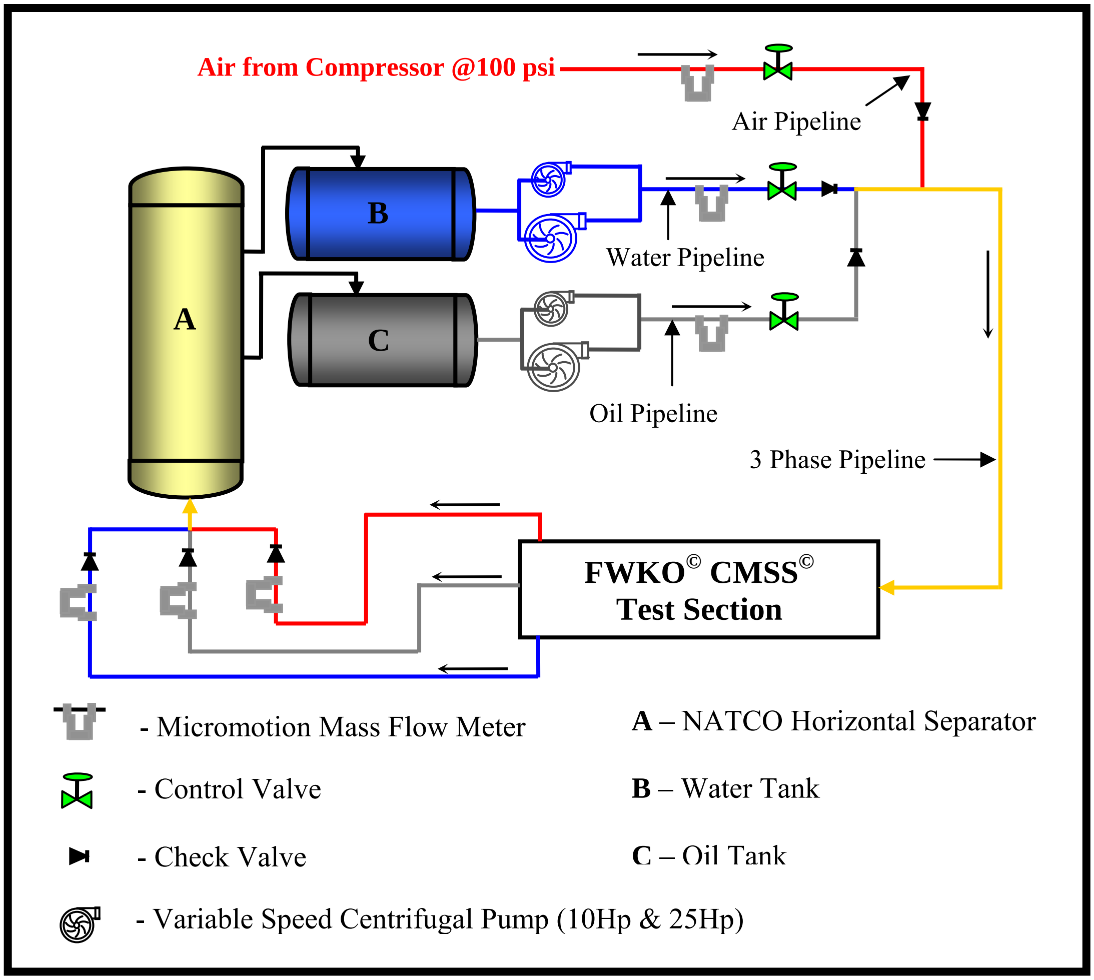

Figure 2 - Schematic of Multiphase Flow Loop used for testing FWKO CMSS©

7.2. Modular Test Section

The three-phase mixture coming from the metering section can flow into any of the three different test stations. This flexibility enables the testing of single separation equipment, such as a GLCC, LLCC, Liquid-Liquid Hydrocyclones (LLHC) or conventional separators and any combination of these, in parallel or series, forming a compact separation system like FWKO© CMSS©. Figure 3 shows a schematic of the modular test section. A special provision has been given for testing hydrocyclone as shown in the figure. Hydrocyclone can be studied for different concentrations at inlet by injecting known quantity of oil directly into the water stream.

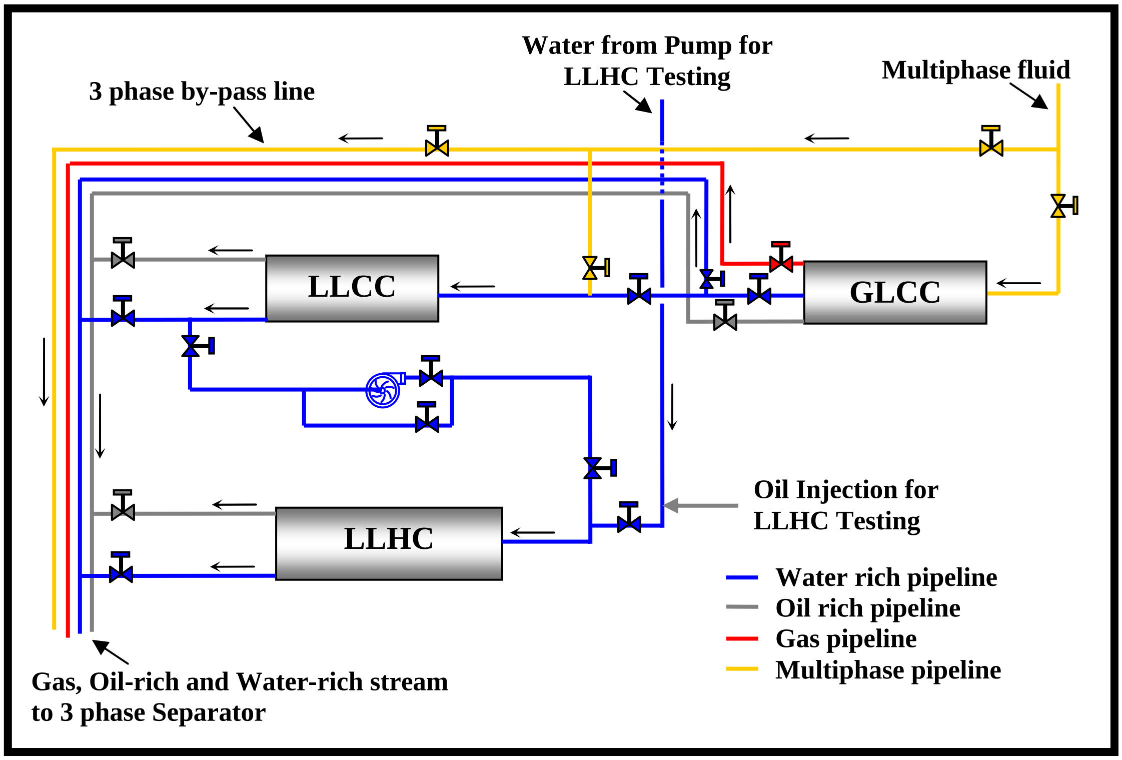

Figure 3 - Schematic of Modular Test Section

The gas, oil-rich, water-stream and multiphase by-pass pipeline return to the 3 phase horizontal separator where they are separated and oil, water are returned to the respective storage tanks while air is vented to the atmosphere.

7.3. GLCC© Test Section

The GLCC, shown in Figure 4, is a 7 feet tall, 3-inch ID vertical pipe, with 5 feet length, 3-inch ID, 27 degrees inclined inlet. The inlet slot area is 25% of the inlet full bore cross sectional area and is connected tangentially to the vertical pipe. The inlet is located 3 feet below the top of the vertical section. The 2-inch ID gas outlet is located radially at the top of the vertical pipe. The water 2-inch ID outlet is located tangentially at the bottom of the vertical pipe. Figure 5 shows a photograph of the actual installation of GLCC with a view of the inlet section. A gas control valve is mounted in the gas stream on top and a differential pressure transducer is used to measure the liquid level in GLCC. An absolute pressure sensor mounted on top measures the GLCC pressure. A second differential pressure transducer is also mounted to measure the liquid level and is used to correct the liquid level for changes in watercut in the GLCC.

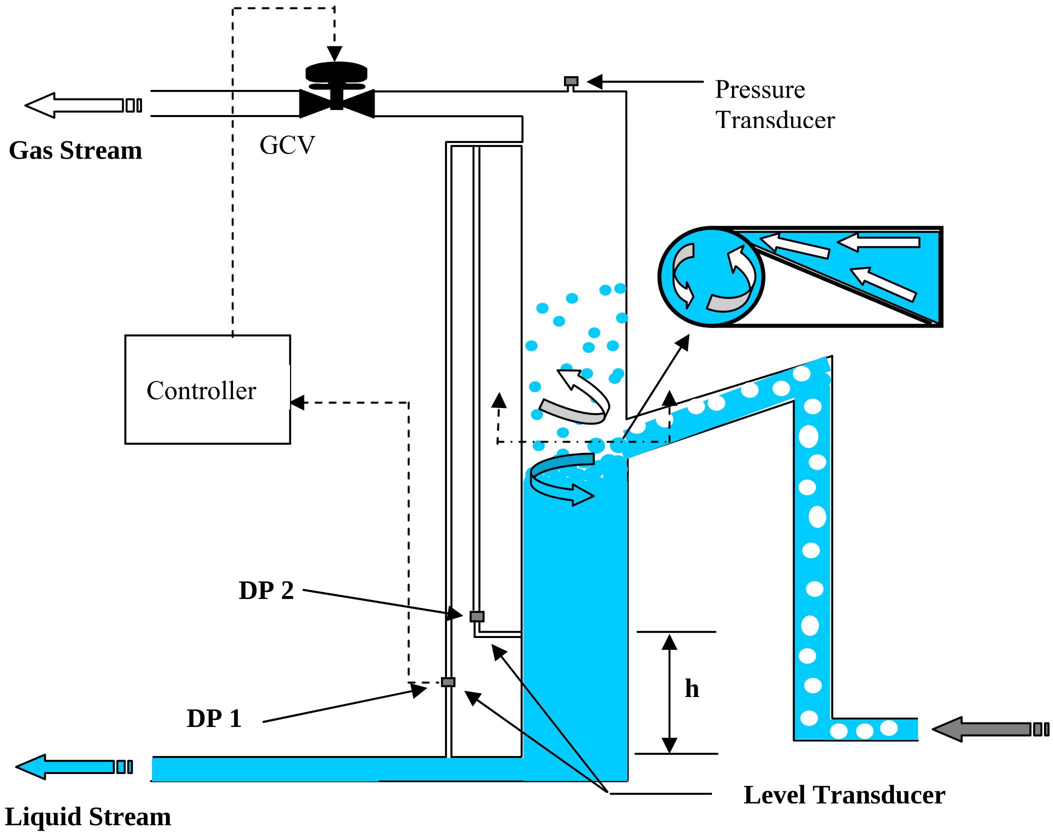

Figure 4 - GLCC© equipped with a Liquid Level Control using Gas Control Valve (GCV)

Figure 5 - View of GLCC© Inlet Section

7.4. LLCC© Test Section

The schematic of LLCC© is shown in Figure 6. It is a 6.4 feet tall, 2-inch ID vertical pipe, with a 5 feet long, 2-inch ID horizontal inlet. The inlet slot area is 25% of the inlet full bore cross sectional area. The inlet is attached to the vertical section 3.3 feet below the top. A 1.5-inch ID concentric pipe located at the top is used as the oil outlet, and the water outlet is a radial, 1.5-inch ID pipe located at the bottom of the vertical section. Based on the studies conducted by Escobar (2005), the internals were modified in the LLCC. Figure 6 shows a cone, 12-inch in length with a diameter of 2-inch at the top end and 1-inch diameter at the bottom end, is inserted right below the inlet of the lower section of the LLCC. An orifice vortex finder with a 0.5-inch diameter is inserted right above the inlet of the upper section of the LLCC. The position of the oil finder is 1-inch above the inlet centerline and it aligns with the top inner pipe wall of the horizontal inlet.

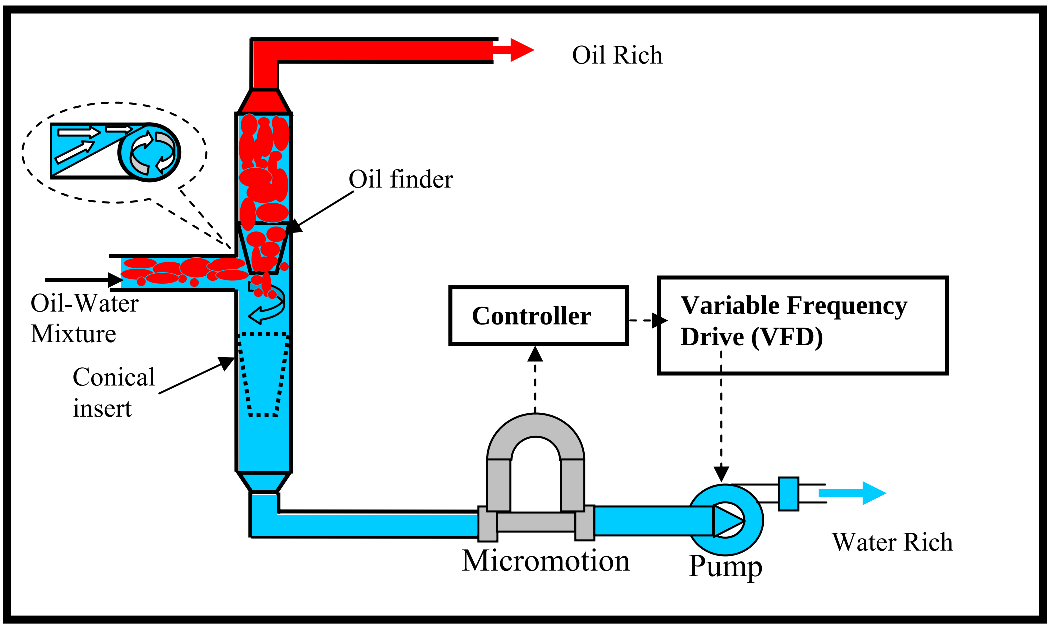

Figure 6 - Schematic of LLCC© equipped with Watercut Control System

The instrumentation provided on the LLCC are absolute pressure transducer to measure pressure at inlet, overflow and underflow, Micromotion mass flow meter to measure the density of mixture and flow rate of fluid in the underflow stream followed by a variable speed centrifugal pump capable of producing 300 ft head at discharge at 125 GPM liquid flow rate with a maximum speed of 3500 rpm. The Micromotion mass flow meter is used to measure the mixture density which is converted into watercut and used as an input signal to control system. A software based controller is used to control the speed of this pump using a variable frequency drive to maintain the set point watercut in the underflow stream. Figure 7 below shows a snapshot of the actual installation of LLCC and its inlet pipe.

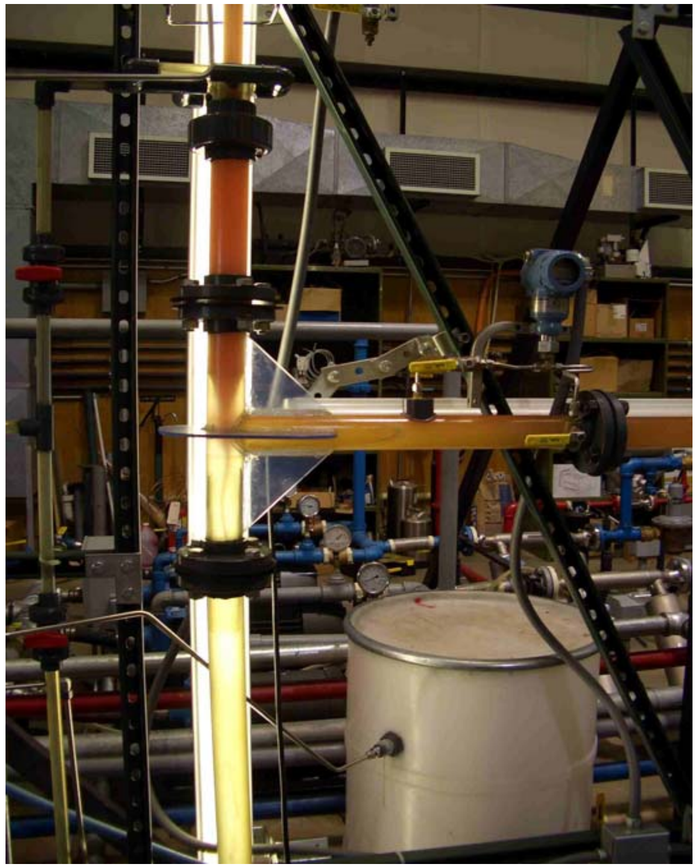

Figure 7 - View of LLCC© in Operation

7.5. Hydrocyclone Test Section

Schematic of LLHC is shown in Figure 8 and a photograph of the LLHC installed in shown in Figure 9. The Hydrocyclone used is a 2-inch NATCO MQ Hydro Swirl Hydrocyclone mounted vertically with a total height of 62-inches. This hydrocyclone was operated in two different configurations. The first configuration is for testing hydrocyclone control system as an individual device, and the second configuration is where hydrocyclone was tested as part of the FWKO CMSS system. Water flows into the test section through a 2" pipe coming from the water tank. This pipe has a split section where the water split stream mixes with injected oil in order to get thorough mixing with the desired oil concentration. The split section is a ½ inch pipe composed of a water paddle meter, a mixing tee and a static mixer. Oil for mixture was pumped using a piston pump with a maximum discharge of 2.5GPH.

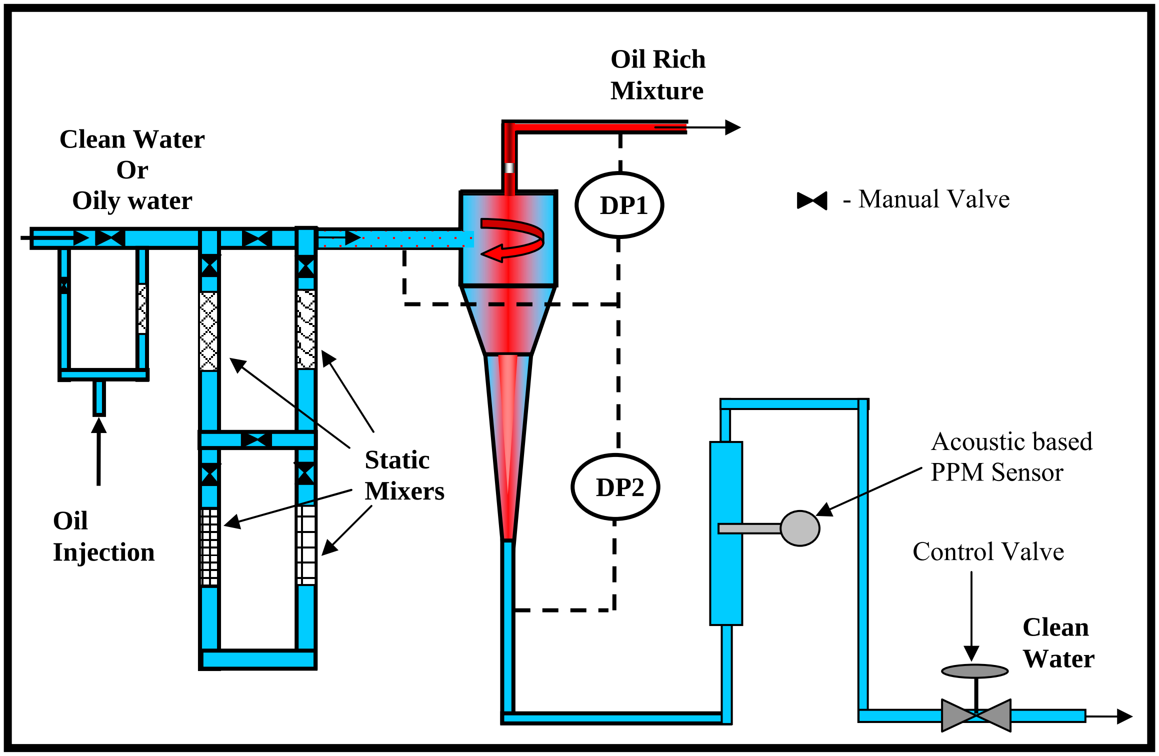

Figure 8 - Schematic of Liquid-Liquid Hydrocyclone Test Facility

Prior to reaching the hydrocyclone, the oil water mixture was designed to flow through a series of mixers, which were chosen based on valve positions, to get the desired droplet size distribution. Droplet size distribution were not measured but kept constant by keeping the mixer in the flow stream the same all through the experiments. During the FWKO CMSS testing the fluid path was maintained the same as during the individual hydrocyclone control testing. This is to avoid any uncertainty in experimental investigation of hydrocyclone. Two differential pressure transducers were used to measure the differential pressure between inlet to overflow and inlet to underflow. Two absolute pressure transducers were used to measure the inlet and underflow pressures. A 2-inch control valve was used in the underflow water stream as part of the control system for hydrocyclone. An acoustic based concentration measuring probe was installed in the underflow section in a 3-inch pipeline upstream of the control valve. This was used to measure the PPM (parts per million) quality in the hydrocyclone underflow stream.

Figure 9 - View of Installed LLHC with DP Sensor

7.6. Instrumentation

Sensors are an integral part of any control system application. Success of a control system most often primarily depends on the type, characteristic and accuracy of sensor being used. In this study, two main sensors used are Micromotion Mass flow meter and Monitek Concentration Meter. Commonly used devices like absolute pressure transducers, differential pressure transducers and temperature transducers have also been used. Details of Micromotion and Monitek meters are given below.

Micromotion Mass Flow Meter (Coriolis Principle):

A Coriolis device such as the Micromotion mass flow meter has been used to measure mass flow rate and mixture density. Knowing the densities of pure fluids, the density of a mixture can be transformed to give watercut. The major components of the meter are its sensor and its transmitter. Figure 10 shows the picture of a Micromotion sensor and Figure 11 shows its transmitter.

Figure 10 - Picture of Micromotion Sensor

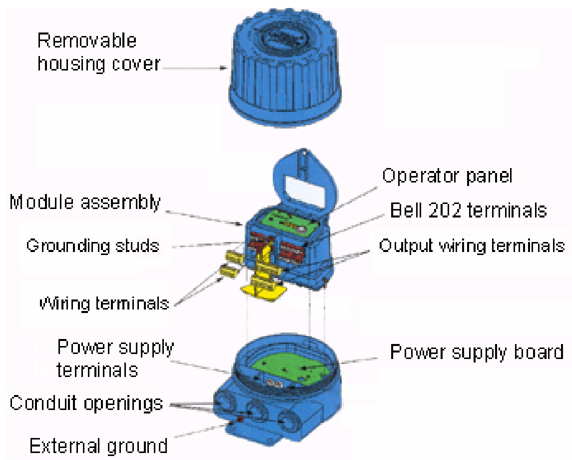

Figure 11 View of Micromotion Transmitter

In the LLCC control system, the Micromotion sensor is used in the underflow pipeline to measure watercut which is the primary input to the control system. In the experimental study of FWKO CMSS, the Micromotion sensor has been used to measure the flow rates and densities of individual phases of liquid upstream and downstream of the compact separation system to study the performance.

Monitek AT3 – Particle Contamination Monitor (Acoustic Principles):

Monitek AT3 is an acoustic based concentration measurement device. The integral parts of this measuring device are its sensor and its transmitter. Figure 12 shows a picture of actual installation of the sensor in underflow of hydrocyclone and Figure 13 shows the picture of its transmitter. The Monitek AT3 device is a microprocessor based, real-time, in-line instrument used to monitor liquid-borne oil contaminants in various process liquids. Use of microprocessor and graphics display provides user friendly interface for setup and calibration. The sensor mounts directly into process piping, thus eliminating the handling error and dead time associate with sampling. The transmitter unit’s LCD display shows the concentration measurement real time. This device is capable of giving a current output (4-20mA) which can be transmitted to the controller as input signal.

Figure 12 - Monitek Sensor

Figure 13 - Monitek Transmitter

Principle of operation: The AT3 sensor transmits acoustic pulses across the path of the a liquid; these pulses are created by electrically exciting the transducer's piezoelectric crystal. Acoustic energy is reflected off any particles or bubbles encountered in the moving fluid. Acoustic reflections received at the transducer are converted back into a electrical signal, which is amplified by a pre-amplifier and transmitted to the receiver. Its amplitude is then compared to a reference voltage level known as detection threshold. The signal is also time-gated to process only reflections from particles in the focal region. Signals that occur in the focal region and are greater than the detection threshold are analyzed by the software algorithm that accumulates counts. The total counts are processed by a mathematical curve-fitting algorithm in the transmitter and a corresponding concentration value in parts per million (PPM) is displayed on the front panel of the transmitter. The Monitek AT3 meter was calibrated by the manufacturer from 0 to 500 PPM. The hydrocyclone underflow in FWKO CMSS could potentially have concentration of oil from 0 to 2500 PPM. This required a new calibration curve. Known concentrations of oil from 0 to 2500 PPM were injected in flowing water stream and calibration curve was created by recording the raw “counts” value in Monitek. Figure 14 shows the new performance curve of this meter after calibration.

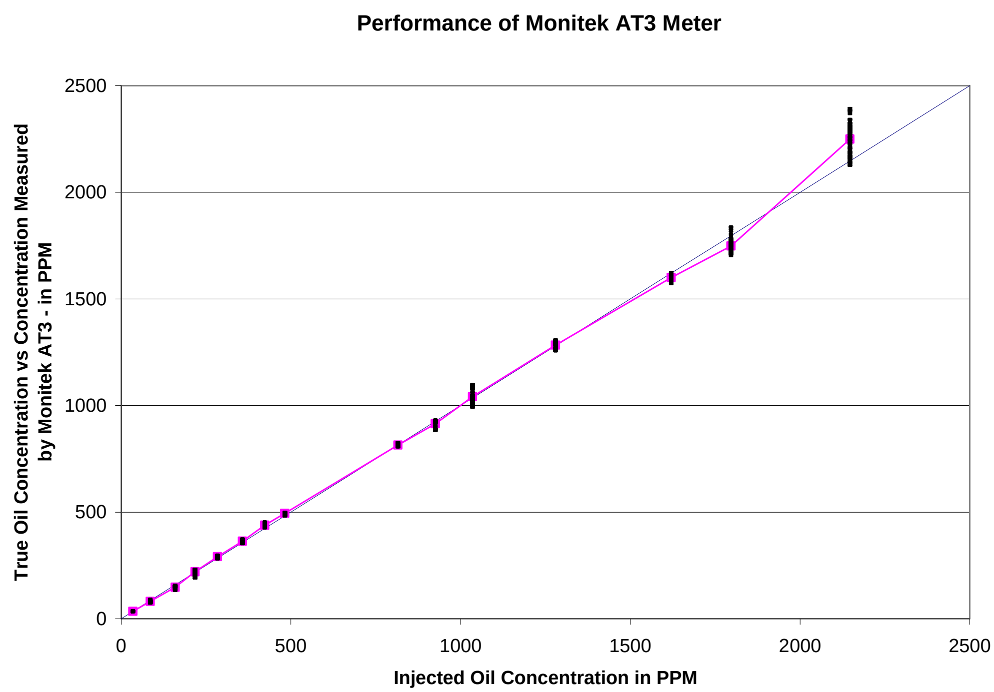

Figure 14 - Performance of Monitek AT3 Meter

7.7. Data Acquisition System

The data acquisition system was built using National Instruments Hardware and LabView Software. All the input and output devices were configured to send or receive a 4-20mA current signal. These signals were connected to the National Instruments SCXI 1001 chassis, using analog input and output modules and terminal blocks. Figure 15 shows the SCXI 1001 chassis which can house 12 input/output modules. Figure 16 shows the isolated analog input module SCXI 1125 and Figure 17 shows the isolated analog output module SCXI 1124. The signal wires from input and output devices were connected to the isolated analog input/output modules using terminal blocks SCXI 1320 shown in Figure 18. All signals are multiplexed from chassis and transmitted to a desktop computer using a GPIB board on the computer.

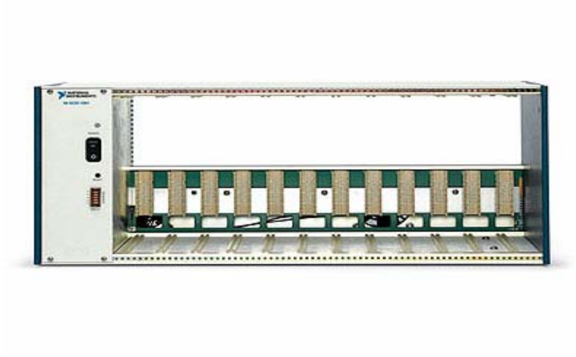

Figure 15 - SCXI 1001 Chassis

Figure 16 - 1125-Analog Input Module

Figure 17 - 1124- Analog Output Module

Figure 18 - SCXI 1320 – Terminal Block

A virtual instrument programming interface was created in LabView 7.0 software for interfacing with input and output channels. A wiring diagram was used to connect the input and output channels to the respective software based controllers. A fuzzy logic controller has been used where necessary and input and output channels were connected to the fuzzy logic controller. Input and output signals that required monitoring were connected to the user friendly front-end displays. Figure 19 shows a view of virtual instrument program designed in LabView for this study. Figure 20 shows the wiring diagram behind the virtual instrument program.

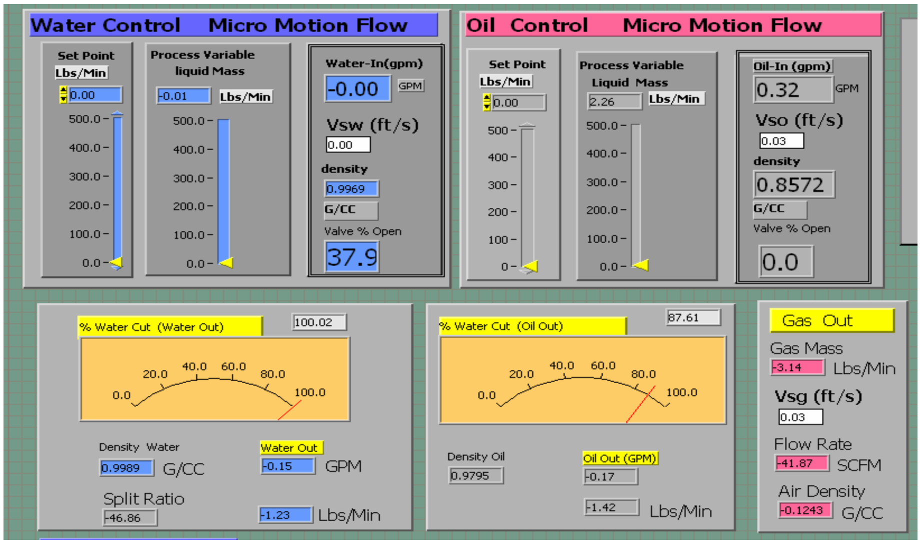

Figure 19 - View of Virtual Instrument Program in LabView™

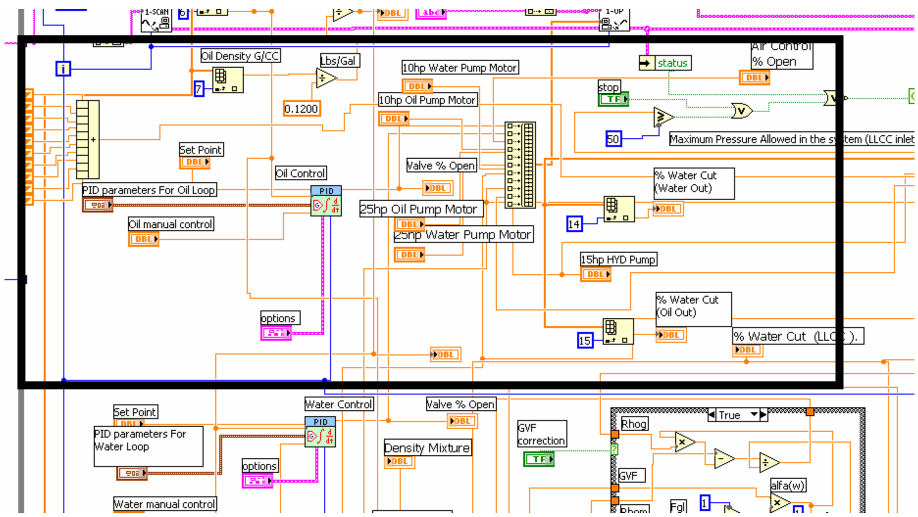

Figure 20 - Wiring Diagram Behind the Virtual Instrument Program

The sampling rate for the input and output channels is user selectable and it was set at 5Hz. All the input and output signals along with the calculated variables have been stored into Excel sheet for every experiment conducted. These values were then analyzed and selected charts have been presented. All the raw data have been presented in the Ph. D. Dissertation of Vasudevan Sampath (Reference 13).

7.8. Working Fluids

The working fluids used were tap water and mineral oil. An oil soluble red color dye was used to give mineral oil a better visual effect during the experiment. The properties of water are presented in Table 1 and mineral oil properties are presented in Table 2 below.

Table 1 - Properties of Water

Density, ρ @ 70°F	1.0 ± 0.003 gm/cm3
Viscosity, μ @ 70°F	0.97 ± 0.08 cP

Table 2 - Properties of Mineral Oil

	Tulco Tech 80
Physical State	Liquid
Color / Odor	Colorless / Odorless
Specific Gravity	0.84 (Water = 1)
Vapor Pressure	<0.1 mm of Hg (@ 70ºF)
Solubility in Water	Negligible (<0.1 Wt. %)
Density	7.1 Lbs/gal
Gravity, ºAPI	36.9
Kinematic Viscosity	14 cSt @ 40ºC
Dynamic Viscosity (calculated)	11.91 cP @ 40ºC

8. Results and Discussions

As a part of the tasks identified for the current budget period, the following specific technical and scientific activities have been completed and results obtained. The deliverables for each activity are also given below.

8.1 Intelligent Control of CMSS©

Introduction:

The objective of Compact Multiphase Separation systems (CMSS©) is to separate oil, water, gas and solid streams to a required specification. Efficient production of oil is directly related to the operation of separation devices. Gravity based separators do not handle foam, slurries and emulsions very well. Novel compact devices introduced in place of gravity based separators to improve efficiency, require proper control systems and testing before application in the field. The main focus is to design and develop new control system strategies for one such system called **F**ree **W**ater **K**nock **O**ut (FWKO) CMSS© as shown in Figure 21. This study also includes development of dynamic simulation platform (DSP) and a new reliability protocol for calculating performance reliability of the CMSS© system.

Objectives:

- Develop new control strategies for FWKO CMSS©.
- Develop a new fuzzy logic controller for a change in set-point control of Hydrocyclone.
- Develop Dynamic Simulation Platform for FWKO CMSS©.
- Conduct experimental investigation for the developed control strategies.
- Perform Reliability Analysis on simulation and experimental data.

Project Status:

- New control strategies for the individual devices like GLCC©, LLCC© and LLHC designed and developed. New Dynamic Simulation Platform for the entire FWKO CMSS© developed and tested for performance. A new reliability protocol established and used to calculated the performance reliability of FWKO CMSS©.

Deliverables:

- New control strategies for FWKO CMSS© and new adaptive fuzzy logic controller.
- Dynamic simulation platform for FWKO CMSS©.
- Experimental database for Improved LLCC©, Transient performance of Hydrocyclones and Performance of FWKO CMSS©.

- A new performance reliability analysis protocol and reliability evaluation of FWKO CMSS©.
- Ph.D. Dissertation of Vasudevan Sampath (Mechanical Engineering) completed in May 2006; Dissertation Title: ***"Intelligent Control of Compact Multiphase Separation System (CMSS©)"***.

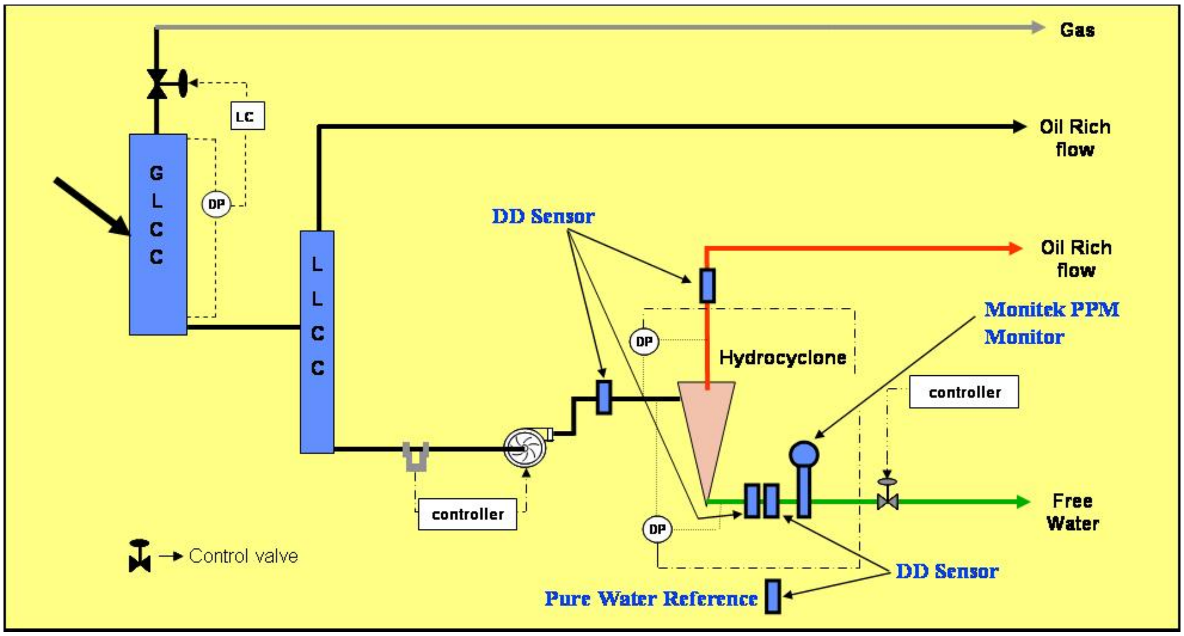

Figure 21 – Schematic of CMSS© System

8.2 Transient Mechanistic Model for GLCC© - Slug Damper Compact Separator System

Introduction:

Most of the studies on vessel separators in the past have been for steady-state conditions, based on average flow rates. However in the field, vessel separators operate under transient flow conditions. Thus, transient modeling is desired for proper design and operation of the separators. Transient mechanistic models and dynamic simulators for GLCC© and Slug Damper (SD) units (shown in Figure 22) have been developed.

Objectives:

- Develop transient models for GLCC© and Slug Damper (SD) units.

- Combine the GLCC© and SD models to develop an overall model for predicting the transient flow behavior of the GLCC©-SD system.
- Develop a simplified pipeline slugging model to be used as input to the GLCC©-SD model.
- Develop a simulator for the GLCC©-SD system.

Impact:

- Compute GLCC performance (GCU & LCO) considering different control strategies.
- Design, verify and optimize GLCC©-SD system dimensions under slugging condition.
- The proposed model is capable of being connected to other device models (upstream and downstream) to evaluate the performance of the overall system.

Final Results:

- A slug generator simulator is developed, which enables the construction of slug trains to be used as input to separator simulators for the prediction of their dynamic behavior.
- Dynamic simulators for the GLCC© and SD units are developed for the prediction of their behavior under transient flow conditions.
- The slug generator, GLCC© and SD dynamic simulators are combined into one simulator for the prediction of the flow behavior of the GLCC©-SD system under slugging conditions.
- The GLCC©-SD simulation results demonstrate clearly the advantage in damping and smoothen the liquid flow rate under slug flow conditions.
- The developed GLCC©-SD simulator can be extended to other separators, such as the gravity vessel separators and liquid hydrocyclones

Deliverables:

- Mathematical model of GLCC©-Slug Damper system
- M.S. Thesis of Eduardo Pereyra (Petroleum Engg.) - completed in December 2005; Thesis Title: ***"Transient Mechanistic Model for GLCC©-Slug Damper Compact Separator System"***

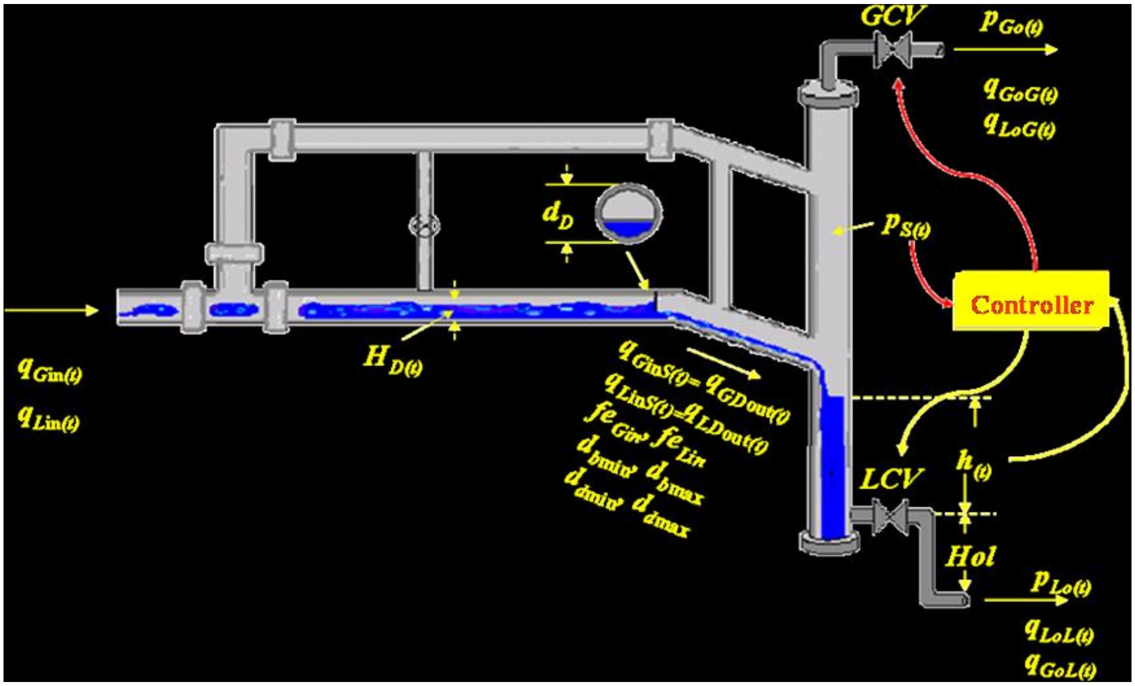

Figure 22 – Schematic of GLCC©-Slug Damper (SD) System Control

8.3 Horizontal Pipe Separator (HPS©)

Introduction:

Increasing costs of installing and maintaining separation facilities on offshore, deep-sea fields launched a search on alternative separation technologies. One alternative to vessel separators (difficult to install and operate at sea/subsea environments) is the use of multiple, compact separation equipment. There are several compact separator designs for gas-liquid and solid-liquid flows, but their use on liquid-liquid flows is more difficult.

This study investigates the use of a long pipe section as a liquid-liquid separator, to complement the use of compact separators in subsea facilities. Pipes are easy to install and maintain, and are always needed to transport fluids between gathering stations and to surface. This study also can help to streamline land separation facilities, where the HPS© can be used as pre-separation/separation device.

Objectives:

- Conduct experimental study on segregation and separation of oil-water mixtures in horizontal pipes.
- Develop a predictive model for the segregation of oil-water mixtures in horizontal pipes.
- Compare model prediction with experimental data and refine it.

Project Status (Final):

- Experimental data from developing oil-water flow gathered from a 3.75" ID, 20-ft long tube, at 10, 30, 50 and 70%WC, for V_{MIX}=0.45 and 0.58 ft/s. Global (overall separation and pressure drop along the pipe), and local parameters (velocity profiles and water cut and droplet size distributions along the vertical at 7.5 and 13.5 ft from the inlet) were measured.
- A predictive mechanistic model for the separation phenomena due to the segregation of oil-water mixtures in horizontal pipes is developed. The model comprises of a hydraulic sub-model and a coalescence sub-model (based in a population balance approach). Model predictions match experimental data fairly well. More data will be acquired in the future for model improvement. Schematic of separation process in a Horizontal Pipe Separator (HPS©) is shown in Figure 23 and a photograph of the HPS© in the Flow Loop is shown in Figure 24.

Deliverables:

- Experimental data base for developing oil-water flow in horizontal pipes.
- Mechanistic model for the prediction of the required developing length for partial or total separation of oil-water mixtures.
- Ph.D. Dissertation of Ciro Perez (Petroleum Engg) - completed in December 2005; Dissertation Title: ***"Horizontal Pipe Separator (HPS©) - Experiments and Modeling"***

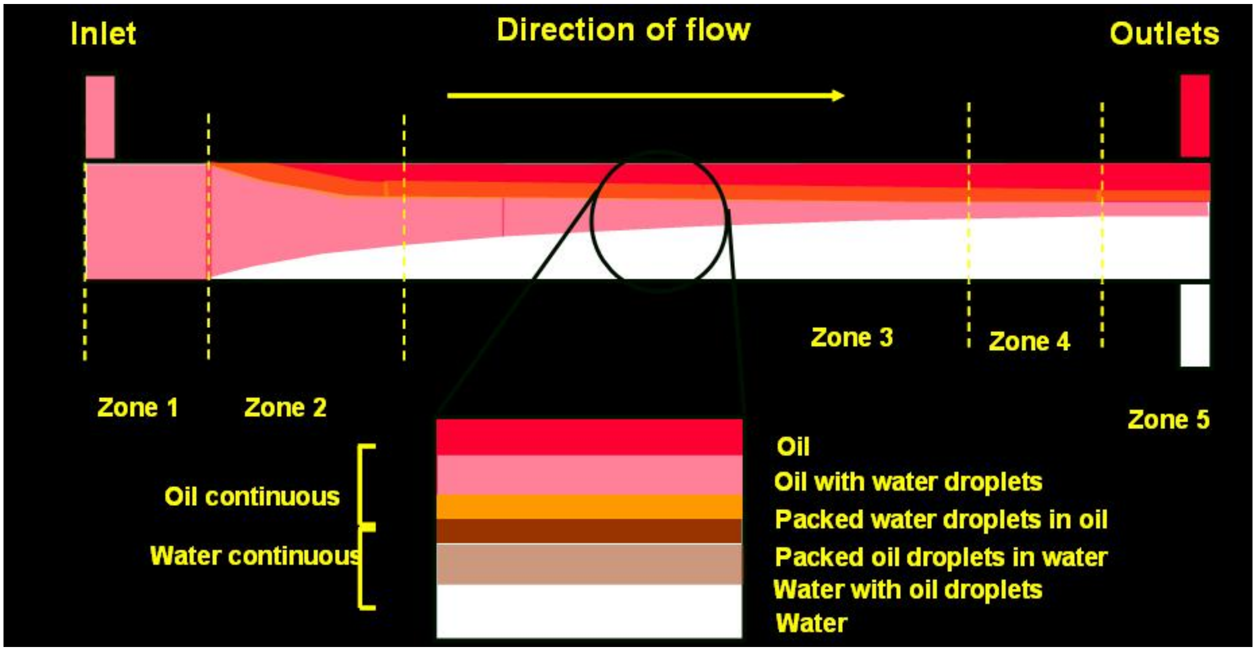

Figure 23 – Schematic of Separation Process in a Horizontal Pipe Separator (HPS©)

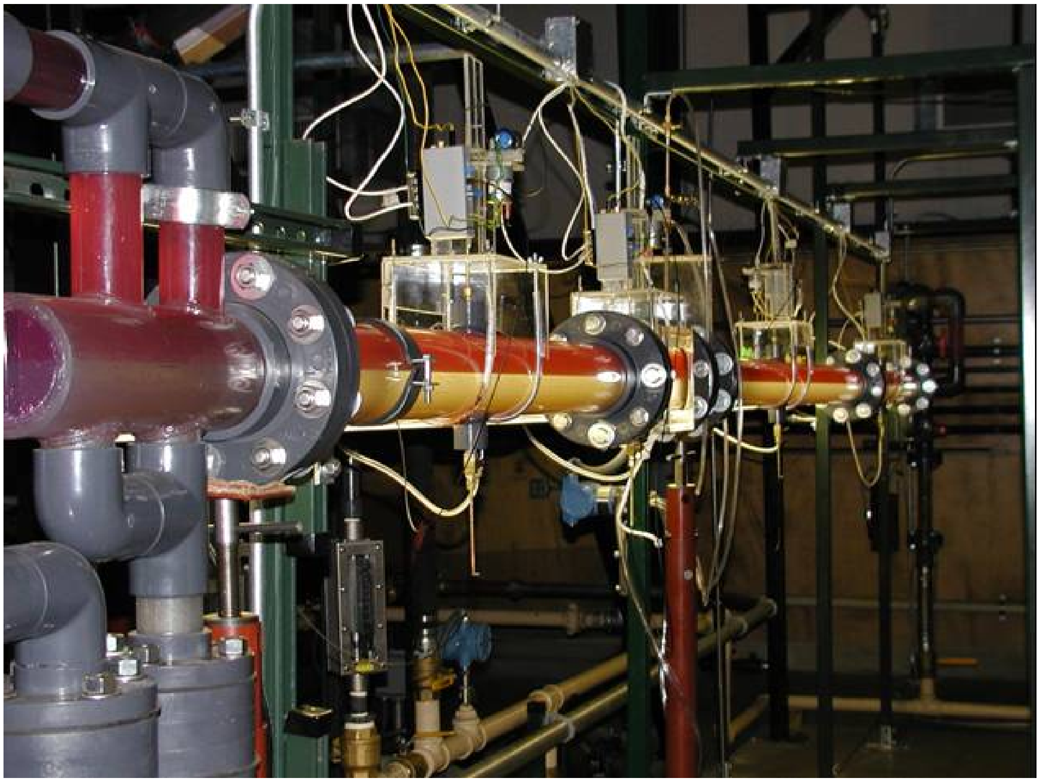

Figure 24 – Photograph of the Horizontal Pipe Separator (HPS©) in the Flow Loop

8.4 Modeling of Oil-Water Flow in Horizontal and Near Horizontal Pipes

Introduction:

Increasing costs of installing and maintaining production and separation facilities on offshore, deep sea fields launched a search on new technologies. In order to develop these technologies, models and experiments capable of characterizing the hydrodynamics of multiphase oil-water flow in horizontal pipes are necessary as primary tasks.

Objectives:

Develop mechanistic models and test against available data for:

- Liquid-liquid flow pattern transition prediction
- 2D liquid-liquid stratified flow
- Diffusion model for dispersed-phase volume fraction

Project Status:

- Literature survey on Lagrangian, diffusion and multifluid models and modeling for multiphase flow. Develop particle tracking considering turbulence-particle interaction (space vs. time and velocity vs. space formulations). Literature survey on experimental data for Oil-Water flow pattern. Develop Liquid-liquid flow pattern transition code. Develop 2D laminar stratified flow code. Develop 2D turbulent stratified flow model. Develop Diffusion model for dispersed-phase volume fraction.
- Documented the results and completed the final report

Deliverables:

- Oil-Water flow pattern for horizontal and near horizontal pipes model
- 2D turbulent liquid-liquid stratified flow model
- Diffusion model for dilute dispersed-phase volume fraction
- Ph.D. Dissertation of Carlos Torres-Monzon (Mechanical Engg.) - completed in May 2006; Dissertation Title: ***"Modeling of Oil-Water Flow in Horizontal and Near Horizontal Pipes"***

8.5 Field Applications of GLCC©/Slug Damper System

The developed GLCC©-Slug Damper (SD) units have been installed in the field by the member companies of TUSTP (Tulsa University Separation Technology Projects (TUSTP), namely Chevron and Systems Measurements Services (SMS). They provide trouble free service in the field operations in Indonesia and California. To date about 10 GLCC©-Slug Damper (SD) units have been installed. The dual GLCC©-Slug Damper (SD) system installed in the Field in Indonesia by Chevron is shown in Figure 25. Also the GLCC©-Slug Damper (SD) System Installed in California by System Measurements Services is shown in Figure 26.

Figure 25 – Dual GLCC©-Slug Damper (SD) System Installed in the Field in Indonesia (Courtesy: Chevron)

Figure 26 – GLCC©-Slug Damper (SD) System Installed in California (Courtesy: System Measurements Services)

9. Conclusions

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

1. Dedicated control systems for GLCC©, LLCC© and Hydrocyclone have been developed for field operation as part of FWKO CMSS© system. Controller designs have been conducted for the proposed control strategies using root locus technique and Matlab/Simulink Software. A new watercut control of LLCC© using a downstream pump has been designed and developed for application in low pressure FWKO CMSS© system.
2. A new dynamic simulation platform (DSP) has been developed to predict the performance of complex systems like FWKO CMSS©. This DSP uses a new idea of combining the steady state device models and the transient control system model to

predict the performance. It has a new droplet tracking feature which helps in studying the effect of droplets on performance and separation efficiencies of the compact separation devices.

3. The different control system strategies developed are tested in a state-of-the-art experimental facility for individual devices for feasibility, characteristics and dynamics of the process variables. The individual device control system strategies developed were found to be successful in operation and are ready for implementation in the field. The results have shown that the control system strategies developed for FWKO CMSS© control the respective process variables successfully.
4. Results of simulation and experimental investigations have shown that using the configuration of FWKO CMSS© developed, the concentration of oil that can be achieved in the free water separated is around 1000 ppm. The flow facility, especially the GLCC© and LLCC©, could withstand a maximum pressure of 45 psi (due to acrylic pipe material) only and the maximum flow rate achieved was 28 GPM due to this pressure restriction. The hydrocyclone has a nominal flow rate of 25 GPM and the underflow purity increases if the flow rate is higher than 30 GPM. Thus the quality achieved is 1000 ppm (parts per million) due to the low efficiency hydrocyclone and flow rate limitation of the loop caused by the pressure restriction. If better quality of water is to be achieved, a high efficiency de-oiler hydrocyclone has to be installed downstream in series to polish the 1000 ppm water achieved in the current FWKO CMSS© system.
5. A new performance reliability study has been conducted successfully on FWKO CMSS© system. The analysis includes the conventional reliability values derived from failure data of components and performance reliability based on performance failure of FWKO CMSS© system. The analysis results also show a high value for conventional reliability from failure data of devices and a low value for performance reliability. A low value for performance reliability shows the importance of re-design and re-investigation in the device performance and re-definition of failure criteria.
6. A comprehensive database for experimental flow pattern maps has been developed, including data from twelve different sources. The predictions of the VKH analysis for the transition from stratified to non-stratified flow in liquid-liquid systems show very good agreement with the experimental data. New physical mechanisms/mechanistic models are

proposed for the prediction of the transition boundaries to semi-dispersed and to fully-dispersed flow. The proposed models simplify significantly the flow pattern map for liquid-liquid flow and agree well with the experimental data.

7. A model for calculation of fully-developed, turbulent-turbulent oil-water stratified flow in horizontal and near horizontal pipes is presented. The model is based on a numerical solution of the basic governing differential equations using a finite-volume method in a bipolar coordinate system, applying a simple mixing-length turbulence model. Simplified versions of the proposed model were developed for laminar-laminar stratified flow and single-phase turbulent pipe flow cases, in order to validate the model and the numerical scheme. The laminar-laminar model was compared with a benchmark solution, showing a very good agreement. The single-phase turbulent pipe flow model was tested against published experimental data, also exhibiting very good agreement.
8. The technology of the developed slug damper system has been implemented in the field at ten locations in combination with the GLCC© system. Figures 25 and 26 show the installation of 2 slug damper units in the field – one in Indonesia and the other in California by TUSTP member companies, namely Chevron and SMS, Inc. Initial results from the field indicate that the dampening and degassing effect of the slug damper (SD) significantly contributes to improvement in the overall separation system performance enhancing the operational envelop for liquid carry-over and gas carry under, especially under slugging conditions.
9. A mechanistic model is developed for prediction of the transient hydrodynamic flow behavior in the GLCC-Slug Damper system. The model enables the predictions of the outlet liquid flow rate and the available damping time. This in turn enables the prediction of the capacity of a given slug damper and the maximum volume and length of the slug it can handle. Comparison between the model predictions and the acquired data reveals an accuracy of +-30% with respect to the available damping time and outlet liquid flow rate.
10. An experimental HPS© facility has been designed and constructed to enable measurements of the following local parameters in the developing region of oil-water flow, at two separated cross sections: local velocity profiles (measured using an in-house developed, continuous flushed pitot tube); water cut profiles (measured using a isokinetic sampling system); and local droplet size distribution (measured using a borescope/video

processing technique). Experimental data have been acquired for mixture velocities of 0.44 and 0.58 ft/s, and water cuts of 10, 30, 50 and 70% (to cover the oil continuous region). All the data were acquired at two metering stations, located at 7.5 ft and 13.5 ft from the inlet, respectively. For each run, the local velocity profiles were measured along the horizontal and vertical diameters, as well as in two additional positions (30º and 60º from the vertical). The water cut profile for each run was measured only along the vertical diameter. For each run the droplet size distributions were also measured along the vertical diameter.

11. The data are acquired for a concentric inlet with and without a mixer. Also, three different outlet configurations were used: straight tee, vessel and fishbone. For each outlet configuration, the water cut in both the oil and water outlet was measured as a function of the split ratio. The separation results of the different outlet designs show similar efficiency, and to the one occurring if the flow upstream of the outlets is split (at the given split ratio) with a horizontal plane (or a wedge). This indicates that the HPS© overall separation efficiency is a strong function of the hydrodynamic flow behavior, and a weak function of the tested outlet configurations.
12. The measured velocity profiles varied from nearly parabolic (for 10% WC) to a shear-type profile, as the water cut increased. The higher velocities are found at the high water concentration zones, while the oil tends to settle and flow at low velocity at the top. The difference in the velocity profiles between the two metering stations is small, and within the experimental error, indicating that the flow is momentum-developed for the experiments, except for 10% WC, where the difference between the profiles is caused by slow settling of water droplets.
13. For the 30%, 50% and 70% water cut experiments; water tends to quickly flow towards the bottom of the pipe, resulting in a small difference in the measured water cut between both metering stations. This also indicates small diffusion-developing flow length conditions. However, for 10% water cut, the changes of the concentration profile between the metering stations indicates slow settling of water droplets, and longer diffusion-developing length.

14. The following deliverables are provided as part of this study:

- Ph.D. Dissertation of Vasudevan Sampath (Mechanical Engineering) completed in May 2006; Dissertation Title: ***"Intelligent Control of Compact Multiphase Separation System (CMSS©)"***.
- M.S. Thesis of Eduardo Pereyra (Petroleum Engineering) - completed in December 2005; Thesis Title: ***"Transient Mechanistic Model for GLCC©-Slug Damper Compact Separator System"***
- Ph.D. Dissertation of Ciro Perez (Petroleum Engineering) - completed in December 2005; Dissertation Title: ***"Horizontal Pipe Separator (HPS©) - Experiments and Modeling"***
- Ph.D. Dissertation of Carlos Torres-Monzon (Mechanical Engineering) - completed in May 2006; Dissertation Title: ***"Modeling of Oil-Water Flow in Horizontal and Near Horizontal Pipes"***

10. References and Bibliography

1. Gomez, L., Mohan, R. and Shoham, O.: "Swirling Gas-Liquid Two-Phase Flow – Experiment and Modeling, Part I: Swirling Flow Field", presented at the ASME/JSME FED summer meeting, Honolulu, Hawaii, July 6-10, 2003, ***ASME J. Fluids Eng.,*** v. 126, no. 6, (November 2004), 935-942.
2. Gomez, L., Mohan, R. and Shoham, O.: "Swirling Gas-Liquid Two-Phase Flow – Experiment and Modeling, Part II: Turbulent Quantities and Core Stability", presented at the ASME/JSME FED summer meeting, Honolulu, Hawaii, July 6-10, 2003, ***ASME J. Fluids Eng.,*** v. 127, no. 6, (November 2004), 943-959.
3. Sampath, V., Wang, S., Mohan, R.S. and Shoham, O.: "A Matter of Separation: Adaptive control technique clears the way for GLCC separators," **DELTA TECH** magazine, a supplement to **INTECH** magazine of the Instrumentation, Systems, and Automation Society-ISA, page 5-10, April 2004.
4. Oropeza-Vazquez, C., Afanador, E., Gomez, L., Wang, S., Mohan, R., Shoham, O. and Kouba, G.: "Oil-Water Separation in Novel Liquid-Liquid Cylindrical Cyclone (LLCC) Compact Separator – Experiment and Modeling", presented at the ASME/JSME FED

summer meeting, Honolulu, Hawaii, July 6-10, 2003, ***ASME J. Fluids Eng.,*** v. 124, no. 4, (July 2004), 553-564.

5. Gomez, C., Caldentey, J., Wang, S., Gomez, L., Mohan, R. and Shoham, O.: "Oil-Water Separation in Liquid-Liquid Hydrocyclones (LLHC) – Part 1: Experimental Investigation", previously SPE 71538, presented at the SPE ATCE, New Orleans, LA, September 30 – October 3, 2001, ***SPE Journal*** 7 (2), (December 2002), pp. 362-372.
6. Wang, S., Gomez, L.E., Mohan, R.S., Shoham, O., Marrelli, J. D. and Kouba, G.E.: "Gas-Liquid Cylindrical Cyclone Compact Separators for Wet Gas Applications", ***ASME Transactions, Journal of Energy Resources Technology,*** v. 125. (March 2003), 43-50. 26.
7. Avila, Carlos M.: "Modeling and Control Systems Development for Integrated Three-Phase Compact Separators," M.S. Thesis, The University of Tulsa, 2003.
8. Avila, C., Wang, S., Mohan, R.S., Shoham, O. and Marrelli, J.D.: "Development of Control System for Integrated Three-Phase Compact Separators, Part I-Experimental Program" Proceedings of ISA EXPO 2003, Oct. 21-23, Houston, TX.
9. Avila, C., Wang, S., Gomez, L., Mohan, R.S. and Shoham, O.: "Development of Control System for Integrated Three-Phase Compact Separators, Part II-Mathematical Modeling" Proceedings of ISA EXPO 2003, Oct. 21-23, Houston, TX.
10. Perez, Ciro Andrés: "Horizontal Pipe Separator-Experiments and Modeling," Ph.D. Dissertation, The University of Tulsa, 2005.
11. Pereyra, Eduardo J.: "Transient Mechanistic Model for Slug Damper/Gas-Liquid Cylindrical Cyclone (GLCC©) Compact Separator System," M.S. Thesis, The University of Tulsa, 2005.
12. Torres-Monzon, Carlos F.: "Modeling of Oil-Water Flow in Horizontal and Near Horizontal Pipes," Ph.D. Dissertation, The University of Tulsa, 2005.
13. Sampath, Vasudevan: "Intelligent Control of Compact Multiphase Separation System (CMSS©)," Ph.D. Dissertation, The University of Tulsa, 2006.
14. Tulsa University Separation Technology Projects (TUSTP) web site: www.tustp.org