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Compact Multiphase Separation System (CMSS^ã)

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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 part July 09, 2003 – October 08, 2004, related to the Budget Period I (July 09, 2003 – October 08, 2004) 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.

The initial phase of the project (Budget Period I – 07/09/2003 to 10/08/2004) focuses 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 project will also design and test an upstream slug generator (SG).

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

² HPS[®] - Horizontal Pipe Separator - Copyright, The University of Tulsa, 2000

³ SD[®] - Slug Damper - Copyright, The University of Tulsa, 2001

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5. Executive Summary

The goal of this six-year (July 09, 2003 – October 08, 2008) 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 six-year, three-budget-period 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 adapt the developed compact separation system for Floating Production Storage and Offloading (FPSO) and subsea applications. At the completion of this project The University of Tulsa will release to the public domain a final report describing their 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) will focus on the development of additional individual compact separation components, such as the horizontal pipe separator (HPS[®]), for obtaining clean oil stream from oil-water mixture, flow conditioning components, such as the helical pipe (HP) and slug damper (SD[®]), for dissipating slugs upstream of the compact separators. The project will also design and test an upstream slug train generator (SG).

The second phase of the project (Budget Period II – 10/09/2004 – 10/08/2006) will include the design and construction of the existing flow loop modifications to enable high pressure testing. Experimental and modeling investigation of the integrated CMSS[®] for different configurations will be carried out in order to evaluate the performance of the individual separation components, integrated in the CMSS[®], and the total system performance. Experimental results will be used to evaluate the individual component's effect with respect to CMSS[®] overall system efficiency. CMSS[®] prototypes will be prepared for field-testing.

In the final phase of the project (Budget Period III - 2006 - 2008) dedicated control strategies will be studied and developed for the CMSS[®]. Also, a universal model for prediction of droplet size distribution, in the individual subsystem components and the integrated system, will be developed. High Pressure testing (up to 1000 psia) with crude oil will be conducted at available suitable experimental loops (such as Colorado Engineering Experimentation Station – CEESI) to evaluate the reliability of the integrated compact separation system and improve the design model, prior to implementation in the field. Software simulators will be developed for the proposed CMSS[®]s, to be used by the industry as design tools. The final product of the project will be the design of a CMSS[®] prototype to be tested in a subsea or FPSO application.

This report presents a brief overview of the activities and tasks accomplished during the part July 09, 2003 – October 08, 2004, related to the Budget Period I (July 09, 2003 – October 08, 2004) 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 and modeling investigations are presented. Subsequently, the technical and scientific results of the activities of this project period are presented with some discussions.

The findings of this investigation are summarized in the "Conclusions" section followed by relevant references.

6. Tasks of Current Budget Period (July 09, 2003 – October 08, 2004)

Task One - Development of Additional Compact Separation Components: (July 09, 2003 – October 08, 2003)

- a. Design, construction, and testing of the Helical pipe separator (HP).
- b. Design, construction, and testing of the Slug Damper (SD[®]).
- c. Design, construction, and testing of the Horizontal Pipe (HPS[®]).
- d. Design, construction, and testing of the unit Slug Generator (SG).
- e. Presentations in Advisory Board Meetings and interim report preparation.

Task Two – Mechanistic Modeling and Experimental Investigation of CMSS[®] Components: (October 09, 2003 – October 08, 2004)

- a. Mechanistic modeling of the helical pipe separator (HP).
- b. Mechanistic modeling of the slug damper (SD[®]).
- c. Mechanistic modeling of the horizontal pipe separator (HPS[®]).
- d. Experimental investigation of integrated multiphase distribution manifold, slug damper and GLCC^{®4} system.
- e. Presentations in Advisory Board Meetings and interim report preparation.

Task Three – Design and test multiple Slug Generator and Solid Separation Unit: (October 09, 2003 – October 08, 2004)

- a. Design and order replacement of all transparent pipe sections with steel sections.
- b. Develop test procedure for high-pressure operation of modified flow loop.
- c. Design, construct and test multiple Slug Generator (SG).
- d. Design/identify, construct/purchase and test Solid Separation Unit (SSU).
- e. Presentations in Advisory Board Meetings and interim report preparation.

⁴ GLCC[®] - Gas-Liquid Cylindrical Cyclone - Copyright, The University of Tulsa, 1994

7. Experimental and Modeling Investigations

The initial phase of the project (Phase I) focuses on the development of additional individual compact separation components such as the horizontal pipe separator (HPS[®]) for obtaining clean oil stream from oil-water mixture, and flow conditioning components such as the helical pipe (HP) and a slug damper (SD[®]) for dissipating slugs upstream of the compact separators. Simultaneously, the project focuses on the development and testing of a unit slug generator (SG). The details of the experimental and modeling investigations for each component are given below.

7.1 Development of Helical Pipe Separator (HP)

The helical pipe separator (HP) is a flow conditioning facility that can be installed upstream of separation equipment. The function of the HP is to decay large slugs in order to avoid operational problems in the downstream separation facilities. This is achieved by both gravity (downward flow in the helix) and centrifugal forces (occurring due to the rotation of the flow in the pipe).

A schematic of the HP test section is given in Figure 1. The helical pipe section consists of a 2-in. flexible transparent pipe coiled in a helical shape. The flexible pipe can be coiled in different helical diameters, up to 2 meters. Up to 7 turns of the helix can be constructed. Rigid inlet and outlet sections of 2-in ID are located upstream and downstream, respectively. An absolute pressure transducer and a differential pressure transducer are also attached to the horizontal inlet section. This differential pressure transducer measures the pressure difference between the inlet section and the sixth turn. A pair of conductance probes is attached at the inlet section and in every single turn from the first to the seventh. The conductance probes are utilized to track and measure the length of the slug as it flows downstream of the helical pipe. Figure 2 provides a schematic of the conductance probe. The conductance probe consists of a hollow copper tubing with a solid insulated copper wire located at its center. The hollow tube is connected to the negative end of an electric circuit whereas the solid wire is connected to the positive end. When water is in contact with the tip of the probe, electrical current flows from the positive end to the negative end and it acts as an electrical switch that closes the circuit allowing current to flow through the resistor ends.

However, when no liquid is touching the positive end, or liquid does not bridge the negative end simultaneously, 0 volts is measured.

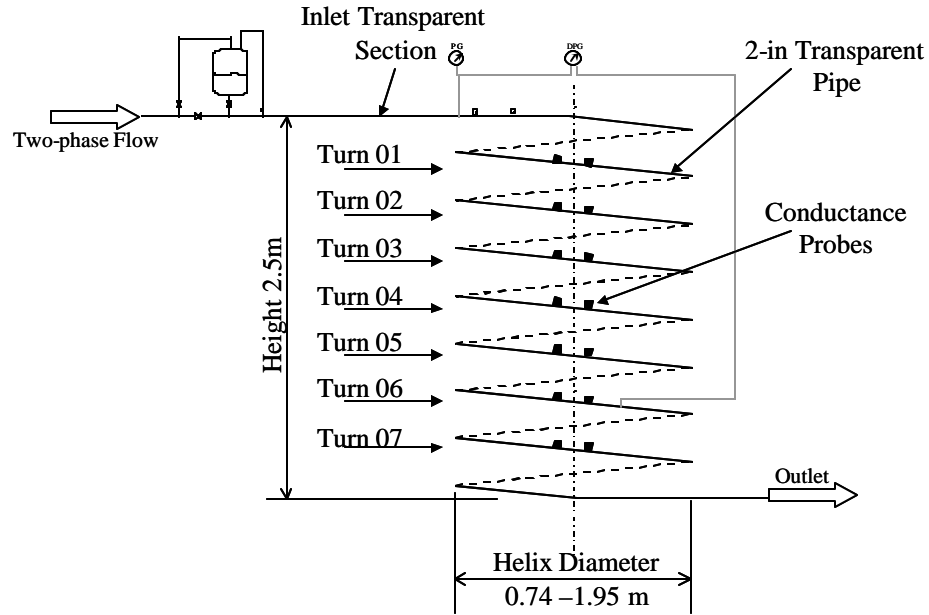


Figure 1: Schematic of Helical Pipe (HP) Test section

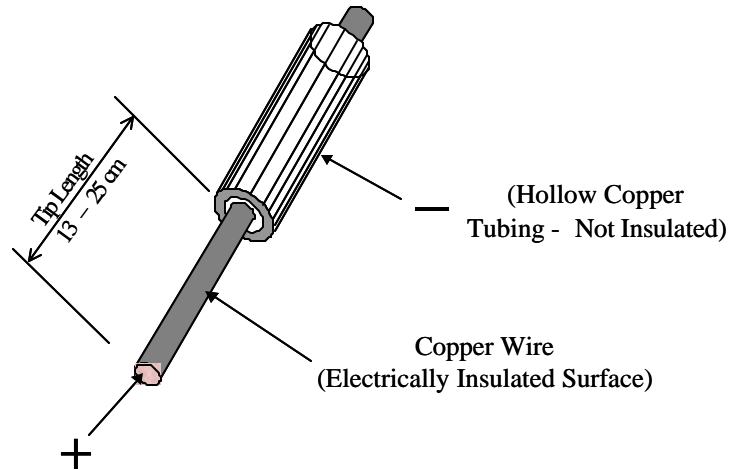


Figure 2: Schematic of Conductance Probe

Thus, the conductance probe can detect the front and the back of the slug body, as shown schematically in Figure 3. Thus, a pair of probes allows the determination of the slug

translational velocity and the length of the slug body and slug units, which are essential for the determination of the slug decay along the HP. To determine the behavior of the slug as it flows through the test section, pairs of conductance probes are located at the inlet of the helix as well as in the turn # 1 through turn # 7.

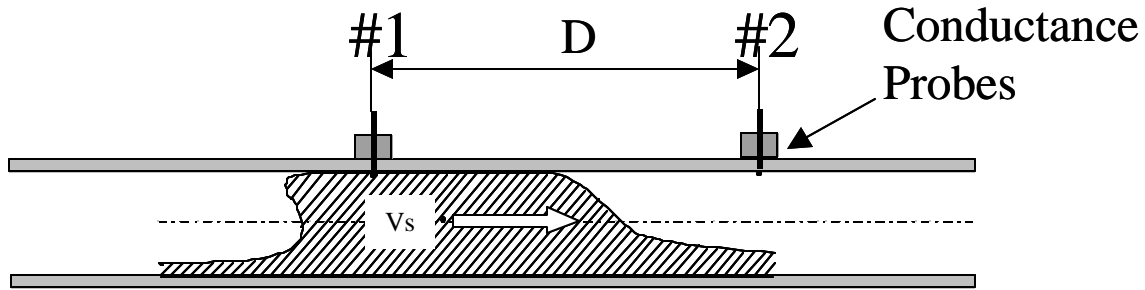


Figure 3: Slug Detection and Measurement with a Pair of conductance Probes

Air and water will be used in this study. The range of the superficial velocities will be:

- Superficial gas velocity: 1, 5 and 10 m/s.
- Superficial liquid velocity: 0, 0.05, 0.1, 0.5 and 1 m/s. A superficial liquid velocity of 0 m/s represents a hilly terrain flow condition where only gas flows in the uphill sections.

For conditions where no natural slug flow occurs at the inlet of the helix, artificial slugs will be generated with a unit slug generator, whose length ranges from those obtained under natural slug flow to severe slugging conditions. Therefore, the range of the slug lengths that will be tested is 20 to 280 pipe diameters.

A mechanistic model is developed based on the flow hydrodynamics and experimental data. The developed model is capable to predict the slug decay along the turns of the HP, and will be used to design HP facilities.

7.2 Development of Slug Damper (SD^ä)

Equipment such as flow meters, level meters, etc. located downstream of compact separators, such as the GLCC[®], cannot tolerate sudden changes in flow rate similar to that occurring during slug flow, even though the separator itself can handle such variation of the flow rates. To alleviate this problem and to increase the operational envelope of the

separation system, a Slug Damper (SD[®]) is proposed to be install upstream of the separation system. The SD[®] functions as a flow-conditioning device, damping incoming large slugs, providing more residence time to the separation system and smoothen the outlet variation in the flow rates.

Figure 4 shows a schematic of the SD[®]. As can be seen, the SD[®] consists of two large diameter legs (larger than the inlet flow-line) located one above the other, with length “L”. The two legs are connected to the GLCC[®], resembling a long dual GLCC[®] inlet. The main operational mechanism is a segmented orifice located in the lower leg, just upstream of the GLCC[®]. As shown in the zoomed view of the figure, the segmented orifice of a diameter “D” is open at the bottom (“H”). Thus, during normal operation (without large slugs) the production goes through the orifice. However, when large slugs arrive at the GLCC[®], the segmented orifice blocks the slugs from flowing into the separator, forcing the liquid to accumulate in the lower SD[®] leg, while the gas is bypassed through the upper leg. Conductance probes are installed along the lower and upper legs in order to monitor the accumulated liquid front propagation.

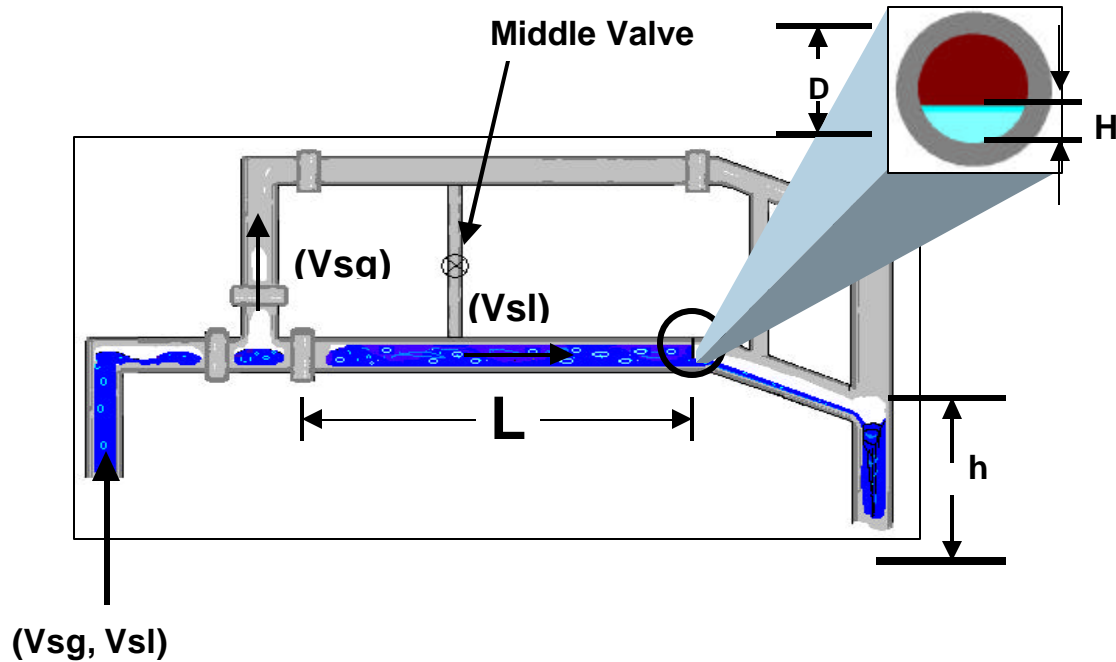


Figure 4: Schematic of Slug Damper (SD[®])

The experimental data acquisition program includes test runs with a large variation of flow rates: superficial liquid velocities from 0.5 ft/s to 2.5 ft/s and superficial gas velocities from 10 ft/s to 40 ft/s. Four different sizes of the segmented orifice will be tested. The following measurements have been acquired during the experimental tests:

- Operational envelope of SD[®]
- The advancement of the accumulated liquid front,
- GLCC[®] liquid level “h”
- Differential pressure across the orifice
- Liquid flow rate downstream of the GLCC[®]
- Static pressure in the SD[®]

The experimentation is followed by detailed mechanistic modeling for prediction of the performance of the SD[®] and integrated GLCC[®]/SD[®] system (for liquid carry-over) for field applications. A mechanistic model for operational envelope of gas carry-under is being developed for the prediction of the hydrodynamic flow behavior and performance of the integrated GLCC[®]/SD[®] system.

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 gas carry-under;
- percent 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 CMSS[®] system. It will allow the user to optimize the CMSS[®] design accounting for tradeoffs in the I.D, height and other geometrical features of the CMSS[®] system. The model will also provide the trends of the effect of fluid physical properties and the information required for determining when active controls will be needed.

7.3 Horizontal Pipe Separator (HPS[®])

The HPS[®] project investigates the separation behavior of oil-water mixture flow through a horizontal large diameter pipe, at low velocities, capable of producing clean oil stream. The scope of the HPS[®] study is to develop a simple, reliable, inexpensive, easy to install and operate separator especially suited for subsea applications. The HPS[®] is constructed simply from pipe sections that are easy to assemble. Also, a HPS[®] system, consisting of a manifold connecting multiple HPS[®] in parallel, can be constructed. This HPS[®] system will be suitable for deployment in deep water operations where the conventional vessel-type separator cannot be deployed, because it generates high buoyancy forces due to its large dimensions and volume.

The objectives of this study are:

- a) Investigate the flow and separation behavior of oil-water mixtures in horizontal pipes
- b) Develop a mechanistic model that predicts separation efficiency for given fluids, geometry and flow rates
- c) Compare and refine the model with data obtained in this study and from literature

Figure 5 shows a pictorial view of the HPS[®] while Figure 6 is a technical schematic of the HPS[®] and the flow loop. As can be seen, the oil-water mixture flows into the horizontal pipe separator through multiple inlet configurations. This will enable determination of the optimal inlet configuration. The flow in the 6" ID, 20' long test section will be monitored carefully to observe the stratification of the flow. The oil and water will be removed from the oil outlet and water outlet located at the end of the horizontal pipe separator. Inlet and outlet flow rates and water cut are measured with a set of Coriolis mass flow meter, 2 at the inlet and 2 at the outlets of the HPS[®].

The instrumentation along the HPS[®] is shown in Figure 7. The oil-water interface level along the pipe is measured with several optical level meters and pitot tubes. Droplet size distribution is monitored utilizing a boroscope connected to a digital camera. Also, several differential pressure transducers are used to measure the pressure drop along the HPS[®].

Operating procedure to be followed is:

- Mix the fluids at the inlet.
- Identify Zones of segregation/coalescence along the HPS[®] using the HPS[®] Instrumentation.
- Identify different zones such as simultaneous flow of oil layer, droplets of water in oil, oil droplets in water, and water layer.
- The thickness of each zone should be function of the axial coordinate along the pipe.

The parameters to be measured are:

- a) At the inlet: Oil and water flow rates and droplet size distribution (proportional to the pressure drop in the upstream mixer).
- b) Along the HPS[®]: Phase profile as a function of the position along the separator, droplet size distribution, velocity profile and pressure drop.
- c) At the exit: Flow rates and water cut of the oil and water streams. Thus, the separation efficiency can be determined.

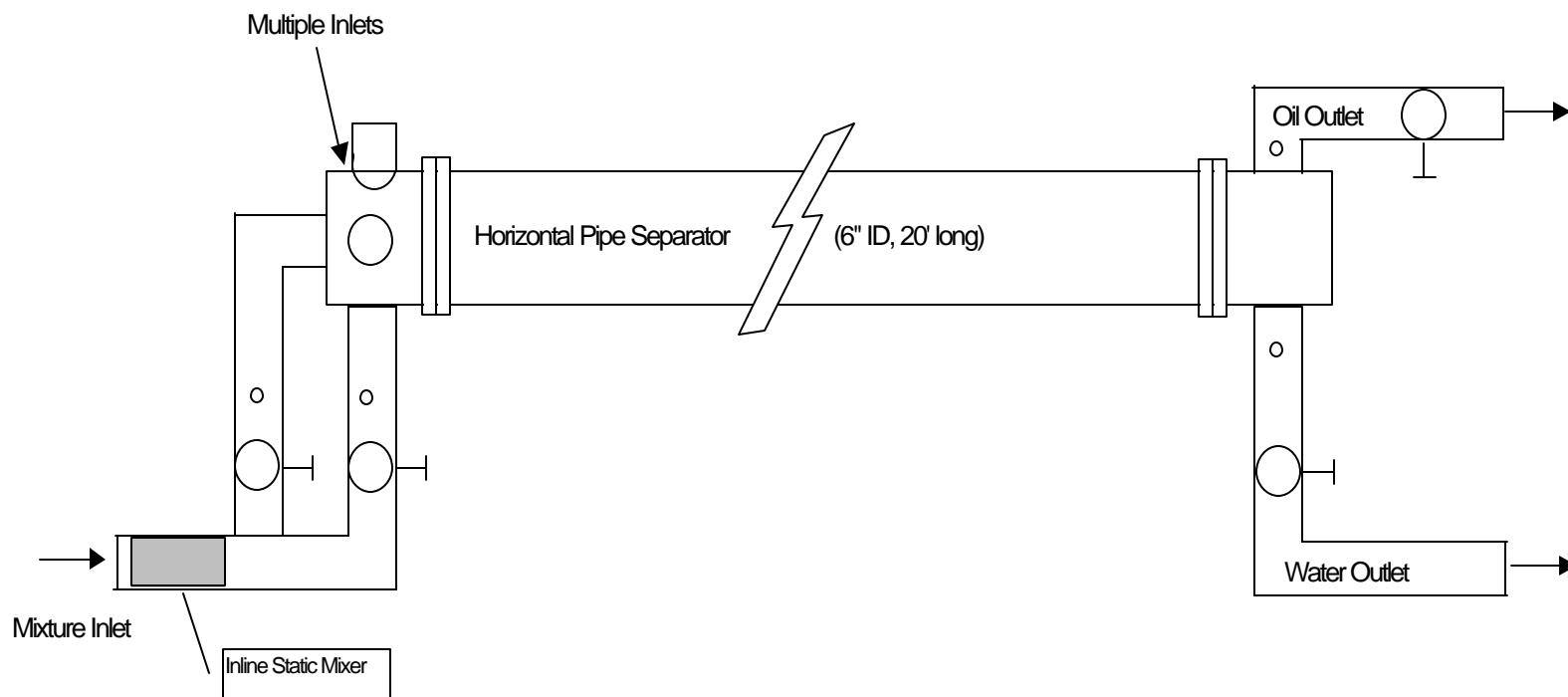


Figure 5: Pictorial View of Horizontal Pipe Separator (HPS[®])

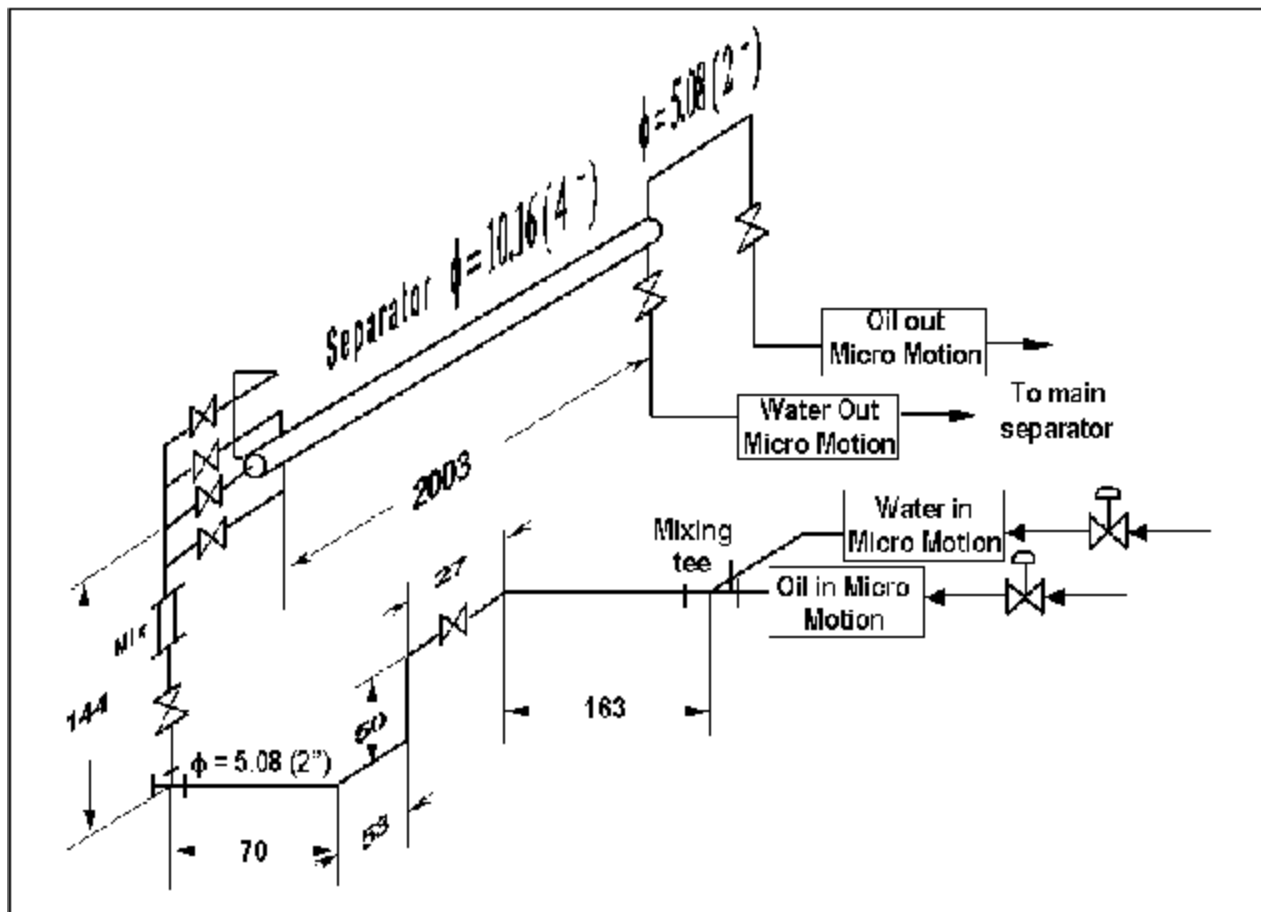


Figure 6: Schematic of Horizontal Pipe Separator (HPS[®]) and Flow Loop

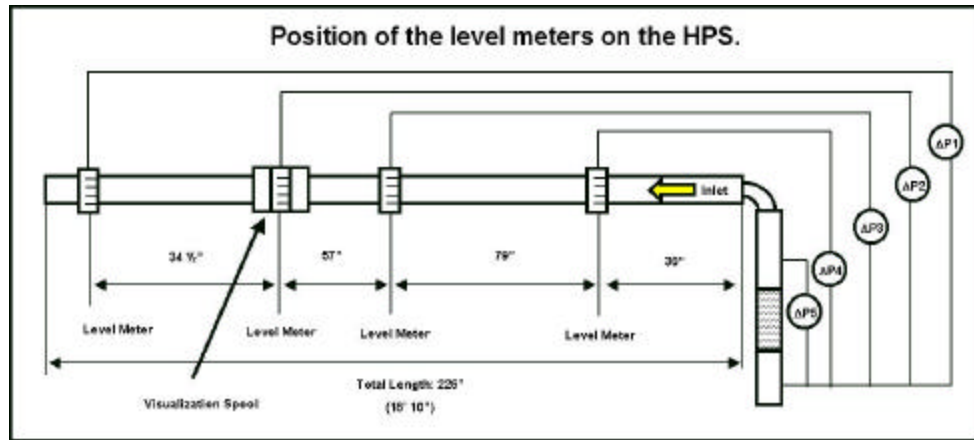


Figure 7. Schematic of HPS[®] Instrumentation

7.4 Design of Slug Generator (SG)

The objective of the slug generator facility is to generate a unit slug of different lengths, so as to simulate slugging conditions occurring in the field. The SG is essential to the development of the CMSS[®] or any other compact separation system. A schematic of the unit SG and the principle of its operation are shown in Figure 8. The unit slug generator consists of a large volume tank with a level indicator. Associated with this tank are three pneumatic ball valves. One of them, in the main line is normally open, allowing normal multiphase flow in the line. The other two valves, in the bypass, are normally closed. A pressure equalizer mechanism is also provided to the slug generator in order to minimize the pressure loss due to the sudden acceleration of the dumped water from the tank into the line. An artificial slug can be dumped into the system by activating the solenoid valves that supply compressed air to the actuators of the three pneumatic valves. As a result, the normally-open valve in the main line is closed while the two normally-closed valves are opened to allow the multiphase flow to enter into the tank from the top, pushing the water into the main line in the form of a slug. Once the dumping of the artificial slug is initiated, an electronic timer is triggered to reset the original state of the pneumatic valves. By this means the length of the artificial slug can be controlled, as it is proportional to the dumping time. Thus, by programming the valves to open and close in a given

interval sequence, a train of slugs of a desirable distribution can be generated that can be sent into the CMSS[®].

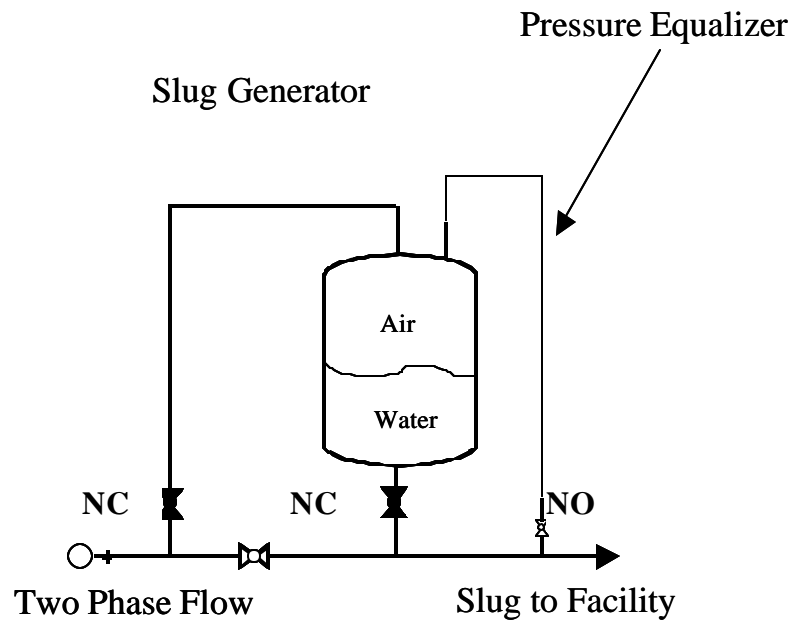


Figure 8: Unit Slug Generator Facility

The design of the unit SG has been enhanced in this project activity (Task 3) to generate a desirable slug distribution upstream of the CMSS[®]. This will enhance the testing of the developed CMSS[®], in particular the proposed control system. The details of the multiple slug generator design is given in Section 8.4.

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:

8.1 Helical Pipe Separator (HP) – Design, Construction, Testing and Modeling

The helical pipe separator is an inlet flow conditioning facility that can be installed upstream of separation equipment (see Fig. 9). The function of the HP is to decay large slugs in order to avoid operational problems in the downstream separation facilities and improve its performance. This is achieved by both gravity (downward flow in the helix) and centrifugal forces (occurring due to the rotation of the flow in the pipe).

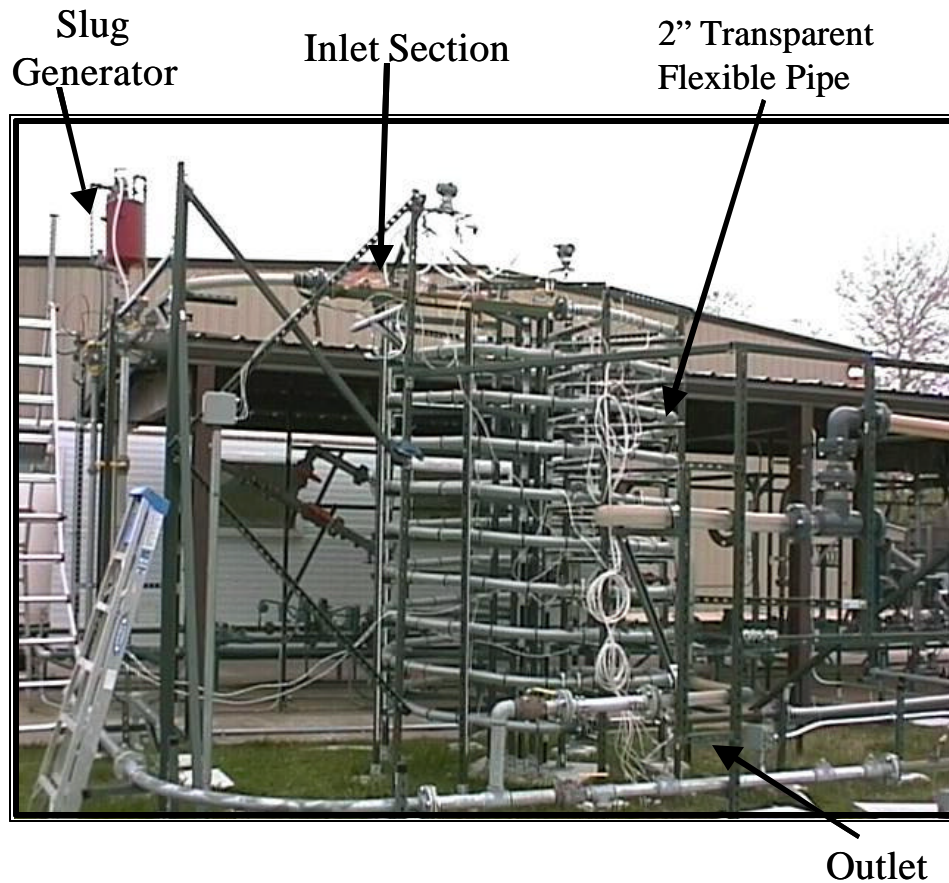


Figure 9. Helical Pipe Separator Test Facility

Detailed experiments were conducted to understand the mechanisms involved in slug dissipation phenomenon in downward inclined helical pipe flow. The data have been acquired for a wide range of superficial gas and liquid velocities, under normal slug flow and also with artificial slugs to study the effects of helical diameter, pitch angle and number of circular turns on slug dissipation. Based on the experimental data a new concept of Slug Dissipation Index has been developed as a quantitative measure of the helical pipe effectiveness. Also, a novel Slug Dissipation Map has been constructed summarizing the slug dissipation phenomena. The experimental results demonstrate that it is feasible to utilize helical pipes as inlet devices for flow conditioning.

Three slug dissipations mechanisms have been identified for the helical pipe, namely, Gravitational Force Mechanism (occurring at low superficial gas velocities, larger helical diameters and characterized by larger dissipation length), Centrifugal Force Mechanism (occurring at high superficial gas velocities, smaller helical diameters and characterized by

smaller dissipation length) and Slug Front Stability Mechanism (occurring at low slug velocities). The mechanistic modeling consists of two parts, the first part is slug dissipation modeling while the 2nd part consists of the prediction of stratified flow behavior in the helical pipe, which serves as an input to the slug dissipation model.

As a result of applying a liquid mass balance over the moving and deforming control volume and considering that the fluid properties, liquid hold up and translational velocities of the interface are constant during the time of dissipation, the slug dissipation is obtained by the rate of change of the slug length, and is given as:

$$\frac{\Delta L_S}{\Delta t_{DISS}} = v_{T2} - v_{T1} = v_{DISS}$$

The slug tail velocity is the succeeding elongated bubble front velocity, moving behind the liquid slug body. it is expressed as a function of slug (mixture) velocity, v_s , and the drift velocity, v_d , in the form proposed by Nicklin (1962),

$$v_{T2} = C_0 \cdot v_s + v_D$$

The velocity of the front is proposed to be the superposition of the velocity obtained from a liquid mass balance at the front of the slug and bubble turning drift velocity and is given by:

$$v_{T1} = \frac{H_S \cdot v_S - H_F \cdot v_F}{H_S - H_F} - v_D$$

The slug dissipation length is given as:

$$L_{DISS} = \left(\frac{v_{T1} + v_{T2}}{2} \right) \cdot \frac{\Delta L_S}{v_{DISS}}$$

Using the combined momentum equation, a similar mechanistic model for stratified flow in helical pipe has also been derived. Detailed experiments were conducted to evaluate the model predictions. Typical comparison of model and experimental data is given in Fig. 10, which show a very good agreement.

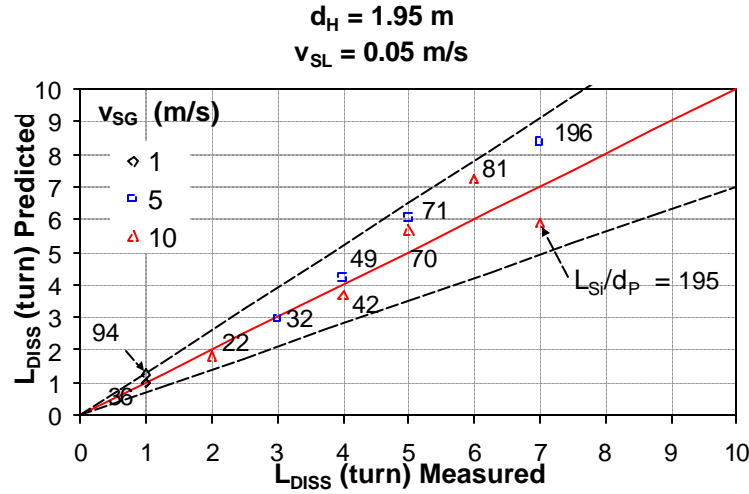


Figure 10. Typical Comparison of Model Prediction and Experimental Data (Helix #1)

8.2 Slug Damper – Design, Construction, Experiments, Modeling and Field Installation

The objective of this project is to provide flow conditioning upstream of the GLCC[®] in order to protect it from large terrain slugs. The slug damper, shown in Fig. 11, below, consists of two parallel large diameter pipes (larger than that of the production line). The lower leg is equipped with a segmented orifice having an opening at the bottom. During normal production, the total flow passes through the orifice opening without being disturbed. However, when a terrain slug is produced, it is blocked by the orifice plate and is accumulated in the lower and upper legs. At the same time, the liquid phase flows through the orifice opening with a smooth low flow rate. The gas is bypassed through the upper leg.



Figure 11. Slug Damper Test Section

This study investigated theoretically and experimentally a novel flow conditioning device, namely, the slug damper, to be used upstream of compact separation systems.

The following were accomplished during the phase of this study:

- Over 200 experimental runs were conducted. Four different segmented orifice openings including 1", 1.5", 2" and 3" (without orifice) were used. The superficial liquid and gas velocities in the 2" inlet pipe were: v_{SL} from 0.5 to 2.5 ft/s and v_{SG} from 10 to 40 ft/s.
- For each experimental run, the measured data included: propagation of slug liquid front in the damper (using a set of conductance probes), differential pressure across segmented orifice, GLCC[®] liquid level, GLCC[®] outlet liquid flow, and static pressure in the GLCC[®].
- Data analysis shows that the slug damper is successful in dissipating the long slugs and provides a fairly constant flow rate into the GLCC[®] when the slug is being accumulated in the damper. Also, the available damping time, which is related to the total volume processed by the damper, and in turn the slug length, is a strong function of the superficial gas velocity

(and mixture velocity). The damper capacity varies in a finite range, even though the mixture velocity varied over a wide range.

- A mechanistic model is developed for the prediction of the hydrodynamic flow behavior in the slug damper. 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 $\pm 30\%$ with respect to the available damping time and outlet liquid flow rate.
- One significant accomplishment of this project is the implementation of this technology – slug damper as a stand-alone unit - in the field. To date, six slug damper units have been installed in the field. Figures 12 and 13 show the installation of 2 slug damper units in the field – one in Indonesia and the other in California by TUSTP member companies, namely ChevronTexaco and SMS, Inc.



Figure 12. CPI, Indonesia - Duri Area-10 GLCC[®]s with Slug Damper installed by ChevronTexaco



Figure 13. GLCC[®] with Slug Damper installed in California by SMS, Inc.

8.3 Horizontal Pipe Separator (HPS[®]) – Experiments and Modeling

The objective of this project is to develop the technology to use horizontal (and near horizontal) pipes as oil-water separators, in remote and high buoyancy working environments, i.e., subsea or deep-sea applications that make it difficult to install a traditional vessel separator. The scope of this study is to analyze the proper flowing conditions in pipes to induce separation of oil and water phases and study the effect of outlet geometry on the separation efficiency.

The fully instrumented test section (18-ft long, 3-inch diameter) developed in this study is shown in Figure 14.

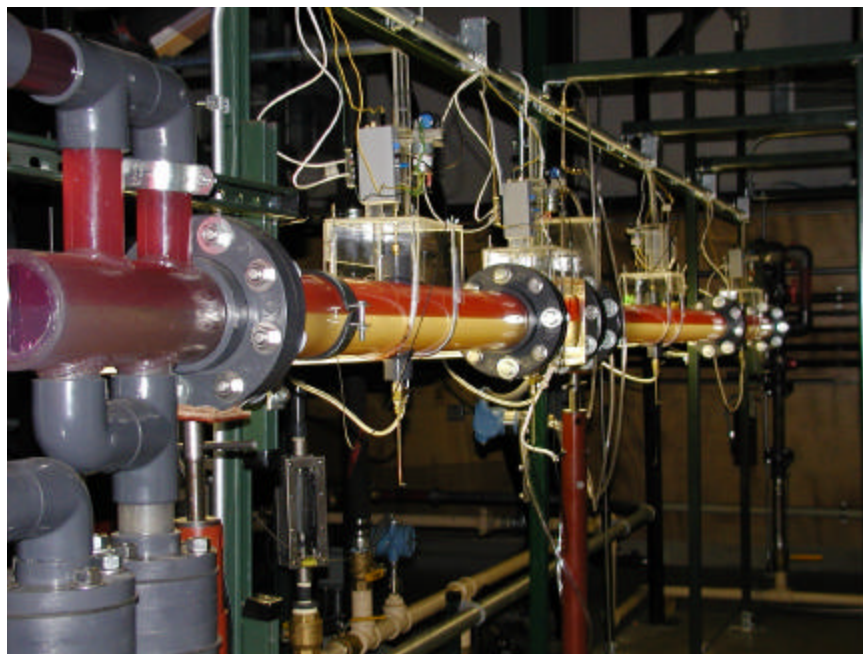


Figure 14. Horizontal Pipe Separator (HPS[®]) Test Section

The following physical phenomena are involved in the HPS[®] separation process: Droplet coalescence/breakup, droplet transport in continuous media, stratified liquid-liquid flow in pipes and physical properties on dispersions. Experimental data has been acquired on oil-water developing flow in pipes, measuring local velocities, holdup and droplet size/droplet size distribution, with different inlet and outlet configurations to properly analyze the oil/water separation process in the HPS[®].

a) A flushed pitot approach was used to measure local mixture velocity inside the HPS[®]. This method showed two problems:

- The zero calibration at static conditions does not correspond to the dynamic conditions one.
- The method did not work well until water cuts increased up to 5%.

To overcome these problems, the method was modified to include the use of velocity profiles at 0, 30, 60 and 90 degrees from the vertical, measured using an integrated approach of both Pitot Tube and Video Velocity Measurement methods. Typical velocity profile using 3 different measurement techniques is shown in Figure 15.

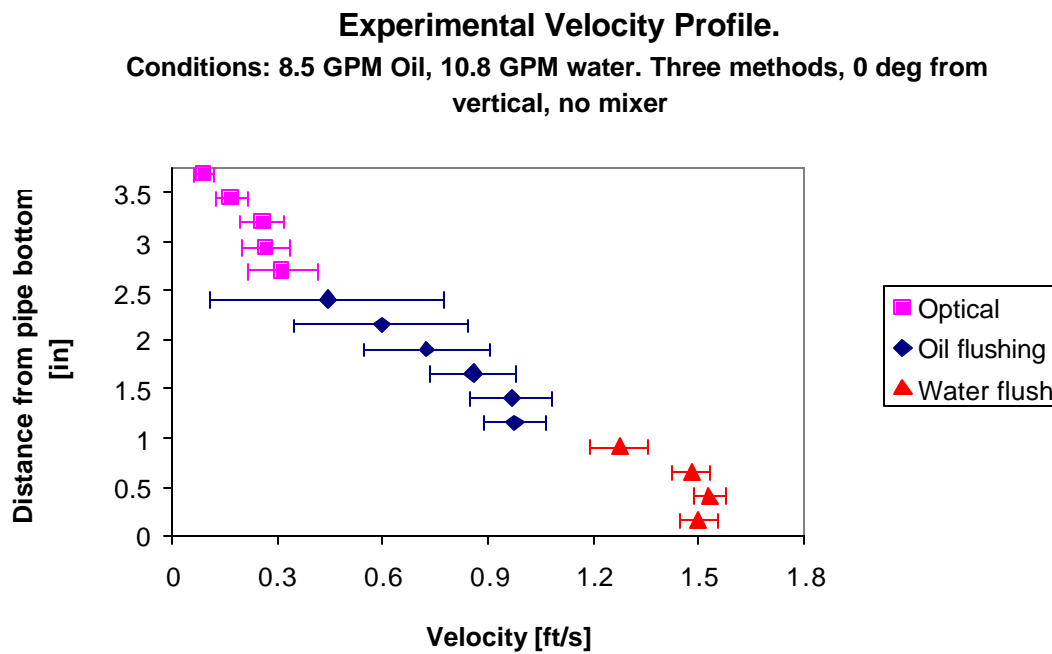


Figure 15. Experimental Velocity Profile (Orientation – 0 deg from Vertical)

b) Water cut measurement was made by isokinetic sampling. Sample watercut profile at the test section is given in Figure 16.

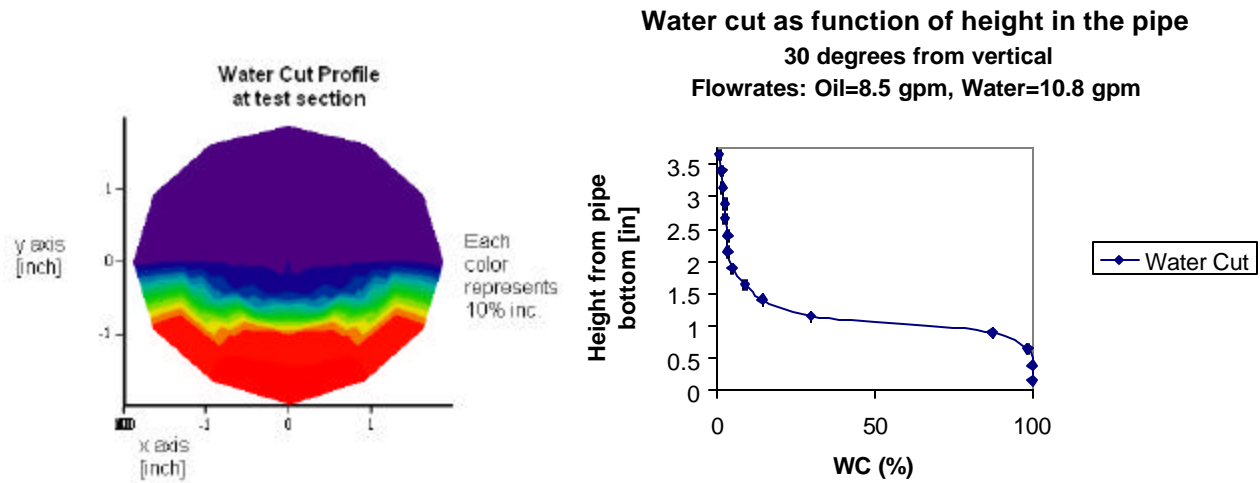


Figure 16. Sample Watercut Profile and Watercut Plot

- c) Several tests were conducted (see Table 1) and velocity and water cut maps were generated at several sections of the pipe for given flow conditions, and a volumetric balance for the mixture and for each phase was made. The balances fairly agreed with the inlet conditions. This confirms the ability of the method to properly measure velocity and watercut inside the HPS[®].

Table 1. Experimental Data Acquired and Analyzed

	With Mixer installed at the inlet 15 gpm (0.436 ft/s)					Without Mixer installed at the inlet 15 gpm (0.436 ft/s)				
	10%WC	30%WC	50%WC	70%WC	90%WC	10%WC	30%WC	50%WC	70%WC	90%WC
Outlets Efficiency	x	x	x	x	x	x	x	x	x	x
Vertical Vel Profile	x	x	x	x	x			x	x	x
Overall Vel Profile			x	x				x	x	
Vertical Water Cut			x	x	x			x	x	
Vertical Droplet Dist.	x	x	x	x						
	20 gpm (Vmix=0.581 ft/s)					25 gpm (Vmix=0.725 ft/s)				
	10%WC	30%WC	50%WC	70%WC	90%WC	10%WC	30%WC	50%WC	70%WC	90%WC
Outlets Efficiency	x	x	x	x	x	x	x	x	x	x
Vertical Vel Profile	x	x	x	x	x			x	x	x
Overall Vel Profile			x	x				x	x	
Vertical Water Cut			x	x				x	x	
Vertical Droplet Dist.	x	x	x	x						
	30 gpm (Vmix=0.87 ft/s)									
	10%WC	30%WC	50%WC	70%WC	90%WC	10%WC	30%WC	50%WC	70%WC	90%WC
	x	x	x	x	x			x	x	x
			x	x				x	x	
			x	x				x	x	

Experimental investigations demonstrate that the HPS[®] is a simple and viable technology for free-oil knockout of oil-continuous flow. Several HPS[®] systems in series can be utilized for successive purification of oil-continuous flow. A 2-layer and a preliminary 3-layer mechanistic model for the prediction of developing flow and developing length on oil-water flows have been developed, enabling determination of the separation efficiency. After completion of model development, comparison between model predictions and the acquired data and other data from literature will be carried out.

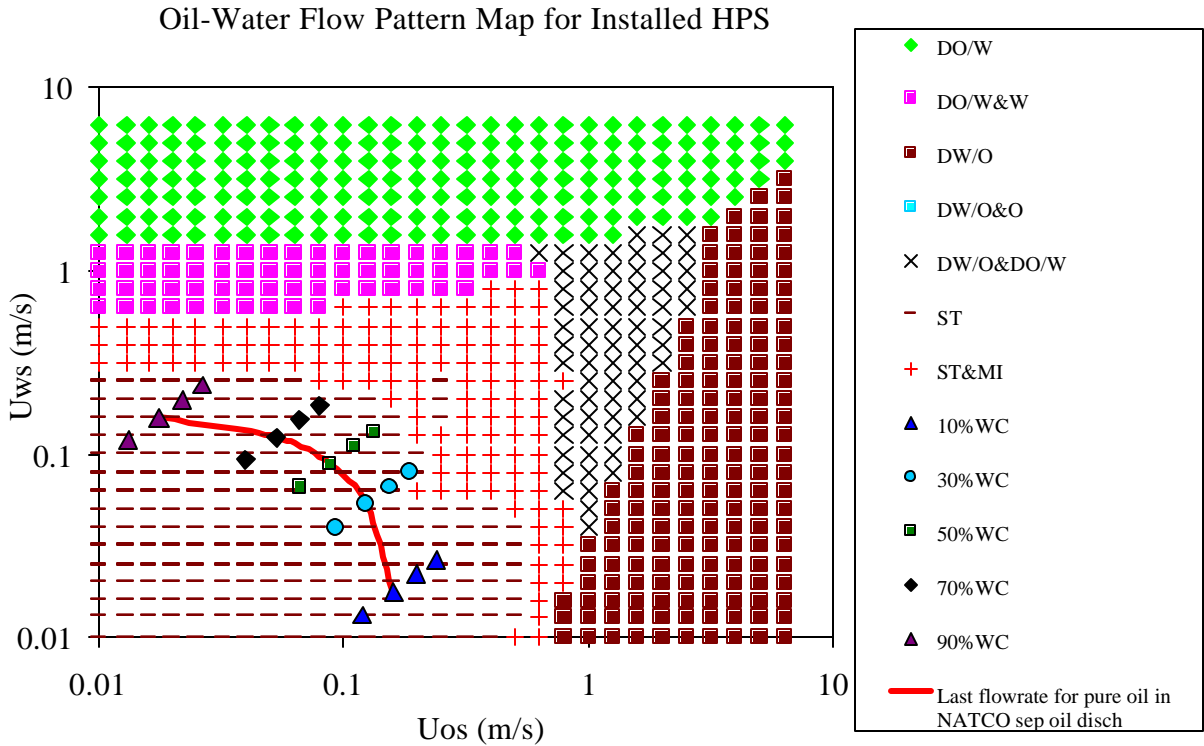


Figure 17. Oil-water Flow Pattern Map for Installed HPS[®]

The presentation at the TUSTP Advisory Board Meeting showed the experimental matrix and the experimental results obtained for the HPS[®]: velocity profiles, water cuts and droplet size distributions. Velocity profiles were shown at the vertical for 10 to 70%WC, 15 and 20 GPM, but in the whole section only for 50% and 70%WC due to flushed pitot tube measurement limitations. Water cuts were measured only for 50 and 70%WC, but droplet size were measured

for all experimental matrix. For the experimental conditions, packed oil-dispersion-in-water at top (with WC as low as 10%) and loose oil-dispersion-in-water at bottom were measured. Small changes in velocity profiles and water cut profiles observed between metering stations. However, segregations of oil and water dispersed-phases and coalescence of oil dispersed-phase were observed. Velocity measurement was difficult by flow dynamics (oscillations) at the top of the pipe. Small variations for different outlets were seen, where the vessel and branched outlet showed better separation than the single outlet when the flow rate at the water leg was smaller than the water flow rate at the inlet. These differences tended to disappear at higher flow rates. The oil-water flow pattern map for the installed HPS[®] is shown in Figure 17.

8.4. Development of Slug Generator (SG) – Unit and multiple – Design, Construction and Testing



Figure 18. Unit Slug Generator Test Facility

A photograph of the unit slug generator facility developed to dump a single artificial slug into the test devices such as, GLCC[®], helical pipe and slug damper, is shown in Figure 18. The unit slug generator consists of a 9-gallon metallic tank with a level indicator. Associated with this tank are three pneumatic 2-in ball valves. One of them, in the main line, is normally open allowing two-phase flow into the downstream facility. The other two valves, on the bypass, are

normally closed. A pressure equalizer mechanism is also provided to the slug generator in order to minimize the pressure loss in the helical pipe due to the sudden acceleration of the water from the tank into the line. An artificial slug is dumped into the system by activating the solenoid valves that supply compressed air to the actuators of the three pneumatic valves. As a result, the normally open valve is closed while the two normally closed valves open to allow the two-phase fluid to enter the tank from the top pushing the water into the inlet of the helical facility. Once the dumping of the artificial slug is initiated, an electronic timer is triggered to reset the original state of the pneumatic valves. By this means the length of the artificial slug can be controlled. This unit slug generator facility has been tested extensively in connection with the helical pipe and slug damper experiments.

The objective of the multiple slug generator (SG) facility is to generate multiple slug units of different lengths, so as to simulate slugging conditions occurring in the field. This will enable us to generate a desirable slug distribution upstream of the CMSS[®] and will enhance the testing of the developed control system. We believe that the SG is essential to the development of the CMSS[®] or any other compact separation system.

The slug generator (schematic shown in Figure 19) consists of two lines, one for gas phase and the other liquid phase, equipped with control valves. The two lines are joined in a “Y” configuration leading to the slug flow line. Sophisticated control with electronic timer will open and close the gas and liquid control valves in a pre-determined sequence so as to generate liquid slugs and gas pockets of different length distributions.

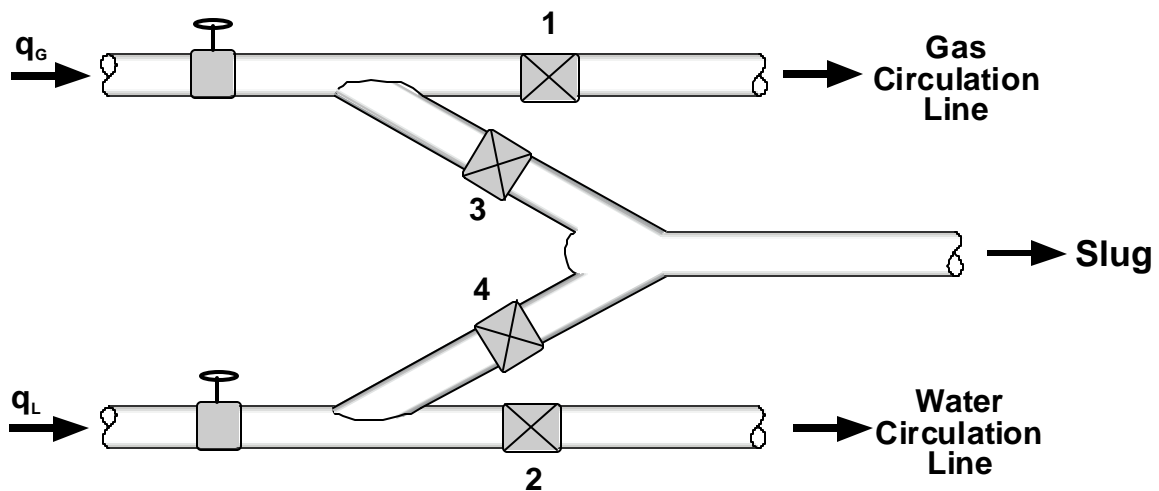


Figure 19. Schematic of Multiple Slug Generator Unit

The designed slug generator unit is currently being constructed. Multiple slug generator will be used to test the compact separator components and the entire CMSS[®] systems and the respective control systems under slug flow conditions. This study will result not only with improved control strategies for compact separators but also for improved hydrodynamic modeling and design of these units under slugging conditions.

8.5 Experimental Investigation of Integrated Multiphase Distribution Manifold, Slug Damper and GLCC[®] System

Gas and liquid flow rates vary from well to well. Conventional manifold is usually used to combine and redistribute the fluids of different wells into downstream parallel separators. The mal-distribution of gas and liquid from the conventional manifold hinders the performance of the downstream separators, resulting in low separation efficiency.

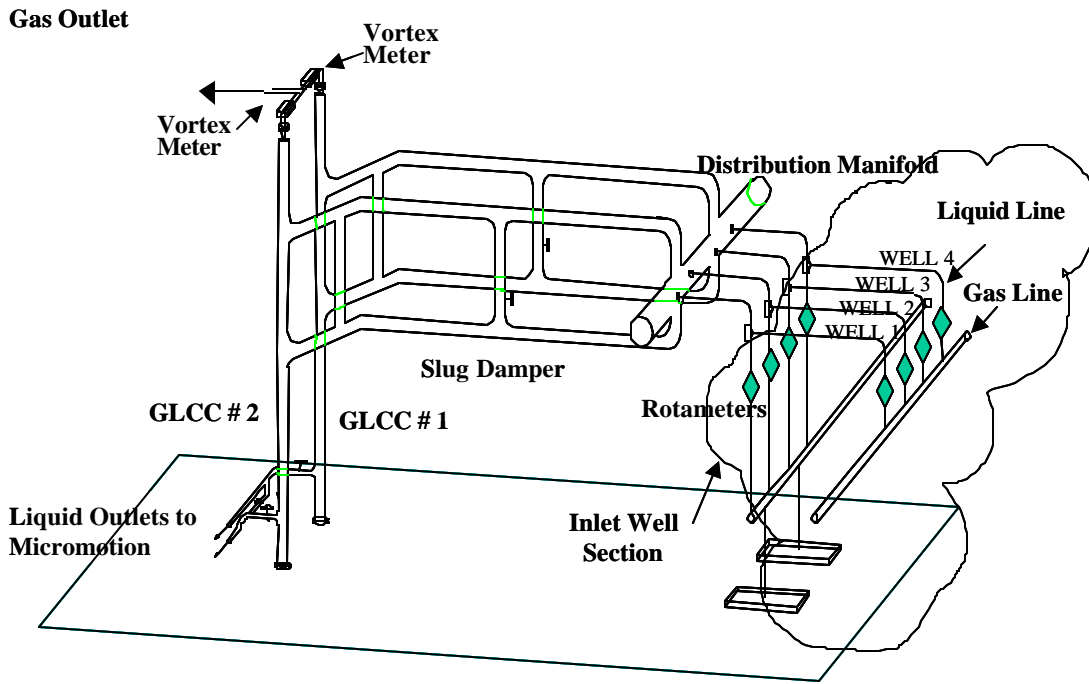


Figure 20. Schematic of Manifold/Slug Damper/GLCC[®] System

The objective of this study is to develop an innovative elevated multiphase distribution manifold integrated with slug damper, GLCC[®] system that provides flow conditioning and maximizes capacity and performance of downstream parallel separators. The scope of this

project is performance testing of the multiphase distribution manifold and determination of operational envelop for liquid carry-over of the new manifold/slug-damper/GLCC[®] system. The gas and liquid split ratios in the Multiphase Distribution Manifold are also obtained.

The multiphase distribution manifold system, shown schematically in Fig. 20, consists of four sections, namely, inlet wells, manifold, slug dampers, and down stream GLCC[®]s. The distribution manifold enhances separation system's performance. It compensates for multiphase flow mal-distribution from different inlet wells and provides pre-separation and additional surge capacity upstream of separation facilities.

The operational envelope for liquid carry-over (LCO), given in Figure 21, provides the capacity of the new manifold/slug-damper/GLCC[®] system. The lower curve is the experimental results for a single stand-alone GLCC[®]; the upper dark blue line corresponds to the theoretically possible operational envelope of 2 parallel GLCC[®]s with equal split corresponding to the single stand-alone GLCC[®]; the rest of the data points present the results for the manifold/slug-damper/GLCC[®] system at different inlet well flow conditions specified in the test matrix.

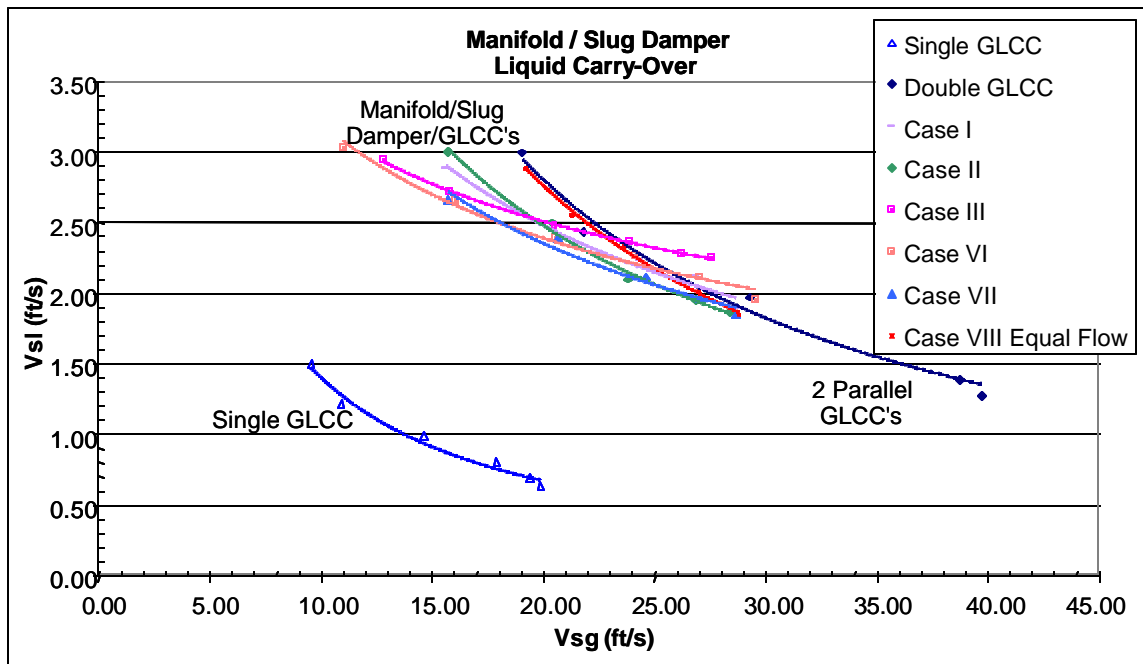


Figure 21 – LCO Operational Envelope of Manifold/Slug Damper/GLCC[®] System

From the experimental investigations, it can be concluded that the distribution manifold enhances separation system's performance. It compensates for multiphase flow mal-distribution from different inlet wells and provides pre-separation and additional surge capacity upstream of separation facilities. It can withstand sudden liquid increments even with high gas flow rates coming into the system and with different inlet well flow configurations.

Two integrated slug damper GLCC[®] systems installed in Indonesia and California are shown in Figures 12 and 13, respectively.

8.6. Experimental Investigation of Sand Separation Unit (SSU)

Production of sand can cause operational problems such as erosion and plugging of lines. Sand separation experiments and modeling will be carried out as part of the 6-year DOE project for development of the CMSS[®]. The experimental program will include utilization and testing of commercial desanders and other appropriate compact devices such as the novel oil-water-sand separator. The theoretical part will include the extension of the model developed for gas bubble and liquid droplet separation to solid-liquid separation via particle tracking. Schematic of flow loop for solid separation studies is shown in Fig. 22.

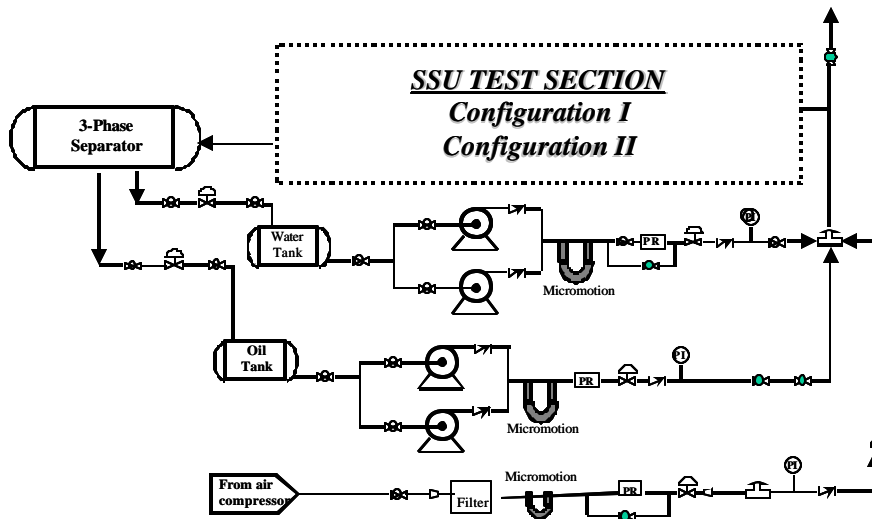


Figure 22 – Schematic of Flow Loop for Solid Separation Studies

Two proposed configurations of the SSU experimental flow loop will be investigated. The first consisting of a slurry injection system (Configuration I – Figure 23), and the second based on a dry sand injection system (Configuration II – Figure 24). The main scope of this

project includes the design/identification, construction/purchase, and testing of the compact SSU. Towards that objective, after detailed studies, the following solid-liquid hydrocyclone has been identified and procured from NATCO as shown in Figure 25. It is a 12-mm Microspin Assembly with 6 liners per assembly meant for treating fluids containing no more than 50-micron solids. This assembly has a d-50 of 5 micron. Preliminary experimental work has been initiated during the current budget period, which consists of acquisition of initial separation data. Future activities include mechanistic modeling, and comparison between data and mechanistic model predictions for dry and oil-coated sand particles. Additional funds are being sought to support the experimental component of this activity.

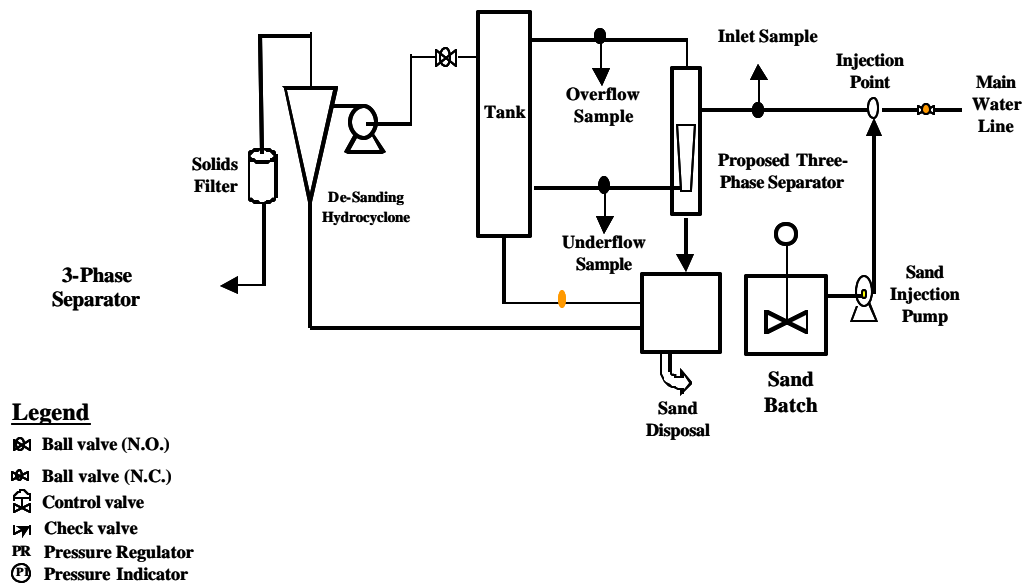


Figure 23 – Schematic of Slurry Injection System (Configuration I)

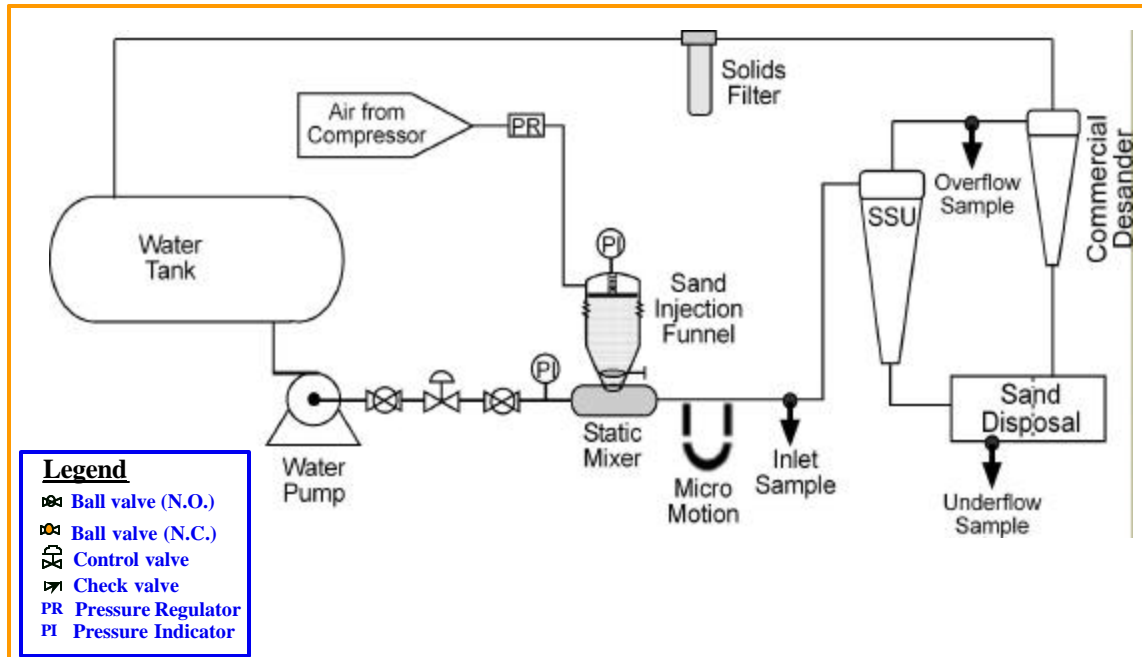


Figure 24 – Schematic of Dry Sand Injection System (Configuration II)

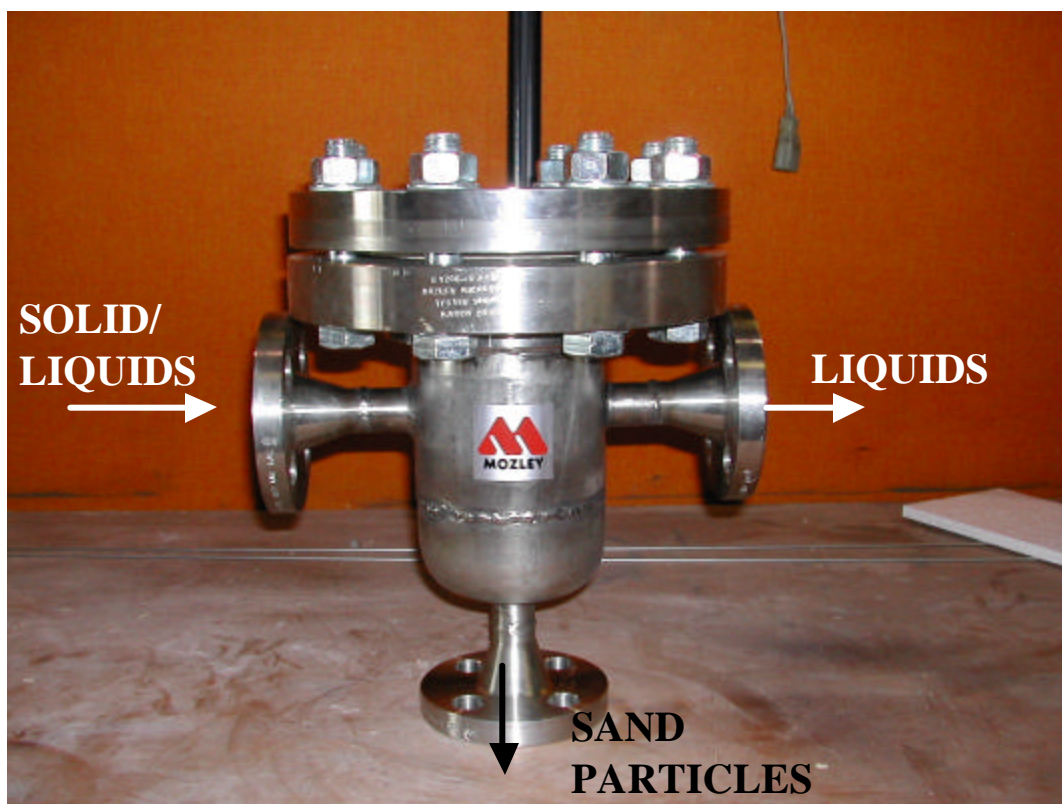


Figure 25 – Photograph of Solid Separation Unit (SSU)

8.7. Intelligent Control of Compact Multiphase Separation System (CMSS[©])

This project has been newly initiated is to conduct a detailed study on advanced control systems, such as fuzzy logic, artificial neural networks, etc., and examine their suitability for compact separation system. The objective of this project is to develop an intelligent control strategy for compact separation systems and conduct dynamic simulation and experimental investigation on the developed strategy.

A compact separation system is a combination of existing Gas-Liquid Cylindrical Cyclone (GLCC[©]), Liquid-Liquid Cylindrical Cyclone (LLCC^{©5}), Hydrocyclone (LLHC), Slug Damper (SD[©]) and various other field-tested equipment. The compact separation system should achieve a good separation efficiency to separate the multiphase flow from a single or combination of wells into a water rich stream, oil rich stream and gas stream.

Literature review for control system development for individual component and advanced control system like fuzzy logic has been conducted in detail. Configuration with all field tested devices and devices under development in TUSTP were shown in two separate schematics at the TUSTP advisory board meeting. Introduction to Fuzzy logic and artificial neural networks control system was presented. Combination of fuzzy logic and artificial neural network as one hybrid system was discussed and its advantages outlined. Application of fuzzy logic to compact separation system was presented. Application of artificial neural network to development of sensor fusion modules was shown. Development of simulation platform in Simulink/Matlab environment was discussed with flowchart and step-by-step communication link between mechanistic model, software code and simulation model in simulink was explained in great detail.

Current work involves development of a simulation platform in Matlab/Simulink[®] for various combinations of the above mentioned equipment, using existing mechanistic model results in the form of a look up table protocol. The simulation results would give a fair indication of implementation structure, which will yield the best results. It would also be a good starting point for control strategy implementation.

Future work will be to implement the most feasible and efficient hardware combination indicated by the simulation and implement control strategy using fuzzy logic and artificial neural

⁵ LLCC[©] - Liquid-Liquid Cylindrical Cyclone - Copyright, The University of Tulsa, 1998

network control system for appropriate individual components and a supervisory control system for the entire system. The final deliverable of this project is an intelligent integrated control system for CMSS[®].

8.8 Differential Dielectric Sensor (DDS[®]) – Experiment and Modeling

The oil industry increasingly demands accurate and continuous measurement of the percent water in crude oil production streams (watercut) over the entire 0 to 100% range in field applications. This will allow an accurate determination of the amount of oil produced as well as learning about the dynamic production status of oil wells, which is important for production management and optimization.

Differential dielectric sensors have been developed by ChevronTexaco for watercut measurement as an independent measurement and in connection with multiphase meters. The significance of this DDS is that it has the potential to measure watercut compensating for changes in oil composition, gas fraction, emulsion state, water salinity, temperature changes and flow rate changes. Most of the developed studies have been focused on empirical data and correlations and thus are limited in their general applicability. The scope of this study is to expand the capability of the current DDS and make it more accurate and predictable.

The main objective of this newly initiated project is to develop a mathematical model for the DDS taking into consideration fluid properties, sensor geometry and operational conditions. As the first part of the project, a mathematical model for rectangular waveguide sensor using polynomial fitting approach has been completed. Improved model has been developed for a rectangular wave-guide to characterize the “hole effect” using a hybrid approach of transmission line method and mode matching technique. More complicated model has been developed and some important calibration skills have been applied for rectangular sensor and now the model can match experimental data very well. This result is also verified by Finite Element Analysis (FEA) simulation. Future activities include: (1) Develop model for circular wave-guide sensor; (2) Conduct experimental testing for validation of the sensor models; and, (4) Optimize and refine the DDS configuration through FEA simulation and finalize the model.

8.9. Development of CMSS[®] - Experiments and Modeling

Dedicated Mechanistic models, as primary design tools, are being developed to characterize the performance of the CMSS[®], utilizing the already developed models for the individual components. Special consideration is given for the interactions of the components,

resulting from their proximity. Mechanistic model will also incorporate the pertinent results from CFD simulations so as to enable the prediction of the flow behavior and global separation efficiency. The final design tool will be a computer code based on the developed mechanistic model for the CMSS[®].

9. Conclusions

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

- a) The feasibility of utilizing helical pipe separators as inlet devices for flow conditioning has been established. Detailed experiments were conducted to understand the mechanisms involved in slug dissipation phenomenon in downward inclined helical pipe flow. Three slug dissipation mechanisms have been identified for the helical pipe, namely, Gravitational Force Mechanism (occurring at low superficial gas velocities, larger helical diameters and characterized by larger dissipation length), Centrifugal Force Mechanism (occurring at high superficial gas velocities, smaller helical diameters and characterized by smaller dissipation length) and Slug Front Stability Mechanism (occurring at low slug velocities). The mechanistic modeling consists of two parts; the first part is slug dissipation modeling while the 2nd part consists of the prediction of stratified flow behavior in the helical pipe, which serves as an input to the slug dissipation model. Also, a novel Slug Dissipation Map has been constructed using a new concept of Slug Dissipation Index summarizing the slug dissipation phenomena.
- b) A novel slug damper has been developed and proven through experimental investigations that it is successful in dissipating the long slugs and provides a fairly constant flow rate into the GLCC[®] when the slug is being accumulated in the damper. Also, the available damping time is a strong function of the superficial gas velocity (and mixture velocity). A mechanistic model is developed for the prediction of the hydrodynamic flow behavior in the slug damper-GLCC[®] system. The model 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 $\pm 30\%$ with respect to the available damping time and outlet liquid flow rate.

- c) The technology of the developed slug damper system has been implemented in the field at six locations in combination with the GLCC[®] system. Figures 12 and 13 show the installation of 2 slug damper units in the field – one in Indonesia and the other in California by TUSTP member companies, namely ChevronTexaco and SMS, Inc. Initial results from the field indicate that the dampening and degassing effect of the slug damper (DSD) 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.
- d) The experimental investigations on the HPS[®] system demonstrate that it is a simple and viable technology for free-oil knockout of oil-continuous flow. The measurement of local velocities, hold up and droplet size distribution are required to properly analyze the separation inside the HPS[®]. An integrated approach of both Pitot Tube and Video Velocity Measurement (when possible) methods was developed to measure local mixture velocity inside the HPS[®]. Oil-water Flow pattern map (as a function of velocity and watercut) has been developed for the HPS[®] system. A 2-layer and a preliminary 3-layer mechanistic model for the prediction of developing flow and developing length on oil-water flows have been developed, enabling determination of the separation efficiency.
- e) A unit slug generator has been designed, constructed and tested. Multiple slug generator unit has been designed for testing the compact separator components and the entire CMSS[®] systems and the respective control systems under slug flow conditions. This study will result not only with improved control strategies for compact separators but also for improved hydrodynamic modeling and design of these units under slugging conditions.
- f) Two proposed configurations of the Sand Separation Unit (SSU) experimental flow loop have been identified - the first consisting of a slurry injection system, and the second based on a dry sand injection system. After detailed studies, a suitable solid-liquid hydrocyclone (12-mm Microspin Assembly with 6 liners per assembly) has been identified and procured for future testing.
- g) A new project has been initiated to conduct a detailed study on advanced control systems, such as fuzzy logic, artificial neural networks, etc., and examine their suitability for compact separation system. The objective of this project is to develop an intelligent control strategy

for compact separation systems and conduct dynamic simulation and experimental investigation on the developed strategy.

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