DOE/BC/15024-1
(OSTI ID: 14127)

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

Semi-Annual Technical Progress Report
April 1, 1998-September 30, 1998

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Report Issue Date: October 30, 1998

Performed Under Contract No. DE-FG26-97BC15024-1

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October 1999

Work Performed Under Contract DE-FG26-97BC15024

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2. Executive Summary

The objective of this five-year project (October, 1997 – September, 2002) is to expand the current research activities of Tulsa University Separation Technology Projects (TUSTP) to multiphase oil/water/gas separation. This project will be executed in two phases. Phase I (1997 - 2000) will focus on the investigations of the complex multiphase hydrodynamic flow behavior in a three-phase Gas-Liquid Cylindrical Cyclone (GLCC) Separator. The activities of this phase will include the development of a mechanistic model, a computational fluid dynamics (CFD) simulator, and detailed experimentation on the three-phase GLCC. The experimental and CFD simulation results will be suitably integrated with the mechanistic model. In Phase II (2000 - 2002), the developed GLCC separator will be tested under high pressure and real crudes conditions. This is crucial for validating the GLCC design for field application and facilitating easy and rapid technology deployment. Design criteria for industrial applications will be developed based on these results and will be incorporated into the mechanistic model by TUSTP.

This report presents a brief overview of the activities and tasks accomplished during the second half year (April 1, 1998 – September 30, 1998) of the budget period (October 1, 1997 – September 30, 1998). The total tasks of the budget period are given initially, followed by the technical and scientific results achieved till date. The report concludes with a detailed description of the plans for the conduct of the project for the upcoming budget period (October 1, 1998 – September 30, 1999).

3. Tasks of the Current Budget Period (Oct. 1, 1997 – Sept. 31, 1998)

Objective: Initial Modeling and Data Acquisition:

- a. Initial development of the mechanistic model for three-phase separation.
- b. Design and expansion of two-phase test facility for three-phase loop.
- c. Preliminary experimental data acquisition of global separation efficiency.
- d. Preliminary simulation of three-phase flow using CFX code.
- e. Interim reports preparation.

4. Technical and Scientific Results Achieved in the Reporting Period

(April 1, 1998 – September 30, 1998)

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

1. Plans for detailed experimental investigations for GLCC control are in progress. Preliminary data acquisition is in progress for control strategy formulation. The experimental investigations are being conducted in the out-door experimental facility using a dedicated GLCC capable of withstanding higher pressures. The newly fabricated GLCC with state-of-the-art control valves and new data acquisition system have already been installed. This GLCC has a new aluminum inlet, designed for high-pressure (200 psi) conditions, with sector/slot plate configuration.
2. Identified a new indoor project location for the experimental facility for three-phase flow in the North Campus of The University of Tulsa and allocated the area. Updated the preliminary floor layout drawing to scale of the three-phase flow loop consisting of the three-phase separator, oil and water tanks, metering section, test section and, related valves and fittings. Construction of the three-phase flow loop is in progress and expected to be completed by November-December, 1998.
3. Several items for the flow loop partially received. Procurement of components needed for the flow loop such as pipes and fittings, gate valves, pumps, and control valves is completed. Three-phase separator, oil and water tanks, two sets of centrifugal pumps for oil and water, flexible piping and the upstream metering section have been installed. Fabrication of the flow loop, support structure for the experimental facility, test GLCCs and downstream metering section are underway.
4. Designated four graduate students to perform the research and experiments. One more student is expected to join in Spring '99.
5. Started development activities to identify strategies for mechanistic modeling for multiphase flow behavior in GLCC. Literature review in progress to identify the issues related to behavior of oil-in-water and water-in-oil dispersions. Several oil/water-mixing strategies formulated based on Computational Fluid Dynamics (CFD) simulation studies. Investigation in progress to identify techniques for integration of GLCCs with hydrocyclones for building three-phase compact separation systems. This is very critical for elevating the compact separation technology from bulk separation to fine separation of three-phase flow.

It is essential to develop an appropriate control strategy for proper operation of a three-phase GLCC. Hence initial experimental investigations are planned for evaluating the GLCC control system performance for different possible control strategies. The layout of the experimental facility for conducting the controls experiments is given in Fig. 1. Construction of the dedicated GLCC for controls investigation is completed in the existing outdoor GLCC flow loop and the experiments are in progress.

A preliminary schematic of the floor layout and the modified layout to scale of the three-phase flow loop consisting of the metering and test section are shown in Figs. 2 and 3. Air is supplied from a compressor and is stored in a high-pressure gas tank. The air flows through a metering section consisting of Micro-Motion[®] mass flow meter and control valves. The liquid phases (water and oil) are pumped from the respective storage tanks and are metered with two sets of Micro-Motion[®] mass flow meters and control valves, before being mixed. Several mixing sections have been designed to evaluate and control the oil-water mixing characteristics at the inlet. The liquid and gas phases are then mixed at a tee junction and sent to the test section. State-of-the-art Micro-Motion[®] net oil computers (NOC) will be used to quantify the watercut, Gas-Oil ratio (GOR), and mixture density. The test section consists of 2 dual stage GLCCs. Initially the test section will be equipped with one dual stage GLCC and later it will be upgraded to 2 dual stage GLCCs. The three-phases from the GLCC outlets will also be metered using micro-motion mass flow meters. The test section construction will be modular so that in place of GLCC any other separators such as hydrocyclones could be used in series to form compact separation systems.

Investigations have been initiated in collaboration with the TUSTP member companies and other universities such as Michigan State University to formulate mechanistic models for integrated compact separation systems. Control valves placed along the flow loop control the flow into and out of the test sections. The flow loop is also equipped with several temperature sensors and pressure transducers for measurement of the in-situ pressure and temperature conditions. Installation of the data acquisition system will follow as soon as the construction of the flow loop is completed. A schematic of the typical data acquisition system for the flow loop is shown in Fig. 4

Two types of GLCC configurations will be considered namely single stage GLCC and dual stage GLCC. The above flow loop can be used for both configurations. These two types of configurations will aid in investigating the function of GLCC as a bulk separator and a full separator. A non-emulsifying oil will be used as the experimental fluid. Flow runs will be conducted initially by using oil-water two-phase and gas will be added as the third phase later. Two types of oil-water interface are possible as shown in Fig. 5. Initial investigation will focus on identifying the nature of oil-water interface and formulation of appropriate separation strategies for the GLCC. Several literature have been identified to provide more information into the nature of the oil-water interface for cyclonic separators of low G-forces such as the GLCCs.

As an essential component of the mechanistic model development for three-phase flow, preliminary Computational Fluid Dynamic simulations have been conducted to investigate the oil-water separation in a two-phase liquid-liquid mixture with water (denser liquid) as the primary medium. The results of CFD flow-simulation studies using the computer code CFX 4.1 are shown in Fig. 6 for three different oil droplet sizes. The simulation time was 20 seconds, the oil specific gravity was 0.885, and the GLCC lower part length and diameter were 4-ft and 3-inches respectively. The magnitudes of radial, axial and tangential velocity components are also given in Fig. 6, which are typical of normal GLCC operating conditions. The simulation results of the droplet trajectory indicate that, it is much easier to separate oil droplets of diameters 1000 micron (1mm) and above from the denser water medium. It is also observed that at diameters of 100 microns and below there is a

much higher probability of oil particle carry-under into the water stream. This is a very significant initial result as it gives a basis for oil droplet monitoring, predicting the oil carry-under and developing strategies for ensuring separation efficiency of three-phase separators. Detailed investigations are planned in the second project year (October, 1998 – September, 1999) to conduct simulation studies for other operating conditions, namely different flow velocities, different fluid densities, and also verification with experimental results.

Items already Received for the three-phase Flow Loop

1. Micro-Motion® mass flow meters (Elite type)	- 6 + 1
2. Transmitters for Micro-Motion® mass flow meters	- 6 + 1
3. Computers for data acquisition system	- 2
4. Pressure Transducers	- 12
5. Temperature Sensors and Transmitters	- 6
6. Hart Data communicator	- 1
7. Data Acquisition System	- 1
8. Conventional Three-Phase horizontal separator	- 1
9. Storage tanks for oil and water	- 2
10. Pumps for oil and water	- 4
11. Gate Valves	- 24
12. Pipes and Fittings	- quantity as required.

Procurement action initiated for the following items (these items are expected to arrive by November, 1998):

1. Upstream Control Valves
2. Downstream Control Valves
3. PID Controllers
4. Test GLCCs
5. Laser printer

5. Description of Plans for Conduct of Project During the Project Year 2 (October 1, 1998 - September 30, 1999)

The second project year research activity is divided into three main parts, which will be carried out in parallel. The first part is the experimental program that includes a study of the oil/water two-phase behavior and control system development for the three-phase GLCC. The second part consists of the development of a simplified mechanistic model incorporating the control strategies and behavior of dispersion of oil in water and water in oil. This will provide an insight into the hydrodynamic flow behavior and serve as the design tool for the industry. Although useful for sizing GLCCs for proven applications, the mechanistic model will not provide detailed hydrodynamic flow behavior information needed to screen new geometric variation or to study the effect of fluid property variations. Therefore, in the third part, the more rigorous approach of computational fluid dynamics (CFD) will be utilized. Multidimensional multiphase flow simulation will provide much greater depth into the understanding of the physical phenomena and the mathematical analysis of three-phase

GLCC design and performance. Further investigations will be carried out, as part of this study, to enhance the potential of a commercial CFD code called CFX to three-phase applications. Following is a more detailed description of the three parts of the upcoming year activities.

A. Experimental Program:

The experimental program will be conducted in two facilities, indoor and outdoor. A dedicated GLCC has been built outdoors, which is capable of withstanding higher pressures, for conducting detailed controls experiments. Control strategy developed in the outdoor facility, will be an essential part of the indoor, three-phase GLCC. This experimental facility which is already completed, will provide necessary vital information about the control system design for the three-phase flow loop. The indoor, experimental facility for three-phase flow, which is being constructed, will be an enhanced version of the existing two-phase flow metering and separation facility. This facility is expected to be ready by November – December 1998 for preliminary experimentation.

B. Three-Phase Flow Facility:

The indoor, three-phase flow loop, which is being built, is described in Figs. 2 and 3. Two types of GLCC configurations will be considered namely single stage GLCC and dual stage GLCC, as described previously. The above flow loop can be used for both configurations. Three schematics of the single stage GLCC and two-stage GLCC are shown in Fig. 7. The second stage GLCC could be from the liquid outlet or from the oil outlet. The GLCC for the indoor facility will be built using transparent PVC pipes so as to enable visual observations of the hydrodynamic flow phenomena, which is essential for the modeling. The modular design of the GLCC will allow easy modification of the inlet, outlet and piping configurations. Finally, the effect of fluid properties can be investigated through use of viscosity and surface tension modifiers to water.

C. Data Acquisition:

In addition to the inlet flow rates of the three-phases, the following measurements will be acquired for each experimental run:

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

D. Mechanistic Model:

A mechanistic model will be developed for the prediction of the hydrodynamic flow behavior and performance of the three-phase GLCC separator.

The input parameters to the model would include the following:

- Operational parameters: range of oil-water-gas flow rates, pressure and temperature;
- Physical properties: oil, gas and water densities, viscosities and surface tensions;
- Geometrical parameters: complete geometric description of the GLCC: GLCC configurations, inlet pipe I.D, inclination angle and roughness, outlet piping I.D, length and roughness;
- Performance characteristics of active liquid level control.

The mechanistic model will enable determination of the performance characteristics of the GLCC, namely:

- plot of the operational envelopes for both liquid carry-over and gas carry-under;
- percent liquid carry-over and gas carry-under beyond the operational envelopes;
- oil in water and water in oil fractions;
- pressure drop across the GLCC;
- liquid level in the separator;
- sensitivity to flow rate fluctuations (with no active control);
- sensitivity to flow rate fluctuations (with active control).

The simplified mechanistic model will enable insight into the hydrodynamic flow behavior in the three-phase GLCC. It will also allow the user to optimize the GLCC design accounting for tradeoffs in the I.D, height and inlet slot size of the GLCC. The model will also provide the trends of the effect of fluid physical properties and the information required for determining when the active controls will be needed. Preliminary framework for the mechanistic model for three-phase flow will be formulated during the investigations of the upcoming year.

E. Computational Fluid Dynamics (CFD) Simulator:

The purpose of the computational fluid dynamics (CFD) modeling is to provide both macroscopic and microscopic scale information on multidimensional multiphase flow hydrodynamic behavior. The CFD model will be general so that it can be utilized for the analysis of the GLCC and other complicated multiphase flow systems. Thus, the numerical simulator will provide a powerful analytical tool, which will also reduce experimental costs associated with testing of a variety of different operating conditions. Constitutive models for the CFD code (CFX) will be developed and will be added to the simulator to capture the important physics of three-phase separation. The CFD activity will be spread through the upcoming two years (October 1998 to September 2000).

A general numerical solution procedure for simulating three-dimensional three-phase flow in complex pipe geometries will be developed based on CFX. The numerical model

will employ the three-fluid model. A turbulent flow model is also required for specifying the constitutive relations in the momentum equations. The eddy viscosity concept will be used to define an effective viscosity for the mixture. The turbulence model will establish the value for the eddy or turbulent viscosity. Both Prantl mixing-length model and a more sophisticated k- ϵ model will be used for modeling this complex flow geometry.

The experimental data acquired on the GLCC and other available data from complex three-phase systems (such as flow splitting at tee junctions), will be used to test and refine the numerical code. For the current project, the CFD model will be used for initial parametric studies of possible design modifications to the GLCC. Moreover, the model will provide detailed performance prediction for untried applications for which no data are available, such as high-pressure subsea separation.

F. Tasks of the Second Project Year Activities: Gas Carry-under and Model Refinement (Oct. 1, 1998 - Sep. 31, 1999):

- a. Measurement of the operational envelope of the GLCC for gas carry-under.
- b. Detailed measurement of gas carry-under beyond the operational envelope.
- c. Development of constitutive models for CFD code for simulation of gas carry-under.
- d. Refinement of mechanistic model for gas carry-under.
- e. Investigation of three-phase separator configurations and verification with experimental results.
- f. Interim reports preparation.

Fig. 1 Experimental Facility for GLCC Controls Experiment

INDOOR PROJECT AREA

Fig.2. Three-Phase Experimental Flow Loop

Fig.4 Instrumentation and Data Acquisition Flow Chart (3-PHASE)

Fig. 5 Oil - Water Interface

OIL/WATER SEPARATION USING GLCC

EFFECT OF SIZE OF OIL DROPLETS

(CFD Simulation using CFX.4.1)

Simulation Time : 20 seconds

GLCC diameter: 3 inches

GLCC Lower length: 4 Ft

Radial Velocity: 0.18 m/s

Axial Velocity: 0.75 m/s

Tangential Velocity: 1.66 m/s

Oil Density: 885 Kg/m³

Fig. 6 Effect of Oil Droplet Size on Droplet Trajectory

Fig. 7 Test section configurations (separated outlets)