FOSSIL ENERGY

DOE/BC/15024-4
(OSTI ID: 773336)

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

Semi-Annual Report
October 1, 1998-March 31, 1999

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Date Published: January 2001

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

The University of Tulsa
Tulsa, Oklahoma

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

DOE/BC/15024-4
Distribution Category UC-122

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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 first half year (October 1, 1998 – March 31, 1998) of the budget period (October 1, 1998 – September 30, 1999). The total tasks of the budget period are given initially, followed by the technical and scientific results achieved till date. The report concludes with a detailed description of the plans for the conduct of the project for the second half year (April 1, 1999 – September 30, 1999) of the current budget period.

3. Tasks of the Current Budget Period (Oct. 1, 1998 – Sept. 31, 1999)

Objective: Controls Study, Gas Carry-under and Model Refinement:

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.

4. Technical and Scientific Results Achieved in the Reporting Period

(October 1, 1998 – March 30, 1999)

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

1. Detailed experimental investigations for GLCC control are in progress. Suitable control strategy has been identified for 2-phase GLCC control after preliminary data acquisition. The control strategy focuses on pressure control using the gas control valve and level control using the liquid control valve. 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. The final objective of the experimental investigation is to extend/identify suitable control strategy for three-phase GLCC. Towards this objective, predictive control strategy formulation using the principles of slug detection is being investigated. A dedicated graduate student is pursuing this study.

2. Construction of the experimental facility for three-phase flow loop is completed. Installation of the data acquisition system and electrical schematics are partially completed. Calibration of the flow meters, pressure transducers, temperature transducers and net oil computers are in progress and expected to be completed by April-May, 1999.

3. Fabrication of the flow loop, support structure for the experimental facility, a 3-inch oil-water test Liquid-Liquid Cylindrical Cyclone (LLCC) separator and downstream metering section has been completed.

4. Designated four graduate students to perform the research and experiments. Experimental investigations on the oil-water separation, emulsion formation, and droplet distribution are in progress.

5. Development activities to identify strategies for mechanistic modeling of multiphase flow behavior in GLCC are in progress. Literature review to identify the issues related to behavior of oil-in-water and water-in-oil dispersions is completed. Several oil/water-mixing strategies formulated based on Computational Fluid Dynamics (CFD) simulation studies.

6. A dedicated graduate student is investigating strategies 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 in a two-phase GLCC 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. Suitable control strategy has been identified for 2-phase GLCC control after preliminary data acquisition. The control schematics shown in Fig. 2, focuses on pressure control using the gas control valve and level control using the liquid control valve. Preliminary investigations indicate that there is considerable improvement (more than three-fold) in the operational envelope of a 2-phase GLCC equipped with a control system. However, the mechanisms responsible for liquid carry-over in a GLCC with control system are different from those responsible in the case of a GLCC without control systems. For example, churn flow is responsible for liquid carry-over in a GLCC with control systems even for relatively large liquid flow rates, whereas in the case of a GLCC without control system, it is primarily caused by annular flow conditions. Detailed experimental investigations are in progress for quantifying the improvement in the GLCC performance using the control systems.

The final floor layout to scale of the three-phase flow loop consisting of the metering and test section is shown in Fig. 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 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 hydro-cyclones 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 and electrical schematics are completed. A schematic of the typical data acquisition system and electrical schematics for the flow loop is shown in Fig. 4. A listing of the various transducers used in the loop with their respective range are given in Table 1.

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 technical grade white mineral oil type Tufflo® 6016 of specific gravity, 0.8571 is used as the experimental fluid along with water. Initial experimental investigations indicate that this oil is capable of forming emulsions at certain oil and water flow conditions. Flow runs are 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 studies indicate that the oil-water interface will be as per Case 2, similar to the gas-liquid interface. 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 and formulation of appropriate separation strategies for the GLCC.

Measurement of the operational envelope for gas carry-under for a GLCC equipped with control system is in progress. Also, 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 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 next reporting period to conduct simulation studies for other operating conditions, namely different flow velocities, different fluid densities, and also verification with experimental results.

Procurement action to be initiated for the following items:

1. Downstream Control Valves
2. PID Controllers
3. Additional 3-phase Test GLCCs

5. Project Work Planned for the next Reporting Period (April 1, 1999 - 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 reporting period activities.

A. Construction of Three-Phase GLCCs:

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. 6. 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.

B. 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. Construction of the indoor, experimental facility for three-phase flow, an enhanced version of the existing two-phase flow metering and separation facility is completed and is being used for experimentation.

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.

C. Initiate Mechanistic Model Development:

Initiate the development of a mechanistic model 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.

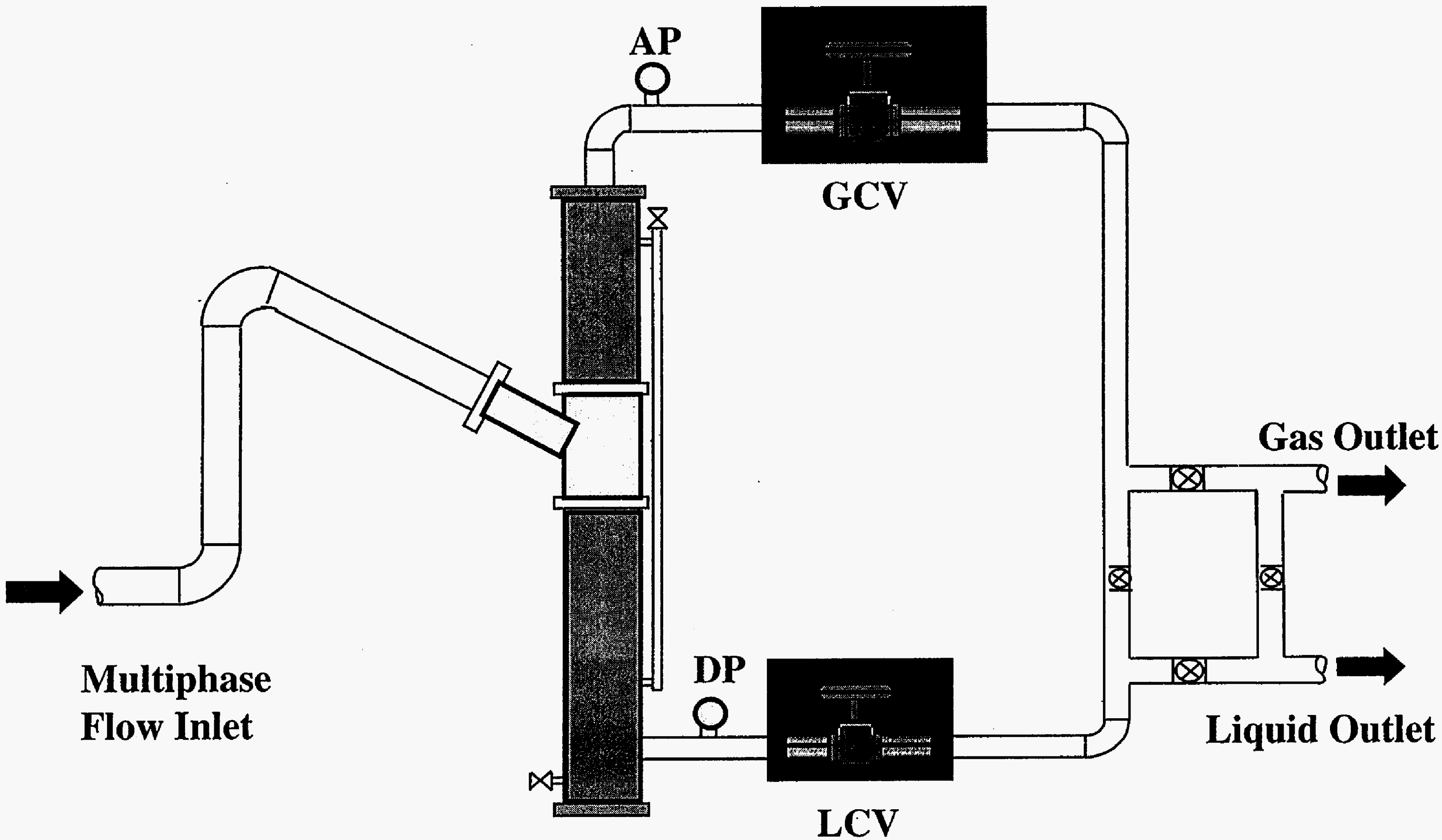
D. Computational Fluid Dynamics (CFD) Simulator:

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).

Table 1: List of Transducers in Indoor Loop

Instrument	Manufacturer	Range		
		min	max	unit
Air density in	Micro Motion	0	1	g/cc
Air density out	Micro Motion	0	1	g/cc
Air mass flow out	Micro Motion	0	25	lbs/min
Air mass flow in	Micro Motion	0	25	lbs/min
Air valve	Fisher	0	100	% open
Oil density in	Micro Motion	0.8	1.2	g/cc
Oil density out	Micro Motion	0.8	1.2	g/cc
Oil mass flow out	Micro Motion	0	1000	lbs/min
Oil mass flow in	Micro Motion	0	1000	lbs/min
Oil valve	Fisher	0	100	% open
Water density in	Micro Motion	0.8	1.2	g/cc
Water density out	Micro Motion	0.8	1.2	g/cc
Water mass flow out	Micro Motion	0	1000	lbs/min
Water mass flow in	Micro Motion	0	1000	lbs/min
Water valve	Fisher	0	100	% open
Absolute Pressure Transducers (Qty – 3)	Rosemount	0	100	psi
Temperature Transducers (Qty – 2)	Rosemount	0	60	^{0}C

Fig. 1. Experimental Facility



8

Fig. 2 :Integrated Level & Pressure Control Strategy

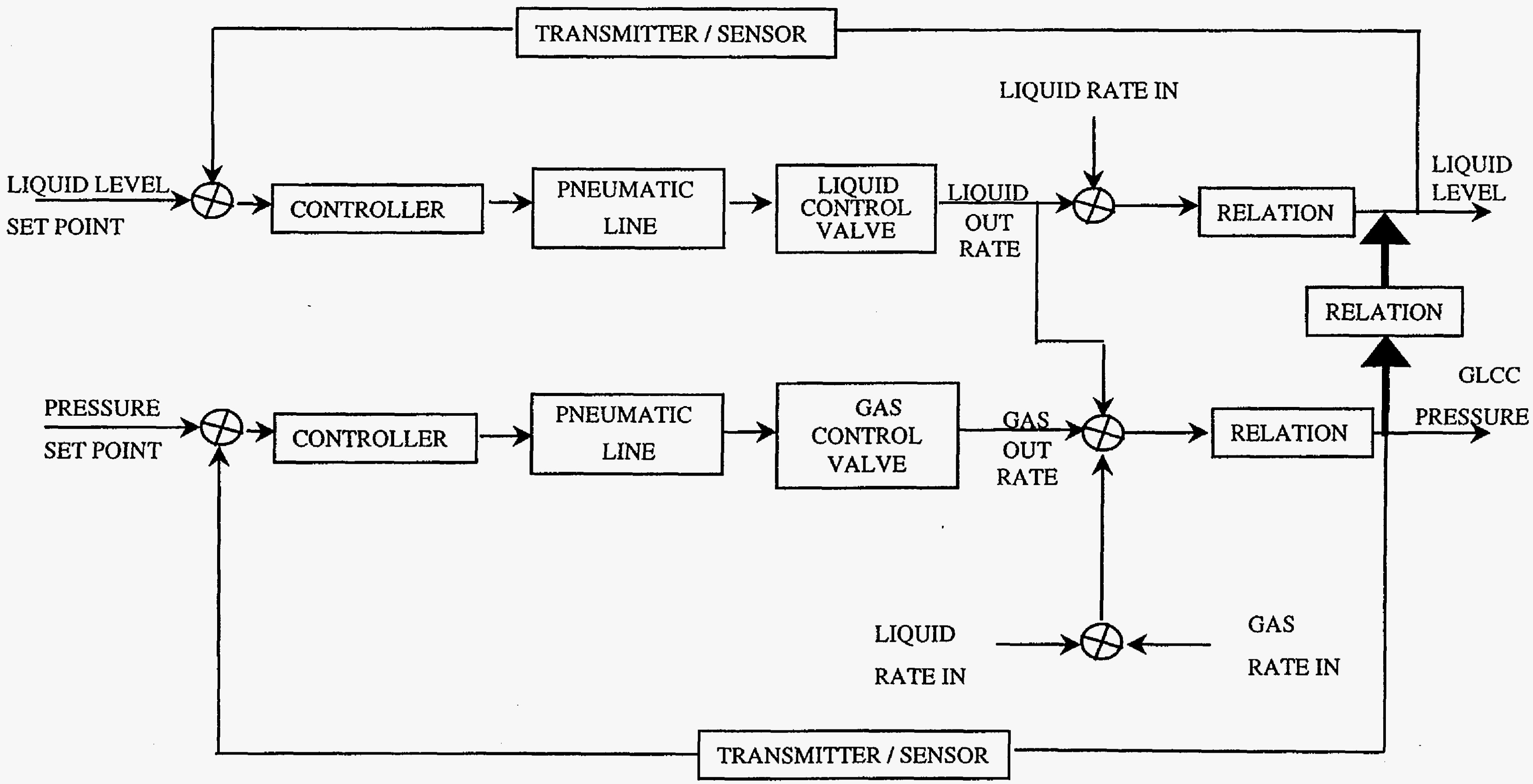


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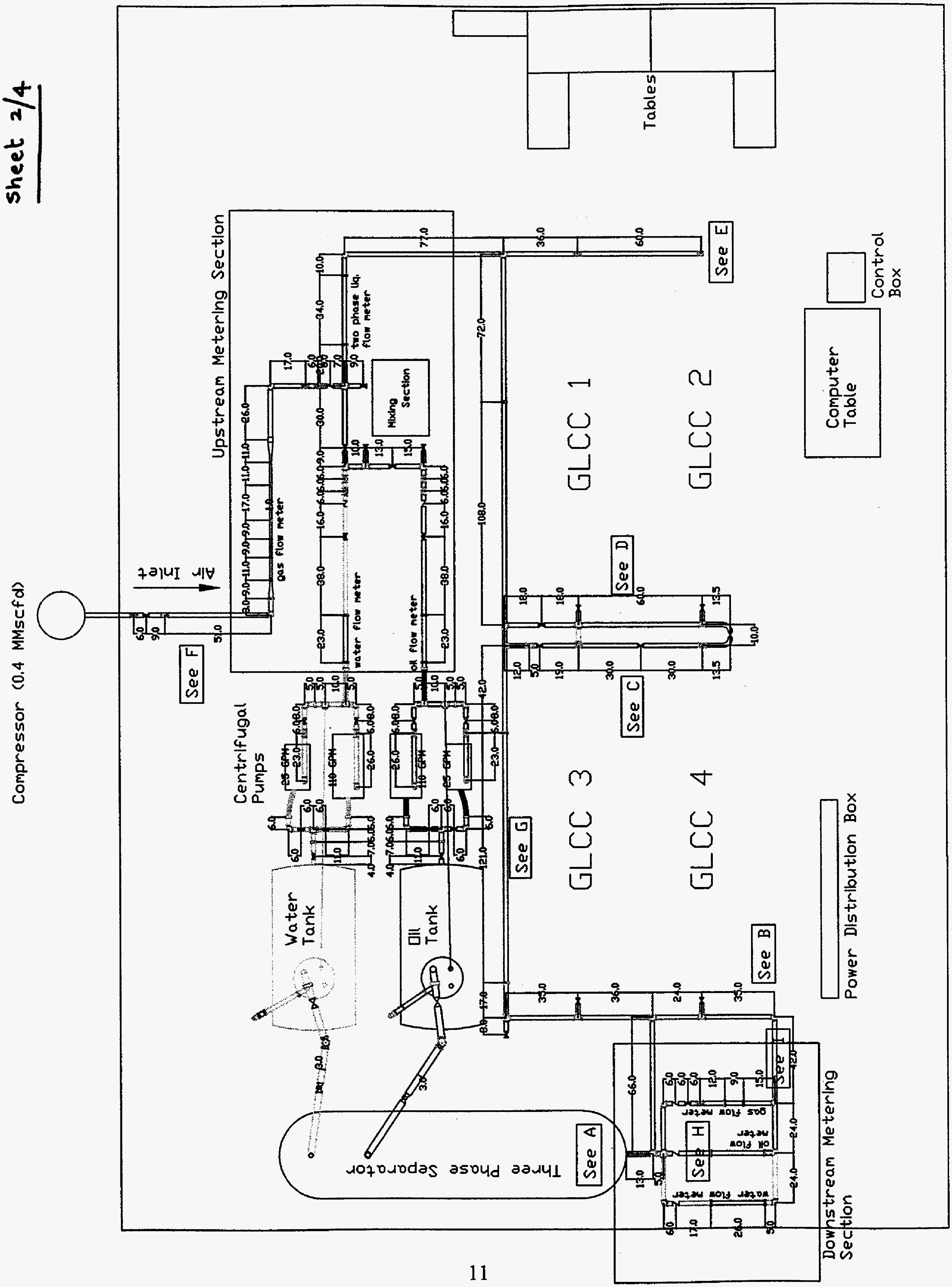
Figure 3.

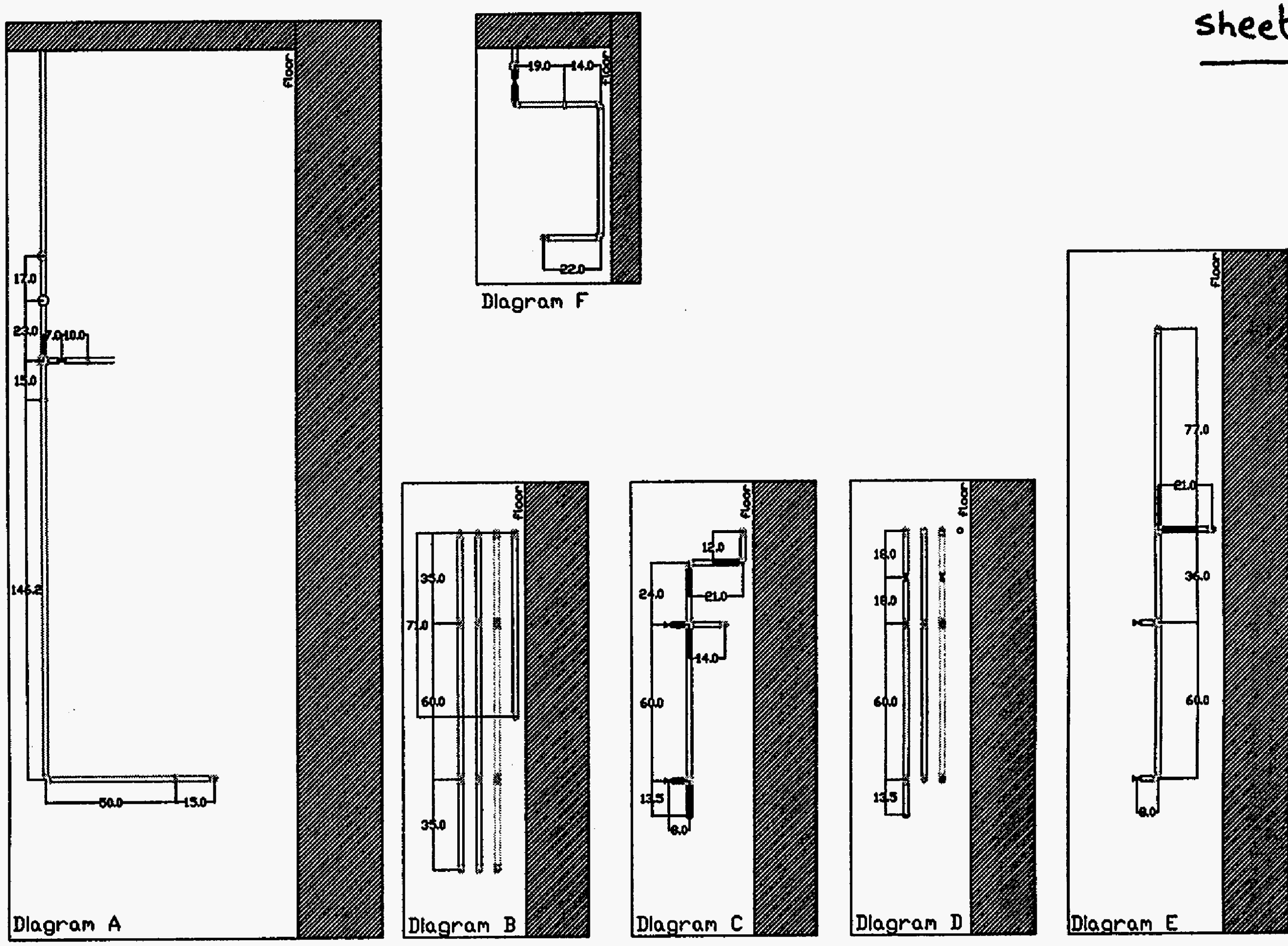
TUSTP Three Phase Separation Facility

Drawn by	Approved by	Date	Scale	Version	Sheet
Richard T. S. Kho	Dr. Ram Mohan	4/2/99	1:25	1	1/4

Tulsa University Separation Technology Projects
Petroleum and Mechanical Engineering Departments
The University of Tulsa
Tulsa, OK 74104


Sheet 2/4
Compressor (0.4 MMscfd)
Air Inlet
See F
Upstream Metering Section
gas flow meter
water flow meter
oil flow meter
two phase liq. flow meter
Mixing Section
See E
Centrifugal Pumps
Water Tank
Oil Tank
Three Phase Separator
See A
See H
Downstream Metering Section
See D
See C
See G
See B
GLCC 1
GLCC 2
GLCC 3
GLCC 4
Tables
Control Box
Computer Table
Power Distribution Box

sheet 3/4



NOTE: ALL DIMENSIONS IN INCHES

NOTE: ALL PIPES ARE 2 INCH NOMINAL, UNLESS STATED OTHERWISE

LEGEND:

- BALL VALVE
- CHECK VALVE
- CONTROL VALVE
- HAMMER UNION
- FLANGE
- MISC. INSTRUMENT (INCL. M.M.)

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Diagram G

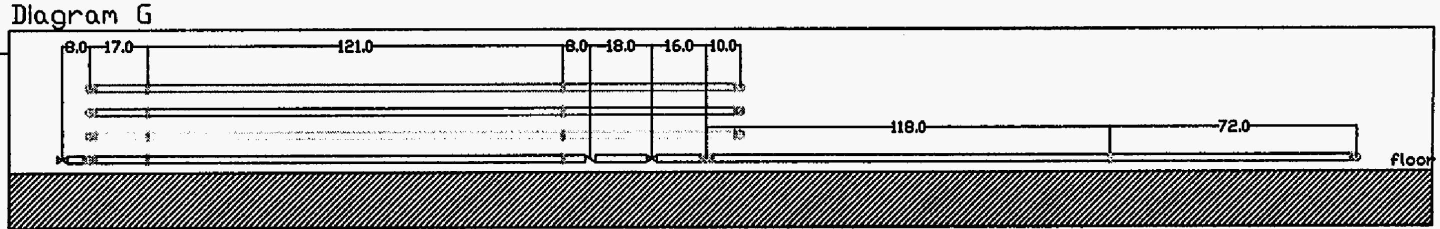


Diagram H

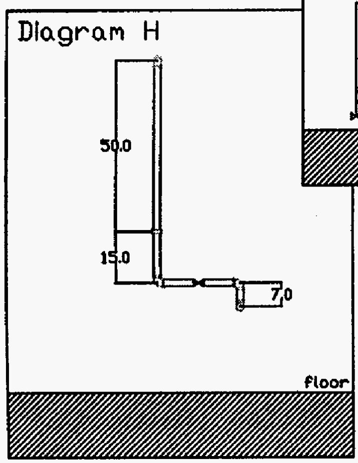


Diagram I

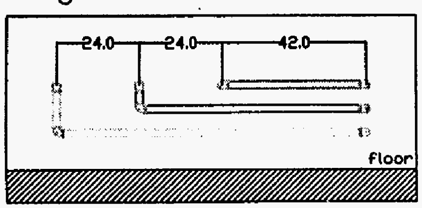
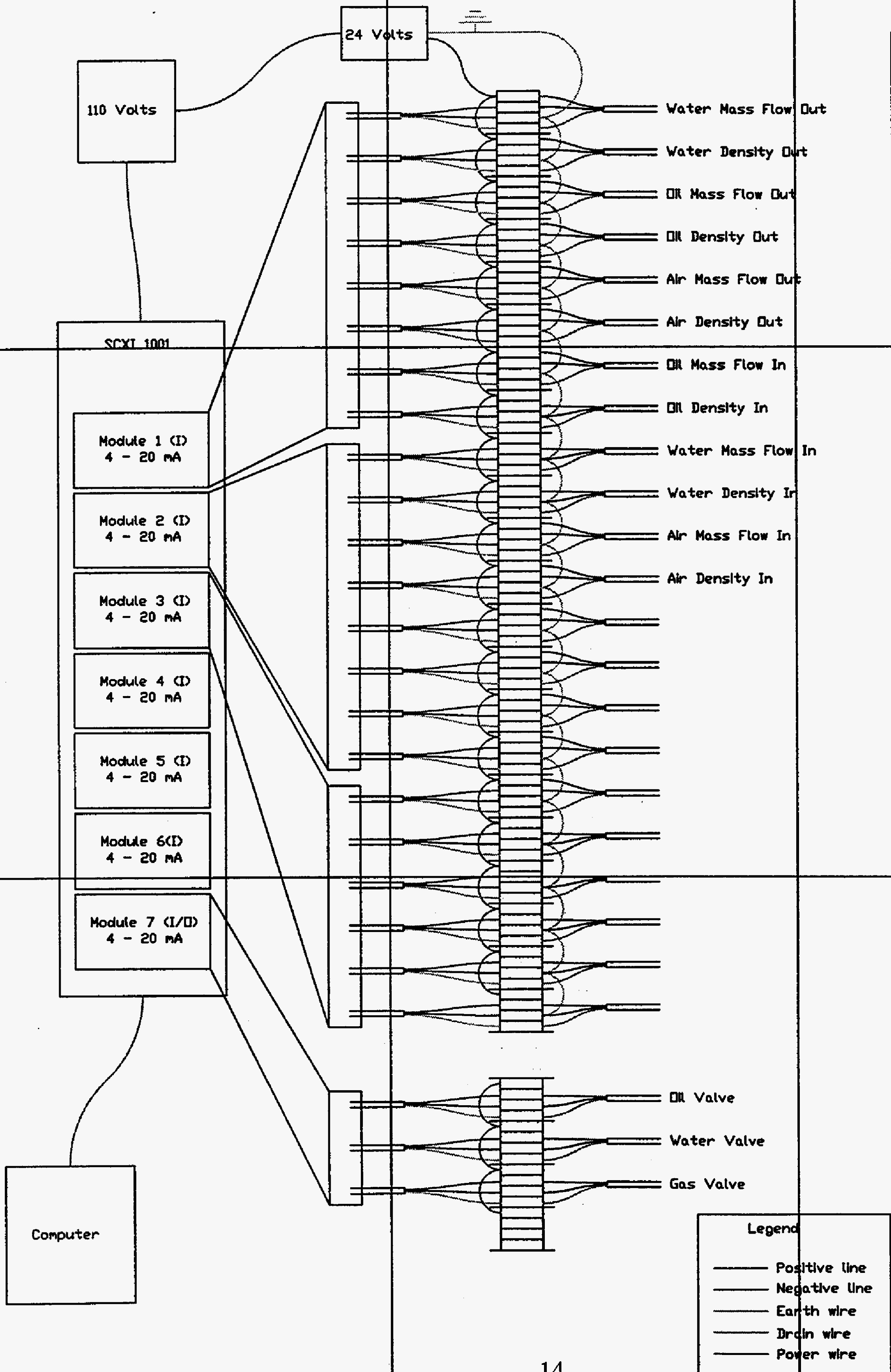


Fig. 4 - Electrical Schematic of Indoor loop (as of April 17, 1999)



	Module	Channel	Label	ARRAY
Water Mass Flow Out	1	0	1	0
Water Density Out	1	1	2	1
Oil Mass Flow Out	1	2	3	2
Oil Density Out	1	3	4	3
Air Mass Flow Out	1	4	5	4
Air Density Out	1	5	6	5
Oil Mass Flow In	1	6	7	6
Oil Density In	1	7	8	7
Water Mass Flow In	2	0	9	8
Water Density In	2	1	10	9
Air Mass Flow In	2	2	11	10
Air Density In	2	3	12	11
Oil Valve	7	0	1	1
Water Valve	7	1	2	2
Gas Valve	7	2	3	3

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Fig. 5 Oil - Water Interface

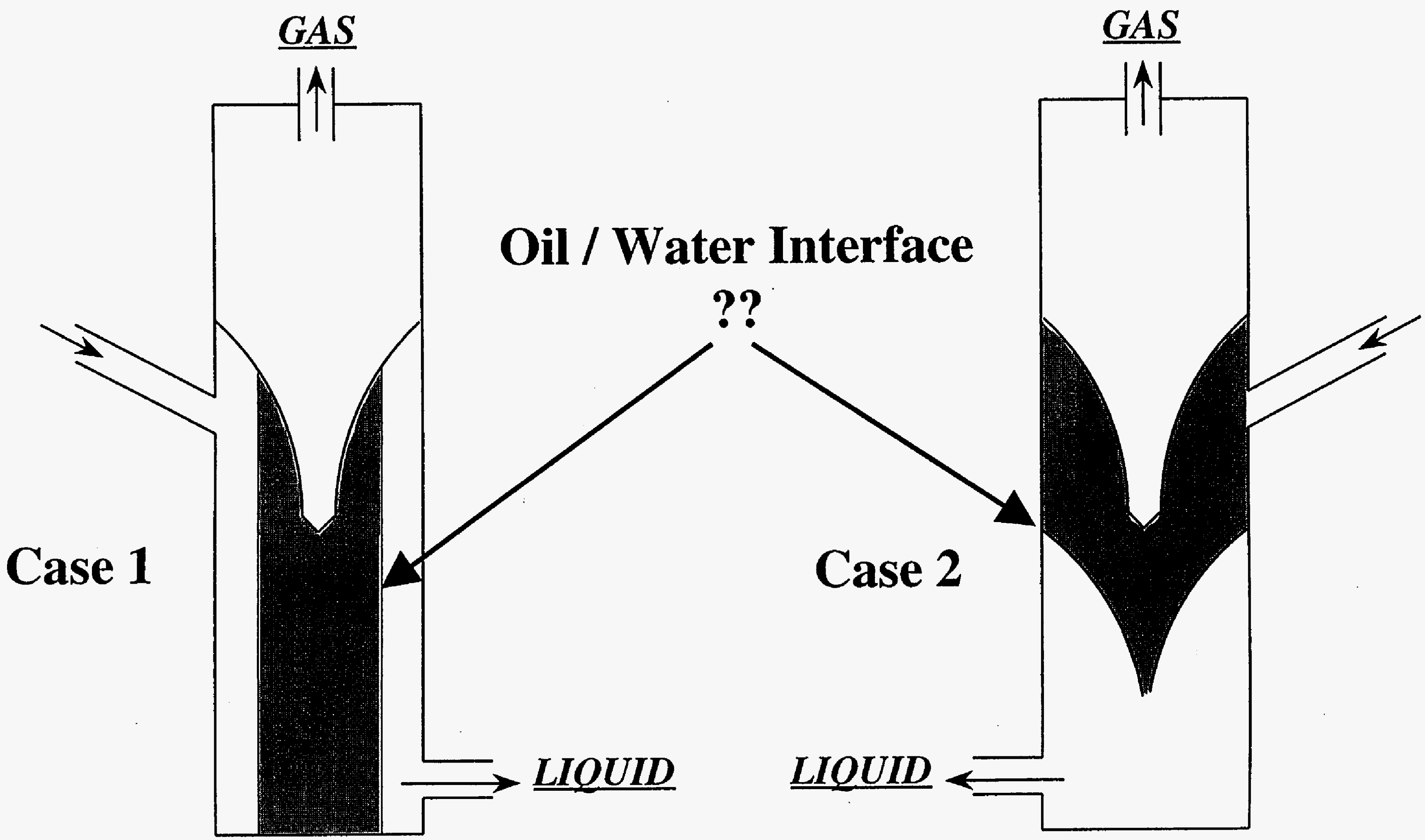

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Fig. 6(a) Single-Stage GLCC

Case 1:

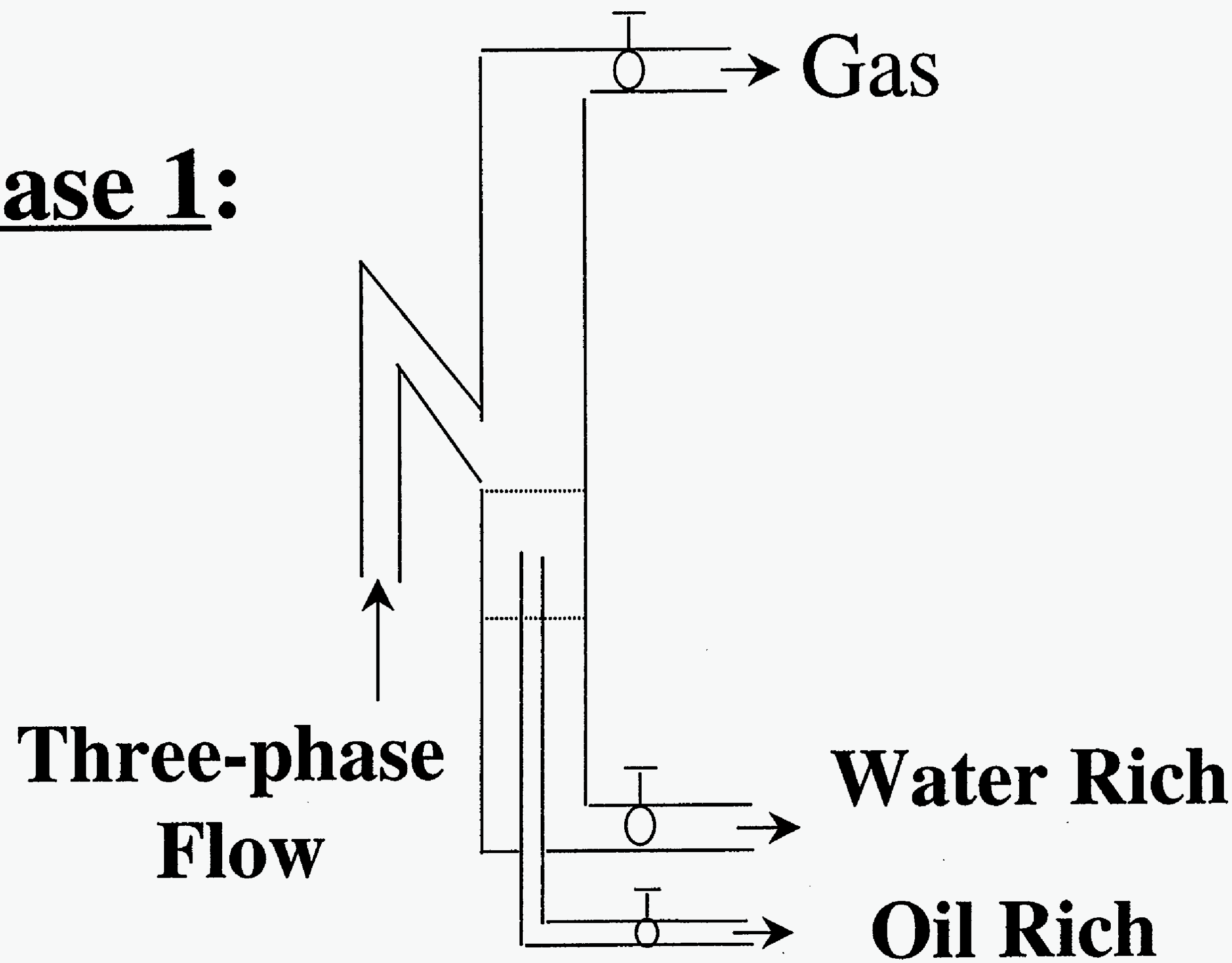

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Fig. 6(b) Two-Stage GLCC

Case 2: