Optimal Control Strategy and Experimental Investigation of Gas-Liquid Compact Separators

Abstract
The deployment of the new technology of gas-liquid compact separators such as Gas Liquid Cylindrical Cyclone (GLCC) requires dedicated control systems for field applications. The control strategy implementation is crucial for process optimization and adaptation, especially when GLCCs are operated at wide range of liquid and gas flow conditions. In this study, a unique and simple control strategy, which is capable of optimizing the operating pressure and adapting to liquid and gas inflow conditions, has been developed. Detailed simulations and experimental investigations have also been conducted to evaluate the performance of the proposed control systems. The significant advantages of this strategy are: the system can be operated at optimum separator back pressure; the system can adapt to the changes of liquid and gas flow conditions; and the strategy can be easily implemented using simple PID controllers available in the market. This provides the oil and gas industry a simple, robust compact separator control technique which has the potential for offshore and subsea applications.

Introduction
Compared to conventional separators, compact separators, such as the Gas-Liquid Cylindrical Cyclone (GLCC) are simple, compact, possess low weight, low-cost, require little maintenance, and are easy to install and operate. GLCCs have been used to enhance the performance of multiphase meters, multiphase pumps, de-sanders, slug catchers, partial separators, portable well testing equipment, pre-separators and primary separators for offshore and onshore operations. They also have the potential for applications as flare gas scrubbers, down-hole separators and subsea processing.

Presently, more than a hundred and fifty GLCC units have been installed and put into use in the field for various applications. The size of these GLCCs varies from 3-in. to 5-ft in diameter and 7-ft to 30-ft in height. Figure 1 shows the largest GLCC in the world, a 5-ft diameter, 20-ft tall GLCC field unit operating in Minas, Indonesia, in a bulk separation/metering loop configuration.

The GLCC separator is a vertically installed pipe/vessel mounted with a downward inclined tangential inlet, with outlets for gas and liquid provided at the top and bottom, respectively. It has neither moving parts nor internal devices. The two phases of the incoming mixture are separated due to the centrifugal/buoyancy forces caused by the swirling motion and the gravity forces. The heavier liquid is forced radially towards the walls of the cylinder and is collected from the bottom, while the lighter gas moves to the center of the cyclone and is taken out from the top.

GLCC in a metering loop configuration, where the gas and liquid outlets are recombined, is capable of self-regulating the liquid level for small flow variations. However, for large flow variations, it is essential to have a control system for proper operation. Also, GLCCs for other applications such as bulk separation, must have suitable control systems so as to prevent the liquid overflow through the gas leg and gas blow out through liquid leg. There is an increasing need to develop appropriate control strategies, design tools and simulators for GLCC control, as its residence time is very small and its applications could be different. Also, the performance of compact separators could be enhanced considerably by incorporating suitable control systems. Development of control systems for GLCC technology can have a tremendous impact in improving the optimization and productivity of the petroleum industry.

The objectives of this study are to develop a mathematical model, establish the optimal and adaptive control strategy, perform dynamic simulations and conduct experimental investigations to evaluate the control strategy. The features of

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the GLCC dynamic model and the dynamic simulators are developed using Matlab/Simulink® software. A unique optimal control strategy is proposed for the first time for real time, optimal and adaptive control of GLCC. This strategy has the capability of minimizing the operating pressure at any liquid and gas flow rates and dynamically adapting the controller for different operating conditions. This provides the petroleum industry with an effective tool for the GLCC control system design, control system implementation and dynamic simulation.

Several investigators have realized that the performance of compact separators could be improved by incorporating suitable control systems. Kolpak                                    and Wang developed hydrostatic models for passive control of compact separators in a metering loop configuration. These models provide the sensitivity of the liquid level to the gas and liquid inflow rates.

Gas-liquid two-phase flow separators may operate under slug flow conditions in the field. The system dynamics are significant for such applications, especially when a control system is added to the separator. Genceli et al. developed a dynamic model and a simulator for a slug catcher. They proposed a liquid level control and pressure control configuration and PI controllers for both control loops. The slug catcher program was primarily used to optimize the slug catcher size.

Mohan et al. conducted detailed experimental investigations on a newly developed GLCC passive control system. They demonstrated that the passive control system improved the GLCC operational envelope for liquid carry-over in a limited range of flow conditions. As a continuation of this work, Wang et al. developed a dynamic model for GLCC control system design and dynamic simulation. Wang et al. conducted detailed experimental investigations to evaluate the improvement in the GLCC operational envelope for liquid carry-over with the integrated level and pressure control system, for a wide range of flow conditions. They have also developed different control strategies and control system simulators for GLCC field applications.

From the above discussion, it can be noted that compact multiphase separation technology research and control system studies are essential for the petroleum industry. Previous studies also demonstrate that the performance of compact separators could be enhanced considerably by incorporating suitable control systems. However, there is an increasing need to develop optimal control strategy and simulator for GLCC control for offshore and subsea applications. The overall objective of this investigation is to expand the state-of-the-art of compact separation technology through development of suitable control strategies and simulators and control system design.

Mathematical Modeling and Control System Design

System Definition. A schematic of the GLCC equipped with control systems is shown in Fig.2. The GLCC geometrical parameters and dimensions are specified based on design criteria corresponding to the operating conditions. The GLCC separator has a two-phase flow inlet and single-phase gas and liquid outlets. The control systems consist of a liquid control valve (LCV) on the liquid leg and a gas control valve (GCV) on the gas leg, a liquid level sensor (such as a differential pressure transducer), an absolute pressure transducer and an LCV position sensor. The control loops can be configured as follows:

1. Liquid level control loop using liquid level sensor, LCV and LCV controller.
2. Liquid level control loop using liquid level sensor, GCV and GCV controller.
3. Pressure control loop using absolute pressure sensor, GCV and GCV controller.
4. LCV position control loop using LCV position sensor, GCV and GCV controller.

Different control strategies can be developed by integrating the above control loops. For example, integrating the control loop 1 and control loop 2 forms the integrated liquid level control strategy and integrating the control loop 1 and control loop 3 forms the integrated liquid level and pressure control strategy. This study focuses on the optimal and adaptive control strategy, which uses the control loop 1 as the primary control loop and the control loop 4 as secondary control loop. Figure 3 is the block diagram of the physical system, which shows the subsystems and control logic. The primary control loop consists of a liquid control valve on the liquid leg, a liquid level sensor (in this case, a differential pressure transducer) and a liquid control loop controller. The liquid level sensor sends the liquid level signal to the liquid control valve to control the liquid outflow to match the inflow, so as to maintain the liquid level around its set point. The secondary control loop consists of a gas control valve on the gas leg, a liquid control valve position sensor and a gas control loop controller. The liquid control valve position sensor sends the liquid control valve position signal to the gas control loop controller. The output signal of the controller drives the gas control valve to control the gas outflow so as to build up GLCC back pressure, which is needed to drive the liquid outflow fast enough to keep the liquid level around its set point, and to maintain the liquid control valve position around its set point (optimum position). All the subsystems in the block diagram are described by Wang et al.5

Mathematical Model. Figure 4 shows the block diagram of the linear model in Laplace domain for the optimal and adaptive control system. All the mathematical derivations of each element in the loop are given in Wang et al.6,8

Control System Design. The control system design is conducted by decoupling the liquid control loop (primary) and gas control loop (secondary) configurations through reasonable assumptions. The primary loop is built by neglecting the links (blocks 19, 21 and 22) between the liquid control loop and the gas control loop. The secondary control
loop is built by ignoring blocks 8, 9 and links \( D_5 \) and \( D_7 \) (blocks 20 and 21). The assumptions can be justified as follows:

1. The gas control loop (secondary) assists the liquid control loop (primary) to control the liquid level by building the back pressure. Thus, designing the primary loop without considering the secondary loop will be a conservative approach.

2. Because the gas control loop (secondary) is used to control the liquid control valve position, the liquid control valve position can be assumed to be constant. Hence blocks 8 and 9 can be neglected.

3. The link \( D_5 \) is the effect of the change of the liquid level on the GLCC pressure. Because we try to control the liquid level around the set point, this effect is negligible. Also, the effect of GLCC pressure on gas outflow rate \( \Delta D \) is ignored for simplicity.

The design of the primary (liquid) control loop controller is given in Wang et al.\(^6\).

The block diagram of the simplified gas control loop is shown in Fig. 5. The dynamic simulations for the integrated system will justify controller designs for both the liquid and gas control loops.

The open loop transfer function for the optimal control strategy is given by,

\[
H(s)G(s) = G_{lc}(s)G_{Gc}(s) = \frac{K_s}{s^2(C_s(s+1)(\tau_s(s+1)))}, \quad ...(1)
\]

where, \( G_{lc}(s) \) is the liquid controller transfer function, obtained from the liquid controller design and given by,

\[
G_{lc}(s) = K_{lc} \frac{(s+0.5)(s+0.6)}{s}, \quad ... \quad ... \quad ... \quad ... \quad ...
\]

\( G_{Gc}(s) \) is the gas controller transfer function, which needs to be determined from the design. \( K_s \) is the system gain, given by,

\[
K_s = \frac{100}{D_1D_2D_3D_4}\left(\frac{\Delta C_{lc}}{\Delta x}\right)_{T=\text{set}}, \quad ... \quad ... \quad ...
\]

Based on the open loop transfer functions, the gas control loop controller design is conducted using the Root Locus Technique\(^9\).

**Simulator Development and Dynamic Simulation**

Based on the optimal and adaptive control system linear model and control system design described above, a control system simulator is built using the Matlab/Simulink\(^6\), as shown in Fig. 6. The control system is configured by sending the liquid control valve position signal to the gas control loop using a position sensor, so as to maintain the liquid control valve around the set point (optimal position) for different input flow conditions. Typically, in the field, the gas and liquid flow conditions can be any combination of the following: liquid rate increase and gas rate decrease; liquid rate decrease and gas rate increase; both liquid and gas rates increase or decrease (production change) and slug flow. The system responses for different flow conditions are evaluated in following cases.

**Case 1** – Positive liquid and negative gas step inputs \((\Delta Q_L = 0.06 \, \text{ft}^3/\text{s}, \quad \Delta Q_G = -0.5 \, \text{ft}^3/\text{s})\). Figure 7 shows the dynamic response of the system at the given flow conditions. Plots (a) and (d) are the liquid and gas flow step inputs. Plots (b) and (e) are the liquid control valve and gas control valve positions. Plots (c) and (f) are the liquid and gas flow outputs. Plot (g) is the liquid level and plot (h) is the GLCC pressure. The following observations can be made from the simulation results:

- The liquid level is maintained around the set point (within ±1 ft) and settles down in about 5 seconds.
- The GLCC pressure drops by 8 psi, goes up by 7 psi, and finally settles down at 8 psi above the set point pressure. The settling time is about 15 seconds. The liquid control valve opens fully quickly and returns to the set point position in about 12 seconds.
- The gas control valve closes slowly and settles down to about −14% close from the initial position.

The liquid control valve opens when the liquid flow rate increases. The gas control valve closes to build up pressure to bring the liquid control valve back to its set point position. The GLCC pressure decreases when the gas-flow rate decreases, but the gas control valve closes more to choke the gas flow in order to gain pressure in the GLCC. The liquid level rises when the liquid flow rate increases, and drops due to the opening of the liquid control valve and the increase in GLCC pressure. The increase in GLCC pressure and the delay of the liquid control valve cause the liquid level to undershoot below the set point.

**Case 2** – Positive liquid and positive gas step inputs \((\Delta Q_L = 0.06 \, \text{ft}^3/\text{s}, \quad \Delta Q_G = 0.5 \, \text{ft}^3/\text{s})\). The system response is shown in Fig. 8. The gas control valve opens about 3% from its initial position due to the increase of gas flow rate. The GLCC pressure overshoot about 10 psi above its initial value and then settles down to about 7 psi above its initial pressure. The liquid control valve opens 5% first due to the increase in liquid flow rate, then closes 18% because of the increase in GLCC pressure. When the liquid level returns to the set point, the liquid control valve returns to its set point position as well. The liquid level does not change much because the gas flow rate increases simultaneously with the liquid flow rate, which causes the increase in GLCC pressure reducing the liquid level overshoot.

**Case 3** – Slug unit input \((\Delta Q_L = \pm 0.06 \, \text{ft}^3/\text{s}, \quad \Delta Q_G = \pm 0.5 \, \text{ft}^3/\text{s})\). From the previous 2 cases, it can be noted that the control system works well for any combination of
Experimental Investigation

Facility. Figure 10 shows a photograph of the GLCC test section. The GLCC body is a 3-inch transparent PVC pipe with a modular 3-inch inclined tangential aluminum inlet. The inlet slot area is 25% of the cross section area of the inlet pipe. The total height of the GLCC is 7 feet, which is divided by the inlet into the lower liquid section and the upper gas section. The liquid leg is a 2-inch gray PVC pipe with a liquid control valve. A differential pressure transducer is mounted on the GLCC to measure the liquid level. The gas leg is also a 2-inch gray PVC pipe with a gas control valve and an absolute pressure transducer to measure the GLCC pressure. The outlet section is constructed either to recombine the gas and liquid legs (metering loop application) or to separate the gas and liquid streams (full separation application). The recombination point is 6 inch below the inlet, which helps to self-regulate the liquid level of the GLCC. For full separation configuration, the liquid and the gas outlets are separated and a suitable control system should be used for proper operation.

Data acquisition was carried out utilizing the National Instruments' LabView data acquisition system. A dedicated input board is used to acquire data from the various transducers located in the flow loop. A separate output board is used to send command signals to the upstream and downstream control valves and the mass flow meters. A sampling rate of 20 Hz is adopted for the experimental investigations. The LabView software is capable of displaying the signal online either digitally or graphically. All the measured data can be downloaded to a spreadsheet and can be plotted in the time domain.

The control systems used for this study are implemented using LabView Control Tool Kit. The mass flow meters and the control valves in the metering section are configured in a closed-loop to regulate the air and water supply rates precisely. Various control strategies could be implemented in the test section using dedicated control systems.

Results. The performance of the optimal control strategy is evaluated experimentally in terms of system dynamics - liquid level, pressure, and control valve positions for the designed controller at different gas and liquid inflow conditions. In order to show the advantages of this strategy over other control strategies, the performance data of the integrated control strategies are also provided.

Integrated Liquid Level and Pressure Control. The set point pressure is very important for proper operation of the GLCC for this strategy. Figure 11 shows the system response for low set point pressure 18 psia. The system performs well at the normal flow conditions ($V_{sl} = 2.2 \text{ ft/s}$, $V_{sg} = 4.0 \text{ ft/s}$). Note that the average liquid control valve position is more than 95% open due to the low set point pressure. There is no more control valve capacity available to accommodate the increased liquid flow disturbance. As can be seen, when a liquid flow disturbance of $\Delta V_{sl} = 0.27 \text{ ft/s}$ is introduced to the GLCC, the liquid level is out of control, increasing up to 65 inch, and the liquid control valve saturated at 100% open. When the liquid flow rate was turned back to normal flow rate, the liquid level went down and the control valve started to activate. The GLCC pressure stayed around the set point. The gas control valve position was about 47% close. The results indicate that the integrated liquid level and pressure control strategy has a limitation at high liquid flow rates or when the LCV is fully open.

Integrated Liquid Level Control. This strategy gives non-unique solution in terms of control valve positions and operating pressure for the same flow conditions. This is because both liquid and gas control loops look at the liquid level without communications between these two loops. When the liquid level settles down around the setpoint, the liquid and gas control valves will maintain the corresponding positions whatever it is. Figure 12 shows the system response for two runs at the same flow conditions of $V_{sl} = 0.55 \text{ ft/s}$ and $V_{sg} = 20 \text{ ft/s}$. Plot 1 shows the system response to large flow surges. Plot 2 shows the system response under smooth operating conditions. The liquid level is controlled around the set point of 35 inch for both runs. The liquid and gas control valve equilibrium positions are different: LCV 50% close, GCV 35% close for run 1, and LCV 65% open, GCV 13% close for run 2. The equilibrium GLCC pressure is 23 psia for run 1 and 16 psi for run 2. The pressure difference is 7 psi. More system dynamics is observed for run 1.

It is clear that the final system operating conditions for the same flow conditions depends on the operating history.

Optimal Control Strategy. The performance of the system is evaluated for different flow conditions in the following cases.

Case 1 – System response for step like liquid flow disturbance. Similar to evaluation of other control strategies, the same flow conditions are used to evaluate the performance of the optimal control strategy for step like liquid flow surges. The initial liquid flow rate is $V_{sl} = 2.2 \text{ ft/s}$ and the gas flow rate is $V_{sg} = 4.0 \text{ ft/s}$. Suddenly, the liquid flow rate is increased by...
The system response. Figure 15 shows the system responses for the following liquid and gas flow conditions: liquid flow rate. Figure 14 shows the system responses for the transition region (10 ft/s to the lowest flow rate of 47.2 ft/s). When the system stabilizes, the liquid rate is decreased by ∆V̇_l = −0.54 ft/s from highest flow rate of 55.0 ft/s to the lowest flow rate of 35.0 ft/s. Then the liquid flow rate is increased back to the initial value. Figure 13 shows the system response for this cycle of flow condition changes. Note that:

• The liquid set point is 35 inch. The liquid level did not change much when the liquid flow conditions are changed. From the liquid level response, it is difficult to even tell when the liquid flow disturbances are introduced to the GLCC because of the fast system response.

• The liquid control valve position set point is 70% open. The average liquid control valve position is controlled very well around its set point position (70% open).

• The GLCC pressure tracked the liquid flow conditions. The larger the liquid flow rate, the higher the average pressure. At normal flow conditions, the pressure is around 25 psia. When the liquid flow rate is increased to the highest, the pressure increased to 29 psia. When the liquid flow rate is decreased to the lowest, the pressure dropped down to 22 psia. When the liquid flow rate is brought back to its initial value, the pressure returned to 25 psia. From the GLCC pressure response it is possible to detect when the liquid flow disturbance enters the GLCC, and what is the transition region (from the start of the liquid flow disturbance to the new equilibrium point of the system).

• The gas control valve follows the trend of the liquid inflow rate, determining the appropriate position for the minimum GLCC pressure.

Most part of the liquid level response is in the transition region, which created a lot of dynamics to the liquid level. When the system reached the equilibrium conditions, the liquid level responses (±5 inch) are much better than that in the transition region (±10 inch).

Case 2 – Effect of liquid flow condition on the system response; keeping the gas flow rate constant and changing the liquid flow rate. Figure 14 shows the system responses for the following liquid and gas flow conditions: V̇_l = 2.2 ft/s, 1.1 ft/s and 0.55 ft/s, V̇_g = 4.0 ft/s. As can be seen, the responses of the liquid level and the liquid control valve positions are similar for the different liquid flow conditions. The liquid level is maintained around 35 inch. At the highest liquid flow rate, the average GLCC pressure is 25 psia and average gas control valve position is 68% close. At the lowest liquid flow rate, the average GLCC pressure is almost atmospheric pressure and the average gas control valve position is almost fully open. At the intermediate liquid flow rate, the GLCC pressure is 17 psia and gas control valve position is 45% close.

Case 3 – Effects of both gas and liquid flow condition on the system response. Figure 15 shows the system responses for three runs. Flow conditions for run 1, run 2 and run 3 are V̇_l = 1.3 ft/s, V̇_g = 12 ft/s; V̇_l = 0.5 ft/s, V̇_g = 24 ft/s; V̇_l = 0.5 ft/s, V̇_g = 35 ft/s, respectively. Note that:

• The liquid level is maintained around the set point of 35 inch for all the flow conditions.

• The liquid control valve position set point is 70% open. The average liquid control valve positions is 70% open for run 1, 60% for both runs 2 and 3.

• The equilibrium GLCC pressure is about 18 psia for run 1, 15 psia for run 2 and 16.5 psia for run 3.

• The average gas control valve position is 37% close for run 1, and almost fully open for both runs 2 and 3.

Based on the above observations, it can be seen that the control system is effective at all the flow conditions. The GLCC pressure and gas control valve positions are automatically adjusted, corresponding to the flow conditions, to allow the liquid control valve operate efficiently.

Discussion. The optimal control strategy for liquid level control by both LCV and GCV provides a feasible approach to overcome the shortcomings of the integrated control strategies. There are three advantages of the optimal control strategy over other control strategies. First, the operating pressure can be minimized according to the liquid and gas flow conditions. This provides a minimum pressure drop across the GLCC, corresponding to maximum production. Second, the system gain can be adapted by the change of the operating pressure for different flow conditions. This is similar to controller gain scheduling, providing a wide operating range of flow conditions for the designed controller settings without significant change in dynamic behavior.

Tuning of the GLCC pressure is not a concern in this case, as the strategy automatically optimizes the GLCC pressure. The only commands we need to provide are the set point liquid level, which is determined based on the best performance of the GLCC for separation, and the optimal liquid control valve position (50% to 70% open), which depends on the control valve characteristics (to provide maximum control valve capacity and high resolution). The control system will automatically track the liquid control valve position (optimal set point position) and find the gas control valve position to build up the minimum GLCC pressure for the respective flow conditions. Also, the controller settings are not sensitive to the flow conditions, which provide a robust control strategy. This is because the optimal control strategy is capable of adaptively controlling the GLCC pressure so as to modify the system gain to match the inflow dynamics. On the other hand, in the optimal control strategy, the GCV controller settings are sensitive to the system if not properly designed. This strategy can lead to larger control valve dynamics.

Conclusions

Based on the detailed theoretical and experimental investigations, the following conclusions can be drawn:

1. A unique optimal control strategy is developed. This strategy is capable of self-adapting and minimizing the operating pressure, providing unique valve positions for
a given flow condition. The controller design and dynamic simulation of the optimal control strategy are also provided. This yields a robust control strategy, which can be applied for any flow conditions without modifying the controller settings.

2. A dedicated simulator is built using Matlab/Simulink® software to evaluated the performance of the optimal control strategy for different input conditions.

3. Detailed experimental studies demonstrate that:
   - The developed optimal control system is capable of controlling the liquid level over a wide range of flow conditions, namely, slug flow, churn flow and annular flow. The time responses of the liquid level and the pressure show that more flow disturbance will cause more dynamics of the system.
   - The liquid level can be well controlled at the expense of larger LCV dynamics, which will reduce the lifetime of the control valve. If liquid level fluctuation can be tolerated over a wider range, the controller gain can be suitably designed causing lesser control valve dynamics.

4. The simulation studies and experimental investigations demonstrate that the optimal control strategy has the advantages of handling large flow variations with the minimum pressure drop across the GLCC. That makes the optimal control strategy the best strategy available for the field.

Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
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<tbody>
<tr>
<td>$c_g$</td>
<td>Gas control valve flow coefficient</td>
</tr>
<tr>
<td>$c_r$</td>
<td>Control valve response time, $t$, seconds</td>
</tr>
<tr>
<td>$c_l$</td>
<td>Liquid control valve flow coefficient</td>
</tr>
<tr>
<td>$D_1$</td>
<td>Constant for GLCC geometry</td>
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<tr>
<td>$D_2$</td>
<td>Constant for liquid flow rate calculation</td>
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<td>$V$</td>
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<td>$V_{sl}$</td>
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<tr>
<td>$x$</td>
<td>Control valve position, %</td>
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Greek Letters

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<tr>
<td>$\tau$</td>
<td>Time constant, $t$, seconds</td>
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<td>$\delta$</td>
<td>Incremental deviation</td>
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Superscripts

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<tr>
<td>'</td>
<td>Denotes parameters in the gas control loop</td>
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Subscripts

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<td>$c$</td>
<td>Controller</td>
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<td>$G$</td>
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<td>Into GLCC</td>
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<tr>
<td>$v$</td>
<td>Valve</td>
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References


**SI Metric Conversion Factors**

\[
\begin{align*}
\text{ft} \times 3.048^* & \quad \text{E} - 01 = \text{m} \\
\text{ft}^2 \times 9.290304^* & \quad \text{E} - 02 = \text{m}^2 \\
\text{ft}^3 \times 2.831685 & \quad \text{E} - 02 = \text{m}^3 \\
in. \times 2.54^* & \quad \text{E} + 00 = \text{cm} \\
\text{psi} \times 6.894757 & \quad \text{E} + 00 = \text{kPa}
\end{align*}
\]

*Conversion factor is exact.*
Fig. 1 - Bulk Separation/Metering Loop for Minas-Indonesia

Fig. 2 - Schematic of GLCC Metering Loop Equipped with Control Systems
Fig. 3 - Block Diagram of Optimal GLCC Control Strategy

Fig. 4 - Block Diagram of the Linear Model for Optimal Control Strategy
Fig. 5 - Linear Model of the Simplified Gas Control Loop for Optimal Control Strategy

Fig. 6 - GLCC Optimal Control System Matlab/Simulink Simulator
Fig. 7 - Step Response for Optimal GLCC Liquid Level Control
(Case 1: $\Delta Q_L = 0.06 \text{ ft}^3/s$, $\Delta Q_c = -0.5 \text{ ft}^3/s$)
Fig. 8 - Step Response for Optimal GLCC Liquid Level Control

(Case 2: $\Delta Q_L = 0.06 \text{ ft}^3/s$, $\Delta Q_g = 0.5 \text{ ft}^3/s$)
Fig. 9 - Step Response for Optimal GLCC Liquid Level Control

(Case 3: $\Delta Q_L = \pm 0.06 \text{ ft}^3/\text{s}$, $\Delta Q_G = \mp 0.5 \text{ ft}^3/\text{s}$)
Fig. 10 - Experimental Facility (GLCC Test Section)

Fig. 11 - Set Point Pressure Effect on System Response for Integrated Level and Pressure Control

Integrated Liquid Level and Pressure Control
Set Point Pressure Effect (liquid disturbance: 0.27 ft/s, SPP=18 psia)
(Vsl=2.2, 2.47, 2.2 ft/s, Vsg=4.0)

- Pressure (psia)
- Level (in. water)
- LCV (% open)
- GCV (% close)

Time (unit: 0.05 seconds)
**Level Control by Both LCV & GCV**

No Unique Solution for the Same Flow Condition

(Vsl=0.55 ft/s, Vsg=20 ft/s)

![Fig. 12 - System Response for Integrated Liquid Level Control](image1)

**Optimal Liquid Level Control**

Liquid Flow Rate Surge (0.27 ft/s)

(Vsl=2.22, 2.49, 1.66, 2.22 ft/s, Vsg=4.0 ft/s)

![Fig. 13 - System Response for Optimal Liquid Level Control (Case 1)](image2)
Fig. 14 - System Response for Optimal Liquid Level Control (Case 2)

Fig. 15 - System Response for Optimal Liquid Level Control (Case 3)