Index

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Use of Multiphase Meters in Process Control for Oil Field Well Testing: Novel Level Controls and Resulting Performance Enhancement

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INTRODUCTION

First oil production from a deep water oil field is to be achieved by the installation of an Initial Development System (IDS). Well testing is required for field development and reservoir management. The well testing system requires high accuracy oil and water rates to provide the data needed for decision analysis in on going drilling programs. The well testing system must also be integrated with other platform operations such as well clean-up after drilling. We have simulated our concept of a certain type of multiphase meter in a feedback loop with conventional separation technology to extend the capabilities of both technologies. Concepts demonstrated here can also be easily applied as reto-fits to existing Separation Facilities which show accuracy or upset problems because of the simplicity and compact size of the additional multiphase meter component and non-disruptive supplementary integration with existing level control systems.

In the asset development scheme, the produced fluids (oil, water and gas) for each deep water well will be piped to the surface and will be measured individually on a small floating platform. Fluid measurement will use a full flow multiphase meter (MPM) in a supplemental feedback control configuration with a conventional but small sized horizontal separator and a dry gas meter, Figure 1. The most appropriate type of multiphase metering devices were chosen using results from Joint Industry Project testing. The MPM will be of a type which uses at minimum , one venturi and one gamma densitometer, Figure 2. The separator will be alternatively operated as a 3-phase separator for low flow rate cleanup of wells after drilling and as a two-phase high flow rate operation for well testing uses.

The MPM will be used to report oil, water and gas rates in the liquid line of the separator and MPM gas rate prediction will also be used for supplemental control of separator level in order to control the gas carried under into that liquid line.

Full flow MPMs can be classified as various types based on the specific combination of sensors used. We have demonstrated through simulation that a venturi-based gamma densitometer type of MPM used in separator supplemental control will:

1. Improve MPM accuracy from approximately 40% to 50% overall (our approximate assessment of performance in testing over the full matrix) to 5 to 10% overall, even if fluid properties vary to some extent.

2. Reduce excessive level changes in separators during severe slugging by about 50%. This observation of improved level control was unexpected and opens the door to new ways of sizing vessels and use of Multiphase meters.

This combination of separator, MPM and feedback control is novel and valuable because:

1. Full bore MPMs evolved with the stated objective of replacing separators, however we are using them in co-operation;

2. The MPM is used in a new level setpoint supplemental feedback control scheme to extend the dynamic range of the small separator and the MPM;

3. Set Point Supplemental control does not interfere with conventional control.
4. High accuracy Gas Volume Fraction (GVF) reporting by MPMs can be leveraged by feedback into High Accuracy Oil rate reporting.

5. Very large slugs overshoot separator level by 50% less using GVF control.

6. Certain types of multiphase meters are revealed to have more value in process control than other types.

7. Knowledge gained from GLCC™ Compact Separation Control Studies [13] has been newly applied to conventional separation systems.

8. Simulation has allowed exploration of features of the Set Point Control scheme for performance, safety, stability, noise immunity, and extreme conditions.

9. Simulation has clarified the necessary lab and field testing needed to further progress use of MPMs in upstream processing facilities.

10. The multiphase meter can be easily added (retrofitted) to existing separation and well testing facilities which are having accuracy or separation problems without interrupting convention level control of the vessels

Texaco has received US patent 6,128,962 [1] for the use of multiphase meters with separation vessels in a feedback system to control gas carried into the MPM. Future applications being studied include difficult fluid processing cases such as with heavy viscous oils, very high watercut and high range of flow rates.

DRIVERS

Several main drivers have determined the recommendations for surface well testing in this project:

1. Accuracy of water detection: Accurate measurement of early production rates of oil and especially including first indication of water flow is essential in planning the further drilling program, field management and well management.

2. Gas / Liquid Separation: Separation Facilities are required for other reasons: <u>Well Cleanup</u> after drilling on an unmanned Dry Tree Unit (DTU) and <u>Backup</u> of production Separation Vessels on a Floating Production Vessel (FPSO) have required the use of separation on both facilities.

3. Size: Size of the Well Test facilities has a significant impact on the cost of the supporting oil platform. Therefore methods to eliminate or reduce the size of separators by improved control systems have significant value.

4. Slugging: Multiphase fluids traveling large distances can re-organize into slugs of liquids and gases traveling a high speeds which can overwhelm the short term capacity of conventionally controlled separators. Oversizing such vessels allows slugs to be handled but at the great expense of size. Improved control concepts for level in the separator will permit smaller separator sizes as well as the use of short residence time compact separation devices such as GLCC™ [10].

5. Potential application of the principles to measurement of the combined production of all of the wells using much larger vessels.

MULTIPHASE METERS

<u>Multiphase Meter Performance – Sweet Spot in Oil Rate Prediction</u>

This report defines "sweet spot" for multiphase metering. A "sweet spot" is defined here as the range of relative composition of oil water and gas over which <u>oil rate</u> can be metered within the accuracy specification for the metering system. Other definitions are possible but for this study we have chosen a definition compatible with use in a process control system which can control composition to some extent. Actual testing errors are used rather than statistical determinations of uncertainty. We have used methods developed for geological data processing [7] and adapted to multiphase data by Marrelli [3,] for visualizing complex data using conventional geological subsurface visualization software[8]. This visualization method which has been adopted by the NEL JIP, MultiFlow II [6] , allows visualization of 'sweet spots" not clearly defined by other methods. We have examined the size and stability of 'sweet spots" as a function of sensor technology used by the multiphase meter.

Previous interpretations of NEL JIP data [5], without commercial reference, can be found in the Proceedings of the North Sea Workshop, 1996. Similarly our interpretations of multiphase meter are also without commercial reference and discussions of performance are restricted to general meter type. Clearly use of multiphase meters in process control will require extensive knowledge of the meter chosen.

We examine now the conditions under which a multiphase meter "sweet spot" can be exploited as part of a process control system. It is known from data generated from oil industry sponsored testing by the National Engineering Laboratories of Scotland [3,5,6], and Figure 5, and Texaco testing at its Humble Flow Facility [4], that each multiphase meter type has a flow rate, gas fraction and water fraction "sweet spot" in which performance is best. This "sweet spot" results from the particular combination of instrumentation used and the proprietary information and models used by the vendor.

Basis of Multiphase Meter Type and "Sweet Spot"

The design of commercial multiphase meters reflect the complexity of multiphase flow. In Figure 4, a pipeline is schematically represented as a P,T,X_g line where X_g represents the fraction of gas to total fluids at local pipeline pressure and temperature. The hypothetical pipeline extends from the hydrocarbon reservoir at high pressure, temperature and low gas volume all the way to atmospheric pressure and ambient temperature where very high X_g may exist. A multiphase meter may lie at any point along this P,T,X_g line and choice of locations depends on primarily cost, accessibility, branches to the flow line from other users and accuracy. In figure 4, the conceptual design of a MPM is presented. The conceptual elements may be assumed, measured, calculated and distributed along the P,T,X_g line. An MPM will provide the steps of:

Uncertainty reduction through some type of flow conditioning;
Density determination or assumptions;
Liquid and Gas Rate determination;
Composition determination (water and hydrocarbon fractions) or assumptions ;
Application of a multiphase flow model; and
Output signals in various formats.

As indicated in Figure 2, multiphase meter types can consist of various combinations of discrete instrumentation including sensors of gamma ray attenuation, temperature, pressure, pressure drop, density, dielectric constant, capacitance, conductivity and inductance. These multiphase measures are then interpreted by proprietary multiphase models and may use mathematical cross-correlation and assumptions about the relative flow speeds of gas and liquids (slip models) to predict the rates of oil, water and gas at that point.

In each case, some assumptions are made concerning the mixing of fluids arriving at the meter, and in some cases, a preliminary "fluid conditioning step" is required in which a mixer element or length of straight pipeline is included. The set of meters using similar basic elements is referred to as a meter type. Each meter type can be provided by more than one commercial vendor.

Data Visualization

JIP testing of several MPMs at several hundred test points each, provided data for Figures 5, 6 and 7. Graphs represent the percentage of gas in total fluids (X-axis) and percentage of water in the total liquids (Y-axis). The Z-axis is color coded and represents the measured error in oil flow rate made by that meter during the test.

Importantly, the surfaces thus displayed are developed by one of us from commercially available interpolation routines called Krieging [7], operating on the NEL JIP data sets. Other algorithmic methods of interpolation are possible with small differences in surface topology. Because of the desire to provide continuous visual information, there are not actual lab data under each pixel. The graphical method used provides intuitive and very rapid understanding of large masses of data, however, misleading conclusions can also be drawn due to possible peculiarities of the software algorithms used. Care and understanding must be used in interpretation of such complex data sets.

In the case of NEL testing [5,6] , Meter vendors set up and calibrated the meter test under one set of known fluids, (left side inserts). In other sensitivity tests, the same meter calibration is maintained while the fluid properties, viscosity in this case, are changed (right side Figure 5, 6).

In this test program matrix, MPM overall oil rate accuracy performance at better than 5% of true value would be considered exceptional, and 10% accuracy is achievable under some conditions. For example, Figure 5 Meter X, left side insert, indicates that accuracy of oil flow rate, indicated in color as the z-axis, can be held to within 5 to 10 % of true value, if the gas and water percentage in the fluids can be held to less than 50%, that is, within the dotted box. Thus a “sweet spot” for Meter X, is defined.

However for Meter M, (Figure 6 left side insert) the “sweet spot” within the dotted box shows that oil rate accuracy can be held to within 5 to 10 % of true value, if the gas percentage and water percentage in the fluids can be held to between 20% and 50%.

In Figure 7, Meter V appears to show two separate small “sweet spots”,(dotted ellipses). Specific reasons for two regions of good performance separated by a region of poor performance is not clear. However, one suggestion based on the visualization for the data in Figure 7 is that there may be difficulty with meter flow regime identification using a too limited set of sensors. Flow regime effects are hypothesized to be most complex when fluids are close to the range where oil/water emulsions and gas/liquid emulsions may be flipping from one continuous external phase to another, for example, at the boundary between the two “sweet spots” in Figure 7. In the case of Meter V, Figure 7, feedback control would be of limited value in improving MPM performance, because a controller would not “know” whether to reduce or increase GVF to achieve improved oil rate accuracy when the measured GVF was in the 30 to 40% GVF range.

It is important to recognize that oil rate errors reported here are of true value, therefore while a percentage error may be large the actual absolute value may be low. Specific objectives of the user is therefore important in evaluating the significance of error.

Multiphase Meter Performance - Sweet Spot Stability for Viscosity Change

Of great importance in process control and validity of measurements is the stability of the multiphase meter's "sweet spot" when operational conditions change. Unfortunately, important production fluid properties of oil density, water salinity, emulsion viscosity, emulsification, foaming and flow pattern are often not well known and can vary during production. NEL JIP testing has demonstrated that small changes in fluid properties such as viscosity changing from 15 to 30 Centipoise, can greatly effect the 'sweet spot" depending on multiphase meter type.

In the case of Meter X, (Figure 5, right side insert) testing shows that the 5% performance zone disappears and the range of 10% oil flow rate accuracy is reduced to a range of less than 40% water and gas percentage.

In the case of Meter M, (Figure 6, right side) similar increase in viscosity from 15 to 30 Centipoise completely eliminates the 'sweet spot'. In all cases examined, MPM performance can decline greatly outside the "sweet spot". Similar effects occur for all multiphase meter types when water salinity is varied. Those salinity effects are not discussed here.

Multiphase Meter Performance - Zero-bounded 'sweet spot"

It is expected that proper operation of the control system in reducing GVF into the multiphase meter would also reduce the meter's hydrocarbon rate errors. If errors rose as GVF and Water composition went to zero, process control would not be as valuable. Therefore a further requirement can be added to MPMs to improve performance in process control, which is a requirement for a zero-bounded 'sweet spot". The Meter X "sweet spot", figure 5, is anchored at zero gas and water percentage, even when viscosity of the oil is changed, whereas Meters M , figure 6, and Meter V, figure 7, "sweet spots" are always significantly above zero gas or zero water. Meter V would be especially difficult to use in process control as in some cases the control system might position the GVF value directly in the center of the worst oil rate performance range.

- Within the limits of noise, MPMs which have a zero-bounded "sweet spot", are expected to increase average hydrocarbon rate accuracy upon reduction of average GVF in the meter.

Because of demonstrated "sweet spot" size and stability and feedback concerns, a type of MPM, using both venturi pressure drop to sense flow rate and gamma ray energy methods for sensing density, has been selected for use in a process control system. Several commercial vendors can supply this type of meter construction.

Value of Testing Multiphase Meters

There is a clear demonstrated difference between commercial MPMs in performance dynamics, in terms of gas and water composition and stability of those performance dynamics as a function of the viscosity of the fluids. The existence of the above "sweet spot" dynamics therefore justify performance testing of MPMs and linking that performance to the fundamental sensor measurements in order to make informed decisions on applications which can not be tested in a laboratory or field environment.

Joint industry sponsored research projects, such as the Texaco operated Evaluation of Multiphase Flow Meter JIP[4] and NEL operated JIP[5,6] have identified multiphase meter "sweet spots". Further, the stability of these "sweet spots" when there are uncalibrated changes in oil viscosity and water salinity has been evaluated for many of the commercially available multiphase meters.

FLUID CONDITIONING

Limitations of Operating a Separation System

Gas/liquid and potentially water/oil ratio in various streams can be controlled by 2 and 3-phase separation systems, however, fluid rate can not be materially altered without very large and impractical storage capabilities.

We are using the term process control to mean only the control of the range of average gas-to-fluid ratio entering a multiphase meter by use of some type of fluid separation system. This control is supplementary to the fluid level control system normally used in conventional oil field gas liquid separation systems. Level control is normally used to maintain a gas and liquid spaces within a separation vessel in which velocities of gas and liquids are slowed sufficiently to allow separation of gases and liquids. The expectation of conventional separation control systems design is to provide for complete separation of gases from liquids. In general this expectation is only met under a restricted range of conditions. In the current design, our expectation is that gases in the gas line of the separator will have no liquids entrained (dry gas) , however liquids in the liquid line of the separator are expected to have less than 50% gas by volume. Gas fraction in the liquid stream will be varied to maintain dry gas streams.

High Water Composition

In the current design no attempt is made to limit the composition of water in the multiphase stream. The most important use of the metering system in this case is for early production of the oil wells in which average water composition of less than 40% is expected. Our expectation is that water composition will therefore be managed to be below 50%. Reliable removal of pure water (oil-free) from multiphase streams is much more difficult than the removal of dry gas, however research groups at TUSTP are pursuing the development of feed-back controlled separation systems to that end. However, in the case of high water composition in late field life, calibration of the MPM water fraction accuracy at higher water concentrations is facilitated by use of the separation vessel to provide pure batches of field water to the MPM for periodic calibration.

Range Control of GVF

Even a perfect control system can not , for example, maintain 30% gas fraction if no gas is available in the pipeline. Thus it will only be possible to hold MPM gas fraction to a range limit, because the supply of gas from the pipeline is not constant or predictable and can not be stored in a significant volume. In general, pipe line effects and oil well properties can cause the instantaneous composition of liquids and gases to fluctuate from 0 to 100%. Setting upper limits on gas composition of the liquid stream is very practical. As illustrated in figure 1, excess gas detected by the MPM, can be routed from the MPM flow line to bypass the meter, by some combination of increasing the opening of the Gas Control Valve of figure 1 or closing the Liquid Control Valve. Conventional control theory allows quantitative determination of the best combinations of Liquid and Gas Control valve actions to achieve stable GVF control.

Quantification of Conventional and Cyclonic Separation Performance

Separation of gases and liquids using centrifugal force has been the major focus of the Industry sponsored JIP, the University of Tulsa, Separations Technology Project (TUSTP) [9,10,11,12,13,14]. Mechanistic models of the cyclonic separation vessel known as the Gas Liquid Cylindrical Cyclone , GLCC™ , have been funded by a Joint Industry Project (JIP) for several years. As a JIP member and as a user of the technology, ChevronTexaco has strongly supported additional efforts to understand how to control the compact separation GLCC™ vessels for optimal performance [13,14]. Knowledge gained and control strategies developed for the GLCC™ is also applied here to advance the state-of-the-art of control of conventional separation vessels to allow reduction in their size and improvement in their handling of large liquid slugs.

Two factors can characterize separators for well testing use: Degree of Separation and Operating Range. Degree of separation is defined here, as the percent incomplete separation into a gas stream or a liquid stream. Operating Range is defined as the set of flow conditions over which a Degree of Separation is valid. Because no separation system can totally separate gas from liquids under all operating conditions, effective control of conventional 1-G separation or the high-G GLCC™ requires both a Degree of Separation and Operating Range specification, [ref: 5,6]. These data can be used in systems analysis of the combination of devices.

Extensive data public and proprietary data [2] is available, relating separator level to gas-carry-under into the liquid stream compact separation systems and conventional systems. Simply stated for both conventional and GLCC™ systems, the lower the gas / liquid interface in separation systems, the higher the resulting gas carried into the liquid leg. While there are clearly complex flow rate effects on the liquid-carry-over and gas-carry-under performance, these effects are not presented here. More complex separator dynamics will be reflected in overall system performance and have been simulated successfully to some extent but are not reported here. Performance characterization of convention separation systems will greatly advance the development of control systems for their improved management.

Models and testing of GLCC™ demonstrated that use of feedback control of vessel level can maintain performance and greatly extend the operational range [ref: 5,]. Conversely, these same results for GLCC™ also indicate that feedback control of vessel level can regulate the amount of gas carried into the liquid stream. These discoveries have opened the way for use of both 1-G and high-G separation tools in new ways as flow conditioners which can deliver fluids with pre-set gas liquid composition.

COMBINING MULTIPHASE METERS AND FLOW CONDITIONING

Our objective is improvement in the performance of a multiphase meter in reporting oil rate, through flow conditioning with a gas liquid separator. The means by accomplishing that improvement is through use of the specific multiphase meter's accurate GVF output. Essentially, good accuracy in the GVF determination is leveraged into good performance of the oil rate measurement, though action of the feedback control network.
The precision with which a control variable such as GVF in the MPM is achieved can not exceed the uncertainty in the control variable. Fortunately, data indicates many types of multiphase meters do well at reporting values of GVF > 30%, Figure 8.

- **GVF Accuracy Required**: The uncertainty in Meter X's GVF output, figure 5, is: GVF Uncertainty < 5% for GVF > 10%.
- **Oil Rate Accuracy Desired**: Our target GVF for flow into the MPM which would allow Oil Rate performance of better than 10% , is GVF < 50%, Figure 5, dashed line.
- **Noise Limitations**: Rapid fluctuation in Meter X output GVF can be reduced by filters and averaging to guarantee stable system response.
- **GVF Setpoint Required:** Our GVF set point for the GVF control system using Meter X can be set at 30 % GVF with the assurance that the control system can achieve a continuing GVF in the target range of GVF<50%.
- **Separator Level Limitations:** The level in the separator can swing between 1 foot and 4.5 feet in order to control the GVF output, assuming there is sufficient gas entering the vessel inlet.

Stability and Set Point Control

Stable process control is defined as that in which significant oscillations in GVF are not induced by the control system and do not grow in amplitude with time. Stable control requires low noise, monotonic response curves and reasonable accuracy from the measurements used in the feedback system. Response time of the remotely operated valves used in the process will most likely be the limiting factor in performance speed.
Separator Level Set point control by GVF feedback from the multiphase meter has been chosen as the most reliable method of superimposing the MPM outputs onto the traditional level control system of the separator.

Two Set Points: Level and GVF

In the current case, we superimpose upon conventional separator level control, the option to use the multiphase meter GVF output to dynamically move the set point of the Liquid Level between the acceptable vessel maximum and minimum values. The GVF control system must have a target or set point similar to the level control system. There are thus two set points,

1. Level setpoint of the separator (1 to 4.5 feet) when no feedback from the GVF control system is available.

2. GVF set point (0.30) which is the basis for the changing of the Level Set point.

3. We have used the conservative strategy of not interfering in any way with the conventional level control system. However, the multiphase meter GVF control loop is superimposed on to the liquid level control loop to maintain the GVF around the set point by manipulating the liquid level set point in the acceptable range. Simply connecting the line from the properly filtered output of the multiphase meter to the setpoint input of the separator level control system will activate the supplementary control system. All Valve actuation is handled by the existing level control system.

Control System Design

The design of a system using meter GVF output for supplementary feedback control can be determined by a conventional engineering methods:

1. Systems analysis of the entire separator / multiphase meter / piping / control valve and closed loop feedback system. In the simulator, connect the output GVF from the MPM to the input Set Point connection of the Level Control System

2. Determine Level control PID settings: Changing by use of electronic filters, the characteristics of the Level feedback signal.

3. Determine GVF control PID settings: Changing by use of electronic filters, the characteristics of the GVF feedback signal.

4. Simulation of the resultant system 1) and 2) above, including, simulation of the worst case time-varying process fluid conditions such as slugging of liquids and gases.

5. Sensitivity analysis: How important are specific setting and dimensions and inlet conditions for the successful operation of the system.

The systems analysis requires a description of the component connections, quantitative mathematical description of the vessel, valve response characteristics and fluid flow properties of the associated piping. Figure 9 provides the linear model of a conventional separator level control system using a differential pressure sensor for level detection. In the system of Figure 9 , the set point of the level control system, H_{set} , is input manually to be a desired level such as 50% of the diameter of the separation vessel.

In the case of Figure 10, we superimpose on the linear model an additional loop which provides the level set point automatically from the multiphase meter's GVF information. In the system of Figure 10, the set point of that control loop, GVF_{set}, is entered manually at 0.3 or 30%.

Proportional, Integral and Differential Feedback (PID) to Force 2nd Order Response

Further to the systems analysis, is a determination of the optimal electronic feedback characteristics, figure 3, (Box labeled GVF Controller) and (Box labeled Level Controller) to add to the system. PID values are determined using conventional engineering analysis of the roots of the closed loop equations.

This GVF Controller element and Level Controller element will tend to force the overall complex system to act like a simple critically damped 2nd order system. These additional feedback characteristics are normally defined in terms of the mathematical operations called proportional, derivative and integral (PID).

These values of PID for both the Level control loop and the GVF control loop, can be translated into vendor specific values and can be dialed into standard industry process control devices such as brand Fisher and Red Lion, Tables 1, 2 and 3. These commercial devices accept the process control variables such as GVF and Level, handle the noise filtering, truncation, and mathematical functions as well as safety, back up, startup and shutdown features.

Simulation is used to confirm that the response to a wide variety of perturbations in level and GVF can be corrected rapidly and with limited oscillations. It is desirable to have the level and GVF change in 2nd order fashion to an abrupt step input. Stable 2nd order response to a step consists of a rise to the control level with one small overshoot. Response to a single step perturbation is sufficient to demonstrate that the system is stable to all other combinations of steps, ramps, and slugs of gas and liquid as long as the system capacity is not overloaded. However a combination perturbation of step-plus-slug is simulated for inspection.

A 2nd order control system can be well understood by its response to a sudden large disturbance, for example, a single or series of slug of liquids and gas. A 2nd order system response to a rapid perturbation is characterized by Response Time, the time to settle to within 2% of the final state, and Overshoot, the percentage of overshoot of the final value. Optimal 2nd order response values usually require minimal overshoot and minimal Response Time but without unstable or dangerous oscillations. Allowable Overshoot is a subjective evaluation by the designer with an understanding of the process needs.

- Short term fluctuations in Meter GVF of smaller duration than Response Time (approximately 15 to 60 seconds) can not be eliminated due to response time limitations of control valves and filtering of the multiphase meter GVF to avoid noise.

Gas Metering in the Bypass Line

While Gas carried under into the liquid stream is tolerable, even desirable, liquids carried over into the gas stream are not tolerable. There are no suitable commercial wet gas meters which can accurately measure gas with entrained liquids. Liquids carried into the gas stream can potentially interfere with down stream processing such as gas compression or may be lost because they are burned with gas disposal. A Wet gas definition is somewhat subjective but can be considered to be gas streams with .01 to .5 ratio of liquid mass to gas mass.

The dry gas flow rate from the separation system will be measured using a commercial vortex shedding meter

Control Valve management

Alternate strategies are possible for adjusting a control valve to keep the separator output GVF within range. Strategies which minimize the movement of the control valves are desirable to reduce valve wear.

Applications within ChevronTexaco have used various types of Setpoint feedback control of separation vessel level. In Setpoint control, rather than manually entering separator level, for example, 50%, that setpoint is automatically calculated by a PLC or PC computer every few minutes using the actual flow characteristics (Gas Volume Fraction- GVF) of the liquid exiting the separator stream as monitored by the Multiphase Meter. For that separator/meter configuration, it is demonstrated here by simulation, that separator performance can be controlled more reliably than by conventional means and that the separator performance range is actually extended and slug control is very improved. Control valve movements tend to be reduced in Setpoint Control systems thus reducing potential wear due to movement.

Equipment Specifications

In order to purchase appropriate MPMs, a sufficiently detailed specification must be generated which allows competitive bidding by multiphase meter vendors. Since most MPMs are of high quality instrumentally, specification of the type of commercially available MPM most likely to perform acceptably and listing of minimum sensors required is deemed sufficient. Factory Acceptance Testing at time of delivery would confirm instrumental competence and quality.

Safety

Safe Operation of the control system is essential. Effects of noise, positive feedback, loss of connection and slug induced overflow of separator capacity were examined. Requirements imposed by the asset team are to configure the system to insure that safe separator control is maintained even if multiphase meter feedback onto the level control system is interrupted or noisy. We have met that safety requirement and demonstrated acceptable performance by adding input liquid slugging, “noise” and “damage” to the simulation.

Addition of Multiphase noise to the GVF data line simulation is demonstrated to be easily handled by appropriate filtering at the PLC inputs, Figure 15. Abrupt removal of all Multiphase meter outputs, simulating a power failure or damaged electrical link demonstrated that safe performance of the conventional level control is maintained, Figure 13,14, however the slug management capability of the separator is now limited by the conventional level control system.

Offshore operation of separation vessels can require level limit detectors which can shut down that vessel if levels are too high or too low. Simulation of large slugging inputs into a separator, demonstrates that use of GVF feedback prevents excessively high or low separator level.

Specific System Design: Control Valve Type

Specific control valve flow characteristics are built into the simulation . The response time of the pneumatic or electric actuators systems are also built into the simulation. These parameters have a strong effect on the system dynamics and must be included if the simulation is to reflect actual installed operation. For the flow rates considered, the liquid control valve recommended for this configuration of GVF control is a 4-inch V-500 Rotary Ball valve of Fisher Type. The recommended response time of the control valve is 5 sec. The control system design should be verified for stability and transient response if the control valve or any other conditions change.

Multiphase Meter Sampling Frequency

Multiphase meters have a variety of output options. Normally they are not provided for use in process control, therefore specifications for output variable and hardware are required. From a control perspective, the recommended multiphase meter minimum averaging duration range for GVF signal is: 1 sec to 60 seconds.

Control Strategy

The "Optimal GVF Control Strategy" integrating the Liquid level and GVF controllers provided stable operation at optimum GVF (nearest to the set point) in the liquid leg of the separator unit.

In this strategy, the output of the level sensor (differential pressure transducer) is sent to the Liquid level controller. The Liquid level controller sends the signal to the LCV (liquid control valve). In the outer loop, the GVF sensor (multiphase meter) sends the signal representing the actual GVF in the liquid leg to the GVF controller. The GVF controller acts upon the sensor signal and sends appropriate signal to change the liquid level set point. An appropriate filter is used to ensure that the operating range of the liquid level set point is within the allowable range. The liquid level controller acts upon the difference between the actual level (as measured by the level sensor) and the setpoint level and changes the liquid leg control valve position accordingly. Thus GVF controller will assist the LCV operation in order to achieve both liquid level and GVF control at optimum conditions.

A powerful feature of Set Point Control is that if the system level is already at the set point or if the set point is moved to an actual existing level, then the feedback signal is effectively zero and no system dynamics are encountered. In this configuration higher system gains can be employed , but without the concomitant effects of high gain unless offset error actually occurs. The block diagrams shown in Figures 3, 9, and 10 and flowchart shown in Figure 11 describe details of this approach.

Separate simulations were conducted to identify the optimum PID settings for the Liquid level and GVF controller for the conditions, namely, GVF as a function of liquid level only. The designed PID settings for the Liquid level and GVF controller are given in the following table to provide insight into the relative values of gain used for a well testing system. Actual systems can not use these values without first designing and simulating the specific process. The settings will depend upon the commercial type of PID controllers, which will be employed. Hence three different configurations are identified and listed below for comparison.

Also, the sensitivity of the values of PID settings on the size of the vessel was also investigated. Initially, a horizontal vessel of 72-inches x 20 feet long s/s is considered and subsequently a horizontal vessel of 72 inches x 30 feet long s/s is considered. Finally a much larger vessel 108 inches x 35 feet was studied to determine worst case responses to very large slugs. Results from the two smaller vessels are given in the tables shown below. It can be noted that with 50% increase in the smaller vessel size, the P, I, and D gains of the liquid level controller are also increased by approximately 50%, indicating a simple scaling of gains as a function of vessel volume may be possible , all other factors being constant. The GVF feedback gain did not change even thought the separator volume changed by 50%. Therefore changes in system volume by mechanical corrosion, sand accumulation, retro-fit are seen as having significant impact on the overall control effectiveness. Very large scale up such as to the 108" x 35 foot vessel will cause large changes in valve actuation time and delay times in pneumatic and electric actuators. These time delays will have significant impact on PID settings and a systems analysis will have to be performed again with large scale up.

Tables: Controller Settings for Liquid Level and GVF Controllers

Table 1 – Liquid Level Controller - Horizontal Vessel 72" OD x 20' s/s

PID (Fisher Type)			PID (Red Lion Type)			PID (Reset Type)		
P gain	I Gain	D Gain	Prop. Band	Int. Time (sec)	Der. Time (sec)	P Gain	Reset Time (sec)	Der. Time (sec)
89	4.5	445	1.13	0.23	5	89	20	5
Level Set Point = 0.5 Dsep			Level Set Point = 0.5 Dsep			Level Set Point = 0.5 Dsep		

Table 2 – Liquid Level Controller - Horizontal Vessel 72" OD x 30' s/s

PID (Fisher Type)			PID (Red Lion Type)			PID (Reset Type)		
P gain	I Gain	D Gain	Prop. Band	Int. Time (sec)	Der. Time (sec)	P Gain	Reset Time (sec)	Der. Time (sec)
133	6.7	667	0.75	0.15	5	133	20	5
Level Set Point = 0.5 Dsep			Level Set Point = 0.5 Dsep			Level Set Point = 0.5 Dsep		

Table 3 – GVF Controller - Horizontal Vessel 72" OD x 20' s/s and 72" OD x 30' s/s

PID (Fisher Type)			PID (Red Lion Type)			PID (Reset Type)		
P gain	I Gain	D Gain	Prop. Band	Int. Time (sec)	Der. Time (sec)	P Gain	Reset Time (sec)	Der. Time (sec)
0.32	0	0	312.5	0	0	0.32	0	0
GVF Set Point = 0 to 0.5 depending upon the meter			GVF Set Point = 0 to 0.5 depending upon the meter			GVF Set Point = 0 to 0.5 depending upon the meter		

SIMULATION OF STEP AND SLUG PERTURBATIONS OF THE CONTROL SYSTEM

In the simulation results Figures 12, 13, and 14 there are 2 sets of 4 each simulator screens. Each set illustrates the time responses of fluids in the separation / meter system:

1. Top Left: The liquid rate perturbation in the inlet line is a step increase or trapezoidal slug in liquid rate (Barrels per Day),

2. Top Right: The resulting gas volume fraction (0 to 1) in the liquid line going to the multiphase meter,

3. Bottom Left: The resulting flow rate in the liquid line going to the multiphase meter, and

4. Bottom Right: The resulting level changes in the horizontal conventional separator.

The MATLAB simulation used the actual geometry, control valves and performance expectations of the separator in combination with a multiphase meter estimation of gas volume fraction similar to that of the function of Figure 6, Meter V.

Figures 12, 13 and 14 show the simulation result for inlet flow rate perturbations of the control system. Figure 12 shows step (Figure 12A) and also step plus slug (Figure 12B) perturbations results of flow to a 66 inch diameter by 20 foot long vessel using the PID settings of Tables 1, 2 and 3.

Figure 12 illustrates the approximation to a 2nd order overshoot to a startup step of 15,000 BLPD (Figure 12 A). Overshoot of Liquid leg GVF (Figure 12A, insert 2) and liquid level (Figure 12A,insert 4) show minor harmonics in the overshoot response and is damped within 40 seconds to the set point control values of level and GVF. Flow rate in the liquid leg (Figure 12A, insert 3) fluctuates because it is not a controlled parameter. Response is therefore considered to be successfully stable and the 2nd order approximation goal is reasonably achieved.

A step-plus-slug was simulated (Figure 12 B, insert 1) consisting of a positive 14,000 BLPD ramp followed by an equivalent negative liquid slug superimposed after a few seconds on a step of 15,000 BLPD rate background. Comparison of the step response, with the more complex step-plus-slug, response to liquid level demonstrates that the dynamics in the step response are present and sum with each new perturbation but the Level and GVF control variables are successfully damped with minimal overshoot. The GVF passing into the multiphase meter (Figure 12B, inserts 2,4) was held to the < 50% target value and in the meter's "sweet spot".

In Figures 13, 14 simulations, GVF feedback was eliminated from the simulation on the left side of each figure, to demonstrate by comparison, features of:

1. Safe operation of the system if GVF feedback were suddenly lost

2. Successful control of GVF in the Multiphase meter

3. Added value of the supplementary GVF feedback in slugging situations.

Items 1 and 2 above are demonstrated through comparison of the step-plus-slug perturbation response in Figures 13 (small vessel A) and 14 (Largest Vessel C) with GVF feedback (Figures 13 A, 14A) and without GVF feedback (Figures 13 B, 14B). Value of the GVF control to slug handling is more obvious with slugs of very large size (Figure 14). However, overshoot of separator level (Insert 4) and multiphase meter GVF (Insert 2) is greater in every case where GVF control is removed. No effects on level control original response was observed.

Noise Effects on Control

Noise of certain types can conceivably induce unstable oscillations into a control system. By filtering and averaging control signals such as multiphase meter output GVF, signal bandwidth can be reduced to prevent positive feedback without significantly reducing system response capabilities. In the simulation trials of Figure 15, random noise, with a flat spectrum over +-10% of signal, was injected into the simulator multiphase meter output GVF during a step-plus-slug perturbation. Figure 15 simulation views are: Top Row Left, perturbation at inlet; Center, GVF entering meter; Right, multiphase meter readings plus noise. Second row Left, Effects of perturbation and noise on liquid flow rate; Center, Effect on Liquid Level in the separator; Right, filtered signal fed into the level set point input. A filter was installed after the injection point, to simulate the type of filtering of noise expected in a field situation. Too much filtering will eliminate the feedback signal, not enough filtering could allow unstable noise effects.

Simulation results showed the control variable GVF to reach and stabilize at the target GVF of 0.3 but with 5 to 10 % random fluctuation. Liquid Level in the separator showed percentage-wise less than 10% fluctuations around the control point. The control system settled to stable control values but with superimposed noise of the magnitude of the injected, filtered noise. No unstable oscillations were detected in level or GVF. The multiphase meter was successfully held in the target range of GVF < 50%.

Low frequency noise in the flow rate to the multiphase meter is not anticipated to cause rate measurement errors, since the fluctuations are well within the meters rate specifications. Improved use of multiphase meters in process control will require continued investigations of the impact on the control system, of specific types of noise and error typical of multiphase.

Assumptions in Design of GVF Control:

The system simulated represents actual performance characteristics of commercially available devices. Performance characteristics of field device may vary greatly and are often difficult to confirm experimentally. Applications in control systems are dependent on reliable component descriptions or on feedback concepts which minimize dependence on precise performance specifications. The following assumptions underlie the simulations in this report.

1. Controller hardware for GVF and Liquid Level control is procured as Fisher Type Controllers AND/OR Red Lion type controllers.

2. The separator is operating under an independent pressure control system configured appropriately and working perfectly. Thus the separator pressure is assumed to be constant in this study.

3. Pressure transducers (especially the differential pressure transducer) for the separator are procured with isolation diaphragms.

4. The design basis is given below:

   Vessels converted from 3 Phase operation in well clean up at 5000 BLPD to Normal 2 Phase Well Test Operation

Horizontal Vessel sizes examined:

A. 72" OD x 20' s/s;
B. 72" OD x 20' s/s;
C. 108” OD x 35” s/s;

Operation @ 440 psig @140 F
Flow Rates may be
Vessels A. and B.
from 10,000 to 40,000 BLPD @ gas rates 1400 scf/stb,
Slug flow investigated , 100% rise/fall @15,000 BLPD rising to 28,000 BLPD and down to 2,000 BLPD over 60 seconds. Gas rate changing proportionally

Watercut is assumed to be less than 30-40%.
And Vessel C.
40,000 to 100,000 BLPD @ gas rates 1400 scf/stb,
Slug flow investigated, 250% rise/fall @40,000 BLPD rising to 100,000 BLPD and down to 0 BLPD over 60 seconds. Gas rate changing proportionally
Watercut is assumed to be less than 30-40%.

5. GVF in the liquid outlet of the separator is assumed to be a predominant function of only the separator liquid level. The relationship between the GVF and the liquid level is a high order function of level and liquid flow rate as shown in data for GLCC devices. However, a linear approximation of the higher order relationship is assumed for the simulator (truncated at 50% level). Further studies determining the separator characteristics will be required to determine the effects of oil viscosity, and flow rate on gas carry under. The GVF control response dynamics will depend on the separator characteristics. However those dynamics are expected to be within the design objective of controlling GVF < 50%.

6. Separator transfer function (level vs. GVF) is independent of inlet conditions.

7. The liquid level set point acceptable range is assumed to be between 1.5-ft and 4.5 feet.

CONCLUSIONS

The objective of providing oil well testing capability meeting the accuracy, facility integration and safety needs of that asset's development team were achieved. Types of Multiphase meters are found to be fundamentally different in properties depending on the physical principals used by the meter's sensors. Venturi-type gamma densitometer multiphase meters are selected as most useful in process control. Reducing gas fraction in a multiphase meter is shown from several sources, to improve that meter's oil rate accuracy.

Conventional and compact separation systems are very capable of flow conditioning fluids to a multiphase meter and provide considerable advantages to the facility. The GVF control system can be supplementary to existing level control. The supplementary nature of the GVF Setpoint Control system using a multiphase meter is easily retro-fitted to old existing facilities in which well test accuracy or level control is a problem.

Simulation was used to determine that a multiphase meter's tested performance could be enhanced by feedback control, leveraging the meter's accurate GVF output into enhanced oil rate accuracy. The general concept of Separator Level Setpoint Control by GVF Feedback was shown to work well.

Simulation showed unexpected benefits of slug control in addition to the expected enhancement of multiphase meter performance.

Specific guidelines were provided in selection of multiphase meters for process control were provided.

Nominal Settings for conventional and GVF PID control are recommended for the Base Cases with the caution that actual installed conditions must be evaluated with respect to this report prior to operation. Simple scaling rules for PID settings may apply for variations of system volume due to corrosion, retro-fit and swap out, all other parameters remaining constant.

Simulation demonstrates that accidental loss of the GVF signal has no negative impact on conventional level control.

Simulation demonstrates that large liquid slugs, which would have tripped level sensors and possibly shut in vessels or wells, are handled effectively by the GVF control system and would allow well testing to proceed without any interruption.

Introduction of noise (up to ±10%) into the GVF control system indicates that appropriate filtering and averaging of the Multiphase meter output allows stable performance regardless of random noise.

The system with GVF control is much more stable with less dynamics compared with the system without GVF control and may have value in reducing valve wear.

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FIGURES

Figure 1: Multiphase Metering System with GVF and Liquid Level Control

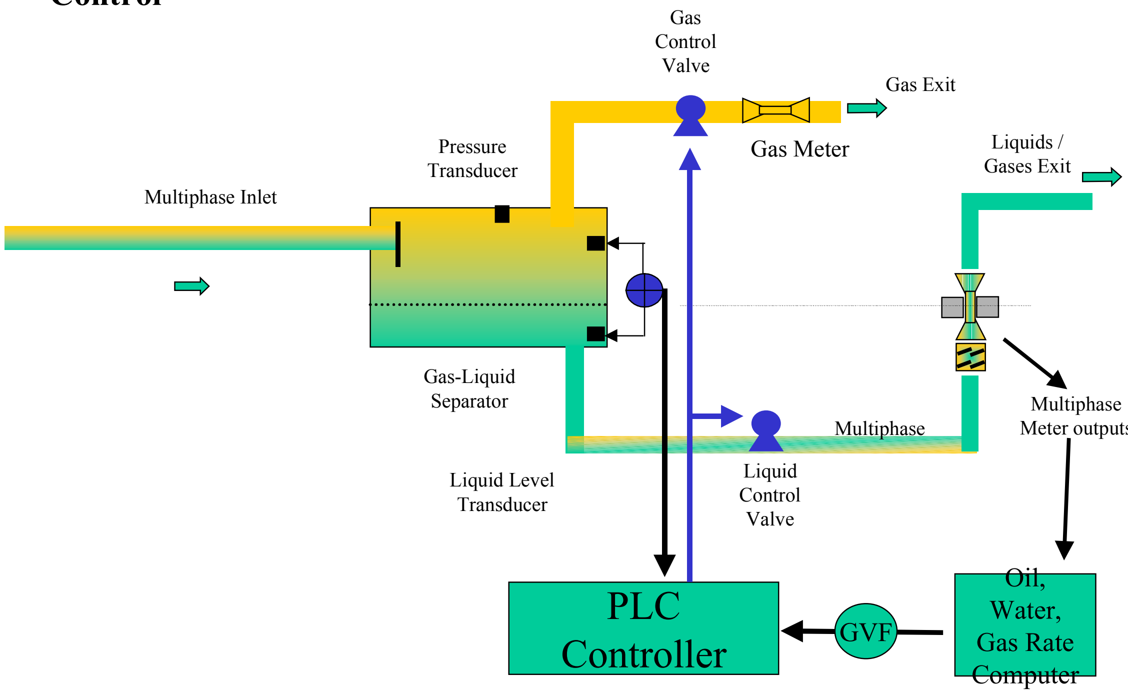

Figure 2: Multiphase Meter Possible Primary Measurements
Gamma Ray Absorption, Differential Pressure, Pressure, Temperature, Dielectric , Capacitance, Conductance & Inductance

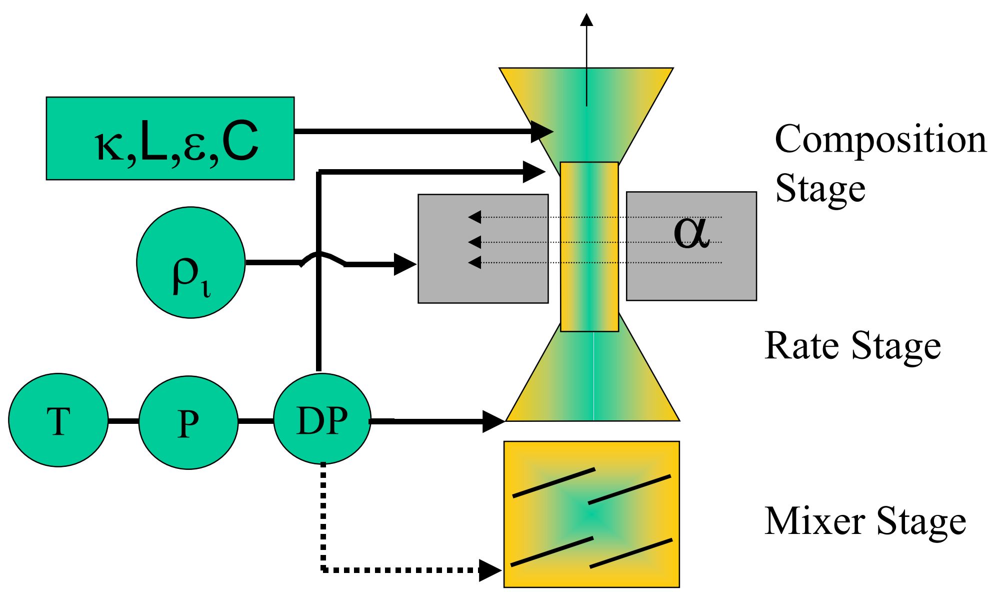

Figure 3: Block Diagram of GVF and Liquid Level Control

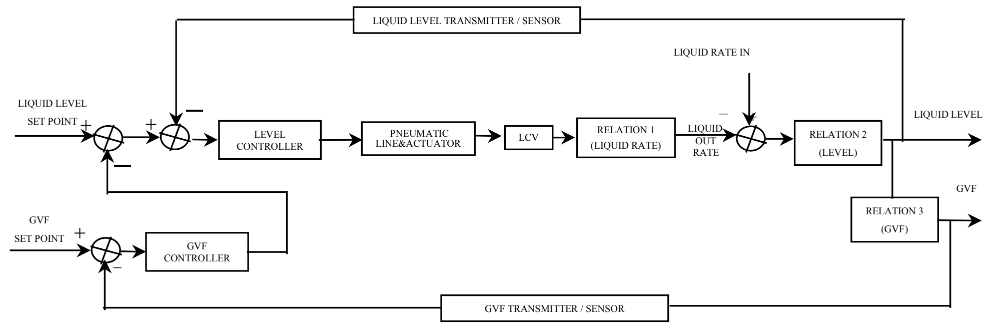

Figure 4: Multiphase Welltest System -Basic Structure

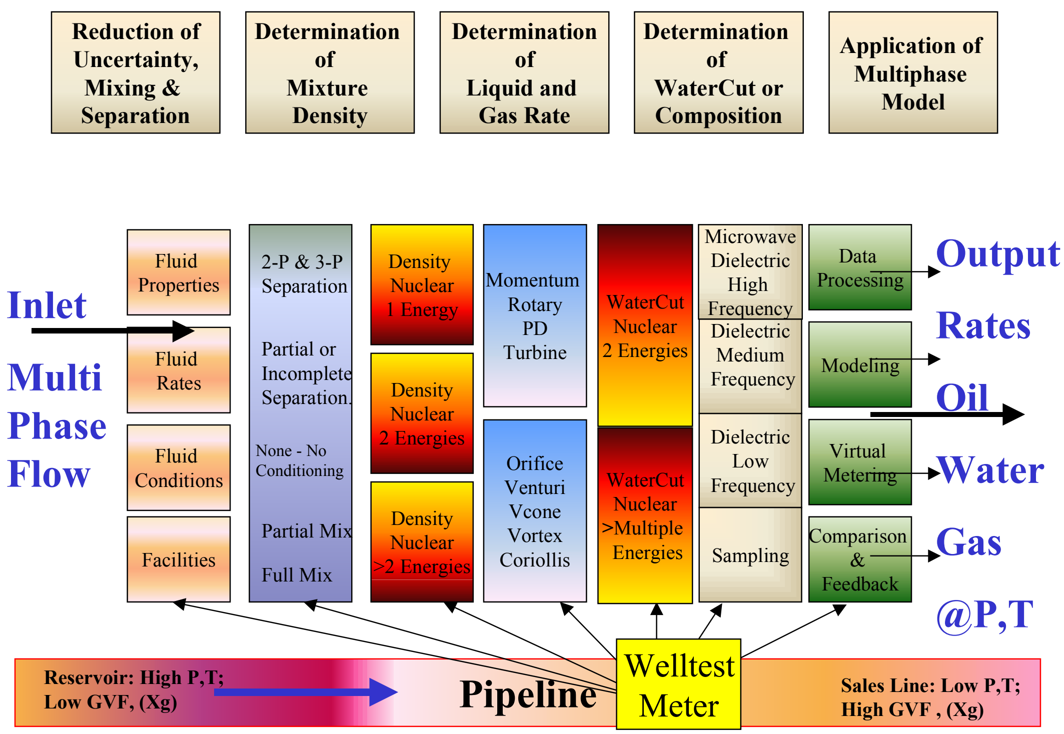

Figure 5: Oil Rate Performance of Multiphase Meter X = Function of Gas Liquid Fraction, Oil Water Fraction and Viscosity

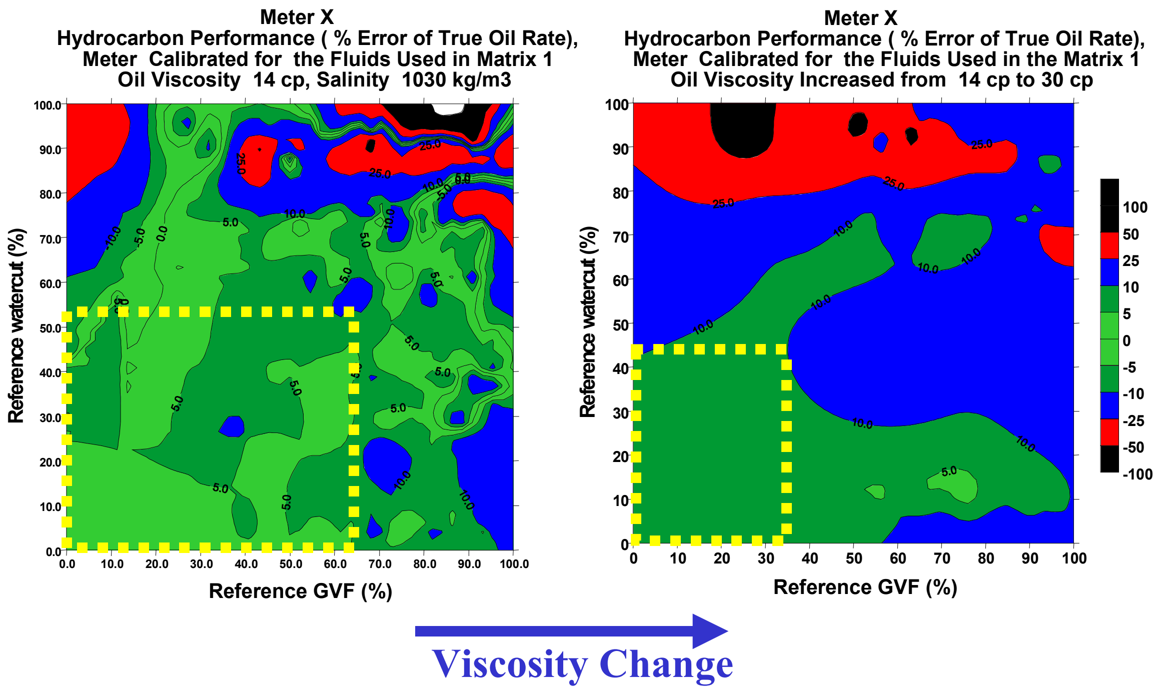

Figure 6: Oil Rate Performance of Multiphase Meter M = Function of Gas Liquid Fraction ,Oil Water Fraction and Viscosity

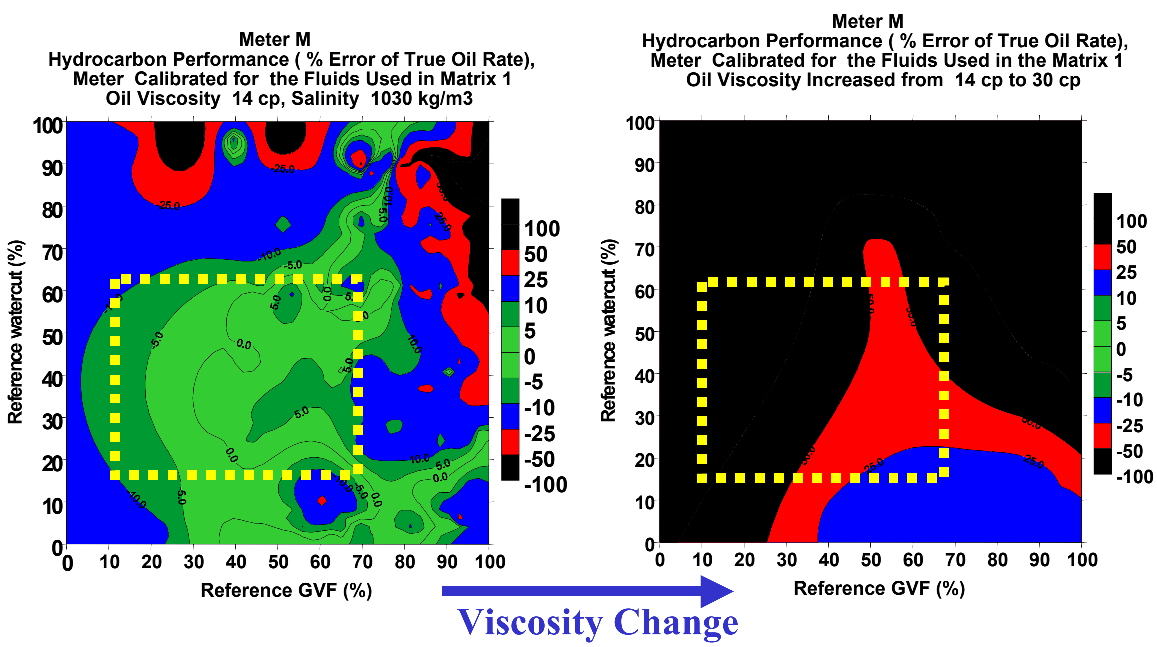

Figure 7: Oil Rate Performance of Multiphase Meter V = Function of Gas Liquid Fraction and Oil Water Fraction:

Multiple unconnected regions of high performance (sweet spots) exist making use in process control difficult

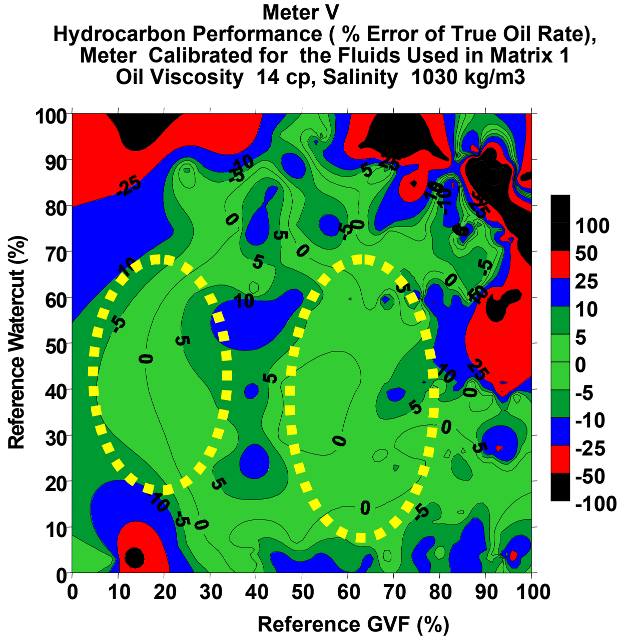

Figure 8: GVF Performance of Multiphase Meter X = Function of Gas Liquid Fraction and Oil Water Fraction:

X_1-High Accuracy GVF used in feedback control; X_2- Low Accuracy GVF region which limits the precision (+- 10%) at which that control variable can be held by a feedback system.

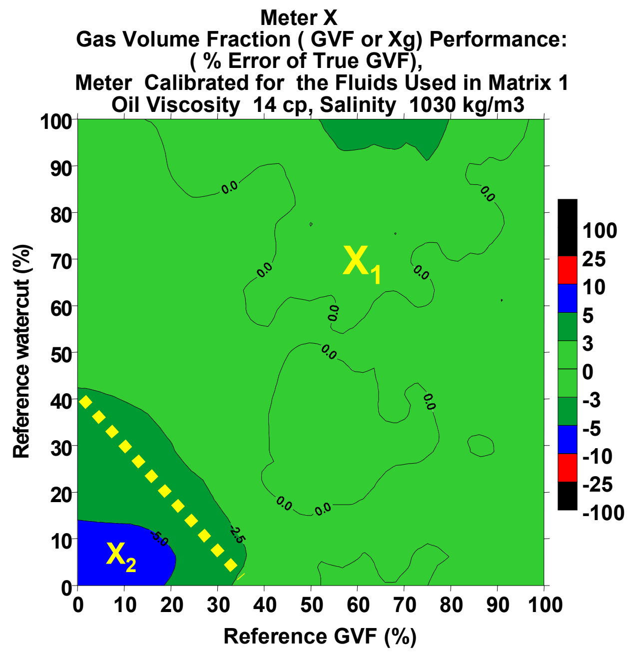

Figure 9: - Linear Model of:
Liquid Level Control using Liquid Control Valve (LCV)

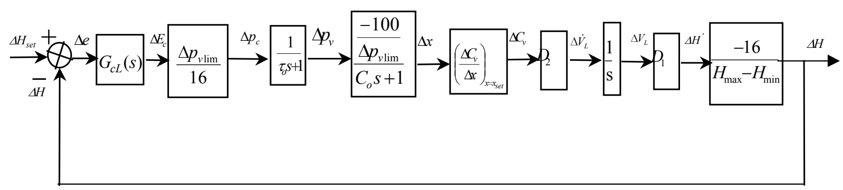

Figure 10: - Linear Model of:
GVF and Liquid Level Control using Liquid Control Valve(LCV)

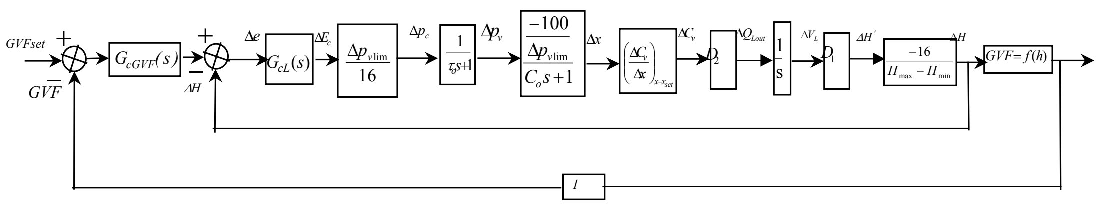

Figure 11: Matlab Simulator of GVF and Liquid Level Control.
Small Vessel
(GVF is considered to be a function of only liquid level)

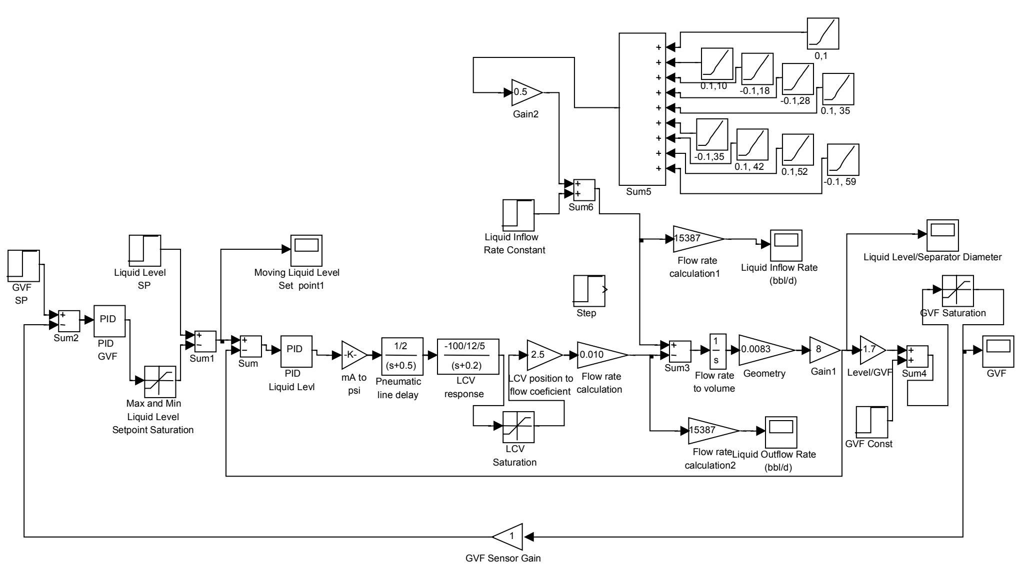

Figure 12: DTU System with GVF Control – Step & Slug Inputs GVF = f (Level); 72” x30’ Horizontal Vessel

Step Input: 15,000 BLPD

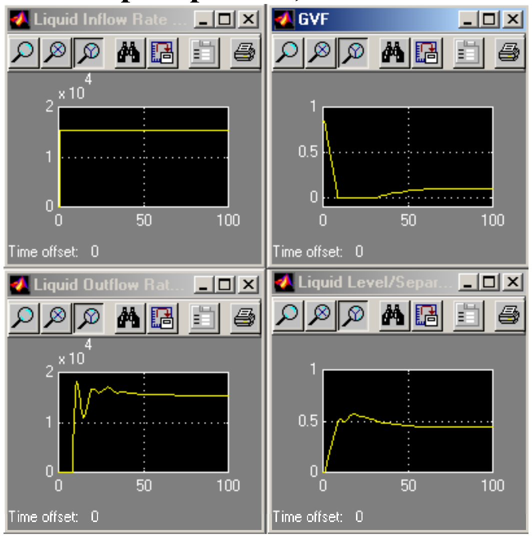

Figure 12A – GVF and Liquid Level Response to Liquid Step Input (GVF set point=0.3; Liquid Level Set Point=0.5)

(Liquid inflow and outflow rates in bbl/d)

Step & Slug Input: +- 14,000 BLPD

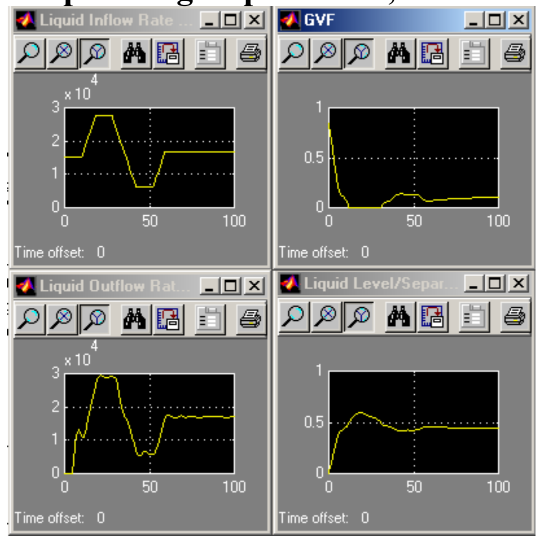

Figure 12B – Liquid Level and GVF Response to Liquid Slug Input (GVF set point=0.3; Liquid Level Set Point=0.5)

(Liquid inflow and outflow rates in bbl/d)

Figure 13: DTU Control System Response to Step 15,000 BLPD & Slug Input: +- 14,000 BLPD

System with GVF Control

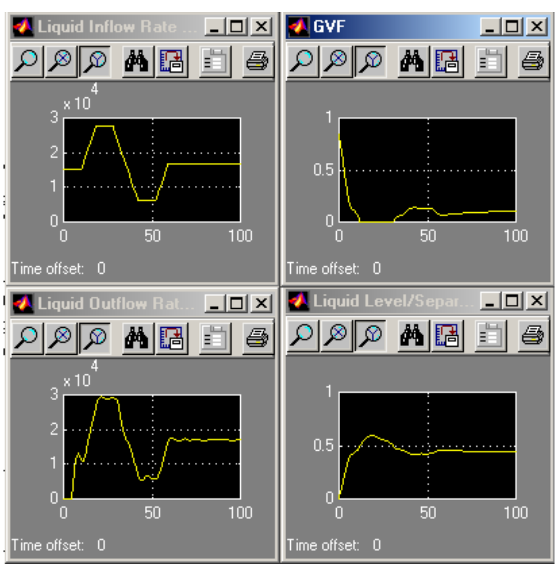

Figure 13A: – Liquid Level and GVF Response to Liquid Slug Input (GVF set point=0.3; Liquid Level Set Point=0.5)

System without GVF Control

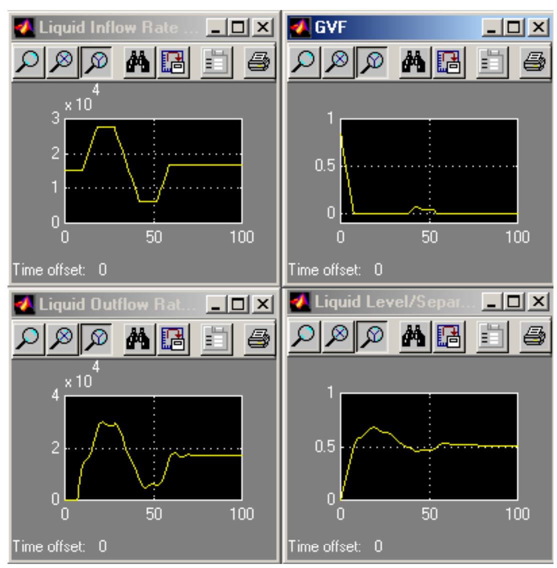

Figure 13B:– Liquid Level and GVF Response to Liquid Slug Input (GVF set point=0.3; (Liquid Level Set Point=0.5)

Figure 14: Effects of GVF Control on Slug Levels in Large Separator :

GVF = f (Level); 108" x 35' Horizontal Vessel
4x increase in vessel size; 250% increase in Slug size

System with GVF Control

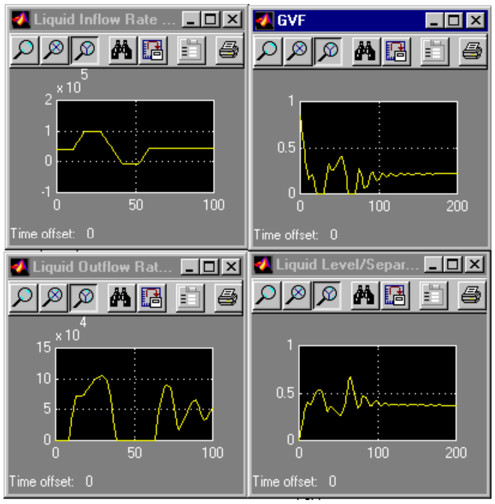

Figure 14A: – Liquid Level and GVF Response to
Liquid Slug Input (GVF set point=0.3;
Liquid Level Set Point=0.5)

System without GVF Control

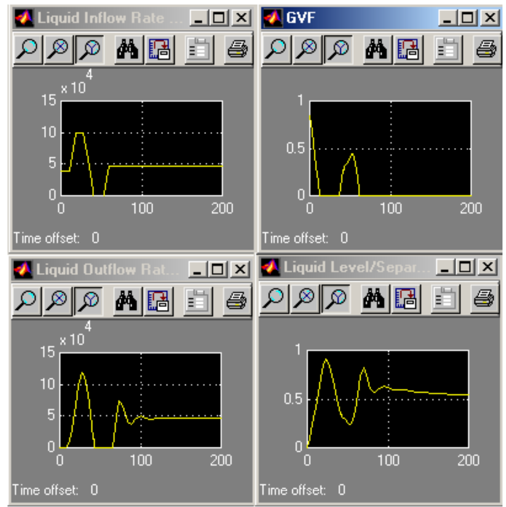

Figure 14B: – Liquid Level and GVF Response to
Liquid Slug Input (GVF set point=0.3;
(Liquid Level Set Point=0.5)

Figure 15: Effects on DTU Control system of Noise: DTU With GVF Control, GVF Meter Noise and Filter

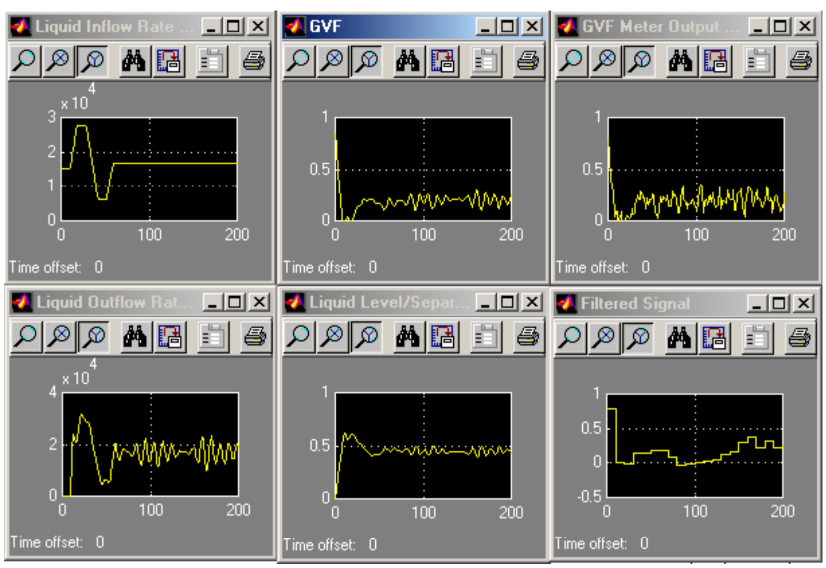

Figure 15: – Liquid Level and GVF Response to
Liquid Slug Input (GVF set point=0.3;
Liquid Level Set Point=0.5)

System with GVF Control, GVF Meter Noise and Filter;