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Abstract

In today's oil and gas industry, the importance of accurate measurement of wet gas flows has become paramount due to the recent growth in production costs and continuous fluctuation in crude oil prices. Typical wet gas applications have Gas Volume Fraction (GVF) ranging from 95 to 100 percent and hence the accurate measurement of the phase fractions, especially the water fraction at such low liquid flowrate is a serious challenge. Standard multiphase flow meters were found to be inadequate to operate in such conditions. Hence significant effort is taken by several manufacturers into research and development of 'wet gas' flow meters which can accurately measure the three-phase flowrates. Taking on the challenge, an inline non-nuclear wet gas metering system was field tested in Argentina to measure the three-phase flow rates under existing field operating conditions and the results were compared to an existing conventional test separator readings to find out if it can serve as a reliable replacement to the expensive test separator.

Introduction

With the aging of the natural gas wells, the reservoir dynamics changes and the once dry-gas flow becomes wet gas. Owing to the challenges in the oil and gas industry, the accurate measurement of wet gas flows has become essential in several applications. Traditionally, test separators were used to separate the phases and then measure each individudal phase using single-phase flow measurement technologies. However, test separators are very expensive, bulky, cannot provide continuous well monitoring, require a lot of space and have high static pressure.

Multiphase flowmetering has become a promising alternative to test separators as they provide the advantage of continuous well monitoring and bring in significant economic savings, but their measurement accuracy has been a serious concern. Also, most of the existing flowmetering solutions include a nuclear source, which brings in problems like shielding, source decay, limitations in detection equipment etc.

Standard multiphase flow meterering devices cannot satisfactorily operate in the wet gas applications. Typical wet gas applications have the Lockhart-Martinelli (X_{LM}) value often expressed in terms of Gas Volume Fraction (GVF), ranging from 95 to 100 percent. The accurate measurement of dry gas component of a wet gas stream and the water fraction at such low liquid flowrate is a serious challenge. Thus, the wet gas flowmeters were developed to measure both the liquid and gas flow rates accurately in these conditions. The meter does not measure the individual flowrates directly, but instead take atleast three independent measurements to determine the total flow rate and two- phase fractions, thereby reporting the flowrates of each phase.

Wet gas flow metering technique has become increasingly popular and achieving the most accurate wet gas measurement is highly crucial, especially in the development of marginal oil and gas fields where regaining the cost of capital investment is very critical. Wet gas flow meters are generally used in the following applications:

Well Testing: where accurate wet gas measurement helps the reservoir engineers and well operators to clearly estimate the well's production potential.

Allocation Metering: where a common pipeline is used to transport wet gas from well head to a central processing facility by several companies making it necessary to accurately measure wet gas.

Process Metering: where condensate might form in the pipeline at certain operating conditions and the wet gas measurement is necessary to assess the scale of remedial treatment needed to remove the condensate.

In this paper, an in-line, non-nuclear, compact 'wet gas' flowmeter is presented, which can simultaneously measure the oil, water and gas flowrates without any prior separation. This meter is based on the field-proven Venturi, Sonar and RedEye measurement technologies. The combination of non-nuclear technologies has a wide operating envelope and offers maximum accuracy in dry and wet-gas streams as well as a stable and predicatable response under multiphase flow conditions. The meter is minimally intrusive with low pressure drop, has no moving parts and has no scheduled maintenance requirements. It just requires a basic field configuration with no frequent recalibrations or field tuning of field parameters. It also has the advantage of low power consumption and high ambient temperature rating, making it suitable for solar panel power and desert applications.

Significance of Testing

The main objective of this paper is to determine the reliability of the flowmeter in the field environment by comparing the measurement of the three phases (oil, water and gas) to the test separator readings. The wet gas flow meter presented here has been extensively tested in various laboratory-type flow loops like Colorado Experiment Engineering Station Inc. (CEESI), Southwest Research Institute (SWRI), National Engineering Laboratory (NEL) etc., where the reference measurements are considerably more accurate and the operating conditions can be well controlled. But to understand the actual capability of the flowmeter, it is necessary to perform testing of the meter in the actual field. This is because a laboratory-type flow loop can never complety simulate the actual field conditions and several operational problems arise while operating the meter in the field environment. Thus, the combination of laboratory type flow-loop and field testing results is crucial to fully understand the capability of the wet gas meter.

Theory

The densities of liquid and gas are an important consideration in flow measurement as they relate to the actual mass quantities of the fluids present. Gas being a compressible fluid, its density changes with line pressure changes but the density of liquid does not change. The gas to liquid ratio density directly influences the response of a DP measurement device.

To account for both the flow rates and densities of the gas and liquid, we define the liquid loading of the gas using the Lockhart-Martinelli parameter (X_{LM}), which is expressed as:

$$X_{LM} = \frac{liquid\ mass\ flowrate}{gas\ mass\ flowrate}\sqrt{\frac{gas\ density}{liquid\ density}} = = \frac{\dot{m}_l}{\dot{m}_g}\sqrt{\frac{\rho_g}{\rho_l}}.$$

The X_{LM} parameter can also be expressed in terms of gas and liquid densitometric Froude number (Fr), which is a dimensional number to express gas and liquid phase velocity.

It has been well established that the DP meter used in wet-gas measurement tends to 'over-read' the amount of gas passing throught it. Over-reading is defined as the uncorrected gas mass flowrate measured in wet-gas conditions divided by that measured in dry-gas conditions. The extent of over-reading is affected by several factors like the operating pressure, the Lockhart-Martinelli parameter and the gas Froude number. Typically, the over-read is a strong monotonic function of X_{LM} with gas Froude number (Fr_g) as the secondary correlating parameter. The gas Froude number is expressed as:

$$Fr_g = \frac{U_{sg}}{\sqrt{g \cdot D}}\sqrt{\frac{\rho_g}{\rho_l - \rho_g}}$$

where U_{sg} is the superficial gas velocity (m/s), g is the gravitational constant (m/s^2), D is the inner pipe diameter (m), ρ_g is the gas density and ρ_l is the liquid density. In general, the Lockhart-Martinell parameter (X_{LM}) value between 0 and 0.3 is usually defined as wet-gas flow and X_{LM} value above 0.3 is defined as multiphase flows.

Another important factor in wet gas metering is the flow regime. Most of the DP correlations for wet gas is defined for gas Froude number ranging between 0.5 and 2 and the most preferred flow regime for the wet gas flowmeter is an 'annular mist flow'wherein the liquid forms a thin film on the pipe walls and the gas flows within the liquid film. At high gas velocities, nearly all of the liquid is present as droplets within the gas stream.

Principle of Operation

The flowmeter has a VS spool that integrates a Venturi nozzle with a Sonar body as shown in Figure 1. Using the venturi nozzle, either fluid density or volumetric flow rate can be determined as output of the momentum balance. For the case of a fluid mixture, the flow is assumed to be homogenous within the nozzle and hence a mixture density can be determined. A linear dependency between mixture density and GVF can be established.

The sonar body has an array of axially distributed sensors mounted on its surface. The bulk flow velocity is calculated from the pressure fluctuations associated with the turbulent flow using phased array processing algorithms. This yields a flow rate with an uncertainty typically better than ± 1%. Since the measured velocity is only slightly higher than the superficial dry gas velocity in wet gas applications, the sonar device itself can provide a good approximation to the total flow rate measurement and hence the venturi can be used to measure GVF in wet-gas configuration.

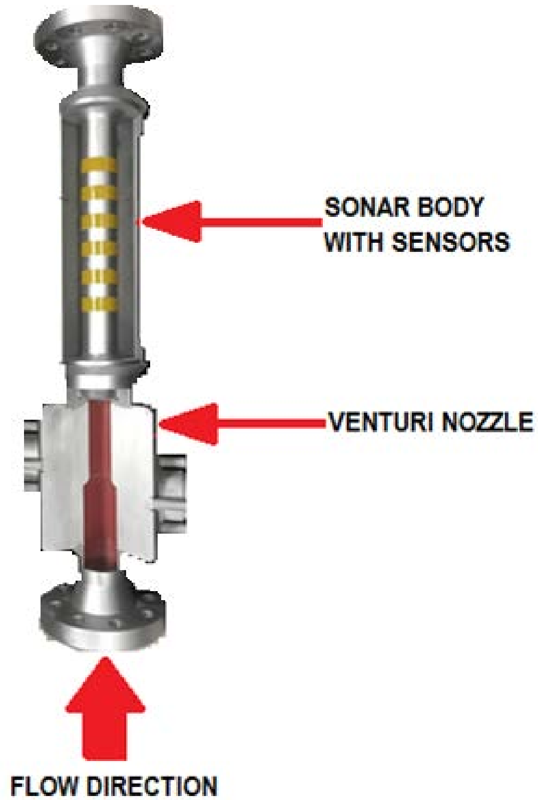

Figure 1: Sectional view of a VS spool.

The RedEye (RE) water cut meter uses Near-InfraRed (NIR) technology to measure the Water-to-Liquid ratio (WLR), which when reported at standard conditions is called Water cut (WC). The RE MP meter can measure 0-100% WC in production streams with GVF upto 99.9% without an external input to correct for changes in water chemistry and GVF. By measuring absorption at key wavelengths, the RE meter can measure the relative concentration of oil and water regardless of the free gas content. Importantly, the absorption is based on the water and oil molecules rather than the dissolved components like salt.

A multivariable transmitter mounted on the venturi spool measures the static pressure, differential pressure and temperature from the RTD, which is clamped on the outer surface of the sonar body to measure the process temperature.

An Alpha Flow Computer (AFC) acquires readings from the individual instruments and runs the multiphase flow algorithms. It also provides well testing, PVT functionality, system diagnostics and local data logging among its user-oriented capabilities. The primary host interface is a RS-485 port (Modbus RTU protocol) through which all the process variables, calibration values and well test control variables are available for remote monitoring. All the key parameters are also stored in an external SD card and the logged data can be easily assessed.

Combining all these instruments, the **V**enturi **S**onar **R**edEye (**VSR**) meter provides the multiphase solution. The strong over-read response of the venturi and slight over-read of the sonar provides excellent contrast to measure the liquid loading of the wet-gas stream. The flow computer calculates the liquid density using the WC along with the oil and water pure phase densities, and then GVF is calculated in terms of the mixture density. An explicit solution is used to solve for GVF if the sonar response is negligible and an implicit solution can be solved iteratively if the sonar over-read is properly correlated to liquid loading.

Calibration of the Meter

The VSR flowmeter is calibrated in the factory for condensate, water and gas flow rate measurement. No field calibration is necessary but PVT data needs to be entered into the Alpha Flow Computer (AFC) for fluid properties.

The venturi discharge coefficient and the sonar velocity measurement coefficient (which is Reynolds number dependent) are determined in the factory by using a single-phase water flow loop with calibrated Magmeter reference. The coefficients are then uploaded into the AFC.

The RedEye meter is also calibrated in the factory for baseline throughput ('Air Calibration'), water absorption (tap water) and configured for standard condensate (absorbance values for condensate loaded). The MVT comes calibrated from the vendor for all three measurements- Static Pressure, Differential Pressure and Temperature, but DP zero adjust needs to be performed annually.

Test Procedure

The tested *Alpha* VSR flowmeter consists of a 2-inch ANSI 600# VS spool, mounted in a skid with a blind “T” upfront which ensures proper flow mixing and a spool section to mount the RedEye MP meter as shown in Figure 2.

Figure 2: Alpha VSR Flowmeter Skid

The flowmeter is installed upstream of a two-stage separator as shown in Figure 3. This ensures that the flowmeter is exposed to an undisturbed flow stream. The first stage separator is a two-phase separator with a turbine meter at the liquid outlet for liquid flowrate measurement and an orifice meter at the gas outlet for gas flowrate measurement. The second stage separator is a three-phase separator with a Coriolis meter for oil flowrate measurement, turbine meter for water flowrate measurement and an orifice meter for gas flowrate measurement.

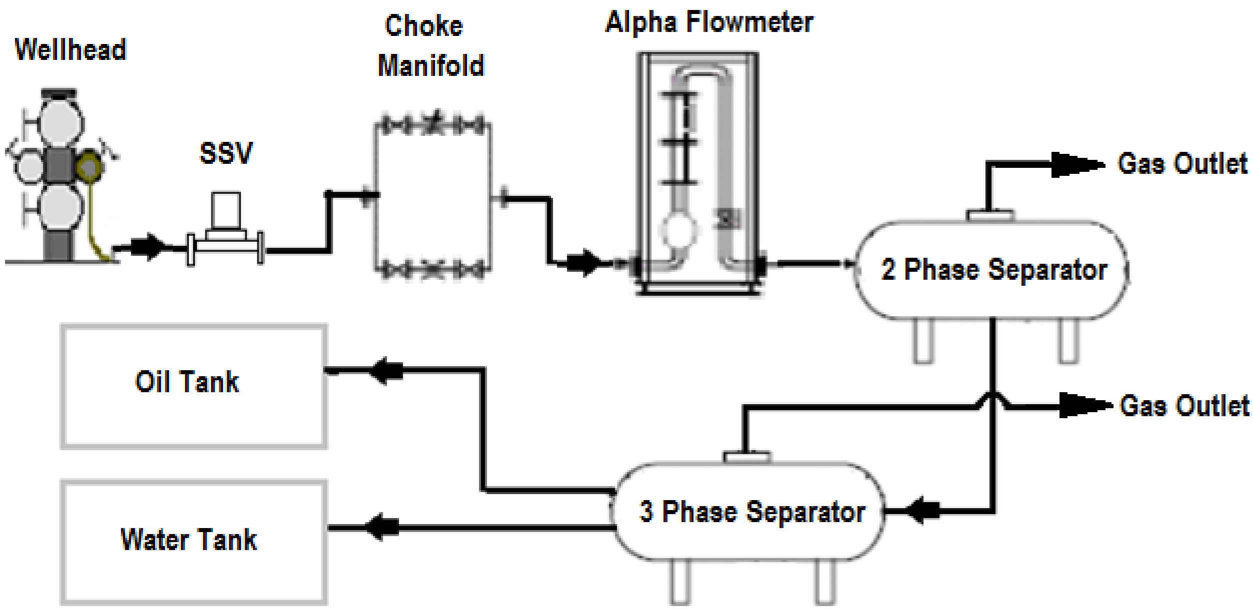

Figure 3: Process Layout

To evaluate the performance and measurement accuracy of the flowmeter, the separator measured values and the well testing procedure are assumed to have absolute accuracy. In reality, test separator in itself has some uncertainities inspite of careful calibration and validation of recent test data to ensure its repeatability. But since it is the only acceptable yardstick for well testing by the operator, they are used as the reference measurement here.

The Alpha Flow Computer can either be located on the skid or remotely in a control room. The necessary PVT data, paramfile and well profile table are loaded into the AFC before the testing began. The test engineers and field oparators also had the responsibility to review the testing and data collection method prior to initiating the test program.

The process flow conditions and the fluid properties are summarized in Table 1.

PARAMETER	RANGE
Pressure	80 - 90 bara
Temperature	47 – 52 °C
Water Cut	2 – 10 %
Liquid Flowrate (at standard conditions)	80-95 m^3/day
GVF	95 – 98 %
Oil Density	67 °API
Gas Specific Gravity	0.72

Table 1: Process Conditions and Fluid Properties

Test Results

When the test is initiated, data is collected simultaneously from the flowmeter and the test separators. For the gas flowrate comparison, the total gas from the two separator gas outlets is added and then compared to the flowmeter readings. And for the liquid flowrate comparison, the second-stage separator's liquid flowrate measurement is compared to the flowmeter readings.

Test results over a period of one week under stable production conditions is used for comparison. Figure 4, Figure 5, and Figure 6 shows the comparison of gas flow rate, liquid flow rate and watercut measurements.

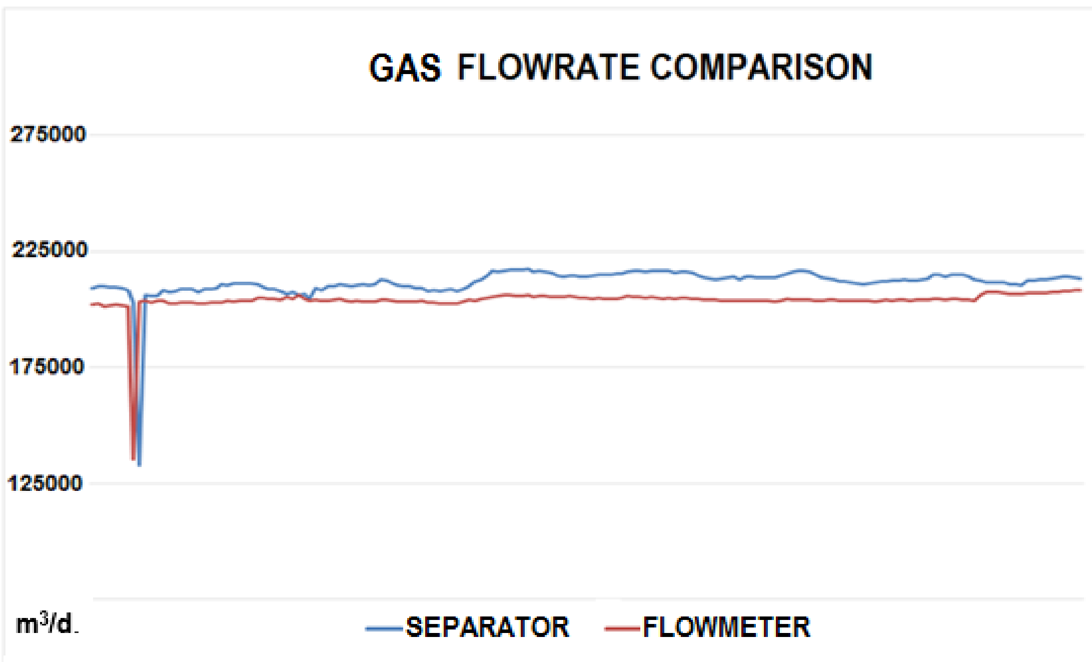

Figure 4: Comparison of Gas flowrate

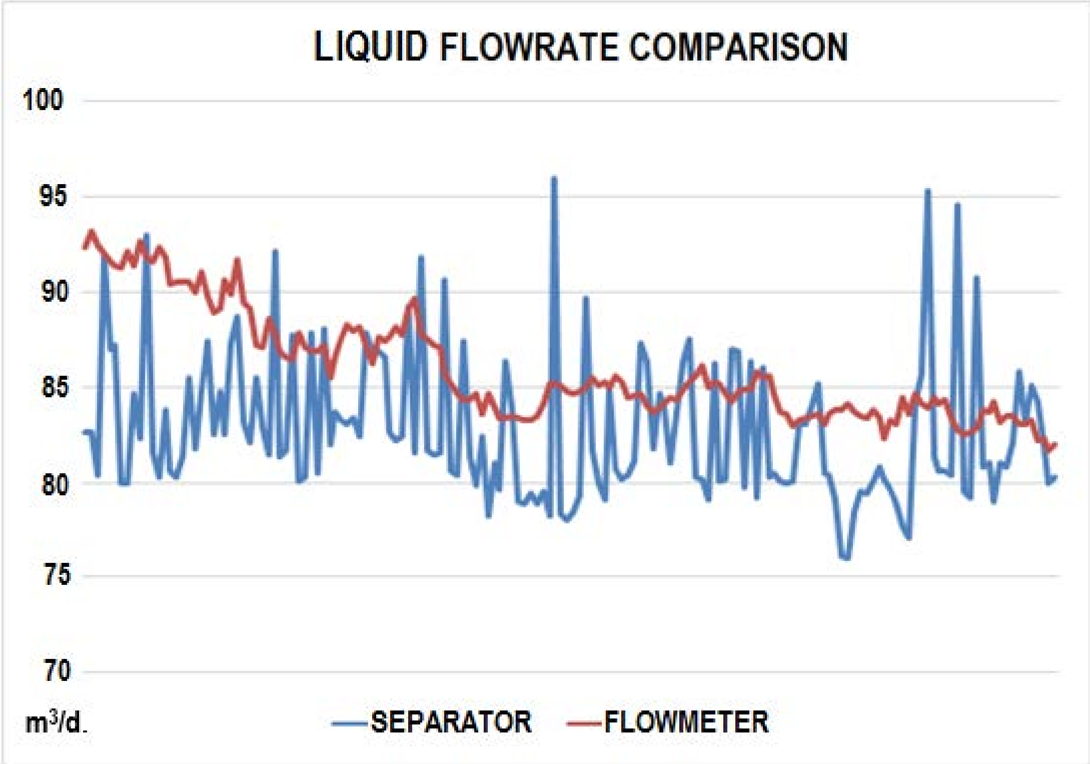

Figure 5: Comparison of Liquid flowrate

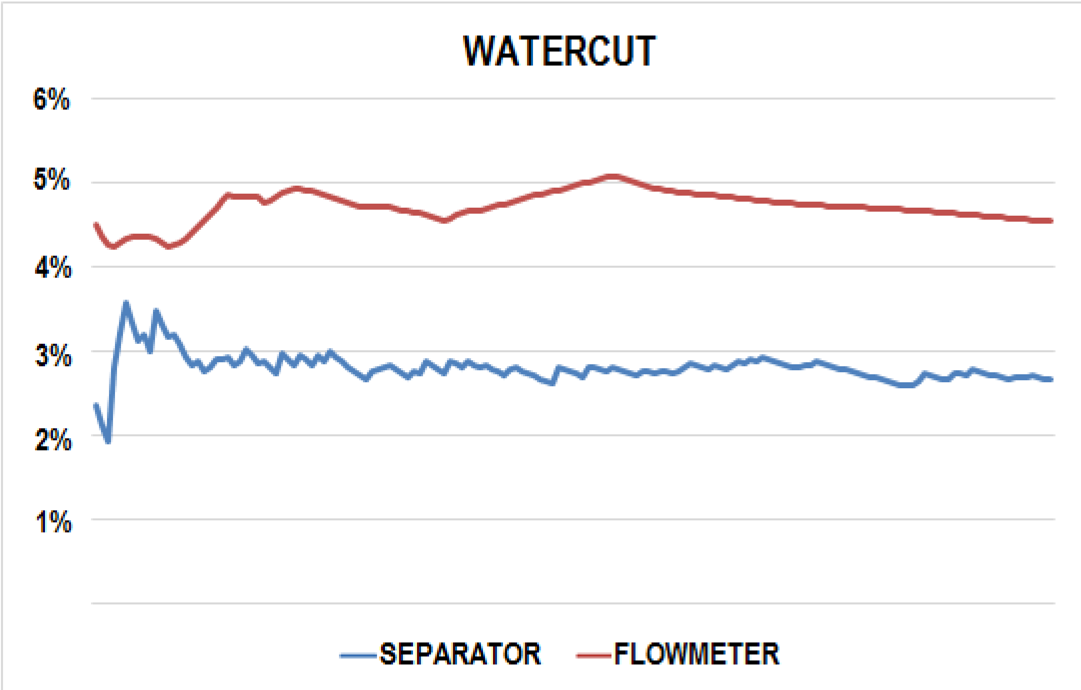

Figure 6: Comparison of Watercut measurement

The resulting percentage deviation of the flowmeter's measurement relative to the test separtor's phase volumetric flowrate readings are summarized in Table 2.

Parameter	Gas Flowrate	Liquid Flowrate	Oil Flowrate	Water Flowrate	WaterCut Measurement
% Deviation	-4%	+4%	+2%	-6%	+2%

Table 2: Percentage Deviation Specification

From the comparison charts for each phase flow rates, it can be seen that the wet gas flow meter measurements are consistent and reliable. The results show that the flowmeter could perform within ± 4% or better from the reference test separator, depending on the flow conditions and the accuracy of the PVT data.

Conclusions

The field testing was completed successfully without any safety incidents and the results were overall considered to be within the accepted uncertainty range. The following conclusions are derived from this testing campaign:

- The validation test results showed that the flowmeter readings are within ± 4% deviation from the reference test separators for both gas and liquid flowrates. This proves good agreement between the flowmeters and test separators and hence establishes confidence in replacing the test seperators with flowmeters in the fields.

- As seen in Figure 5, the flowmeter provides steadier liquid flow measurement compared to the test separator, which has limitation in maintaining stable small liquid volumes. This shows the advantage of flowmeters in low liquid flowrate applications.

- On the watercut measurements, the readings from the flowmeter showed good agreement with the test separator, with just + 2% deviation from the test separator.

- For light oil applications such as this, two-stage separators are required to obtain the total gas volume whereas a 'single' Alpha VSR meter was able to measure it. This adds to significant savings in terms of cost and space.

- No operational problems were observed during the testing, which is a major factor when considering the suitability of a meter, especially in remote locations. Operators also confirmed ease of reporting the real-time flow rates at line and standard conditions, both on the touch panel display and digitally over Modbus.

- Replacing the test separator with the flow meter thus helps in accurate flow measurement of all the phases, continuous well monitoring, significant cost savings and operational ease.

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