A HIGH-ACCURACY, CALIBRATION-FREE MULTIPHASE METER

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INTRODUCTION

The need for accurate and reliable measurement of three-phase flow streams is well documented. To this end Daniel have developed a high-accuracy multiphase flowmeter "MEGRA" based on the sound measurement principle of (multiple energy) gamma ray absorption. The ultimate aim of such technology is to replace the measurement function of the traditional test separator with a cheaper, lower-maintenance and calibration-free alternative. At present, due to its high-accuracy water-cut (WC) and real-time performance, MEGRA has also been utilised for well management programs downstream of traditional test separators.

The flow-rates of the individual water, oil and gas phases are derived from a measurement of the bulk flow through an annular Venturi, combined with phase fraction information deduced from the absorption of gamma-rays within the multiphase fluid. The gamma-ray technique has the advantage over other multiphase metering methods in that it is applicable over the full range of water-cuts from 0 – 100% and does not depend upon the nature of the emulsion present.

This paper outlines the basic principles behind the multiphase flow measurement and highlights some of the advantages of the present technology. The use of relatively low-energy gamma-ray emissions and high-resolution solid-state detectors lends an enhanced sensitivity to the measurement. Consequently, water-cuts and gas volume fractions can be determined to high accuracy (< 2%) in relatively short measurement times (~ seconds).

A significant issue with commercially available multiphase meters is how well they cope with variations in their operational environment. Of particular interest is the sensitivity of a meter to changes in the salinity of the produced water, since not only is it a common occurrence, but one with potentially debilitating effects on most meters. The MEGRA multiphase meter has the potential to sense and compensate for such salinity changes. Furthermore, the method can be extended to achieve calibration-free operation in the field, with only a factory characterisation required.

It is generally accepted that multiphase meters face one of their severest tests in high gas volume fraction (GVF) applications, where the process flow may be less homogeneous and differences can arise between the liquid and gas phase velocities. Traditionally, operation under these conditions has been attempted through the use of mixing elements that somehow aim to homogenise the flow, via the measurement of key process parameters at frequencies matching the time-scale of turbulences within the flow, by the incorporation of advanced flow models and slip corrections or by some combination of these techniques. Another approach, now practical through recent advances in compact separator technology, involves rough separation of the process flow into a (wet) gas and (gassy) liquid stream, which are in turn monitored by a conventional gas-sensor and multiphase meter respectively.

On a stand-alone basis MEGRA uses a combination of basic flow conditioning, fast sampling and correction algorithms for operation under high gas-content conditions. However, its superior performance within the lower part of the gas fraction envelope, also make it ideally suited for integration with modern compact separator technology or for extending the well-testing capacities of existing test separators. This paper focuses mainly on the latter operating region and presents the results from field trials completed to date, which demonstrate the quality of metering performance achieved under live operating conditions of this type.

BASIC PRINCIPLES

Bulk Flow-Rate Measurement

The basic mechanical arrangement of the Daniel MEGRA multiphase flowmeter is shown in Figure 1. The bulk flow-rate is measured by means of an annular Venturi device integrated into the meter-body, which produces a differential pressure, ΔP . For the case of homogeneous flow, the total volume flow-rate of the mixture, Q_m, may be derived from the pressure drop across the Venturi and the mixture density, ρ_m, by:

$$Q_m = C \cdot \sqrt{\frac{\Delta P}{\rho_m}}$$

The constant, C, incorporates both geometrical terms and a standard coefficient of discharge. The mixture density is derived from the individual densities of the water, oil and gas components, weighted by their phase fractions as determined by the composition measurement.

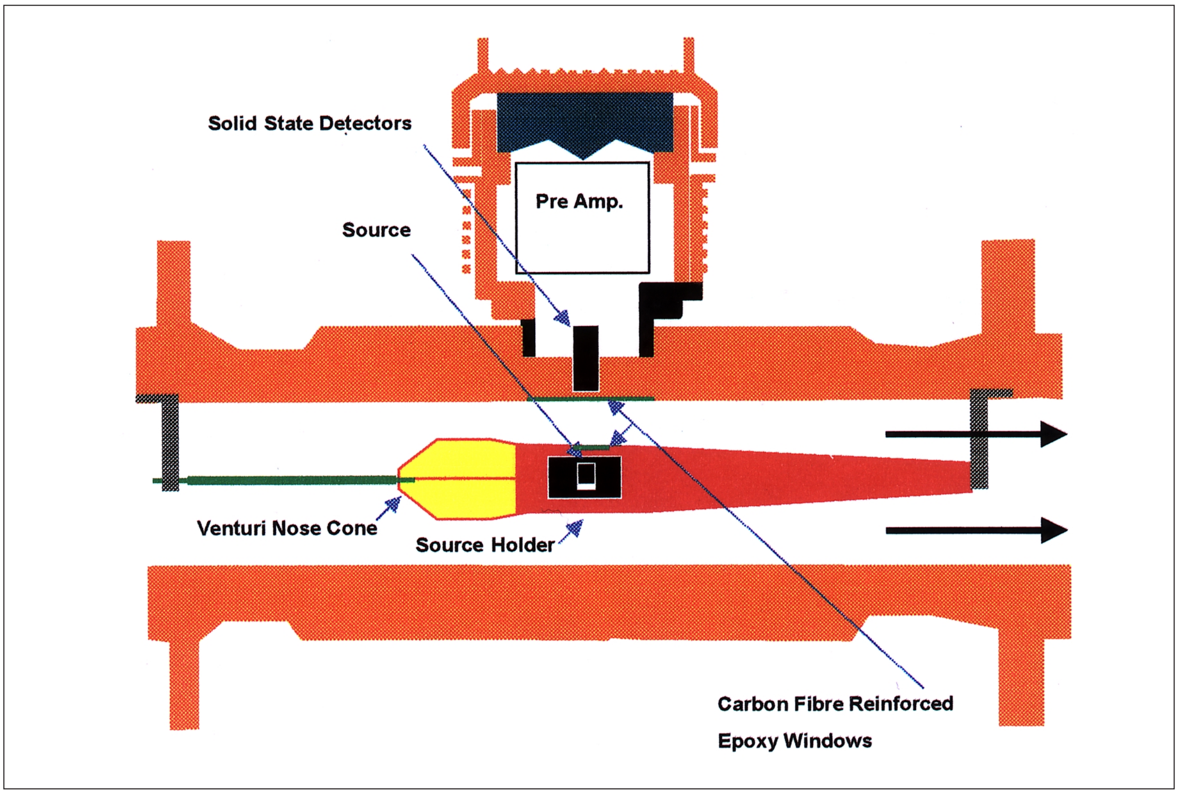

Figure 1: Schematic diagram of the Daniel MEGRA multiphase flowmeter, showing the concentric Venturi system used for bulk flow measurement and the radioactive source / detector arrangement from which phase fraction information is derived. The nose cone may be interchanged to alter the b-ratio.

The Venturi centre-body serves the secondary purpose of housing the radioactive source used in the gamma-ray absorption measurement. To ensure sufficient accuracy in the fraction measurement (following section), a fluid absorption path of ~ 20mm is required. With a standard Venturi arrangement, this would pose a severe limitation to the gross flow-rates achievable, but the concentric design allows the required path-length to be maintained for almost any cross sectional area of the fluid flow. In practice, the Venturi information can be replaced with that from any meter capable of measuring the total flow of the multiphase stream.

Composition Measurement

Composition measurement by gamma-ray absorption is now a well-established technique in multiphase metering. Gamma rays produced by a collimated radioactive source, in this case housed in the centre of the meter, propagate through the multiphase fluid towards a gamma-ray detection device. As they pass through the fluid, they are attenuated to different degrees, depending upon the fractions of water, oil and gas present. Since evaluation of these fractions, (α_w, α_o and α_g respectively), corresponds to the determination of *two* unknowns (a constraint being that the phase fractions must add to unity), gamma-ray absorption must be measured at a minimum of *two* distinct energies. Mathematically the problem may be stated as follows. For a multiphase mixture, occupying a region of path-length D, the measured count-rate I_m, at a given energy E, is:

$$I_m(E) = I_v(E) \cdot \exp[-\mu_m(E) \cdot D] \qquad \text{where} \qquad \mu_m(E) = \alpha_w \mu_w(E) + \alpha_o \mu_o(E) + \alpha_g \mu_g(E)$$

Here, $I_v(E)$ represents the empty pipe (vacuum) count rate at energy E, and the linear attenuation coefficients of the mixture (m) and pure phases (w, o, g) in obvious notation. By measuring at two distinct gamma-ray energies, where the absorption coefficients of the three phases are sufficiently different, a set of linearly independent equations is obtained which can be solved for two of the unknowns, α_w and α_o say. The remaining fraction, α_g , is given by closure. The system of equations can be written in a convenient matrix notation:

$$\begin{bmatrix} \mu_m(E_1) \\ \mu_m(E_2) \\ 1 \end{bmatrix} = \begin{bmatrix} \mu_w(E_1) & \mu_o(E_1) & \mu_g(E_1) \\ \mu_w(E_2) & \mu_o(E_2) & \mu_g(E_2) \\ 1 & 1 & 1 \end{bmatrix} \cdot \begin{bmatrix} \alpha_w \\ \alpha_o \\ \alpha_g \end{bmatrix}$$

The elements of the [3 ¥ 3] matrix are obtained from a calibration process that involves filling the meter with samples of the pure fluids (water, oil and gas) in turn, or alternatively can be calculated from tabulated gamma-ray attenuation coefficients. This latter concept, which requires only a single empty-pipe count-rate measurement in the field, will be referred to as "calibration-free" operation.

The Daniel composition meter of Figure 1 uses an ^{241}Am radioactive source, located at the centre of the metering stream, to provide gamma-rays of several energies up to 60 keV. The gamma-rays traverse a finite section of the process flow, where they are either absorbed by the fluid or are detected by a solid-state detector mounted on the exterior of the pipe. Due to the relatively low energy of the gamma-rays, the fluid path-length is restrained to around 20mm. To avoid the high gamma-ray losses that would otherwise occur on passage through the pipe walls, low-absorption Carbon Fibre Reinforced Epoxy windows are used to provide process isolation in the vicinity of the measurement path. Peltier-cooled solid state detectors provide sufficient energy resolution to distinguish the closely spaced lines of the Am-241 gamma-ray spectrum (Figure 2).

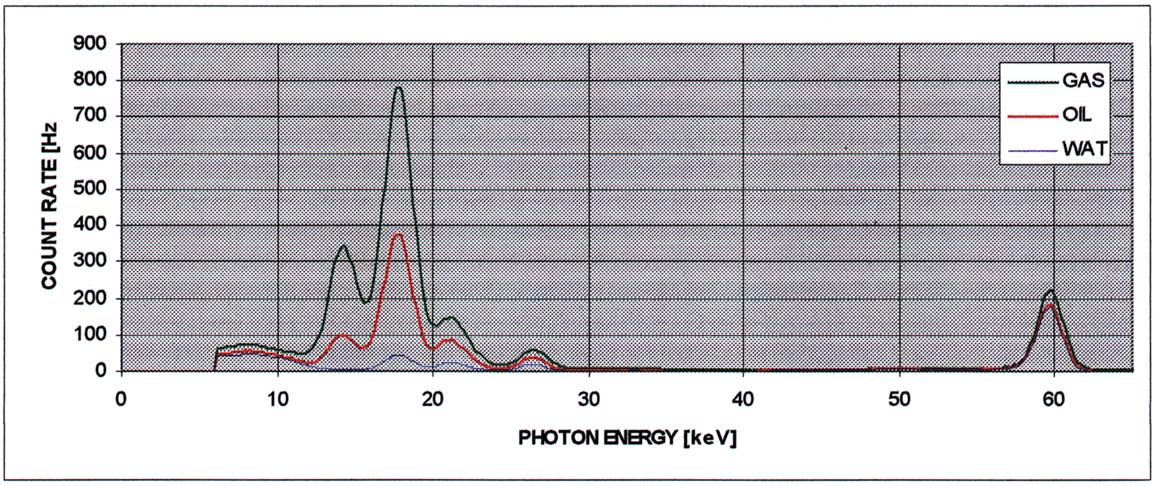

Figure 2: Typical gamma-ray energy spectra for the pure phases as measured by the solid-state detectors.

Measurement at two energies is a minimum requirement but in practice all gamma-ray lines of sufficient intensity (14, 18, 21, 26 and 60 keV in this case) are incorporated into the fraction calculation to improve the accuracy of the results.

With suitable optimisation [1,2] of the various design parameters (source energies, fluid path-lengths etc.), the MEGRA multiphase meter has proved capable of measuring phase fractions to an accuracy of better than 2% (absolute) over the full range of water-cuts and gas volume fraction, in measurement times of only seconds.

The MEGRA multiphase flowmeter has various advantages over competing technologies that also employ the gamma-ray absorption principle. The high contrast between water, oil and gas, at the lower energies employed here (Figure 2) contributes significantly to its water-cut measurement performance. Even at energies as low as 60 keV, the differential between oil and water is greatly reduced. At the higher energies commonly used in other multiphase meters (e.g. the 30 and 360 keV lines of Ba-133 and the 660 keV line of Cs-137) the contrast between oil and water becomes diminishingly small (Figure 3). Far longer counting times are then necessary to obtain the same statistical accuracy in the fraction measurement, and any inhomogeneity which occurs in the multiphase flow during this extended measurement period, will lead to an error in the derived fractions which must somehow be corrected for.

All technologies that incorporate radioactive sources must of course address the issue of radiation safety. The basic mechanical design of the MEGRA flowmeter, where the source is fully enclosed within the pipeline, has obvious security advantages. This arrangement also ensures that external radiation levels are negligibly small, since the stainless steel which forms the meter-body also provide adequate shielding for the relatively low energy emissions from the source. Another advantage of Am-241 is its comparatively long half-life (450 yrs compared to 10 yrs for Ba-133) which means that frequent replacement or adjustment of the source position to maintain the original reference count-rates, is unnecessary.

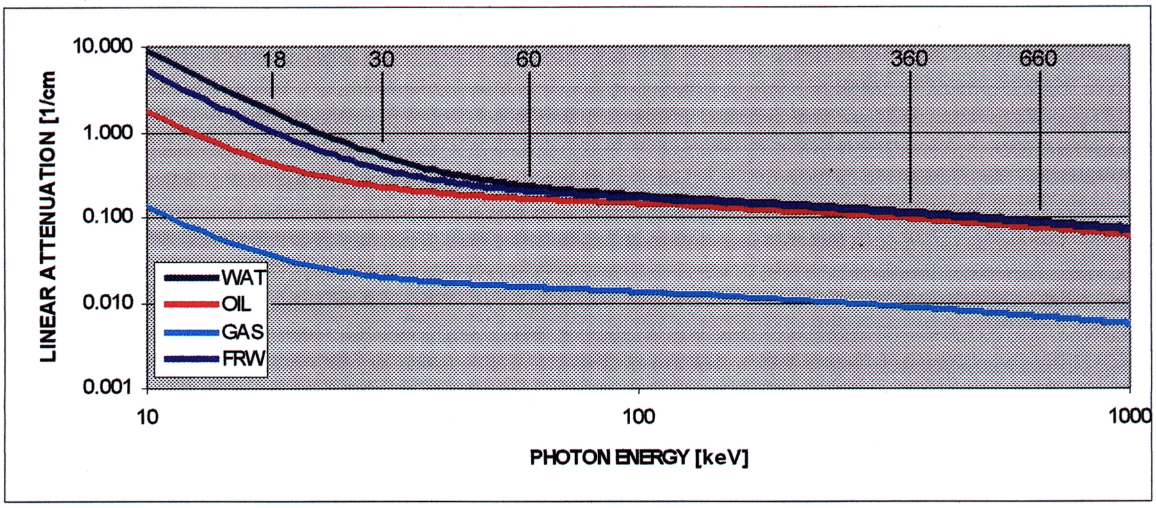

Figure 3: Photon linear attenuation coefficients for fresh and saline water (S = 100 kg/m3), oil and gas. Also shown are the most common gamma-ray energies employed in commercial multiphase flowmeters.

Salinity Evaluation

In practical multiphase metering applications there exists the possibility that the salinity of the production water will change with time, particularly in the case of water-injected reservoirs. For all multiphase flowmeters employing the gamma-ray absorption technique, such changes can lead to significant errors in the measured phase fractions if the reference count-rates (for 100% water) are not suitably corrected. In fact, most metering techniques (conductivity, microwave etc.) are similarly affected by changes in production water salinity.

As detailed above, a gamma-ray absorption measurement at *two* distinct energy levels provides sufficient information to evaluate *two* unknown parameters (α_w and α_o say), as required for complete phase fraction definition. However, with the present system, *three* (or more) gamma-ray energies can be resolved (Figure 2), which have sufficiently different responses to the individual fluid components (Figure 3) that a *third* unknown parameter, namely the salinity, can potentially be derived [2]. At the higher energies typically utilised by other manufacturers the contrast between the fluids is much reduced, rendering this technique somewhat impractical.

To include the salinity as a free parameter in the computation, the linear attenuation coefficient of the saline water is expanded in terms of the fresh water coefficient, μ_f , and the salinity S.

$$\mu_w(E) = \mu_f(E) + K \cdot S$$

The dependence upon S is essentially linear, the constant K comprising the *mass* attenuation coefficients of the fresh water and the salt type, as well as a salt solubility factor. Increasing the number of energy levels to three, to allow for the extra degree of freedom, yields a system of equations that now forms a [4 ¥ 4] matrix of a type similar to that derived earlier.

However, solution of this system of equations requires data of greater statistical accuracy than can be recorded during a typical measurement cycle of a few seconds. Fortunately, salinity changes in the field generally occur on a time scale far greater than this (months perhaps) and therefore it is possible to concatenate data from a large number of measurement cycles, over which the salinity may be assumed to remain constant. (The phase fractions may of course vary from cycle to cycle). As before, any information available from additional energy levels present (a 4^{th} or 5^{th} in this case) may be incorporated into the algorithm, with the effect of improving the overall accuracy of the result, or of reducing the necessary acquisition time. Figure 4 shows the computed salinity for a set of saline water reference fluids, derived with only a few minutes of accumulated data.

$$\begin{bmatrix} \mu_m(E_1) \\ \mu_m(E_2) \\ \mu_m(E_3) \\ 1 \end{bmatrix} = \begin{bmatrix} \mu_f(E_1) & \mu_o(E_1) & \mu_g(E_1) & K(E_1) \\ \mu_f(E_2) & \mu_o(E_2) & \mu_g(E_2) & K(E_2) \\ \mu_f(E_3) & \mu_o(E_3) & \mu_g(E_3) & K(E_3) \\ 1 & 1 & 1 & 0 \end{bmatrix} \cdot \begin{bmatrix} \alpha_w \\ \alpha_o \\ \alpha_g \\ \alpha_w \cdot S \end{bmatrix}$$

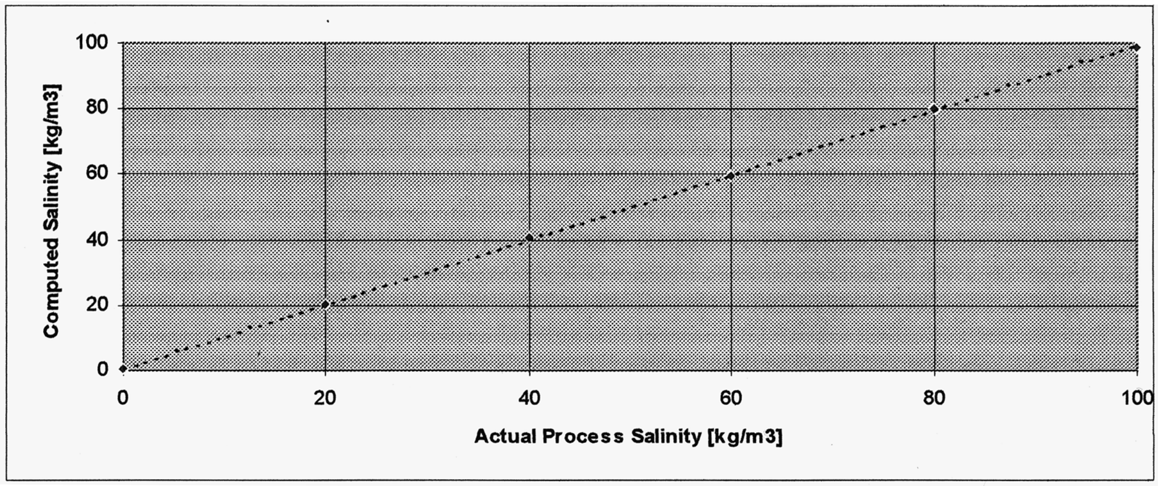

Figure 4: Water salinity as computed by MEGRA for a variety of saline reference solutions. At high water-cut, an accuracy of ±1 kg/m3 can be achieved with only a few minutes of accumulated data.

At lower water-cuts, longer accumulation times (stretching to several hours) are necessary to achieve the same accuracy in salinity. Fortunately, even in the worst case of injection-water breakthrough, the time scale for significant changes in the process water salinity is likely to be of the order of days.

Calibration Free Operation

With suitable characterisation of the meter in the factory (in terms of its precise geometry, signal processing corrections etc.) it is possible to commission a meter in the field with only a single empty-pipe count-rate calibration as a reference point. Provided adequate information is available about the oil, water and gas components (from sampling and laboratory analysis for example) then the absorption characteristics of these pure phases can simply be entered as numerical coefficients. This in itself constitutes a major simplification to the installation and calibration procedure. With the added ability to determine water salinity dynamically (as described above), the calibration procedure can be simplified even further. Only the fresh water attenuation coefficients are then required and these are well established. The oil and gas characteristics (composition and density) must still be supplied, but small errors in these quantities are far less detrimental to the accuracy of the overall fraction calculation [3].

PRACTICAL APPLICATIONS

Initial field applications of the MEGRA multiphase flowmeter were primarily on the gassy-liquid outlets of test-separators and in-line conditioning devices. To this end, static laboratory tests, which demonstrated a measurement accuracy of better than 2% over the full GVF and WC range, were extended to a series of flow-loop measurements that encompassed the operating envelopes of these initial applications.

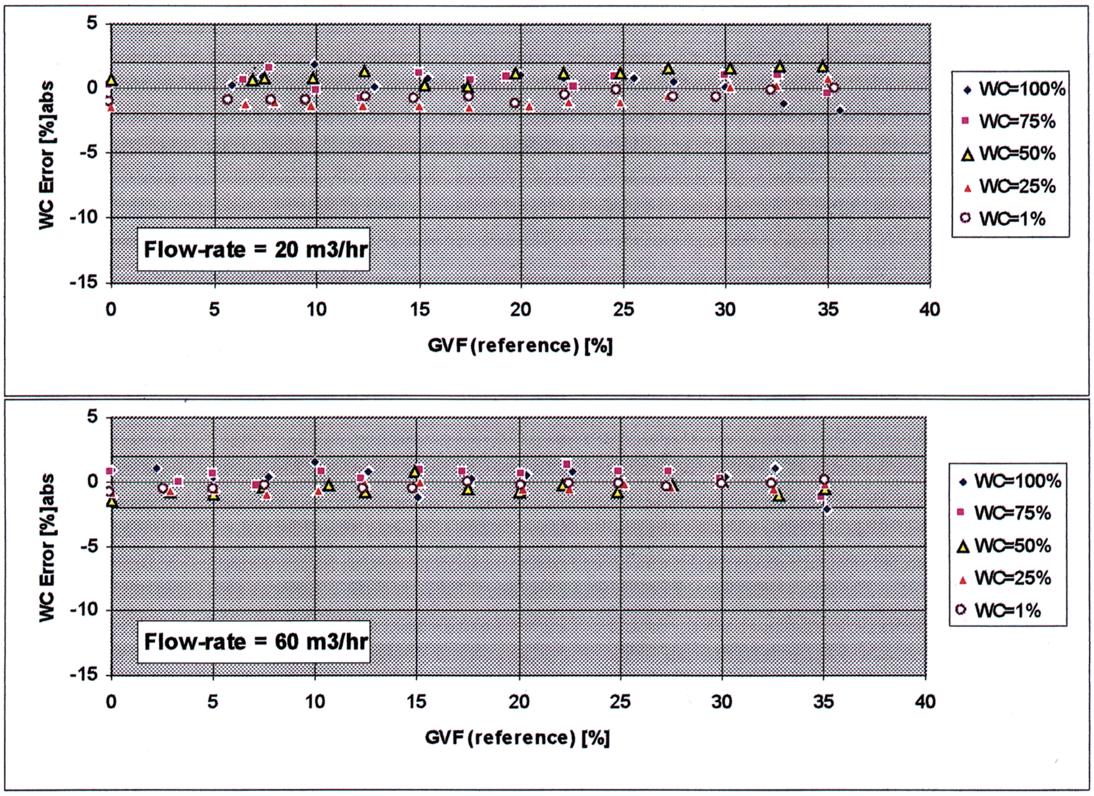

Figure 5: MEGRA Water-Cut error vs. Gas Volume Fraction at WCs from 1 to 100%. (From flow testing at Shell RTS's Donau flowloop, Rijswijk, The Netherlands).

Figure 5 shows the water-cut performance of the MEGRA multiphase flowmeter at two distinct liquid flow-rates. The data were recorded at Shell's Donau Flowloop in Rijswijk, The Netherlands. A water-cut accuracy of better than 2% (absolute) was maintained over the full WC range and up to GVF's of more than 35% - far in excess of the gas content specified for any of the initial field applications.

One advantage of MEGRA's high water-cut accuracy and fast time-response is aptly demonstrated by the results of extended field trials carried out at the onshore production site of NAM (Rotterdam) in The Netherlands. Traditionally net oil production was monitored at this site by bulk flow-rate measurements at the output of a test separator coupled with periodic sampling of the oil/water content of each reservoir stream. The results, however, were occasionally anomalous, particularly for some of the high water-producing wells. With a MEGRA multiphase flowmeter installed at the "liquid" output of the test separator, the reason for some of these discrepancies became clear. A rapid cyclic behaviour was evident in the water-cut of some streams (Figure 6), which had not been previously recognised [4]. To verify the integrity of the MEGRA data, a sequence of manual samples were gathered from the liquid outlet, at a period of about two minutes. As Figure 6 shows, the samples show excellent correlation with the synchronised MEGRA values. (The MEGRA cycle time was increased by a factor of ten for this test, simply to aid with time correlation of the data sets.

With the usual dwell time of just a few seconds, the water-cut oscillation in this well was observed to be even more pronounced). The cyclic behaviour has not been fully explained, but the disadvantage of estimating the water-cut of a well from process samples taken randomly in time is clearly demonstrated. The MEGRA multiphase flowmeter has now replaced periodic sampling as the primary source of WC information at this site, and due to the high-quality real-time data that it provides, forms an integral part of their reservoir management system.

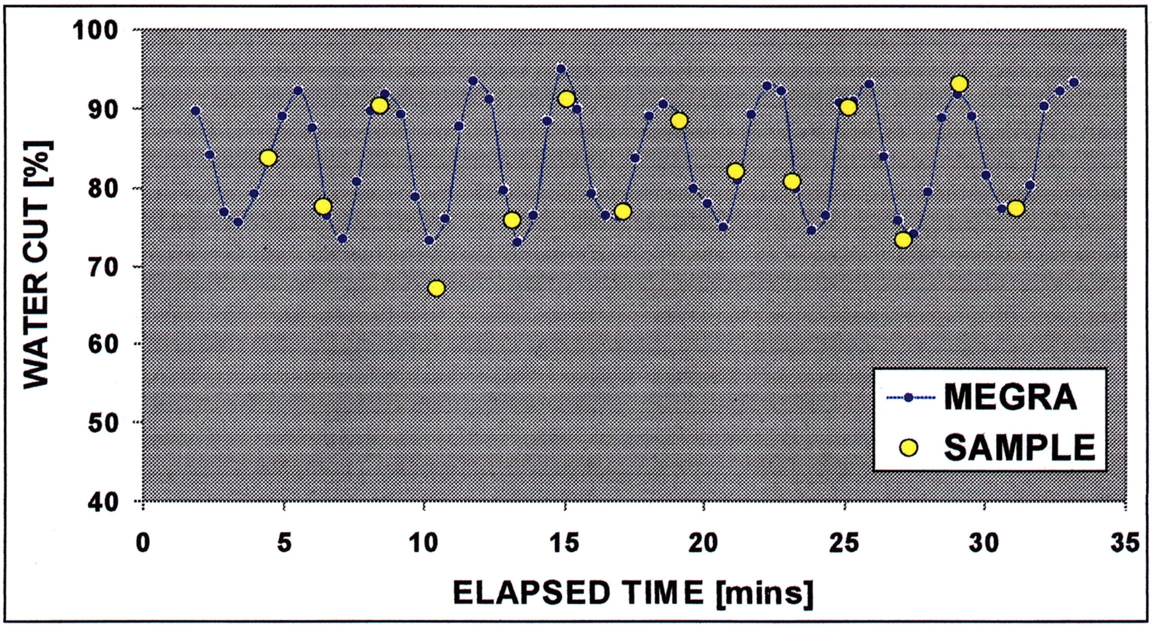

Figure 6: Water-cut data for the high WC well "RTD4" of NAM's Rotterdam production site (The Netherlands) as measured by MEGRA and simultaneous local sampling.

A second series of field trials, commissioned by Shell BSP's Production Systems Optimisation Team (Rasau Field, Brunei), compared the MEGRA's metering performance directly to that of a high-accuracy Coriolis meter. The devices were mounted in series on the "liquid" output of the field's test separator. The comparison highlighted some serious short-comings in the water-cut accuracy of the "two-phase" meter in the presence of breakout gas, and once again provided detailed tracking of the multiphase stream's real-time behaviour.

Figure 7 shows the results of a well test, with the test separator operated in "dump" mode [5]. Here the separator follows a fill and drain cycle, during which partial separation of the oil and water appears to occur. The resultant oscillations in the stream's water-cut profile had not been previously recognised, but are clearly demonstrated by the MEGRA data. The results show that to obtain a representative WC under such conditions, well tests must be of sufficient duration to smooth out these variations. Furthermore, local sampling at a single point in time can not be regarded as a good indicator of the average WC of such a stream. Samples taken at the well-head on the other hand, where the liquid phases remained well-mixed, were in excellent agreement (± 2%) with the flow-weighted MEGRA WC values.

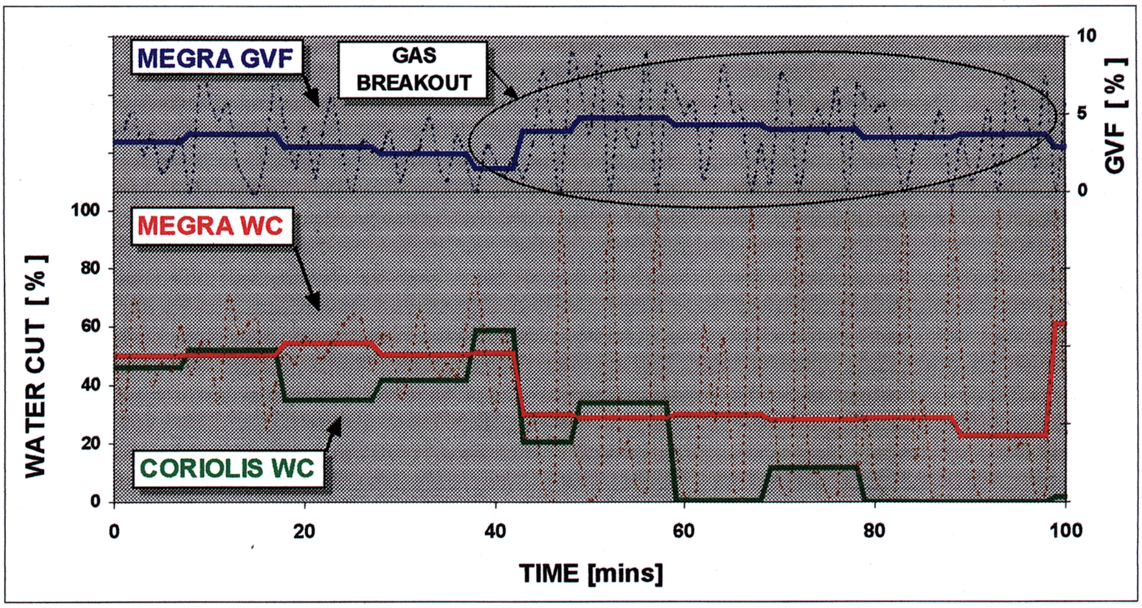

Figure 7: Multiphase flow composition as measured by MEGRA and Coriolis meters in series. The data [5] were gathered from the output stream of a test separator operated in "dump" mode (BSP, Rasau Field, Brunei). The upper section of the graph (right axis) shows the instantaneous (thin line) and averaged GVF (thick line) as measured by MEGRA. The lower section (left axis) shows the independent WC measurements of the two meters. The "real-time" MEGRA data is updated every few seconds. The averaged values, derived over the same integration period as the Coriolis meter, are for comparison only.

MEGRA shows that the gas content of the output stream varies from about 0 to 10% (Figure 7) and is strongly correlated with the presence of oil, as might be expected. In regions of high gas "breakout", the Coriolis meter exhibits substantial errors. In the highlighted section the gas content exceeds 2% and the Coriolis WC reading deviates by as much as 70% from the MEGRA value. (The Coriolis meter is unable to distinguish between a reduction in fluid density due to increasing gas or decreasing water content).

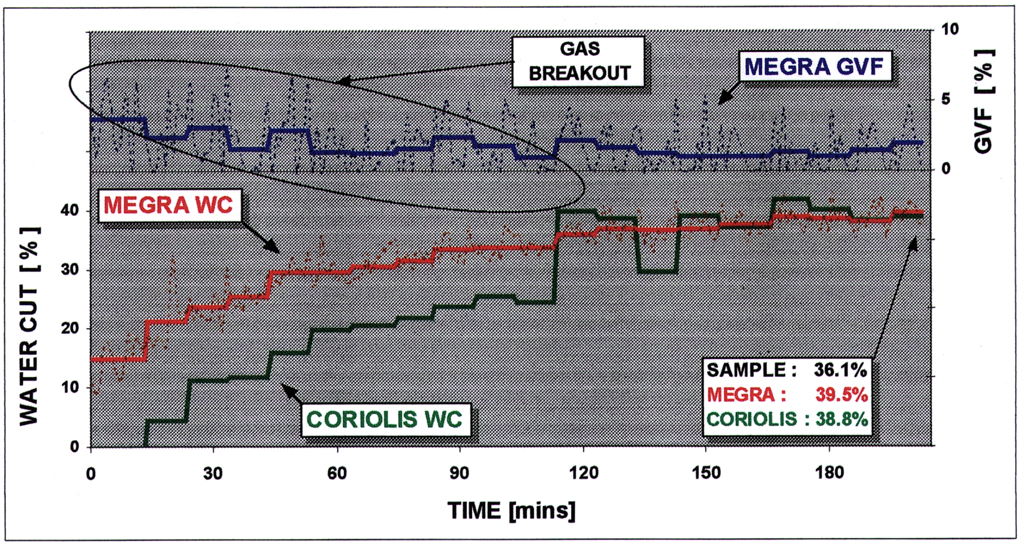

Figure 8: As for Figure 7, except in this case the test separator was operated in "continuous" mode.

Figure 8 shows a similar well-test, this time with the separator operated in "continuous" mode. A gradual rise in the water-cut is obvious as a new well is routed to the test separator. Fluctuations in the WC of the output stream, while finite, are much less pronounced in this case, and local samples are marginally more reliable. In regions of low gas content (less than 2%) the MEGRA and Coriolis water-cuts agree to within a few per-cent. Sampling estimates also lie in reasonable proximity. However, where the oil content of the stream is large (near the start of the test), so too is the associated gas breakout. Again this seriously hampers the WC performance of the two-phase meter. The MEGRA on the other hand is unaffected by the presence of the gas.

SUMMARY AND CONCLUSIONS

A high-accuracy multiphase flowmeter, based on the gamma-ray absorption principle, has been developed, tested and is now commercially available. The use of relatively low-energy gamma-ray emissions, with respect to competitive multiphase meters, lends this technology an enhanced sensitivity to variations in the component phase fractions. Consequently, water-cuts and gas volume fractions can be measured to high accuracy in relatively short measurement times (seconds). A further advantage of this underlying sensitivity is that additional process parameters can potentially be derived, and a method of measuring changes in the process water salinity, which seriously affects most multiphase flow measurements, has been described and demonstrated. The ability to measure such changes provides a useful tool for reservoir monitoring and the detection of injection-water breakthrough etc.

In live applications the MEGRA multiphase flowmeter has proved to be dramatically superior to the traditional well-test methodology of bulk flow-rate measurement and periodic sampling. The hazards of the latter approach, when the process composition is rapidly varying have been highlighted. The advantages of employing a multiphase meter (over a conventional WC meter) in liquid streams where gas carry-under or breakout may potentially occur have also been demonstrated. The high quality of the real-time process data provided by MEGRA has already gained substantial interest for well-management purposes.

Overall, the ultimate aim of the MEGRA multiphase flowmeter – to replace the measurement function of the test separator – has been fulfilled. Equipment weight and space, as well as capital costs and maintenance are substantially lower. The improved accuracy in the phase fractions (from ~ 10% for the test separator to ~ 2% for MEGRA) and the associated reduction in well-test times and operator intervention also lead to markedly reduced operating costs.

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