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ABSTRACT

The CSIRO gamma-ray multiphase flow meter (MFM) determines the flow rates of oil, water and gas in pipelines from oil wells. The MFM consists of two specialised gamma-ray transmission gauges, and pressure and temperature sensors, which are mounted on a pipe carrying the full flow of the well stream, and processing electronics which are located in a control room.

The MFM was first demonstrated in three field trials in Australia. MFM and test separator flow rates were compared using least squares regression. The relative errors (r.m.s. difference/mean flow of component), averaged over all trials, were about 4% for liquids, 8% for oil, 5% for water, and 8% for gas. These include both MFM and separator errors. The MFM has been in routine use on the West Kingfish platform since November 1994.

The MFM was recently tested over a wide range of flow rates at Texaco's flow facility, Humble, Texas. CSIRO's analysis of the trial results shows that the MFM determined water cut to an r.m.s. error of 2.0%, with scatter about the line of best fit being 1.6%. By comparison of MFM and Texaco flow results, a slip correlation has been developed which led to, over the gas volume fraction (GVF) range 0 to 90%, relative errors of 6.6% for liquids, 6.2% for gas, 8.0% for oil, and 8.1% for water.

1. INTRODUCTION

CSIRO developed and field tested a gamma-ray multiphase flow meter (MFM) over the period 1989-1995 as part of a project sponsored by ERDC, Esso Australia Ltd., The Shell Company of Australia Ltd., WAPET, and Western Mining Corporation (WMC). The project was coordinated by the Australian Mineral Industries Research Association Ltd.

The field trials[1-3] undertaken during the sponsored project were on the Vicksburg offshore oil platform (1992), at the oil processing facilities on Thevenard Island (1993), and on the West Kingfish offshore oil platform (1994-95). These oil facilities are respectively operated by WMC, by WAPET and by Esso Australia. The first two facilities are on the North West Shelf, Western Australia, and the West Kingfish platform is in the Bass Strait off the Victorian coast.

In each trial, well streams were sequentially routed past the MFM which was mounted on a "test" pipeline joining the test manifold to the test separator. The bores of the test pipelines were 139.7 mm (Thevenard Island and West Kingfish platform) and 73.7 mm (Vicksburg platform). Pressures ranged from 640 to 2800 kPa, and fluid temperatures from 24 to 96^{0}C.

The flow rates determined by the MFM and by the test separator were compared using least squares regression, and the relative errors (r.m.s. difference to mean component flow) calculated. The relative errors, averaged over all trials, were about 4% for liquids, 8% for oil, 5% for water, and 8% for gas. These include both MFM and separator errors.

This paper describes the gamma-ray MFM, the results of the eighteen week trial (1994-1995) and of the later routine use (1995-1996) of the MFM on the West Kingfish platform, and the recent trial at Texaco's Humble facility. Comments are then made on various aspects of the MFM based on CSIRO's experience in its use particularly in field trials.

2. THE GAMMA-RAY MFM

2.1 Principles

The MFM consists of two specialised gamma-ray transmission gauges, and pressure and temperature sensors, which are mounted on a pipe carrying the full flow of the well stream, and processing electronics which are located in a control room (Figure 1). The first gauge, a density gauge, measures the intensity of 662 keV gamma-rays (^{137}Cs) transmitted through the fluids in the pipeline. The second, a dual energy gamma-ray transmission (DUET) gauge, measures the transmitted intensities of 59.5 and 662 keV gamma-rays from ^{241}Am and ^{137}Cs.

All flow rates are calculated from separate determinations of water cut (WC) and flow rates of liquids and gas. Water cut is determined by dual energy gamma-ray transmission. The flow rates of liquids and gas are determined mainly from measurements of mass per unit area of liquids across a diameter of the pipeline by the density gauge; flow velocity from cross-correlation of the outputs of the two gamma-ray transmission gauges; and operating pressure and temperature in the pipeline. Gas volume fraction is calculated from the internal diameter (I.D.) of the pipe, the densities of oil and formation water at the line operating pressure and temperature, and the combined thickness of oil and water in the gamma-ray beam. In calculation of liquids and gas flow rates from these measurements, a correction is applied to make an allowance for slip between the liquid and gas phases. Oil and water flow are respectively determined by multiplying liquids flow by (1-WC) and by WC.

The DUET gauge determines the mass fractions of oil and water in the liquids. The basis of this determination is the difference in atomic number of the oil and the formation water. The intensity of the transmitted 59.5 keV gamma-rays depends both on the atomic number of the fluid constituents and the mass per unit area of the fluids in the gamma-ray beam. The intensity of the transmitted 662 keV gamma-rays depends on the mass per unit area of fluids in the gamma-ray beam. Water cut is determined by combining these two measurements and the densities of the oil and formation water at the pressure and temperature of the flowing stream of multiphase mixture.

2.2 Hardware and Software

Figure 1 shows a schematic of the MFM mounted on a vertical pipe, and Figure 2 the MFM mounted on a vertical section of pipe at Texaco's Humble flow facility. The DUET gauge is mounted onto a "ring" which is a squat steel cylindrical shell through which the multiphase flow passes. This ring is bolted between two flanges of the pipe. The density gauge is mounted on a C-frame which is mounted on a saddle welded to the mainline pipe.

The DUET gauge requires low atomic number windows to ensure adequate transmission of the low energy (59.5 keV) gamma-rays. Thick windows of carbon fibre reinforced epoxy composite are incorporated into the DUET gauge ring. These have been designed to pass the American Petroleum Institute's "Fire Test for Soft-seated Quarter Turn Valves" (API Spec. 6FA). The inside surface of the carbon fibre epoxy window, exposed to the multiphase fluid, is shaped to match the curvature of the cylindrical inner walls of the ring, which has the same I.D. as that of the production pipeline.

The very narrow beam of gamma-rays emerging from the radioisotope source containers traverse a diameter of the pipeline. The transmitted gamma-rays are absorbed in the NaI crystal of the scintillation detector. For the DUET gauge, the intensities of the ^{241}Am and ^{137}Cs gamma-rays are separately determined using pulse height analysis. The scintillation detector, high voltage supply and preamplifier of each gauge are mounted in an approved flameproof container. The electrical signals from the preamplifier are carried via armoured cables, first to a flameproof junction box and from there to the processing electronics which are housed in a control room. Power is carried by the same armoured cable. The processing is undertaken by a fast nuclear counting system, and the outputs, in the form of counts per five millisecond time interval, are processed by an industrial 80486 DX computer. The computer outputs the flow rates, water cut, and various other parameters which are displayed in computer graphics. The MFM presents the flow rates of oil, water and gas as separate 4-20 mA signal outputs.

3. WEST KINGFISH PLATFORM

Esso Australia Ltd. operates, for the Esso/BHP Joint Venture, all the oil platforms and gas production facilities in the Bass Strait, Australia. The MFM trials were undertaken on the West Kingfish oil platform which lies 70 km from the coast in 80 m depth of water. There are about 20 wells in production on the platform. The densities of stabilised oil and formation water are respectively 0.802 and 1.023 g cm^{-3} at STP. The flows from each of the 20 production wells are measured by the test separator twice a month.

The MFM was mounted on a vertical upflow section (ID: 139.7 mm) of the test pipeline which carries the full flow of the multiphase mixture from the test manifold to the test separator. The length of straight vertical pipe upstream of the density gauge was 1500 mm (11 pipe bores).

3.1 Eighteen Week Trial

The eighteen week trial of the MFM on the West Kingfish platform was undertaken from November 1994 and March 1995. Prior to start of trial, all meters at the separator outputs were upgraded/replaced to ensure the best accuracy and reliability possible within operating constraints on the platform. Sand was cleared from the test separator. After installation of the MFM, the count rates for both gauges, and pressure and temperature, were sequentially measured with the pipe full of oil, formation water, and gas. These measurements are the basis of the calibration of the MFM for the specific characteristics of the fluids from the oil field.

The MFM was calibrated by least squares regression of MFM and separator measurements obtained during the first (two week) round of well tests. The calibration, common to all well flows, was later found to be the same as that determined from the results of all well tests undertaken over the eighteen week trial.

The results of the trial are shown graphically in Figure 3, and the relative errors are detailed in Table 1. The MFM and separator results are obviously well correlated. The relative errors quoted are the combination of the errors both of the MFM and of the separator. Two sets of relative errors are given in Table 1. The first corresponds to all well measurements taken as separate data points, similar to those shown in Figure 3. The second corresponds to one data point for each well, each point being the average of all measurements on the same well over the eighteen week trial. The relative errors calculated using these averages for each well are considerably lower than those for all the well measurements treated separately.

3.2 Routine Use on Platform

Esso has continued to use the MFM on the WKF platform since the eighteen week trial under an arrangement with the CSIRO and involving CSIRO monitoring its operation via modem. The MFM has been in routine, 24 hours per day, operation. It soon became apparent that, for a good assessment of the MFM, CSIRO would also require a continuous record, over the one hour period of each well test, of the flows measured by the test separator output meters. This recording of separator flows was achieved in February 1996, with 30 second updates fed to the MFM computer.

The experience from the comparison of MFM and test separator flow determinations from March to the present date is that the MFM and separator determinations of liquids, water and gas flow rates generally agreed well, with accuracies for the MFM approximately the same as for the 18 week trial above.

4. TRIAL AT HUMBLE

The MFM was tested over a wide range of liquids and gas flow rates, gas volume fractions (GVFs), and water cuts, at Texaco's multiphase flow facility, Humble, Texas. CSIRO's analysis of the trial results, subsequent to the trial, has shown that the MFM determined water cut in all streams (GVFs: 6-98.4%) to an r.m.s. error of 2.0% over the range 0 to 100% water cut, and using least squares regression, to an r.m.s. difference of 1.6% (Figure 4). A slip correlation was developed by comparing the MFM and Texaco flow results. The MFM and Texaco liquids and gas flow rates were then compared using least squares regression. Over the gas volume fraction range 10-90%, the relative errors were 6.6% for liquids, 6.2% for gas, 8.0% for oil, and 8.1% for water.

The MFM slip correlation, determined from comparison of MFM and Texaco flow data, was applied to predict the flows at the West Kingfish platform. The liquids flows were determined to 15% (scatter about regression line: 5.4%), and the gas flows to 11%.

A calibration for liquids and gas flows, based on Australian field trial experience, was incorporated into the MFM for the trial at Humble. The Australian calibration was shown to determine liquids and gas flows at Humble to relative errors respectively of 13% and 15%, for mixtures with GVFs in the range 25 to 85%, and more in error over a wider range of GVFs. This is a reasonable agreement considering that the range of GVFs experienced in Australia was limited to 65 to 87%, and the Australian experience was based on light oils, compared with the medium density crude used at Texaco's facility.

5. DISCUSSION

Comments are now made on various aspects of the MFM based on CSIRO's experience in its use particularly in field trials.

5.1 Determination of water cut

The accurate determination of water cut is a feature of the gamma-ray MFM. The determination of water cut by the DUET gauge is independent of flow regime, continuous phase (oil or water), and emulsion, and sand and corrosion inhibitor at levels normally occurring in well streams. The offset and scatter in water cut determined during Humble trial were small, with offset of about 1.2% and scatter of 1.6%.

5.2 Reliability

The prototype MFM has proved to be reliable on the West Kingfish platform. The carbon fibre epoxy windows in DUET gauge ring have been demonstrated successful, with the windows showing no detectable wear over 22 months on-line. There have been two failures of the MFM equipment over the extended period of its operation on the platform: a hard disk crashed irretrievably within 2 weeks of installation, and a fan in the processor box failed after 7 months of operation (not entirely unrelated to the fact that a 12 volt rating fan was by mistake put on a 15 volt line). Both of these breakdowns occurred in the processing electronics in the control room, and none have occurred in the head units mounted on the pipeline.

One reason for the reliable operation of the MFM is that it is non-intrusive and does not depend on use of moving parts as with, say, turbine meters. The West Kingfish trial has demonstrated that the advanced prototype of the gamma-ray MFM is highly suited to unattended operation on offshore oil platforms.

5.3 Calibration

Ideally, MFMs should be configured based on knowledge of the properties of the well fluids, pressure and temperature, and the geometry of the pipeline, to have a universal equation covering all flow conditions. In practice, the MFM at its present stage of development requires calibration for liquids and gas against known flow rates to give the on-line calibration. We have extended the calibration over a range of flow rates and conditions based on the results of the Humble field trial and the Australian field trials, but further experience is required for some flow conditions not yet experienced.

The calibration for liquids and gas flow rates depends at present on deriving a correlation for slip based on MFM and separator measurements, as undertaken at Humble. Once the slip corresponding to a particular set of flow conditions has been determined, this calibration can be used in any future installation of the MFM for these flow conditions. The determination of oil and water flow rates simply depends on the liquids and water cut determinations.

The determination of water cut is now well understood, and calibration has now been simplified to making sequential measurements with the pipe filled with (static samples) oil, formation water and gas, and knowledge of the densities of oil and formation water, and the solubility of the gas in the fluids, as a function of pressure and temperature. The gamma-ray measurements required for calibration on static samples are normally undertaken on-line at the field site.

5.4 Operational advantages

The MFM has important operational advantages over the test separator/output meters system. The MFM is more reliable and requires far less operator support and time for determination of the well flows. The MFM operates continuously with operator intervention only being required to switch the appropriate stream through the pipe on which the MFM is mounted. Since the MFM can be mounted on the pipeline between the manifold and the production separator, there is no need for stabilisation of the well flow prior to the MFM measurement. With the test separator, each well must be stabilised prior to determination of flow rates because it operates at a different pressure to that of the production separator.

Operator intervention is required with the test separator when there is a considerable change in flow rates of oil or water or gas to ensure that the single phase output streams are routed to the appropriate output meter. For example, on the West Kingfish platform, the output oil and water streams are monitored by turbine meters, with both high and low flow meters on each stream. The gas flow output is metered by a high range orifice plate and a low range vortex meter. The one MFM on the West Kingfish platform measures all the component flow rates from all the wells fed to the platform; six single phase flow meters are required for use with the separator. The MFM has been shown to operate over a much wider range of flow rates of liquids, oil, water and gas than can be handled by the test separator and its output meters.

The MFM does not require regular maintenance such as removal of sand from the separator.

5.5 Engineering and other developments

The MFM can be adapted for use on a wide range of pipe diameters simply by adapting the design of DUET gauge ring or use of an appropriate diameter carbon fibre/epoxy spool piece. The DUET gauge with the ^{241}Am and ^{137}Cs radioisotope pair is suitable for use on pipelines with diameters between about 4 and 12 inches. For smaller diameters, use of ^{137}Cs (Ba K X-rays and 662 keV gamma-rays) would be appropriate.

The full limits of the MFM's operating envelope have not yet been determined. For example, there is little doubt that the GVF range can be extended considerably beyond the 10 to 90% GVF range which the authors have previously assumed were the limits to the operating envelope.

The simplicity and reliability of the MFM indicates its suitability for subsea development.

6. CONCLUSION

The gamma-ray MFM, successfully demonstrated in three Australian field trials and in long-term operation on the West Kingfish platform, is now suitable for routine use off-shore on platforms. CSIRO has recently gained considerable experience with the operation of the MFM over a wide range of flow rates, during the trial at Texaco's multiphase flow facility at Humble, Texas. This trial greatly extended the operating envelope over which the MFM has been successfully demonstrated.

7. ACKNOWLEDGMENTS

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8. REFERENCES

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Table 1. Relative errors for flows and water cut corresponding to the average, for each well, of the measurements over the eighteen weeks trial, and to each individual well treated separately.

Parameter measured	Relative error (%)	
	Mean for each well	All individual measurements
Liquids	2.8	3.9
Water Cut	2.4	3.3
Gas	6.3	7.6
Oil	5.1	7.9
Water	4.0	5.2

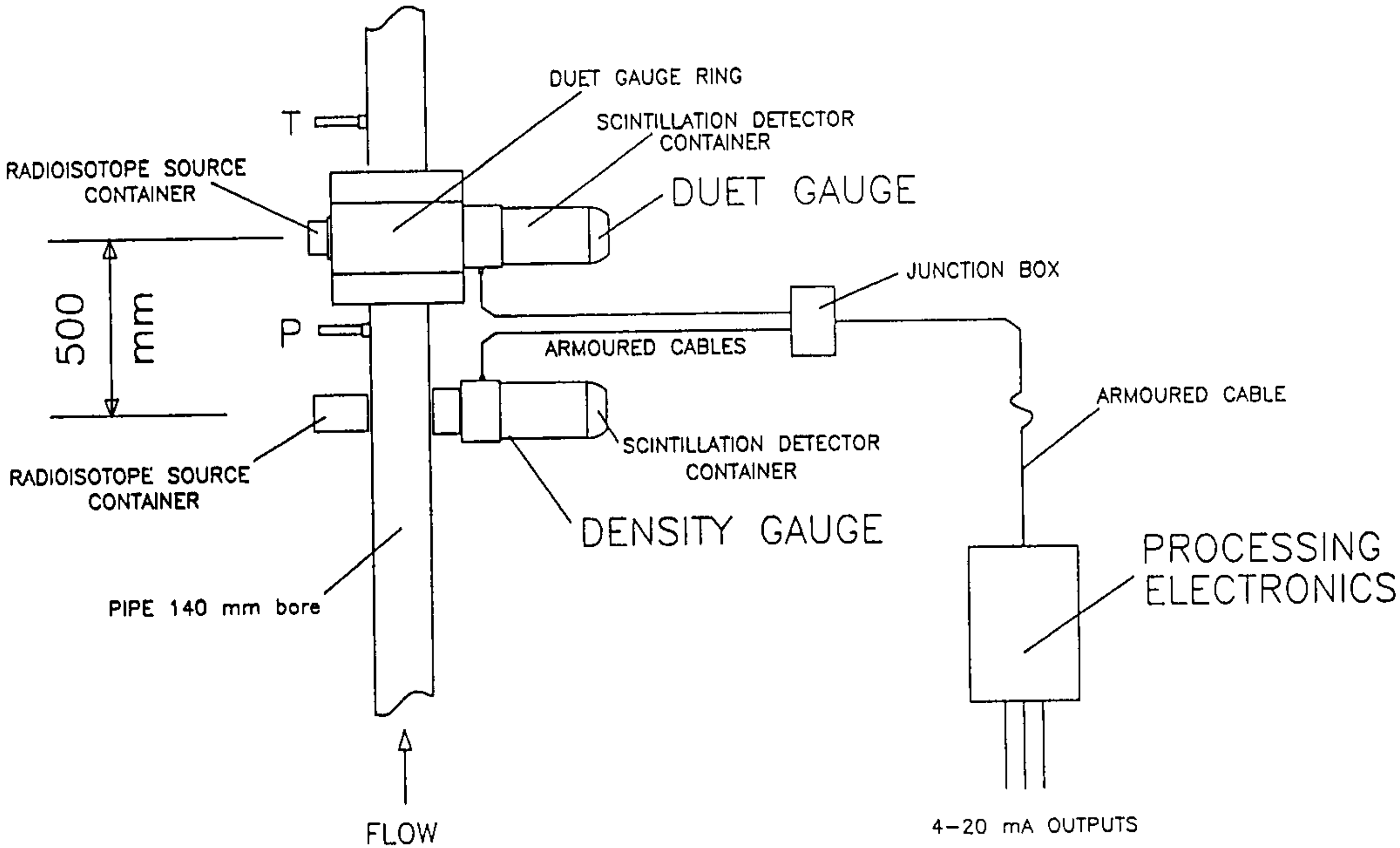

Figure 1. Schematic of the CSIRO MFM mounted on a six inch pipeline. P and T are pressure and temperature sensors.

Figure 2. Photograph of the CSIRO MFM mounted on a pipeline at the Humble facility.

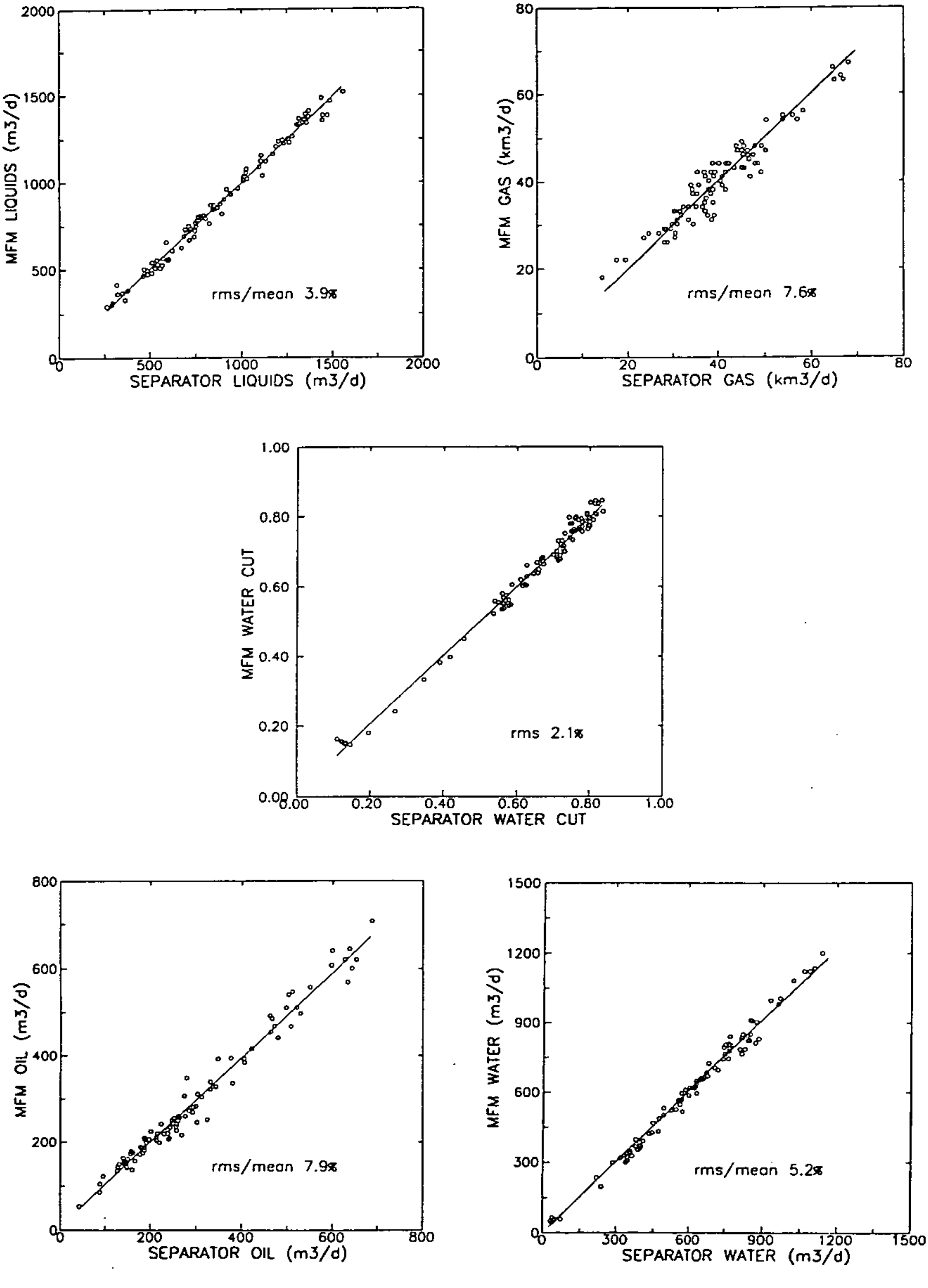

Figure 3. MFM and separator determinations of flow rates and water cut during the 18 week trial on the West Kingfish platform.

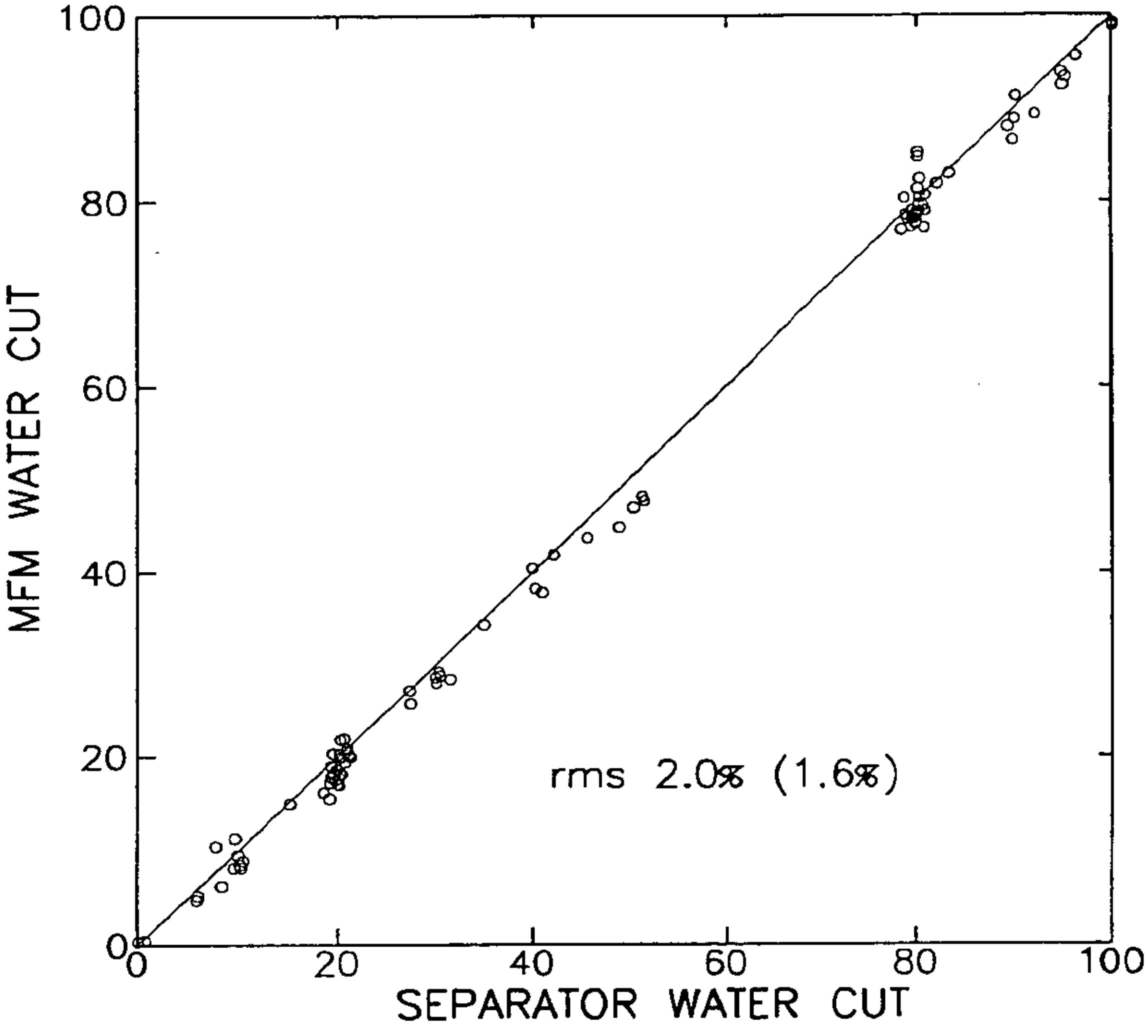

Figure 4. MFM and separator determinations of water cut at Texaco's Humble flow facility.