NORWEGIAN SOCIETY OF CHARTERED ENGINEERS

NORWEGIAN SOCIETY FOR OIL AND GAS MEASUREMENT

NORTH SEA FLOW MEASUREMENT WORKSHOP 1993
26 - 28 October, Bergen

Field Experience with the Multi-capasitor Multiphase Flow Meter

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SUMMARY

The multi-capacitor multiphase flow meter (MCF) has been tested at three field locations covering a wide range of crude properties and process conditions. Results of the field tests show excellent repeatability, and good agreement between the MCF and reference measurements of liquid flow rates. An apparent systematic over-reading of 20% for gas flow rates in the field is currently being investigated. Calibration in the field is straightforward. Installation requirements, though not fully defined, have been shown not to be very severe, since slugging flow is stable even through complex pipework.

INTRODUCTION

The multi-capacitor flow meter, a device for measurement of flow rates in multiphase slugging flow, has been developed in a joint project between Shell Research in the Netherlands and the manufacturers (Kongsberg Offshore) in Norway, with Norske Shell as co-sponsor. The operating principle has been described elsewhere [1]. Briefly, flow rates are derived from the output of an array of capacitive sensors mounted on two plates in the flow line parallel to the flow direction. These sensors measure the cross-sectional areas of the pipe occupied by liquid and gas, the velocity of the liquid in the liquid-filled part of the pipe and the velocity of the slug passing down the pipe. On the assumption that the slugs travel at the same velocity as the gas, the flow rates are calculated from the product of the cross-sectional areas occupied by the liquid and gas and their respective velocities. The Mark 1 MCF operates with watercuts up to around 40%.

The meter has now been extensively tested in two laboratory flow loops and at three different field locations. It is the purpose of this article to describe the experience with the meter in the field, highlighting where necessary the differences encountered between laboratory and field environments.

Very little is known in detail about instantaneous flow conditions in well flow lines since production is usually measured using a test separator, which acts as a large buffer smoothing out any possible short-term fluctuations in flow rates. This complicates the selection of test sites for multiphase meters since these meters are designed for certain types of flow or ranges of steady conditions, and these requirements must then be matched to the available test-separator data, which are usually averaged over periods of 4 up to 24 hours.

One lesson drawn from the MCF field trials is that 24-hour test data can be misleading as a basis for assessing the suitability of a site as a test location – or of a meter for a given application – since the dynamics of well production are then excluded from the assessment [2].

FIELD DATA

The three field locations for the initial MCF trials were Marmul in south Oman, Ramlat Rawl in north Oman and Rabi in Gabon. These sites were selected as representing a wide range of crude characteristics and operating conditions. Marmul produces medium heavy, viscous crude, Ramlat Rawl lighter, thin crude and Rabi light, waxy crude. Table 1 summarises the oil properties and selected well test data for these fields. The operating ranges for the 3-inch and 4-inch Mark 1 MCF, based on laboratory data, are given in Appendix A. The 3-inch version was selected for the trials in Oman and the 4-inch version for Gabon.

It is generally accepted that gas-lifting can cause instabilities in well production, even at a constant gas injection rate. What is perhaps less well known is that steady beam pumping does not necessarily prevent large fluctuations in production. The wells available for testing at Marmul were all beam pumped and all showed cyclic variations in production with periods varying from well to well from 30 minutes to 2.5 hours and minimum flow rates for both oil and gas as low as zero. Figure 1 shows control-room chart recordings of gas flow rate and test separator liquid level for two typical wells under test. The cyclic nature of the production, at a frequency much higher than that of the separator's normal dump cycle, is clearly evident. At the other two locations the wells were either free-flowing or gas-lifted/assisted, and production rates were steady except for the usual day-and-night variations caused by changes in ambient temperature.

Table 1

Oil properties and typical well test data from MCF test sites

	Marmul*		Ramlat Rawl*		Rabi**		
WELL	M-23	M-50	RR-01	RR-04	RAB03	RAB76	RAB26
Gross liquid flow (m3/d)	98	106	118	232	279	460	525
Liq. superficial velocity (m/s)	0.25	0.26	0.29	0.58	0.35	0.58	0.66
Associated gas flow (st.m3/d)	1610	5073	16800	31900	16900	58300	21900
Line pressure (kPa)	200	200	900	900	600	690	700
Gas superficial velocity (m/s)	2.0	6.3	4.7	8.9	3.5	10.6	3.9
Gas volume fraction (%)	88.9	96.1	94.2	93.9	93.4	94.8	85.6
BS&W (%)	27	23	39	0	0	0	40
Dry oil density 15 °C (kg/m3)	918	922	870	870	854	854	854
Kin. viscosity 25 °C (mm^2/s)	480	610	15	15	25	25	25
Kin. viscosity 50 °C (mm^2/s)	110	150	4	4	8	8	8
Dyn. viscosity 50 °C (mPa.s)	101	138	3.5	3.5	7	7	7

* 3-inch MCF ** 4-inch MCF

REFERENCE MEASUREMENTS

A major difference between laboratory and field tests is the quality of the reference measurements. The Shell Group has considered field measurement requirements in the past and concluded that an uncertainty of ± 10% for each phase (oil, water and gas) is acceptable having regard to operational and reservoir-engineering requirements. Shell operating companies generally achieve this target, though less stringent standards can be accepted in practice for the accuracy of water and gas flow-rate metering in remote oil fields, since these phases are usually re-injected.

An analysis of field measurements using the guidelines for uncertainty calculation contained in the ISO 5167 recommendations for flow meter installations shows that a properly engineered and maintained test separator can limit the uncertainty in the flow rate to ± 5% for gross liquid flow, ± 10% for net-oil in the watercut range up to 40%, and ± 10% for gas flow, provided the orifice size is chosen to give a reading around mid-scale. These uncertainties are based on the usual practice of testing a number of different wells with different characteristics on a test separator, while using average fluid properties such as gas and liquid density and integrated values for pressures and temperature to calculate the flow rates for all wells.

The reference instruments used for the MCF field trials are given in Table 2. An orifice meter was initially used for the gas flow rates at Marmul. However, the large cyclic production fluctuations from any single well made it impossible to choose a single orifice diameter to cover the full range of gas flow rates encountered during a well test. A vortex meter with a specified rangeability of 30:1 was therefore installed instead. Even this meter could not cope with the full range of fluctuation, however. The small excursions down to zero flow beyond the lower end of the range do not, however, add substantially to the measurement uncertainty. The reference measurements for Ramlat Rawl were obtained from a gathering station connected to the remote manifold by 16 km of 8-inch diameter production flow line. In Gabon, local test-separator reference measurements and regular slugging flow - ideal for MCF evaluation - were present, but the waxy nature of the crude was also reflected in the quality of the production gas used for the pneumatic instrumentation, which caused occasional blockages and spurious measurements.

Table 2

Reference Instrumentation

Location	Liquid Gross	Watercut	Gas
Marmul	1-inch Micromotion Coriolis meter	Coriolis density measurement	1.5-inch Vortex
Ramlat Rawl*	pd meter	Hydril probe	Orifice
Rabi	2-inch OILGEAR PV meter	Manual sampling and analysis	Orifice (selected by operator)

* at gathering station 16 km away

TEST DURATION

It is another lesson of the MCF field trials that conclusions on meter accuracy cannot be based on only a limited series of measurements. Fluctuations in individual well production and uncertainties in the reference measurements both lead to the conclusion that a proper assessment of test-meter accuracy can only be obtained by testing and re-testing a large number of representative wells.

In Gabon, some 18 tests over 7 wells were required before a clear picture of the MCF performance emerged. Even this number does not allow a meaningful statistical analysis of the results that could have, for instance, revealed possible erroneous measurements. Wells producing outside the specification of the MCF were also tested to confirm the meter's operating range. The complete evaluation programme at Rabi covered almost four weeks of well testing. A total of five weeks was spent testing at Marmul. The one week spent testing the four wells at Ramlat Rawl was barely sufficient for a complete evaluation, since the lack of local reference measurements required more short- and long-term repeatability tests to be performed to demonstrate the consistency of the meter.

RESULTS

Marmul

When the Marmul 24-hour well test data are plotted on a flow map with the flow regimes superimposed (open circles in Figure 2), the flow rates appear in the slugging flow area and conditions appear very suitable for use of the MCF. However, the large flow fluctuations illustrated in Figure 1 cause the flow regime in the line to move continually in and out of slug flow. This is made worse by liquid accumulation and water separation in the low parts of the flow line during the no-flow periods, followed by violent flow of the accumulated liquid during the peak flow periods. Bubble, plug and stratified patterns have all been observed and problems with short-circuiting of the capacitive sensors by free water were also encountered during these peak flow periods.

The MCF measurements were repeatable in the absence of free water, even during operation in the bubble or stratified flow regime. In a limited number of wells, the discrepancy between MCF and test-separator measurements of both gas and liquid flow rates could be kept to within about ± 20%. However, the Mark 1 version of the MCF cannot be recommended for application under the particular process conditions found at Marmul.

Ramlat Rawl

The oil properties and steady flow conditions at Ramlat Rawl were well suited to the MCF (Figure 3). From the flow map, one of the four wells available for testing would appear to be in the annular flow regime. However, in practice all wells were found to be slugging. The flow regime at the MCF seems to be more determined by the long 6-inch flow lines than by the relatively short 3-inch metering loop.

Although a detailed comparison between MCF and reference data will not be presented here, the one-week trial of the MCF at the four Ramlat Rawl wells has shown:

- good agreement with previously known production data.
- excellent short- and long-term repeatability.
- ease of calibration on-site.
- robust hardware, which gave no problems during transport, installation or daily use exposed to the outside desert environment.
- no down time due to well testing.

The meter has remained installed at Ramlat Rawl as the only means of testing the wells there. (In addition to the four wells covered by the present study, a fifth well has since been added and a further well is due for completion some time in 1993.) A test procedure and test frequency have been agreed with local Operations to provide experience with the meter and to generate information on its long-term reliability. The Ramlat Rawl MCF was still producing good results six months after the initial installation. The meter diagnosed a rapid increase in watercut in one of the wells, which has subsequently been closed-in pending a workover.

Rabi gathering station A

In Gabon the meter was installed upstream and in series with the test separator at Rabi gathering station A. Seven wells within the range of the meter were available for testing. By listening to the flow noise in individual flow lines, one can judge whether a flow line is slugging or not. In this case, all flow lines appeared to be slugging – even the two wells shown by Figure 4 to be in the annular flow regime. This could be confirmed in one case using the MCF, but the largest producing well could not be tested because of test-separator throughput limitations.

The wells tested had a range of gross liquid flow from 120 to 740 m3/d, gas production ranged from around 5,000 to 60,000 n.m3/d (at 1 bar and 15 ºC) and watercuts from 0 to 40%. The results, illustrated in Figure 5 and listed completely in Table 3, show no systematic difference between the MCF and test-separator measurements of liquid flow rates, with an error band of ± 5% attributed to each. For gas, the MCF shows a systematic over-reading of 20% compared with the test-separator measurements, with an error band of ± 10% attributed to each. This error is thought to be caused by differences in slugging characteristics between the laboratory (short, regular slugs) and the field (long, less frequent slugs). This is being investigated further. If this difference is shown to be typical for other field installations, the error can be removed by a simple correction factor. Repeatability of the MCF measurements was at least as good as for the test separator. Wells with watercut higher than the specified 40% were also tested but, as expected, these proved to be outside the meter's operating range.

OPERATIONAL EXPERIENCE

Slugging flow

A major task during development of a flow meter based on slugging flow is determining how many flow lines actually operate in this flow regime. A short survey of selected representative well flow lines was carried out in north Oman, where the wells are either gas-lifted, gas-assisted or free-flowing. The objective was to obtain a good estimate of the percentage of flow lines likely to be slugging at the wellhead, and also at the manifold where the lower pressure gives higher gas volume fractions in the line.

Flow regimes were identified using a portable clamp-on system. Basically this system uses an accelerometer as a sensitive, selective microphone to listen to flow noise, in particular to the passage of liquid slugs.

At or near the wellhead, 10 out of the 11 flow lines visited (91 %) were found to be slugging.

A total of 30 well flow lines were surveyed at the manifold; of these, 26 (87 %) were found to be in slugging flow.

A number of other observations were made.

- Flow lines with gas volume fractions above 99%, where one would normally expect stratified or even annular mist flow, were slugging directly at the wellhead and maintained this slugging regime right up to the manifold. Either the well is functioning as a slug generator, or the slugging envelope in live crude is different from that reported for laboratory flow loops.
- Slugging appears to be stable. Once formed, slugs are maintained even on steeply descending flow lines where flow might be expected to become stratified.
- Care must be taken with acoustic survey equipment at or near manifolds. Some experience is required to distinguish flow noise from mechanical noise – and from flow noise generated in neighbouring flow lines and transmitted to the flow line under survey by mechanical coupling.

Meter calibration

The MCFs installed at Ramlat Rawl and Rabi were given the algorithms and constants determined for the laboratory flow loop. No fine tuning or adaptation to local conditions was required. Calibration requires signal levels from the individual sensor plates in both air and dry oil. The meter was calibrated at Ramlat Rawl using a purpose-built calibration rig in the shape of an inverted U-tube with the meter mounted at the bottom of the U. In this case dry oil was available from one of the wells, but this is not essential since this thin crude separates rapidly, allowing water to be tapped off until the MCF is completely filled with dry oil collecting at the bottom of the calibration rig. In Gabon, the meter was mounted at the lowest point in the flow loop. Dry oil was again available, so the meter could be calibrated simply by emptying and filling the loop while recording the MCF readings.

Wax fouling

A secondary aim of the MCF test in Gabon was to determine the effect of waxy crude on the meter. The MCF senses flow fluctuations using two vertical plates in the flow line parallel to the flow direction [1]. During the tests, these plates became coated with wax. This could be detected easily and quickly from the MCF trend signals. The standard wax-removal procedures used by Shell Gabon (heating, steam cleaning or chemical injection) were all successful in removing or preventing this build-up of wax without affecting the operation of the MCF.

Installation effects

At all three test sites the multiphase meter was mounted in a flow loop specially constructed for the test, with a straight upstream section ten metres long and a straight downstream section three metres long, each having the same diameter as the MCF. Conditions further upstream of the MCF were, of course, very different from in the laboratory. The fluids produced at each well flow through up to several kilometres of undulating 6-inch diameter flow line, then through the test header, a number of sharp bends and changes in height and (for some tests at Rabi) also through a heat exchanger before arriving at the MCF. This complex geometry might be expected to have a detrimental effect on the performance of the MCF by interfering with regular slugging flow, but no such effects were observed in practice.

The minimum installation requirements for the MCF still have to be determined, but they are clearly less severe than originally thought in view of the observed stability of the slugging flow regime.

DISCUSSION

The Mark 1 MCF tested at Ramlat Rawl will remain installed as the only means of testing the remote wells at this location. Operational experience is being fed back to both Shell Research and the manufacturers (Kongsberg Offshore) to help in the continuing development of these meters. A number of other applications are being considered for the Mark 1 MCF, mainly for installation at manifolds in order to remove test-separator-related bottlenecks. These applications will generate the experience and confidence needed for installation of the MCF in individual flow lines – the original target of multiphase meter development.

Another Shell Group operating company now considers the MCF as a real option for the development of a satellite field some 20 km from existing processing facilities. A decision on how to proceed will be taken this year. This company is also keen to evaluate the next version of the MCF, which will be designed to cope with higher watercuts. This Mark 2 meter is a candidate for application in the further development of an existing onshore field in 1995.

The development of the Mark 2 MCF is proceeding on schedule. This new version aims at metering gas and liquid flow rates across the full range of watercuts. The first prototypes were ready in August 1993 for testing and refining in the laboratory. A field test of this new MCF is planned in Nigeria when laboratory testing is complete. Continuing developments are targeted at adding watercut measurement in waterexternal emulsions, extending the operating range to neighbouring flow regimes and producing a subsea version of the meter.

REFERENCES

[1] D. Brown, J.J. den Boer and G. Washington: "A multi-capacitor multiphase flow meter for slugging flow," The North Sea Flow Measurement Workshop, October 1992.

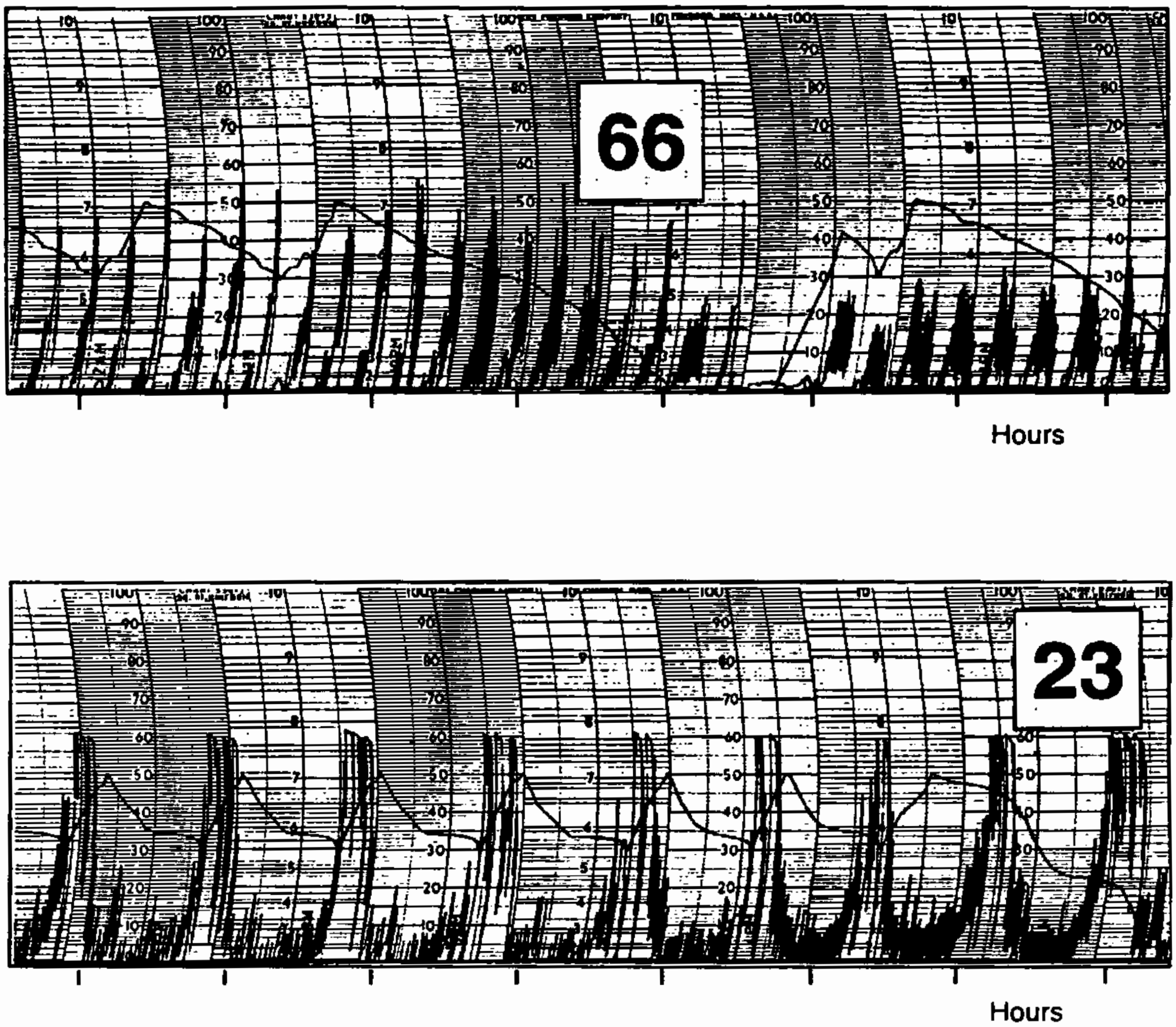
[2] C.J.M. Wolff: "The required operating envelope of multiphase flowmeters for oil production measurement," The North Sea Flow Measurement Workshop, October 1993.

APPENDIX A: The operating ranges for the Mark 1 MCF

The MCF depends on intermittent flow for its operation. On the basis of experience in the Shell Research multiphase test loop, the approximate operating ranges for the 3-inch and 4-inch Mark 1 versions are:

3 inch	LIQUID	60 - 800 m^3/day
	WATERCUT	0 - 40 %
	GAS	450 - 6500 actual m^3/day, (line conditions)
4 inch	LIQUID	120 - 1600 m^3/day
	WATERCUT	0 - 40 %
	GAS	800 - 12000 actual m^3/day, (line conditions)

(a)



(b)

Figure 1 Test-separator chart recordings for Marmul Wells MM66 (a) and MM23 (b).
In each chart, the high-frequency trace represents the gas flow rate measured at the separator outlet, while the low-frequency trace shows the liquid level in the separator as a function of time. The separator works on a dump cycle between 50% and 30% full. The slope of the latter trace is roughly equal to the liquid flow rate, since the effect of tank rounding in the liquid-level range covered is slight. The apparent time shift between low liquid flow and low gas flow, seen most clearly in the chart for Well MM23, is an artefact due to displacement of the recording pens. The time between successive peaks for Well MM23 is approximately 1 hour. The chart for Well MM66 shows more frequent peaks, approximately four per hour, and also includes a test stop (full dump) and start sequence clearly seen on the liquid level trace. Actual flow rates could be estimated from these recordings, but are not required to illustrate the fluctuations in well production.

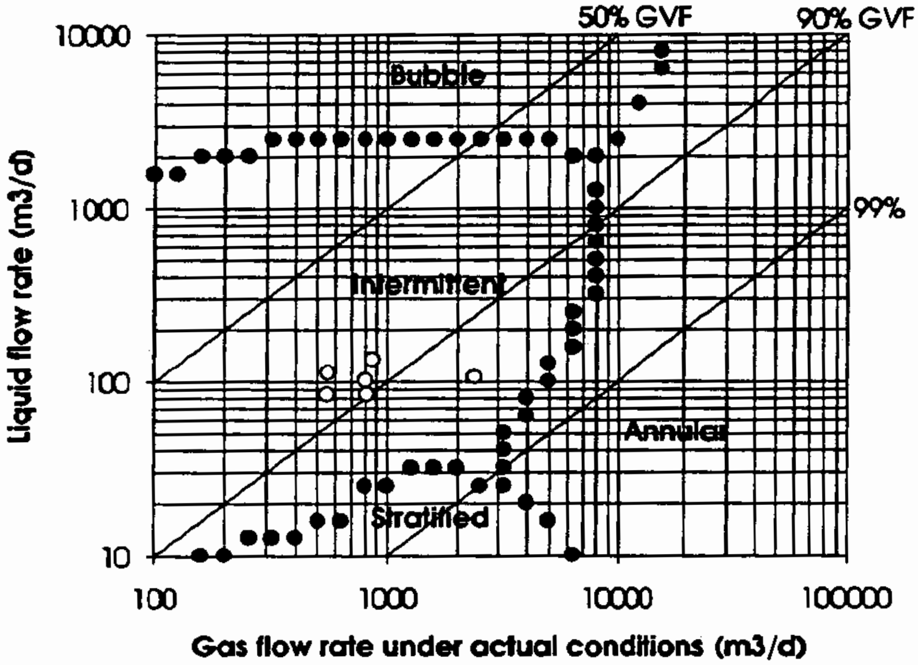


Figure 2 Flow regimes in Marmul 3-inch flow line

The boundaries between the different flow regimes are calculated with the aid of software developed at Shell Research Amsterdam, after input of the relevant operating parameters (in the present case: oil density=920 kg/m3, oil viscosity=200 mPa.s (40 C), line pressure=200 Kpa). Each open circle in this graph represents 24 hour average gas and liquid flow rates derived from routine production monitoring. **Intermittent** includes both slug and elongated bubble (plug) flow regimes.

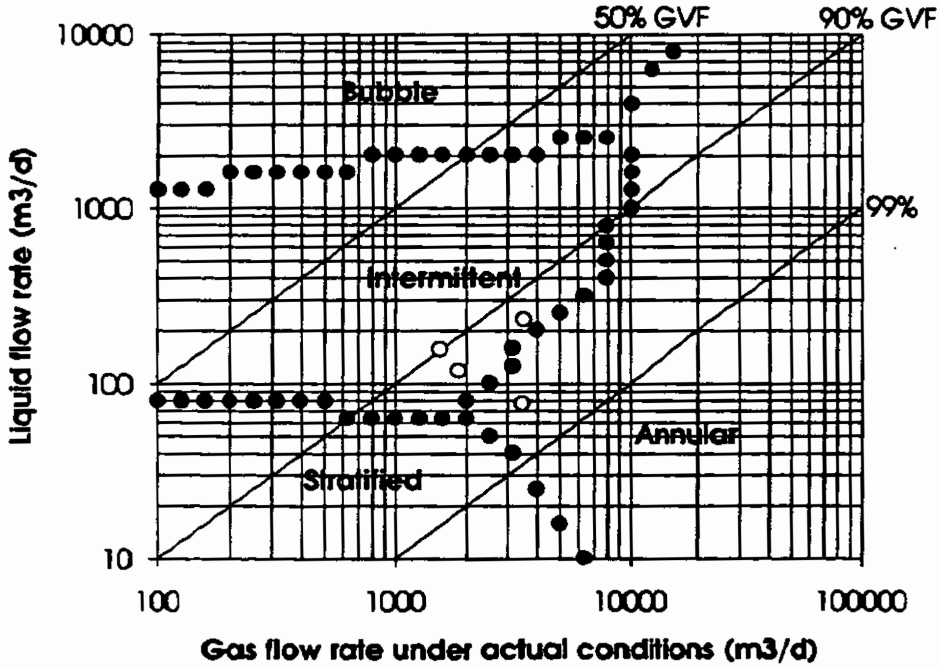


Figure 3 Flow regimes in Ramlat Rawl 3-inch flow line

Operating parameters: oil density=870 kg/m3, oil viscosity=6 mPa.s (40 C), line pressure=900 kPa. Other details as in Figure 2.

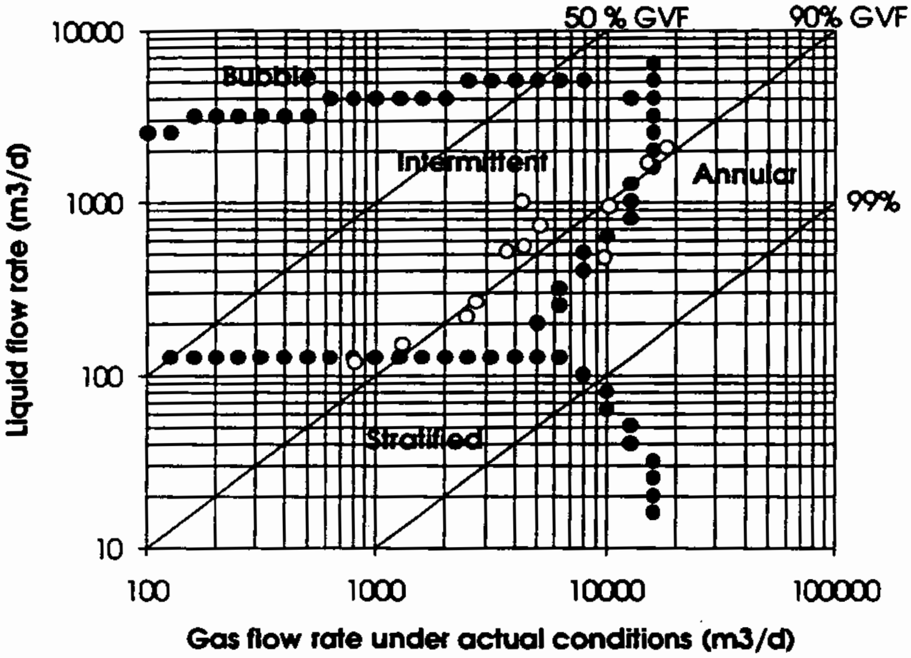


Figure 4 Flow regimes in Rabi 4-inch flow line

Operating parameters: oil density=854 kg/m3, oil viscosity=10 mPa.s (40 C), line pressure=600 kPa. Other details as in Figure 2.

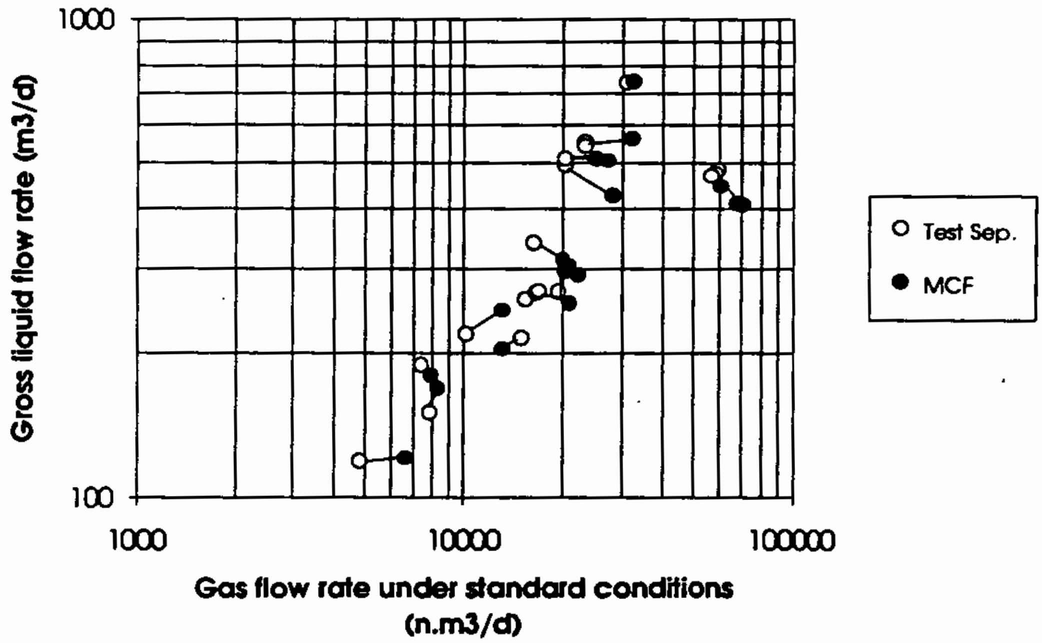


Figure 5 Results of MCF field trial in Rabi 4-inch flow line

Corresponding test-separator and MCF measurement points are joined by a tie-line.

The liquid flow-rate measurements show no systematic difference between MCF and test separator, and an error band of +/- 5% for both.The gas flow-rate measurements show a systematic difference between MCF and test separator of +20% (to be studied further), and an error band of +/- 10% for both.

Table 3

Results of MCF Field Trial in Gabon

	MCF readings				Test-separator readings				Difference	
Well ID	Liq. m3/d	Gas n.m3/d	W.C. %	GOR n.m3/m3	Liq. m3/d	Gas n.m3/d	W.C. %	GOR n.m3/m3	Liq %	Gas %
03-1	304	20870	0	69	268	19480	0	73	13	7
03-2	296	20360	0	69	259	15350	0	59	14	33
03-3	291	22340	0	77	266	16570	0	62	9	35
03-4	254	21040	0	83	269	16820	0	63	-6	25
03-5	313	20130	0	83	339	16310	0	48	-8	23
04-2	121	6680	0	55	119	4840	0	41	2	38
06-2	169	8330	0	49	151	7820	0	52	12	7
06-3	245	13080	0	53	219	10200	0	47	12	28
33-1	180	7930	2	44	189	7390	0	39	-5	7
33-2	740	32650	0	44	733	31150	0	43	1	5
62-1	204	13170	8	65	215	15000	6	70	-5	-12
76-1	445	60900	0	137	481	59800	0	129	-7	2
76-2	408	70600	0	173	474	58960	0	124	-14	20
76-3	410	67900	0	166	468	56700	0	121	-12	20
26-2	504	27360	40	90	553	23400	40	71	-9	17
26-3	562	32200	42	99	540	23600	40	73	4	36
26-4	426	28260	38	107	493	20300	40	69	-13	39
26-5	510	25200	43	87	509	20400	40	67	0	23
								Average	0	+20
								Standard deviation	± 8	±14

W.C. = watercut GOR = gas/oil ratio

Liquid flow-rate measurements show no systematic difference between MCF and test-separator results, and an error band of ± 5% for each.

Gas flow-rate measurements show a systematic difference between MCF and test-separator results of + 20% (to be further investigated), and an error band of ± 10% for each.