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Extended Abstract

Application of the Magnetic Resonance Multiphase Flowmeter to Heavy Oil

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1 INTRODUCTION

In the upstream oil and gas industry, mixtures of oil, gas and water are produced. To measure these fluids simultaneously inline, KROHNE has developed and manufactured a multiphase flowmeter based on Magnetic Resonance (MR). This measurement principle allows for a very direct measurement of the hydrogen atoms present in the oil, gas and water, resulting in accurate values for the flowrates as well as in information on the flow regime and velocity profiles [1] [2] [3]. The Magnetic Resonance multiphase flowmeter has been extensively tested at international multiphase flow laboratories [3] and in applications in the field, as presented e.g. at last year's North Sea Flow Measurement workshop [4].

Fig 1 - The magnetic resonance multiphase flowmeter (M-PHASE 5000)

In this year's presentation, we will focus on applications concerning high viscous oil, also known as heavy and extra heavy oil. It is well known that not only the production, transport and processing of heavy oil is challenging, but also metering of such high viscous oils using conventional technologies has its limitations. We will present results obtained with our MR based multiphase flowmeter on mixtures of viscous oils, in which the oil viscosity ranged between 190 cSt and 2200 cSt, the WLR ranged between 0% and 40% and the GVF ranged between 23% and 90%. Based on these results we will show the suitability of the MR measurement principle to heavy and extra heavy oil applications.

2 HEAVY OIL AND EXTRA HEAVY OIL

In the oil industry, viscous oils are often referred to as heavy oil and extra heavy oil and they can be characterised amongst others by their asphaltenic content, their API gravity (below 22 API for heavy oil and below 10 API for extra heavy oil) and their viscosity, which ranges typically between 100 cP and 10000 cP.

Whereas in the early years of the oil industry, mainly the conventional and easy to produce resources have been produced, it can be observed that in the past decades production has shifted to unconventional resources such as (extra) heavy oil[1]. The world reserve of unconventional resources is about equal to that of conventional resources [5].

As the cost of production for heavy oils is higher than for conventional oil, the need for accurate multiphase flow measurements to optimize the well and reservoir management is even more apparent for these demanding applications. There are, however, quite some challenges in the measurement of multiphase flows of heavy oil. The challenges are related amongst others to differential pressure measurements, the tendency to form emulsion and the complex composition of heavy oil. However, the M-PHASE 5000 makes use of a fundamentally different measurement principle (MR) and does not rely on differential pressure measurements. Therefore, we will focus in this paper on the performance of the magnetic resonance multiphase flowmeter on multiphase mixtures containing viscous oil, to share our observations and to demonstrate its suitability for heavy oil applications.

3 EXPERIMENTAL SET-UP

In the KROHNE Research and Development laboratory, a compact multiphase flow loop has been built. In Figure 2 a schematic representation of the flow loop is shown and in Figure 3 a picture of the loop is shown.

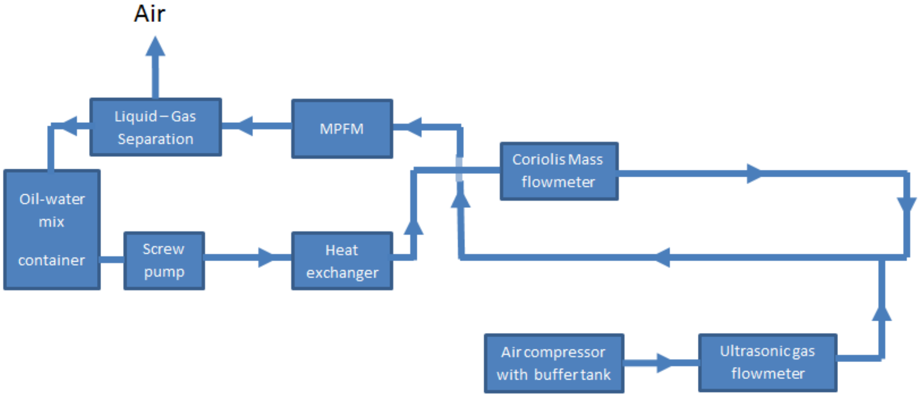

Fig 2 - Schematic representation of the multiphase flow loop at the KROHNE Research and Development laboratory.

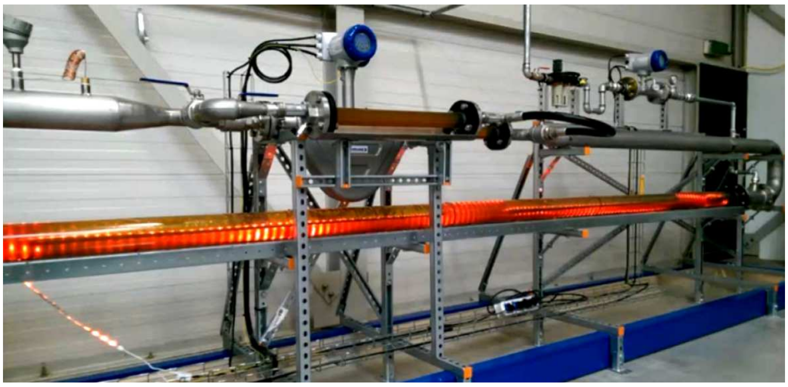

Fig 3 - Picture of the upstream part of the multiphase flow loop, including the transparent section for flow visualization.

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[1] *In the remainder of the paper, when mentioning 'heavy oil' we actually refer to heavy oil as well as extra heavy.*

In the multiphase flow loop a two-phase mixture of oil and water is pumped via screw pumps through 4" lines. By means of a heat exchanger the temperature of the mixture is controlled. As reference the oil-water mixture is measured by a Coriolis mass flowmeter. The uncertainty on the liquid flow rate is 2% of the measured value (MV). Furthermore, the WLR is determined on basis of the density measurement of the Coriolis mass flowmeter using the density of pure water and of oil as reference values. This yields an uncertainty on the reference WLR of 1% absolute error. Compressed air is injected downstream of the Coriolis mass meter. The compressed air represents the gas phase and the flow is measured by means of an Ultrasonic flowmeter, which results in an uncertainty of 2% of the MV. In the flow loop a transparent pipe section of several meters length is installed to allow visualisation of the various flow regimes that occur in the flow loop. The three phase mixture flows through the MR multiphase flowmeter (3" internal diameter) after wich the air is separated from the oil-water mixture.
In Table 1 some specifications of the multiphase flow loop are listed.

Table 1 - specification of the multiphase flow loop

Parameter	Range	Unit
Line pressure	0 – 3	barg
Line temperature	20 - 35	°C
Flow range gas	0 – 50	am^3/h
Flow range liquid	2 - 20	m^3/h
Viscosity range	1 - 2200	cSt

4 FLOW REGIME

A very convenient part of the multiphase flow loop is the long transparent pipe in which the multiphase flow regime can be observed. In the tests described in this paper, we have worked with mixtures of viscous oil (190 cSt to 2200 cSt) in the range of conditions as described in Table 2. For all these conditions it was observed that the flow regime developed into a slug flow or plug flow. This can be understood by considering that the viscous forces in the liquid phase are such high, that the gas phase cannot drag the liquid along to establish a stratified, or stratified wavy flow. Consequently, the main transport mechanism of the fluids is slug flow and plug flow.

In field applications of heavy oil flowing through horizontal production lines, the prevailing flow regime is also expected to be slug flow and plug flow. On one hand this is related to the remark made above, explaining why stratified flow is not possible and on the other hand this is caused by the fact that in typical heavy oil applications the characteristic GVF and liquid flowrates are relatively low, and as such, not enabling mist flow.

4.1 Slug Velocity

As described in the previous section the dominant flow regime in heavy oil applications is expected to be slug flow. Therefore in this section we will focus on the slug flow regime and try to understand the flow dynamics of this flow regime. The slug flow regime has been the focus of many research studies and some practical relations have been derived to describe slug flow. For example one of the relations found in literature [6] describes the velocity of the liquid inside a slug, v_{LS}, as function of several parameters:

$$\mathrm{v}_{\mathrm{LS}} = \frac{\alpha_{\mathrm{G}} \mathrm{v}_{\mathrm{G}} + \alpha_{\mathrm{L}} \mathrm{v}_{\mathrm{L}} - (1-\alpha_{\mathrm{LS}})\,\mathrm{v}_{\mathrm{GS}}}{\alpha_{\mathrm{LS}}} \tag{1}$$

Where α_G and α_L are the gas fraction and the liquid fraction, respectively, and α_{LS} is the liquid fraction inside the slug; v_G and v_L is the actual velocity of gas and liquid respectively, and v_{GS} is the velocity of the gas inside the slug. Note that ($\alpha_G v_G$) is the average superficial velocity for the gas and ($\alpha_L v_L$) is the average superficial velocity for the liquid.

Under the assumption that the velocity of the gas inside the slug is equal to the velocity of the liquid in the slug, equation 1 simplifies to:

$$\mathrm{v}_{\mathrm{LS}} = \alpha_{\mathrm{G}} \mathrm{v}_{\mathrm{G}} + \alpha_{\mathrm{L}} \mathrm{v}_{\mathrm{L}} \tag{2}$$

which is equal to

$$\mathrm{v}_{\mathrm{LS}} = \left(\mathrm{Q}_{\mathrm{v,G}} + \mathrm{Q}_{\mathrm{v,L}}\right)/\,\mathrm{A} \tag{3}$$

where $Q_{v,G}$ and $Q_{v,L}$ are the volumetric flowrate of gas and oil respectively, and A is the cross-sectional area of the pipe. Equation 3 can be a very powerful relation when designing flowlines that have to handle slug flow.

Some remarks can be made with regard to equation 3:

- For the derivation of equation 3 it is assumed that the velocity of the gas inside the slug is equal to the velocity of the liquid in the slug. A sensitivity analysis shows that in case there is a small difference in these velocities (slip) this only has a small effect on the correlation in equation 3.
- It is important to note that the velocity of the liquid in the slug (v_{LS}) is not equal to the velocity of the slug. When visualising slug flow, it can be observed that the slugs move like a wave pattern through the pipe with a certain (phase) velocity. The liquid inside the slug, however, moves at a lower velocity than this phase velocity. This can be understood as liquid is constantly fed into the slug at its front and drained from it at its tail.
- It can be found in literature [6] that the ratio between the phase velocity of the slug and the velocity of the liquid in the slug depends on the flow regime; for laminar flow the ratio is approximately 2, and for turbulent flow it is approximately 1.2.

Given the remarks made above it is interesting to check whether the simple relation for the velocity of the liquid in the slug (equation 3) is valid for both laminar and turbulent slug flow.

4.2 SLUG VELOCITY MEASUREMENT

To validate the applicability of equation 3 to slug flow of viscous oil, tests have been performed on the multiphase flow loop at the KROHNE laboratory. The focus of the study is to see whether indeed equation 3 is applicable, both to laminar flow and to turbulent flow.

The MR multiphase flowmeter is applied to measure the velocity of fluids inside the pipe. For this purpose the so-called convective decay method is applied [2], in which the decay of the magnetic resonance signal is measured as function of time, and from this decay the liquid velocity is derived. In case of slug flow, this automatically yields the velocity of the liquid inside the slug. The reference flowmeters of the multiphase flow loop are applied to determine the total volumetric flowrate of the liquid and the gas.

For the tests, several batches of oil-water mixtures have been made with oil viscosity of 190 cSt and WLR ranging between 0 to 40%. Further details on the tested conditions can be found in Table 2. Due to the screw pumps immediately oil-water emulsions are formed. For low WLR the emulsions are oil continuous, resulting in a high effective viscosity and laminar flow inside the slug, with a maximum Reynolds number of approximately 1000. For WLR approaching 40% the emulsion changed to water continuous resulting in a low effective viscosity and turbulent flow inside the slug with a minimum Reynolds number of approximately 35000. From the Reynolds numbers it can be derived that indeed the flow is either laminar (Re<1000) or turbulent (Re>35000), and flow conditions in the transition between laminar to turbulent are not to be expected.

Table 2 - Summary of the test conditions

Parameter	Min. Value	Max. Value	Unit
Line pressure	~ 0		barg
Line temperature	~ 25		°C
Oil viscosity	190		cSt
Fresh water viscosity	1		cSt
Flow range gas (air)	5.0	35.6	am^3/h
Flow range liquid	4.0	19.0	m^3/h
GVF	23	90	%
WLR	0.0	40	%

In figure 4 the results of the slug velocity measurements are shown. It can be observed that the measured liquid velocity in the slug can be described using the theoretical prediction (eq. 3). The measured data points follow equation 3 closely. For laminar flow conditions the match is better than for turbulent flow conditions for which the deviation is in the range of 10%. However, it should be noted that equation 3 still describes the trend observed in the experiments. We have not investigated why the match for the laminar flow data is better than for the turbulent flow data, but perhaps it is related to the assumption made to derive equation 2 from equation 1; it is assumed that the gas velocity in the slug is equal to the liquid velocity in the slug. This is an interesting topic for further research; however it is not in scope of the current paper.

The experimental results lead to the conclusion that despite the difference for laminar and turbulent slug flow regarding the ratio between the phase velocity of the slug and the actual liquid velocity in the slug (1.2 for turbulent flow and 2 for laminar flow), it is possible to describe the liquid velocity in the slug with a single relation (equation 3) for both conditions.

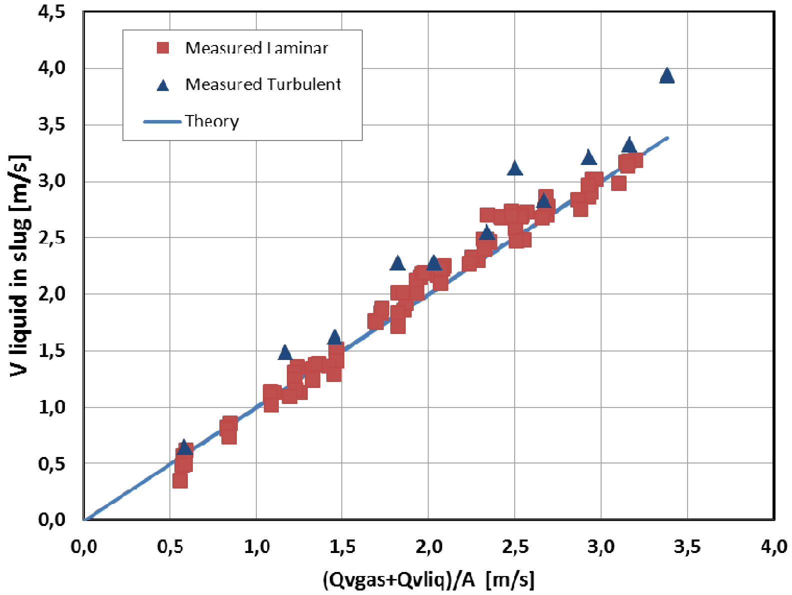

Fig4 - Results of the measured liquid velocity in a slug as function of the total volumetric fluid flow rate divided by the cross-sectional area. The liquid velocity has been measured using the magnetic resonance multiphase flowmeter. The line denotes the theoretical prediction according to equation 3. The red squares represent the measured values for oil continuous emulsion (laminar flow), and the blue triangles represent the water continuous emulsion (turbulent flow). Q_{vgas} and Q_{vliq} denote the volumetric flow rate of gas and liquid, respectively, and A denotes the cross-sectional area.

5 MEASURED FLOWRATES

In the previous section we have demonstrated that the MR measurement principle is suitable to measure liquid velocity in the slug flow regime. As presented in previous papers [2], [3], [4] not only the fluid velocity can be measured, but also the volumetric flowrate of liquid and gas and the water to liquid ratio can be measured using MR. For the conditions as described in Table 2 the volumetric flowrates have been measured. In figures 5 to 7 the results are plotted.

It can be observed in figures 5 to 7 that over the entire range of the tested conditions good accuracy is achieved for the volumetric flowrate for liquid and gas as well as for the WLR. For the volumetric liquid flow rate the accuracy was better than 5% of the MV, for the measured volumetric gas flow rate the accuracy was better than 10% of the MV and for the measured WLR the accuracy was better than 1% absolute.

Visual inspection of the flow regime, showed that for all test points the flow regime corresponded to slug or plug flow. The WLR was varied in the experiments in discrete steps (0%, 2%, 6%, 12%, 20% and 40%). For all tested WLR values similar accuracy has been achieved for the volumetric flowrates of liquid and gas. As discussed in §4.2, for WLR below 20% the slug flow was laminar and for the condition with WLR of 40% the slug flow was turbulent. The accuracy on the measured volumetric flowrate for liquid and gas was achieved for both the laminar and the turbulent slug flow.

The data plotted in figures 5 to 7 is measured for oil viscosity of 190 cSt, however similar performance has been obtained for higher oil viscosity (700 cSt, 1100 cSt and 2200 cSt).

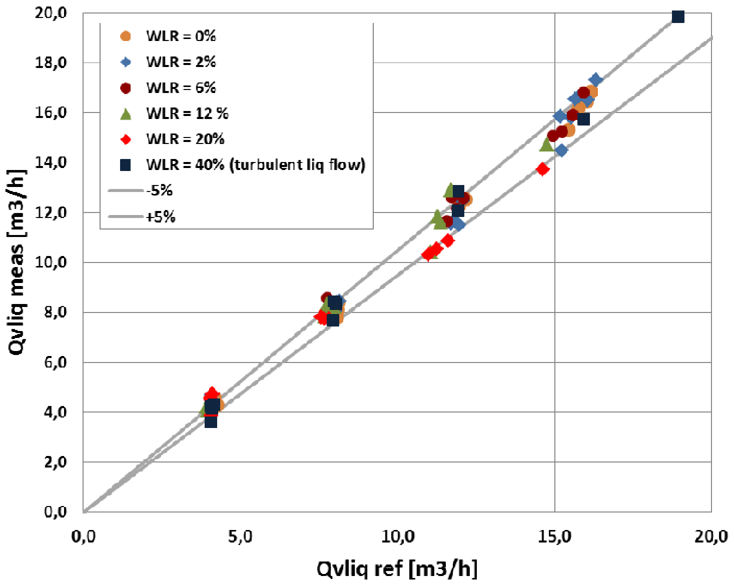

Fig5 - The measured volumetric flowrate of liquid as function of the reference values for the volumetric liquid flowrate. All measurements have been performed with oil viscosity of 190 cSt. The WLR has been varied in discrete steps as denoted in the legend of the graph. The GVF has been varied from 23%-90% for each WLR. The standard deviation in the measurement is less than 5% of the MV.

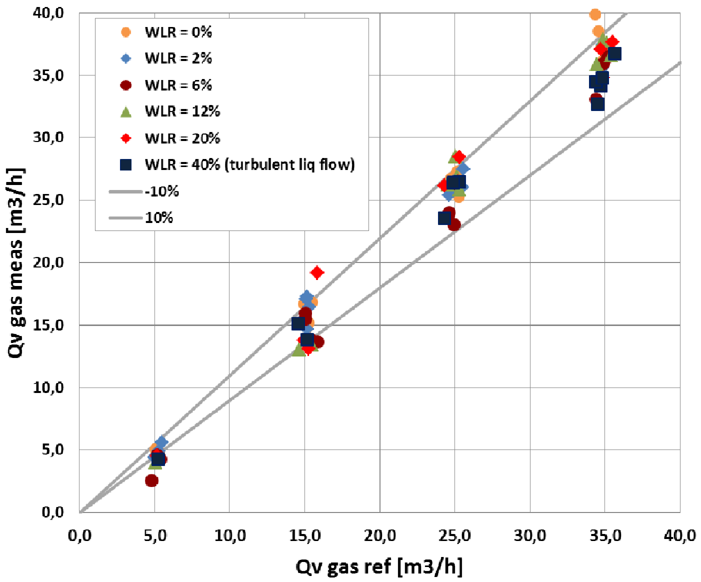

Fig 6 - The measured volumetric flowrate of gas as function of the reference values for the volumetric gas flowrate. All measurements have been performed with oil viscosity of 190 cSt. The WLR has been varied in discrete steps as denoted in the legend of the graph. For each gas flowrate the liquid flowrate has been varied between 4 to 19 m^3/hr. The standard deviation in the measurement is less than 10% of the MV.

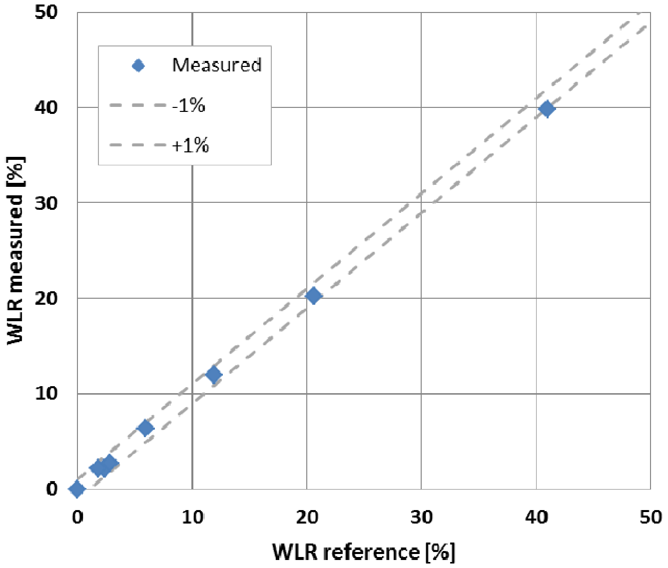

Fig 7 - The measured water-liquid ratio (WLR) as function of the reference values as measured by the Coriolis mass flowmeter. The dotted lines denote a deviation of ±1% absolute of the WLR value.

6 SUMMARY AND CONLUSIONS

In the oil and gas industry a shift can be observed from production of conventional resources to the production of unconventional resources. One of these unconventional resources is heavy oil. As the production cost of heavy oil is typically higher than for lighter oils, a clear need is present for optimal well and reservoir management in order to make production of heavy oil economically feasible. One aspect of good well and reservoir management is accurate multiphase flow measurement and for heavy oil applications this can be quite challenging. Therefore, in this paper we have focussed on multiphase flow measurement of mixtures of high viscosity oil, gas and water.

In the multiphase flow loop at the KROHNE Research and Development Laboratory, multiphase flow measurements have been performed using the magnetic resonance multiphase flowmeter. In the experiments the focus was on high viscosity oil. From observation of the flow patterns it is concluded that slug flow is the dominant flow regime for multiphase flow of high viscosity oil.

From literature, relations are available that describe the correlation between the velocity of liquid in a slug as function of the total volumetric liquid and gas flow rate (equation 3). By means of liquid velocity measurements based on magnetic resonance it has been shown that for a wide range of conditions equation 3 can be used to estimate the velocity of liquids in slug flow. The relation is applicable to varying WLR, even when the flow changes from laminar slug flow to turbulent slug flow.

The magnetic resonance measurement principle is not only suitable to measure fluid velocity; it also enables accurate volumetric flowrate measurements. In the multiphase flow loop, measurements have been performed to demonstrate the performance of the multiphase flowmeter for high viscosity oil. For oil/water/gas mixtures with oil viscosity between 190 cSt and 2200 cSt, the WLR has been varied between 0% to 40% and the GVF has been varied between 23% and 90%. The accuracy achieved in the volumetric flowrate was better than 5% of the MV for the liquid flowrates, better than 10% of the MV for the gas flowrates and better than 1% absolute for the WLR.

A final conclusion that can be drawn is that magnetic resonance is indeed a suitable measurement principle to measure multiphase flow of high viscosity oil.

7 NOTATION

α	fraction	Q_v	volumetric flowrate
A	cross-sectional area	GVF	gas volume fraction
G	gas	MPFM	multiphase flowmeter
GS	gas in slug	MR	magnetic resonance
L	liquid	MV	measured value
LS	liquid in slug	WLR	water liquid ratio
v	actual velocity		

8 ACKNOWLEDGEMENTS.

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9 REFERENCES

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