

Fluid characterisation in a subsea on-line multiphase fluid sampling and analysis system

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ABSTRACT. The trend in subsea petroleum production systems in offshore field developments points towards integrated production and processing facilities at the seabed along with more extensive use of multiphase transportation technology. The SOFA (Subsea On-line multiphase Fluid sampling and Analysis) system designed by Christian Michelsen Research in cooperation with the University of Bergen is an autonomous metering station for permanent installation subsea. The SOFA carries out fluid analysis subsea, and the current method of transfer of fluid samples to surface by a remote operated vehicle is avoided.

A laboratory prototype for capturing multiphase fluid samples in a dedicated measurement chamber/sample container has been built and tested. This is equipped with ultrasound sensors, a dual modality densitometer (DMD) gamma-ray system, pressure and temperature sensors, which together with conductivity, permittivity or similar measurements will be used as a multi-modality system for fluid characterisation.

This paper presents experimental results for fluid sampling and characterisation based on multimodality. The focus is on detection and monitoring of water salinity, water density and oil density. In addition, perspectives for operational use are discussed.

1. INTRODUCTION

The use of subsea production systems in offshore oil and gas field developments has increased dramatically during recent years, both in Norway and abroad. The trend is towards integrated production and processing facilities at the seabed along with more extensive use of multiphase transportation technology. This causes an increasing demand for accurate multiphase flow measurements and measurement of fluid properties. Fluid properties are

needed for more accurate multiphase flow meter (MPFM) readings, process optimisation, well management and production allocation. Fluid characterisation should be carried out near the subsea wellhead or the subsea manifold in order to detect changes in composition or fluid properties as early as possible.

Christian Michelsen Research (CMR) started the development of a new concept called “Subsea Online Fluid sampler and Analyser” (SOFA) in 2003 (Baker et al. 2007, Spilde et al. 2008), with the aim of enabling subsea multiphase fluid sampling, single-phase fluid characterisation, and possibly also measurement of fluid fractions and multiphase flow rates.

1.1. The SOFA concept

The principle of the SOFA concept is to build an autonomous metering station for permanent installation subsea so that transfer of fluid samples to the surface by remote operated vehicle (ROV) is avoided. The system could be installed as an integrated part of a subsea tree or manifold, and is expected to become a particularly valuable and cost efficient tool for optimisation of subsea separation processes and well management. Figure 1 shows a schematic which compares the SOFA concept to a traditional multiphase flow meter.

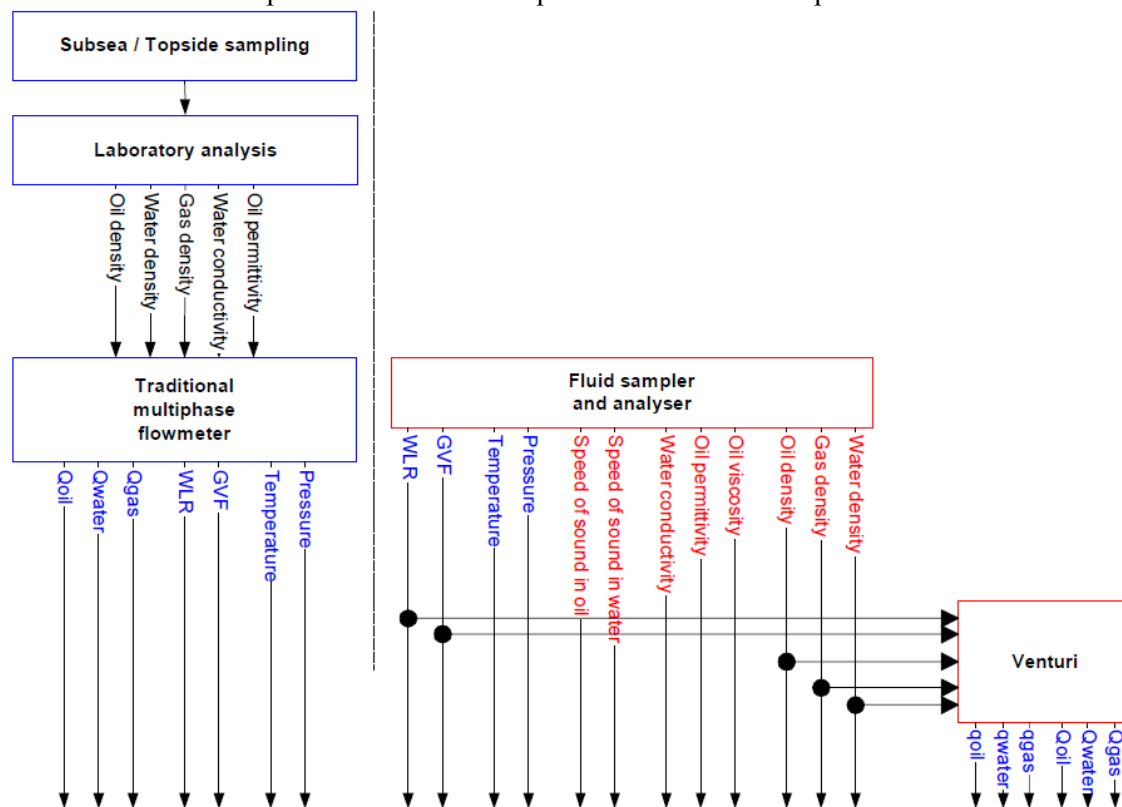


Figure 1. Schematic of a traditional multiphase flow meter (left) the SOFA concept (right). Here q is the volumetric flow rate of the components, Q is the mass flow rate, WLR is the volumetric water liquid ratio, and GVF is the volumetric gas volume fraction.

The SOFA concept comprises a number of separate modules and technologies, and CMR and the University of Bergen (UoB) have built a first experimental prototype of the SOFA system, see figure 2. The concept poses two major challenges; the representative sampling of the multiphase flow into the measurement chamber, and secondly an accurate measurement of the fluid properties. A prototype design for capturing multiphase fluid samples in a dedicated measurement chamber/sample container has been built and tested. The sampling system will be briefly discussed in section 2.1. The focus for the remainder of this article is the measurement methods applied after the multiphase sample has been taken. Measurements on single separated phases allow for more accurate results and additional measurement results depending on the number of parameters influencing the various measurement technologies.

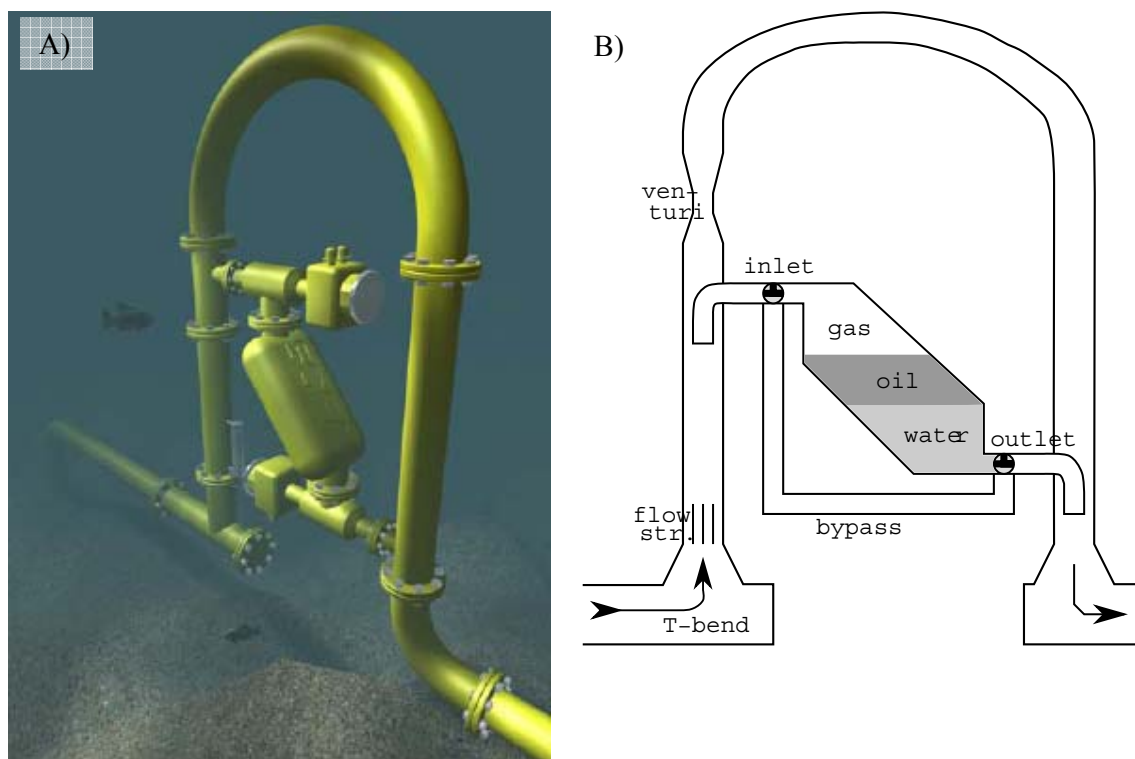


Figure 2. An artist's view of a SOFA installation at the sea bed (A), and (B); a schematic of the laboratory prototype for flow rig testing. See figure 3 for detailed image and schematics of the fluid analysis chamber.

1.2. Fluid analysis technologies

The fluid sample is taken by means of a pitot tube inserted into the main pipe flow as shown in figure 2B. During sampling both the inlet and outlet pitot tubes are open so that the chamber is flushed with the process flow, and after approximately one minute the flow through the chamber is redirected outside the chamber through the bypass line. The fluid sample will then be left to separate into single phases, and single phase fluid analysis will be attempted using technologies based on gamma-rays (transmission and scattering) and ultrasound (level and speed of sound). The configuration of the measurement chamber is

shown in figure 3. In addition electromagnetic characterisation will be used, but is not currently implemented in the chamber design. Also, the chamber is equipped with temperature and pressure transducers. The volume of the chamber is approximately 5 litres ($\sim 10 \times 10 \times 50 \text{ cm}^3$ oriented at 45 degrees).

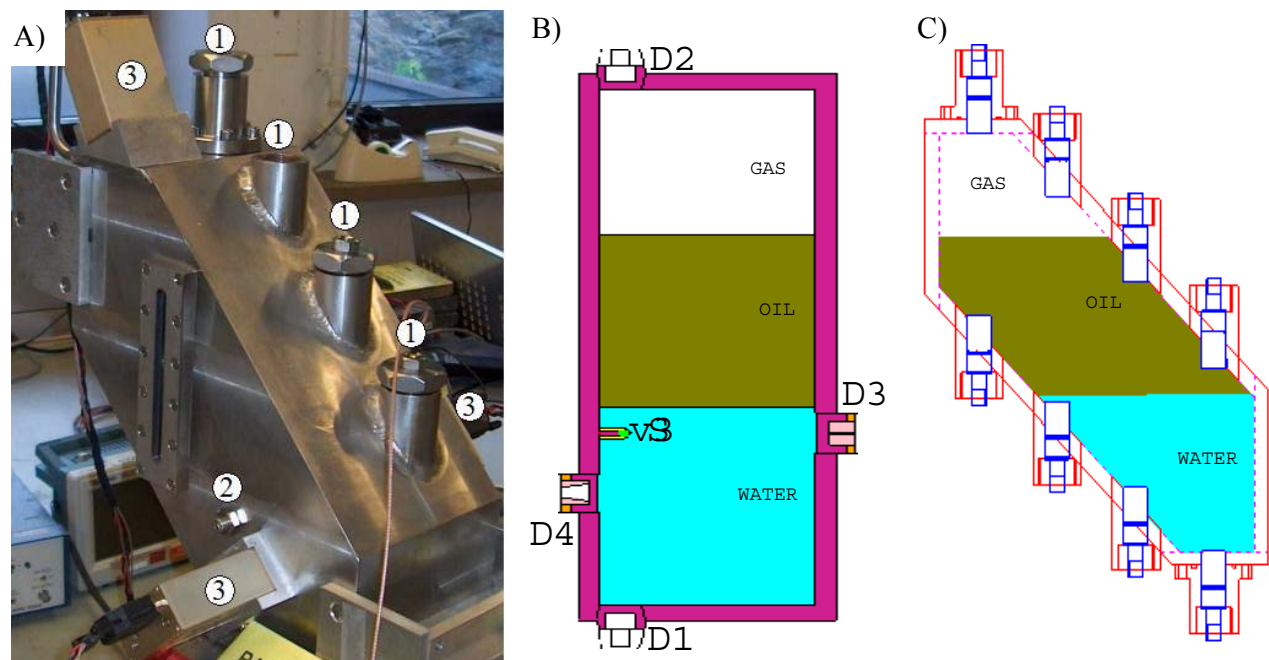


Figure 3. A) Prototype fluid analysis system with ultrasound and gamma-ray instrumentation. In addition the chamber is also equipped with pressure and temperature sensors. The gamma source (labelled 2 in the image) irradiates the radiation detectors (all detectors labelled 3 in the image) B) Gamma-ray measurement setup (cross-section of fluid analysis chamber in the plane of gamma-source and detectors). The source irradiates detectors 1-3 directly for transmission measurements through the respective phases, while detector 4 only measures scattered radiation from the water-phase. C) There are four pairs of ultrasound transducers (labelled 1 in the image) operating both as transmitters and receivers; four transducers on top of the chamber and four at the bottom.

1.2.1. The acoustic measurement system comprises four pairs of ultrasonic (US) transducers operating in pulse-echo and transmission modes (Stavland 2005). Since a level measurement on a single interface usually is possible with two transducer pairs, both level and speed of sound in the two phases can be found. The transducers are in direct contact with the fluids and will have to deal with the high pressures and temperatures (HPHT) of the process. The chamber is currently instrumented with CMR's HPHT NISEP-transducers (5 MHz, max. 150 °C and 700 bar).

1.2.2. The Nucleonic measurement system will allow for transmission measurements of gamma-rays at 60 keV emitted from a Am-241 radio-isotope source (Berntsen 2005). The source is inserted slightly into the chamber in a titanium housing in order to irradiate all the transmission detectors. For detection of the gamma-rays, semiconductor CdZnTe-detectors are used. In addition to transmission measurements, detector 4 is shielded from directly

transmitted photons and only measures photons scattered from the water phase at the bottom of the chamber. This provides for Dual Modality Densitometry (DMD) as described by Holstad and Johansen (2005). All gamma-ray measurements presented in this paper are based on a counting time of 2 minutes.

1.2.3. *Electromagnetic measurement system.* In addition to acoustic and nucleonic measurement technologies, electromagnetic (EM) measurement technologies are considered used in the SOFA. Several electromagnetic technologies are being considered and some initial tests show that some of the technologies have potential for use in the SOFA chamber.

2. EXPERIMENTAL RESULTS AND DISCUSSION

2.1. Sampling and water cut measurements

Although fluid characterisation is and has been the main focus for the SOFA project, representative sampling of the flow would give valuable additional information. This information is, however, available also from commercially available multiphase flow meters. If the sampling in the SOFA system is representative, the volume and mass flow rates can be found by the use of a venturi meter as shown in Figure 1. CFD modelling was used in the first design of the sampling probe, and such simulations will also be used in the further developments of the system. Experiments have confirmed that the current sampling geometry does not give a volumetric representative sample for the gas fraction, but it ensures collection of sufficient amounts of all phases. And notably; the water cut of the sample is representative (see figure 4) in all flow regimes, although the gas volume fraction (GVF) is not (Bruvik and Hjertaker 2009). Further development of the measurement geometry will be needed in order to get accurate flow rates, and the initial experiments have indicated how the sampling geometry can be further refined and optimised.

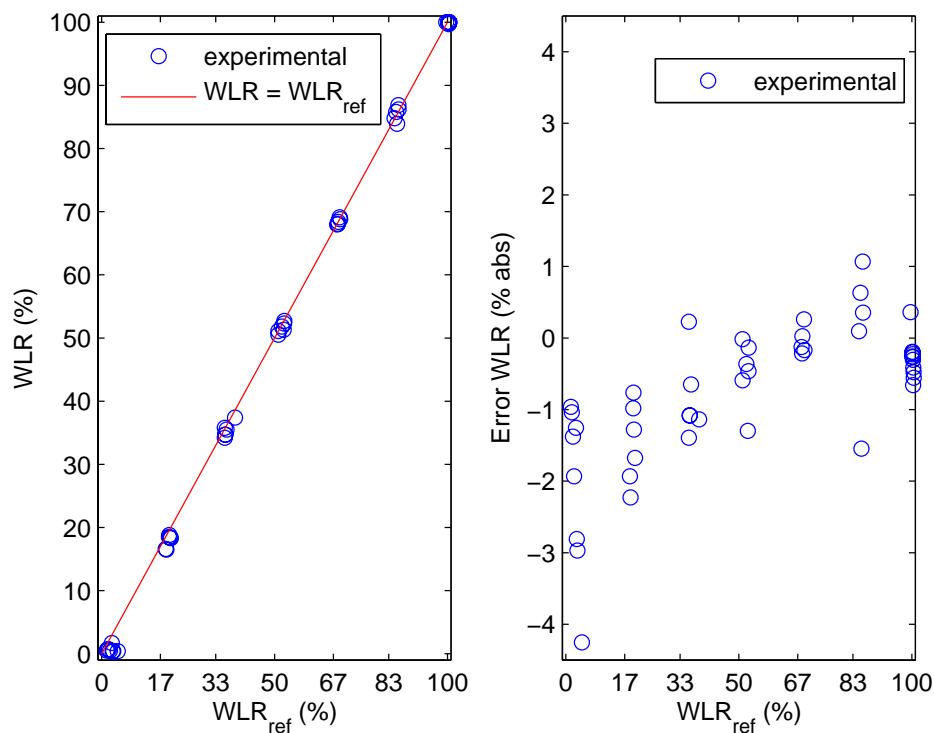


Figure 4. Water cut measurements as measured with the US instrumentation in the SOFA chamber. For water cuts larger than a few % the error is within the +/-2 % absolute accuracy of the Coriolis reference meter in the flow rig. Repeated water cut measurements are done in different flow regimes in the vertical process tube while sampling.

The challenges regarding representative sampling may be solved in several ways. For example, density measurements of the main flow can be used for GVF measurements so that only the water cut is needed from the SOFA. Also, if the SOFA is used as an analysis unit only, volume fractions are not needed from the SOFA. This will be the case if the unit is utilised to give process parameter values needed as input to other instruments, such as multiphase meters relying on accurate salinity, density and permittivity values. The main objective, characterisation of the fluids, is therefore possible as long as a significant amount of each phase is present in the sample.

2.2. Oil density

The oil density can be measured by gamma-ray transmission measurements using detector 2 as shown in figure 3B. The levels of the interfaces will be known from the US level measurement, and the attenuation in water will be found from transmission measurement to detector 3. The only unknown parameter then, in the path from the source to the detector 2, is the density of the oil (assuming the density of the gas is small compared to that of the liquids).

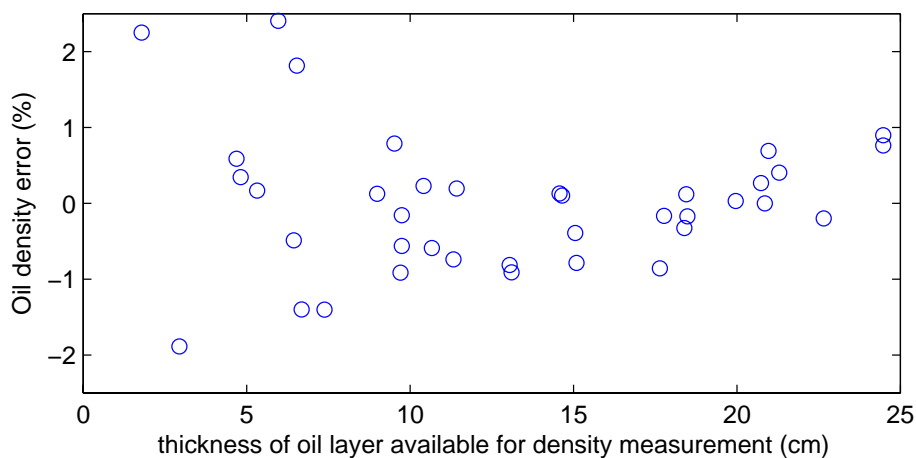


Figure 5. Relative error in oil density measurement by gamma transmission (D2 in figure 3B) measurement for all relevant measurement points in figure 4.

The oil density (diesel oil density, $\rho = 840 \text{ kg/m}^3$) was found accurate to 1 % by gamma-ray transmission measurements (figure 5) if the thickness of the oil layer between source and transmission detector was larger than 10 cm (WLR < 60 %). Since the speed of sound (u) in the oil is found by the US measurements, the adiabatic compressibility (κ_S) can also be found; $\kappa_S = 1/(\rho \cdot u^2)$.

2.3. Water salinity and density by gamma-ray-DMD

The density of the water depends on the salinity and possible process additives such as Mono-Ethylene-Glycol (MEG) (to prevent hydrate formation in multiphase transport systems). Water salinity might be an indicator of well production conditions, and salinity and density are important inputs to MPFMs. Demonstrated here are results for Chloride (Cl) salts of Sodium (Na), Calcium (Ca) and Strontium (Sr).

The results plotted below are from gamma-ray transmission and scatter measurements (i.e. DMD) in the fluid analysis chamber as shown in figure 3.

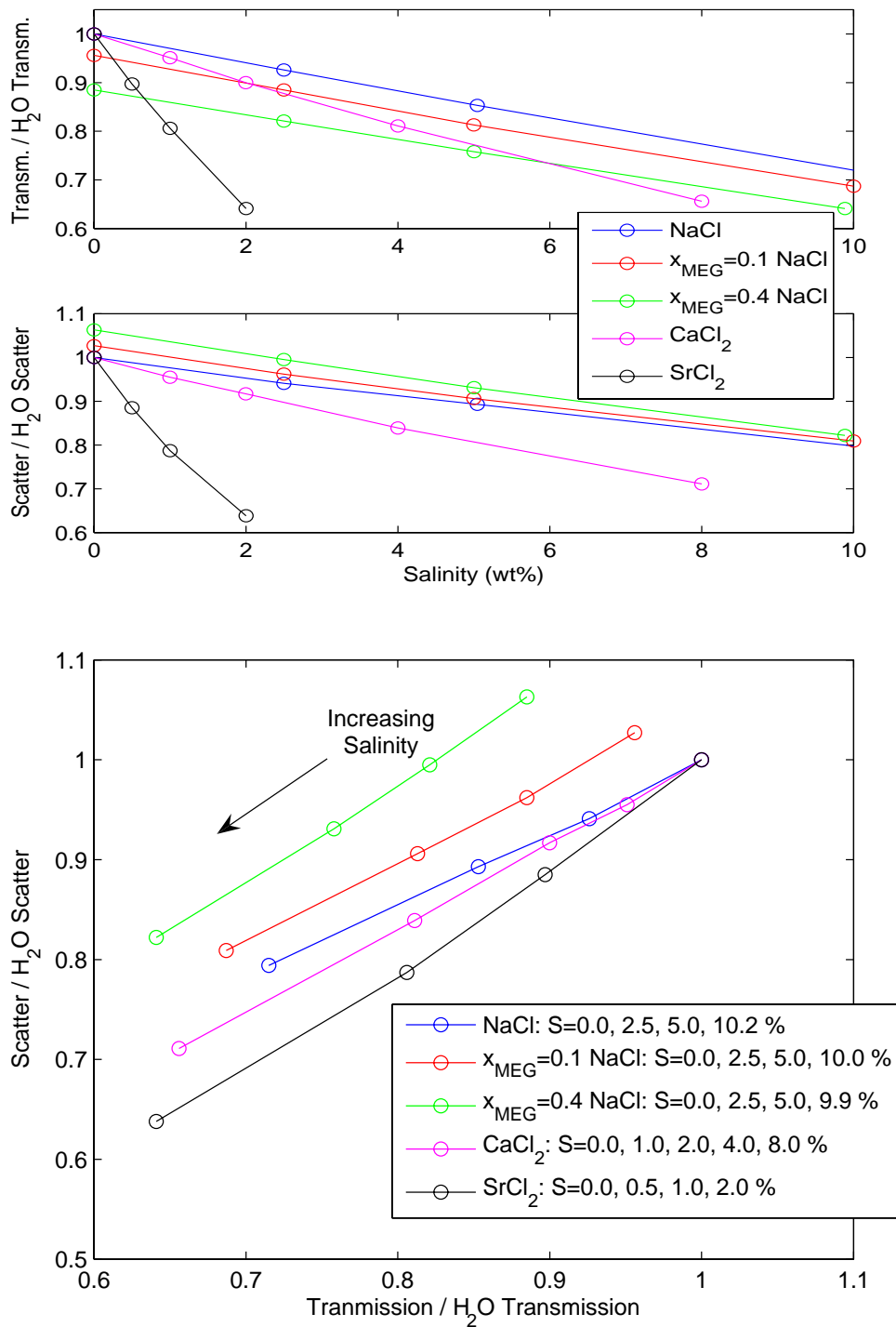


Figure 6. Gamma-ray transmission and scatter measurements (relative to pure water). Top figures shows transmission and scattered radiation as a function of salinity, and in the lower figure they have been combined to provide a ‘map’ of the DMD-space.

As figure 6 shows; the salinity and MEG content (given as the molar fraction of MEG to MEG and H₂O) can be found in the DMD-plane for single salts and MEG/NaCl-brines. However, an arbitrary mixture of salts and/or MEG cannot be uniquely identified and additional measurements, such as permittivity measurements must be added in order to quantify more variables. See section 3 for further details.

If the salinity and salt composition is found then the density of the produced water can be found from the equations and data in Krumgalz et al. (2000) (but this is deemed outside of the scope of this paper). See also Holstad and Johansen (2005) for salinity and density measurements found through utilization of the DMD principle.

2.4. Speed of sound in the aqueous phase

As mentioned in section 1.2.1 the speed of sound (SOS) in the phases can usually be found in addition to the level measurement by US. In figure 7, measured values for the SOS are shown¹.

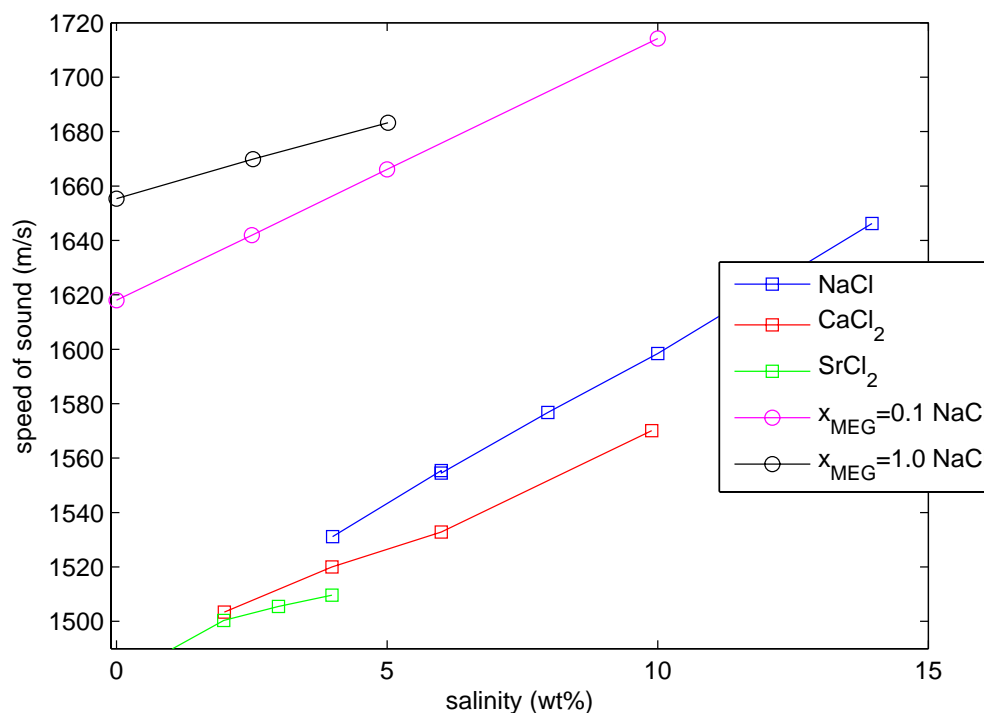


Figure 7. Speed of sound as a function of salinity and MEG content (mol fraction).

Different types of salt impact the SOS differently, and notably; MEG increases the SOS significantly. Still, nothing can be said conclusively from a SOS measurement alone – a high

¹ Measurements with MEG are not conducted in the SOFA chamber, but with a dedicated ultrasonic velocity meter.

SOS of about 1620 m/s could be due to 10 % mol MEG or 13 % salinity of NaCl. These alternatives could be distinguished by looking at the DMD-measurement result represented in figure 6.

2.5. Permittivity of water (and oil).

The (relative) permittivity (ϵ) of liquids can be used as an indicator of liquid composition and quality.

Initial measurement results show that the uncertainty of the permittivity measurements of oil achieved with some electromagnetic technologies is higher than what is desired since crude oil permittivity is usually about 2.3 with small variations not detectable due to excessively short propagation times. However, water/MEG-mixtures can be analysed with reasonable accuracy since the permittivity is higher with larger variations ($\epsilon_{\text{H}_2\text{O}} = 80$, $\epsilon_{\text{MEG}}=44$). Experiments have shown that a change in the MEG concentration in the water phase causes a detectable reduction in propagation time and permittivity. More EM technologies (Folgerø 1996) will be evaluated for electromagnetic characterisation of the fluids to achieve more accurate results, in particular of the oil phase. The permittivity of the oil is one of the parameter values utilized in traditional multiphase meters, and accurate permittivity measurements will help reduce the uncertainty in such meters.

2.6. Separation properties

Separation of oil and water depend on a multitude of parameters such as the viscosity, surface tension, and amount of surfactants in the liquids. Since the sample taken into the chamber will separate, the time this takes can be used to give an estimate of the 'separability' of the oil and water mixture. Figure 8 shows how both the gamma-ray system and the acoustic system can be used for monitoring of the separation process.

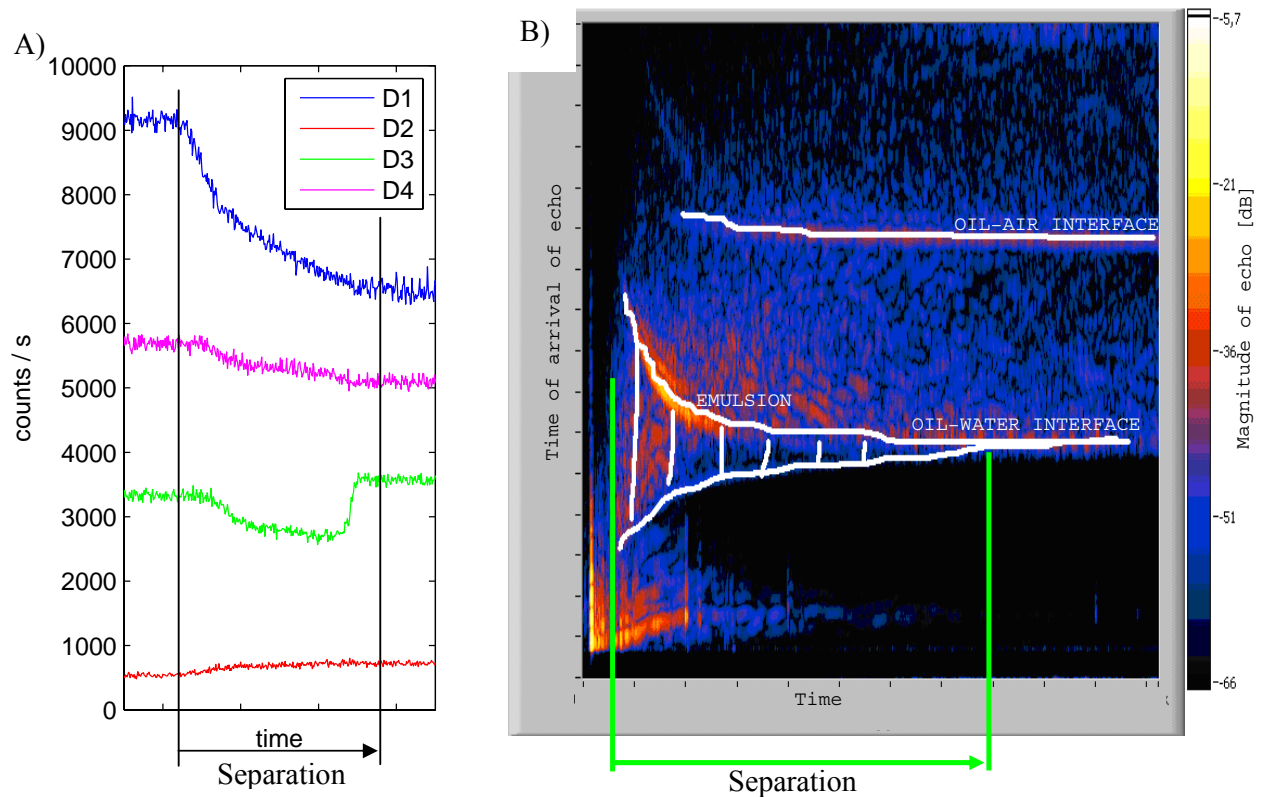


Figure 8. Oil/water separation time measured with gamma-ray instrumentation (A) and ultrasonic pulse-echo measurements (B). The ultrasonic measurements are not done in the SOFA chamber, but a separate test chamber with a different transducer and oil-water mixture for evaluation. Both methods can perform measurements during the separation of oil and water in a chamber and thereby give an estimate of a qualitative separation time; about 5 minutes for the diesel-water mixture in A) and 10 minutes for the vegetable oil-water mixture in B).

3. MULTIMODALITY

The technologies presented above work together to analyse the fluids - e.g. the ultrasonic level measurements are primarily used to get a fraction measurement, but the fluid levels found are also used as input to the gamma transmission measurement to find the density of oil, and to the measurement of permittivity. Further, each of the measurement technologies (gamma-DMD, US and EM) presented are sensitive to different parameters of interest. However, individually none of them produce conclusive measurements of any basic key parameters such as produced water composition and density. For instance, a high speed of sound in the aqueous phase might be due to 'some' MEG or a high salinity, and, a low level of gamma ray transmission might be due to 'some' MEG, 'some' NaCl, or a 'little' SrCl₂. The electromagnetic measurements might be considered to be sensitive to the permittivity only and hence the content MEG alone. However, in practice the permittivity measurements will be influenced by the conductivity and hence the salinity and composition of the water. Consequently all measurements must be combined in order to characterise the produced water.

Figure 9 and the text below gives one example of the need for multimodality when characterising fluids.

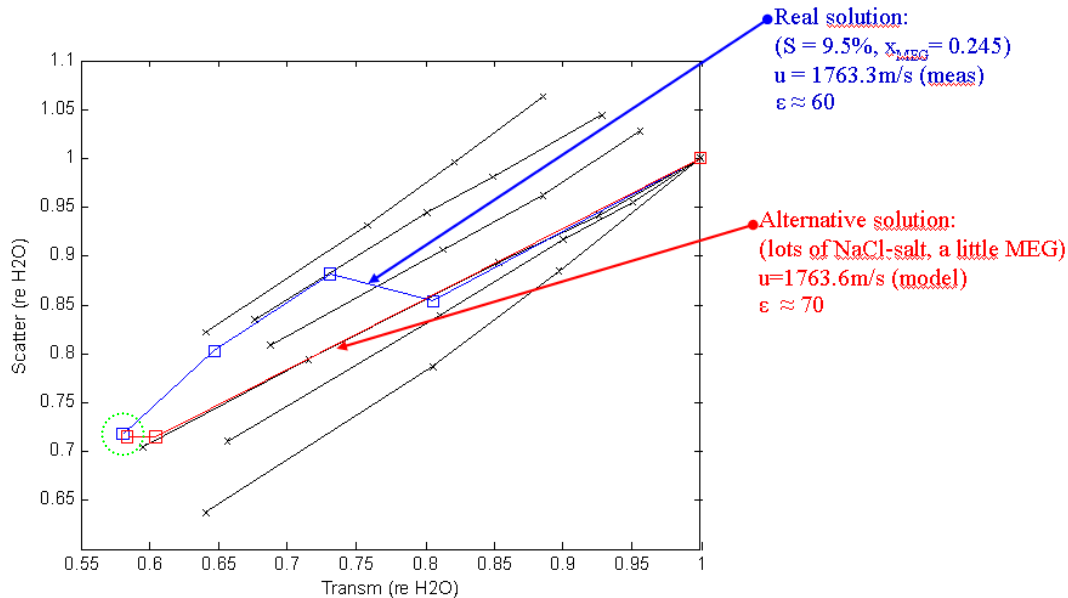


Figure 9. Example of multimodality. A solution similar to a realistic brine with MEG, is measured with DMD (at coordinates 0.57, 0.72 - and plotted over the ‘DMD-grid’ of figure 6). The DMD-measurement is not conclusive since an alternative (and not highly improbable) alternative solution also exists. The speed of sound measurement also happens to be equal (within the measurement uncertainty) for the two brines, and the correct brine can only be identified by including permittivity measurements.

4. PERSPECTIVES ON OPERATIONAL USE

CMR is currently evaluating the possibilities for continuation of the SOFA project. Depending on partners and feedback from the industry, water characterisation, liquid characterisation (oil and water) or three phase characterisation will be focused. Future applications include both permanently installed and mobile, e.g. suitable for ROV operations, analysis chambers.

Status evaluations and initial feedback from the industry have indicated various possible applications for the SOFA. As previously mentioned, the concept was first developed to give online measurements of parameters needed as input to flow meters. This had been identified as a technology gap due to the current need for time consuming and costly ROV-operations to collect samples for laboratory analysis. The SOFA can be installed in connection with multiphase flow meters and give continuously updated information for more accurate flow measurements.

Another possible application is a diagnostic tool used together with ROVs. In some cases where permanently installed instrumentation does not give sufficient information about the process, ROVs may be used to collect samples of the fluid. A SOFA measurement chamber

mounted onto the ROV will then be able to give prompt information about the fluid properties, and the sample can be directly re-injected into the flow.

5. SUMMARY AND CONCLUSIONS

The SOFA setup and fluid analysis scenario may in the future provide online information on the parameter values that are needed as input to traditional multiphase flow meters in addition to information for well- and reservoir management, as well as production optimisation. This strongly reduces, or possibly eliminates, the need for samples collected by ROVs. Combined with gas fraction measurements, and a Venturi flow meter, the SOFA setup can also in some applications replace multi-phase meters since, as demonstrated here, it may give accurate information on water cut in addition to water and oil density.

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