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Oil-Water Flow Measurement for Custody Transfer Applications

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Abstract

In the Oil & Gas industry, the ownership or custody transfer (CT) of crude oil is measured using Flow Metering and Sampling. Flow Metering quantifies the total amount fluid while Sampling quantifies the fluid composition – for example, the water fraction and other compounds thereby correcting the Flow Metering for its Oil-Cut. Any small inaccuracies in sampling may result in the sale or purchase of expensive water – resulting in significant financial exposure, incorrect government taxations and consequently affecting our weekly shopping too. Worse still, the absence of periodic sampling and failure to detect some undesirable compounds such as (inorganic and organic) chlorides could be catastrophic – not only economically but also politically. Therefore, the central tenet in Sampling is the creation of homogeneous mixture in the pipeline so that accurate representative samples could be extracted. However, achieving a homogeneous mixture of oil and water - two fluids that don't like to mix, is challenging. To that end, following current industry standards, OGM has developed the SmartMix® Sampling System and tested it using two flow loops of different sizes, the SMPFL and LMPFL. For prototype development at the University of Cambridge, the SMPFL together with magnetic resonance imaging (MRI) is used to characterise the mixing profile. For industrial scale testing, the LMPFL together with Multiport Profile Proving (MPP) device is used to validate the performance and integrity of the technology. The test results achieved better than 97% mixing efficiency, significantly exceeding the 90% requirement stipulated by the current industry standards.

1. Introduction

The Flow Metering and Sampling of unrefined or refined petroleum fluids are the two key components of measurement in custody transfer (CT) applications.

CT typically refers to the transaction of petroleum fluids at the point of sale where there is exchange in ownership (or custody) of the product fluid. The point of sale for these fluids could be at on-shore pipelines, off-shore floating production storage and offloading (FPSO) facilities or refinery inputs. In this paper, the petroleum fluids considered are liquids – including condensates.

In general, the CT measurements serve as the "cash register" of the Oil & Gas industry. Flow Metering is concerned in quantifying the total amount (or quantity) of liquid in transaction with uncertainties as low as ±0.15% while Sampling is concerned in quantifying the composition (or quality) of the liquid product with the objective of achieving a combined measurement uncertainty of ±0.25%. For example, in an Oil-Water flow, any small inaccuracies in sampling means the sale or purchase of expensive water and may result in significant financial exposure and incorrect government taxations thereby affecting our weekly shopping too. In addition, any failure in the accurate and periodic sampling of petroleum fluids that may have inorganic chlorides (salts) could be damaging and must be detected via sampling so that it can be removed from the oil using desalting (or water washing) before entering refineries. More critically, the presence of organic chlorides, which form covalent bonding with the hydrocarbon, must be detected by sampling as its concentration ought to be maintained below 1 ppm, which otherwise may significantly damage the refinery, with serious economic and political consequences – particularly between nations that depend on transboundary energy supply.

Automatic Pipeline Sampling, invariably, undergoes through five stages as depicted by **Figure 1** and as stipulated by the major industry and international standards such as ISO 3171 [1], API 8.2 [2], IP/EI 476 [3] and ASTM D4177 [4]. In brief, the sampling stages are: a) Stream conditioning-mixing, b) iso-kinetic sample extraction, c) sample collection and handling, d) sample re-mixing for analysis and e) sample analysis and reporting. The chain of uncertainty increases with the number of stages used. But, in this paper, it is argued that a two-stage approach may be much beneficial to lower the uncertainty. In addition, although all the five stages of sampling are equally important, the first two stages – namely, the creation of homogeneous oil-water mixture through stream conditioning-mixing and the iso-kinetic extraction of representative samples in a flow or time proportional way proved to be very critical for the measurement accuracy and integrity.

Figure 1. The five sampling stages according to ISO 3171

It is widely understood that sampling standards such as ISO 3171 and API 8.3 require the creation of a better than 90% homogeneous mixture in the pipeline to extract representative samples. However, achieving homogeneous mixture of oil and water - two fluids that don't like to mix, particularly without creating the undesirable stable emulsion, is one of the serious challenges in CT application. Although significant effort has been made to improve the mixing efficiency of devices in sampling systems for over forty years, Sampling remains "The Elephant in the Room". In fact, the current trend in the CT community appears, may be due to the challenging nature of sampling, to look away from and focus all efforts to lower the uncertainties in Flow Metering. However, evidence suggests that as oil wells age, pipelines tend to carry crudes with larger than 5% water cuts, which is observed to affect the uncertainty of even the most modern and popular flow meters significantly [5, 6]. Moreover, iff sampling is to correct Flow Metering, the current 90% mixing efficiency or homogeneity required by the leading standards [1-4] must be significantly improved.

2. Flow Testing and Calibration Laboratory

OGM invested significantly and built an integrated flow testing and calibration facilities (FTCF) to conduct extensive internal and collaborative R&D projects towards our effort and vision to produce leading Products & Technologies for the CT applications that satisfy our customers' needs.

OGM's integrated FTCF is depicted by **Figure 2** and is also described elsewhere [7]. In brief, the FTCF consists of the small multiphase flow loop (SMPFL) with a 2.5" nominal pipe diameter, the large multiphase flow loop (LMPFL) with 10" nominal pipe diameter, the liquid meter calibration loop (LMCL) and the high performance computing (HPC). The LMPFL is a four times scale-up version of the SMPFL and both use de-ionised water and synthetic oil.

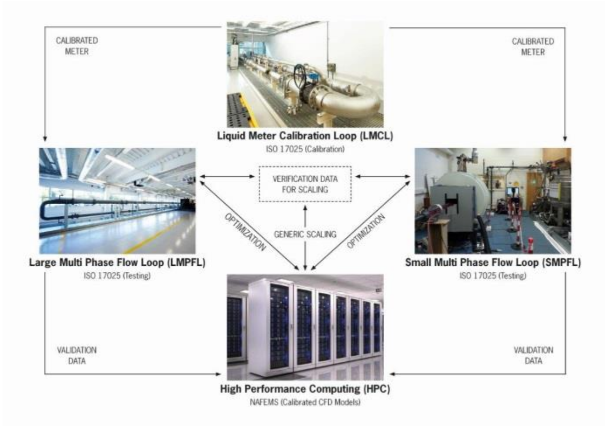


Figure 2. Integrated Flow Testing and Calibration Facilities.

The SMPFL has a maximum flow capacity of 18 m^3/hr while the LMPFL has 148.5 m^3/hr. The SMPFL has 25D straight pipe length, which is the distance between the device under test (DUT) and the water injection point. The length is 110D for LMPFL. Both the SMPFL and LMPFL are fitted with a flow through aerospace grade coalescer to separate the oil and water with better than 100 ppm separation capacity but when the water cut is not exceeding 10% (v/v). The LMCL can be used to calibrate flow meters with size ranges from 1" up to 12" and with flow range from 0.6m 3/hr to 800 m3/hr. On the other hand, the HPC uses the NVIDIA K20 GPU computational hardware heterogeneously coupled with Sandy Bridge CPU cores delivering both high power efficiency and a sustained aggregate performance of 32 "Teraflops". One of the main tools that runs on the HPC is the OpenFOAM platform to develop and validate multiphase computational fluid dynamics

(MCFD) tools so that they can be used as a design guide or design tool for the development of our Products and Technologies. To this end, the key objective in the design philosophy for the FTCF is to create an ISO 17025 certified testing and calibration hub so that collaborative improvement could be to improve current CT measurement devices. In particular, the system level testing of Flow Metering and Sampling devices or skids through traceable international standards. During the commissioning of the SMPFL and LMPFL, all single phase (oil or water) flow meters are calibrated in the LMCL, whose master meters are calibrated either in an ISO 17025 certified third party laboratory or using compact provers.

Once the integrity of the measurements in the SMPFL and LMPFL are verified, the SmartMix® Sampling System tests on both loops are characterised for their performance and the data is used to validate the MCFD results.

It is now widely accepted that a validated and/or calibrated MCFD models could be used to simulate large diameter pipelines, ranging between 24” and 56”, which would have been otherwise impossible to conduct physical experiments as such size flow facilities do not exist. This synergistic approach of using numerical and physical experimentation via the integrated FTCF will open up a new vista for accelerated and cost effective innovations.

2. The SmartMix® Sampling System

The development, validation and field installation of the SmartMix® Sampling System (here after simply called the “Sampling System”), with its LJICF Technology [8] and Advanced Control System (ACS) is described elsewhere [7, 9-11]. Therefore, the focus here is to provide only its salient features mainly focusing on the validation test results. The challenging conditions in the mixing and sampling application involve low fluid viscosity and low density while the same is true for low velocity and horizontal pipe orientations.

The Sampling System is depicted by **Figure 3**. The operating principle of the patented technology is unique at least in three ways compared to similar systems that are currently available in the market.

First, after receiving (analog or digital) signals for the flow rate and pressure inside the pipeline, the ACS actuates the variable speed drive (VSD) of the pump and the (inner, outer) automatic control valves so that the required injection flow is extracted iso-kinetically through the Scoop.

Second, at the discharge side of the pump, the flow splits in to two streams, where the Inner Stream traverses through the inner flow meter, the Sampling and Analysis Module and the inner automatic control valve before forming the Inner Jet of the Twin Nozzle™. The Outer Stream traverses through the outer flow meter and the outer automatic control valve before forming the Outer Jet of the Twin Nozzle™. The mode of interaction between the Inner and Outer Jets (as Weak-Jet and Strong-Jet) in response to the pipeline dynamic and process conditions [12-14] is one of the key basis for the technology.

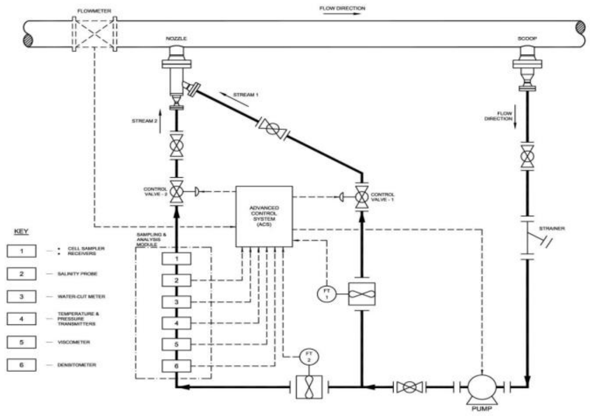


Figure 3. The SmartMix® Sampling System.

Third, the ACS is not only responding to the pipeline conditions, it also uses stochastic type automatic control and dynamic optimisation, where the arrays of instruments in its Sampling and Analysis Module are used to aid the control more effectively. Furthermore, the ACS also controls the (inner/outer) automatic valves so that the required flow rate and the required inner to outer stream flow ratio is ensured and achieved. These (analog, digital) readings from the water cut meter, densitometer, viscosity meter as well as pressure and temperature transmitters are the critical sensors and actuators to improve the mixing homogeneity or efficiency of the developed Sampling System.

Therefore, the operation of the Sampling System - particularly its mixing duty, is directly dependent on the real time process dynamics and fluid properties, heralding on-demand mixing that may save significant power consumption. For typical sampling systems with operational life time as long as 15-20 years, the power savings that can be gained can’t be understated – both as an OpEx and in saving the environment.

2.1 Sampling System Proving by Water Injection

Figure 4 depicts an industrial scale Sampling System, where proving by water injection (PWI) is used to quantify the mixing efficiency, sample extraction, sample handling, shear mixing and KF analysis, with the lowest possible chain of uncertainties.

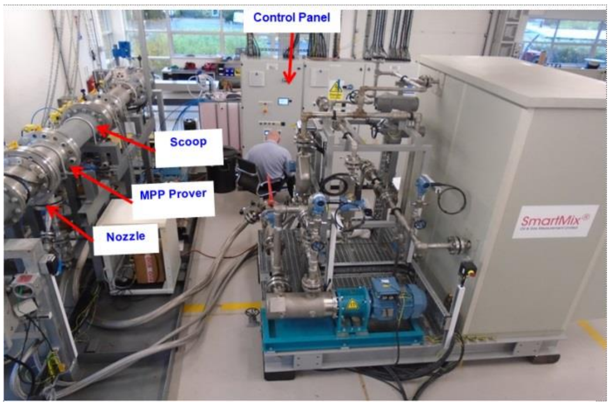


Figure 4. The SmartMix® Sampling System under test in OGM's Large Multi-Phase Flow Loop (LMPFL).

PWI is carried out [10,11,14] using the multiport profile proving (MPP) device which is depicted by **Figure 5**. The MPP device has six ports, where one is positioned along the pipe axis while the other four are placed symmetrically. Two of the probes are position 20 mm away from the inner wall of the pipe while the other two are positioned at half the radius (R/2) above the pipe centre and below the pipe centre, respectively. The sixth probe is placed at the inner base of the pipe so that even the smallest water droplet could be captured. All the probes have an internal diameter of 8 mm, which is larger than the minimum 6mm diameter recommended by ISO 3171.

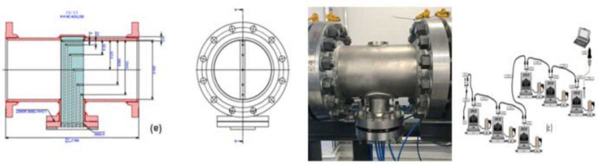


Figure 5. Multiport Profile Proving (MPP) device with six ports for proving by water injection (PWI).

All the six probes are each connected to six flexible tubes of equal length, which in turn are connected to six mini-Coriolis flow meters with density measurement functionality. When samples are extracted via the six probes, all the tubes open to six atmospheric receivers that are placed at a level and lower elevation. Before any PWI test, the MPP is tested extensively and proven to achieve "true" iso-kinetic sampling with good velocity matching.

The PWI protocol follows ISO 3171 and API 8.2 and is depicted by **Figure 6**. First, for several minutes, the loop is purged using oil at its maximum flow rate. Then, a baseline water cut is introduced by selecting one of the ranges between 1% and 4%, where up on the sampling system mixing pump starts creating homogeneous mixture.

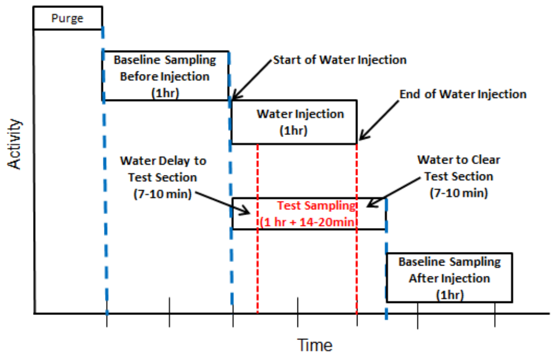


Figure 6. Typical Activity-Time diagram of proving by water injection (PWI) of a sampling system.

After an hour of time-proportional sampling (15 grabs/minute of 1cc each) is taken in the fast loop using the Maurer™ cell sampler as shown in **Figure 6**, the ACS turns on the water pump, which allowed to raise the baseline water cut by 0.5%. However, due to the distance between the injection point and DUT (~110D), there is a delay for the water to arrive at the measuring or mixing point, which must be accounted for. Similarly, there is a delay for the water to clear when the injection is stopped. The final hour sampling is similar to the first hour sampling, which provides the steadiness of the baseline water cut. The mixing efficiency of the sampling system is evaluated according to ISO 3171 section 15.

3. Tests and Test Results

Two types of nozzles, SLIT Nozzle and NJ4, are considered and tested at the LMPFL. A variant of NJ4 nozzle was also tested for high water cut range between 3% and 70%, where the test was carried at an accredited flow loop in Schelkovo, which has a 6" nominal diameter.

3.1 SLIT Nozzle

The test conditions are provided in **Table 1** and the PWI results are depicted by **Figure 7**. Further computational fluid dynamics (CFD) results are depicted by **Figure 8**. The physical experiment results for the SLIT nozzle shows that the composition distribution to be homogeneous. The probe location 2 indicates the central MPP probe while positions 1 is the ratio of the probes 20 mm from the pipe wall and 3 is the ratio of those at half the radius (R/2). The result shows excellent mixing.

Table 1: PWI test condition for the SLIT Nozzle

	R1	R2	R3	R4	R5	R6	R7	R8	R9
U(m/s)	0.2	0.4	0.6	0.2	0.4	0.6	0.2	0.4	0.6
WC(%)	1	1	1	2	2	2	4	4	4

The results in **Figure 8a** show the initial evolution of mixing. The top and bottom contours show a slice taken parallel to the stream wise direction while the middle is a slice taken perpendicular to the stream wise direction. The pronounced vorticity provides the mixing energy dissipation rate. This is observed more clearly in **Figure 8b**, with the same slice direction as in **Figure 8a** but at a later time.

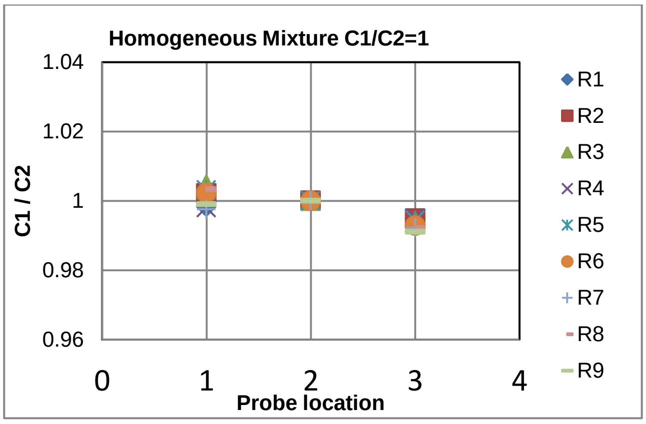
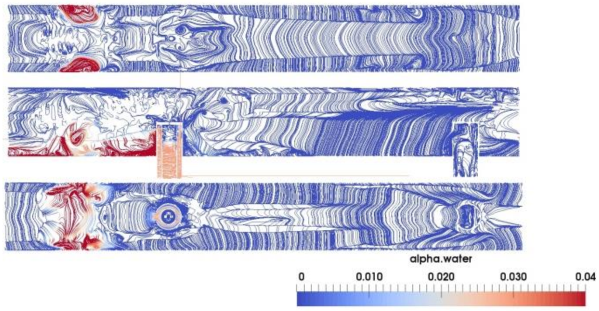


Figure 7: PWI results of the SLIT nozzle with probe location

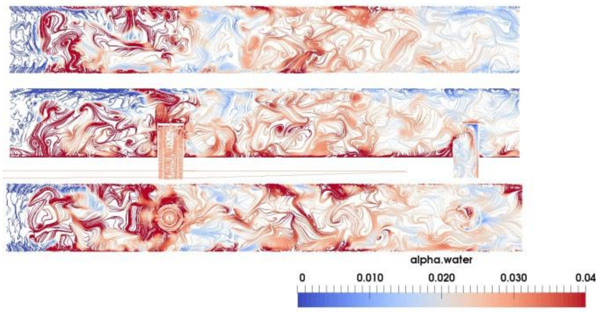
Both the CFD simulation and the PWI test via the MPP device indicate very good mixing is achieved. However, the five stage sampling protocol that is in practice today appears to be a very laborious and sometimes laden with errors with increased chain of uncertainties. A direct measurement method is preferred, such as “mix and measure” [11,14].

3.2 NJ4 Nozzle

The test condition for the NJ4 nozzle is provided in **Table 2** and the PWI results are depicted by **Figure 9**. A CFD simulation for this case is ongoing and will be reported elsewhere. Therefore, only the physical experiment is provided, again, the result shows excellent mixing.



(a)



(b)

Figure 8: CFD simulation result of SLIT nozzle for R9 case.

Table 2: EPWI test condition for the SLIT Nozzle

	R2	R3	R5	R7	R8
U (m/s)	0.4	0.6	0.4	0.2	0.4
WC(%)	1.5	1.5	2.5	4.5	4

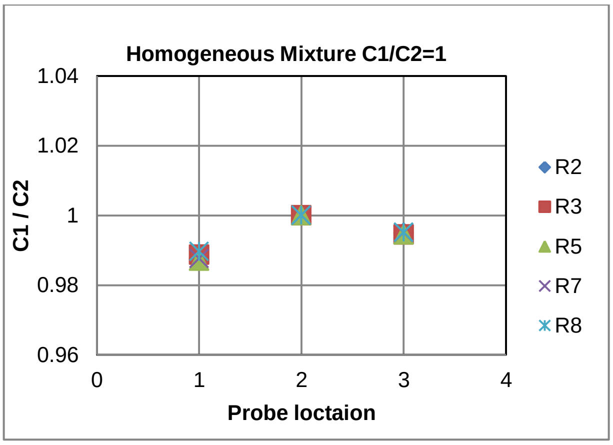


Figure 9: PWI results of the NJ4 nozzle with probe location

3.3 High Water-Cut Test at Schelkovo

The test conditions for the high water cut cases that are conducted in Schelkovo are shown in **Table 3.** The sampling results in **Figure 10** are not a proving or PWI tests as depicted by **Figure 6**.

The Schelkovo flow loop is a well instrumented facility. However, the description of the flow loop is beyond the scope of the current paper and therefore will be described elsewhere. Instead, we focus on the test condition and the result in this case. **Figure 10** shows that for the tests done, all achieved the ISO 3171 and API 8.2 mixture homogeneity requirements. The performance of the mixing device indicates that This is a remarkable

Table 3: PWI high water cut test condition for the NJ4 Nozzle

	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10	R11	R12
U(m/s)	0.45	0.65	0.85	0.45	0.65	0.85	0.45	0.65	0.85	0.45	0.65	0.85
WC(%)	3	3	3	20	20	20	45	45	45	70	70	70

The well instrumented Schelkovo facility allowed to

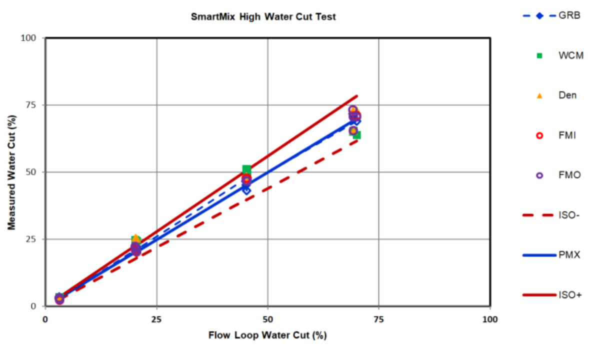


Figure 10: High water cut test a the Schelkovo facility

The high water cut test was a significant success as our initial product proving tests were limited to only 6% water cut. This demonstrates the versatility of the technology. The laboratory analysis (for the oil-water sample) proved repeatable and it is also proved that the Sampling System's compliance and its high performance in mixing. For the entire test data presented, the mean absolute error is ±0.14% with a standard deviation of ±0.117%.

7. Conclusion

The Sampling system developed was tested with two nozzle families. The performance of both the SLIT and NJ4 Nozzles were excellent, providing higher than 97% mixing efficiency, compared to the 90% mixing efficiency stipulated by international standards. The challenging Schelkovo test with high water cut doesn't appear to affect the performance of the Sampling System, showing its versatility.

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