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Infrastructure at IFE Multiphase Flow Laboratories

Institute for Energy Technology

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Report title

Infrastructure at IFE Multiphase Flow Laboratories

Summary

In December 2013, the Research Council of Norwegian (RCN) awarded IFE and SINTEF a MNOK 50 grant under the INFRASTRUKTUR program, including a MNOK 10 sponsorship from Statoil. The aim of the project has been to upgrade the multiphase flow laboratories at both institutions in order to support, safeguard and strengthen the Norwegian industries' leading international position in subsea technology and multiphase transportation technology.

In this report a description of IFE's part of the project is given in detail, from the original plans for the project to the actual investments done. At IFE, the investments have focused on enabling detailed measurements of multiphase flows, such as measurements of phase distribution, velocity profiles and turbulence characteristics, drop/bubble/particle size distribution, wall shear stress, flow development and fluid characteristics. Some instruments are off the shelf and others, such as the IFE X-ray Tomography system, have been custom made for IFE. The X-ray development also included significant in-house software development for data analysis. A significant part of the project also included upgrading the laboratory process equipment, including a new gas booster, a new gas scrubber and a new liquid-liquid separator.

Changes made in the original plan have resulted in a better cost benefit ratio in the budget. Some instrumentation and equipment have been purchased in addition to the original plan. At the time of writing some minor equipment has not fulfilled the commissioning in a satisfactory way, and will need more attention to give satisfactory results. Personnel costs were underestimated in the original plan and have been increased throughout the project, in large to meet the demands of the in-house developed software.

In sum, the infrastructure project has produced a quantum leap for the Norwegian multiphase flow research community, which would not have been possible without the contributions from RCN and Statoil. The available instruments at IFE now form part of a national infrastructure for multiphase flows which will serve both the petroleum industry as well as other relevant industries in the years to come. At the time of writing, for example, one of the high speed cameras at IFE are being used in a hydropower experiment at NTNU.

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1 Introduction

This report describes the IFE part of the INFRASTRUCTURE project financed by the Norwegian Research Council (NRC) and Statoil during the two year period 2014-2015.

The NRC program “National Financing Initiative for Research Infrastructure” is available to the Norwegian research community to ensure recruitment of new researchers as well as promoting Norway as an attractive partner for international research cooperation.

In this round, IFE and SINTEF prepared a common application for the National Multiphase Flow Laboratories which lately has received a great amount of attention from the industry and the media.

The total cost of the infrastructure investment is MNOK 50 over two years, with a 50/50 split between IFE and SINTEF, including a 20% contribution from Statoil.

The main objective is to establish new, unique laboratory infrastructures for advanced experimental studies of multiphase pipe flow and flow assurance phenomena, relevant for the oil and gas industry. SINTEF’s industrial scale flow loop at Tiller will be expanded from a two-phase gas-liquid flow facility to a three-phase gas-oil-water facility. The medium scale laboratory at IFE will be equipped with new instrumentation that will provide new measurements of multiphase flow details.

1.1 Relevance

The Norwegian supply industry has built a significant strength in subsea technology, based upon deep knowledge and innovative technology in the area of multiphase flow. Several countries have ambitious programs to develop a competing industry for the subsea market. The proposed infrastructure will give the Norwegian industry improved competitive advantages in the global market.

The Infrastructure places IFE in a position where it is capable of utilising the institute's unique expertise in the new focus areas of detectors, measurement and instrumentation.

1.2 Vision and scientific goals

The vision of the project is to realize a state-of-the-art experimental infrastructure for multiphase flow, utilizing an optimal combination of the unique know-how and existing experimental capabilities at SINTEF and IFE.

SINTEF will expand the Large scale Flow Loop at Tiller to include water as the third fluid phase. By running three-phase experiments at an industrial scale, loop equipment can be tested and verified at low risk and engineering software can be verified against industrial scale experiments.

IFE will invest in instrumentation to measure flow at a new level of details. This is necessary to develop mechanistic flow models for new parameter ranges, supporting engineering software and decision making.

2 Multiphase flow at IFE

The multiphase flow activities at IFE have a long history, from developing the first version of OLGA in 1979 to a full department for Process and Fluid Flow Technologies in IFEs Petroleum sector with expertise in theory, modelling and simulation combined with experimental facilities.

Nowadays, our activities include five laboratories for different aspects of multiphase flow or flow assurance.

2.1 Well Flow Loop

The Well Flow Loop (WFL) is our main laboratory with R&D activities as well as testing facility for instrumentation or process equipment. It was built in 1994 and has been under continuous upgrades and modification to satisfy the needs of the industry. In 2012 and 2013, the WFL was undergoing a building extension funded by IFE.

It is a closed multiphase oil-water-gas flow loop with a test section extended to 50 m length (2014) with internal diameter 100 mm. The two liquid phases are normally tap water and an oil phase. The test rig utilises a high molecular weight gas, SF6 (sulphur hexafluoride), which has a density of ~50 kg/m3 at 10 bar pressure, in order to simulate high pressure flow conditions found in oil and gas pipelines. The test section is built in transparent PVC.

Most of the infrastructure consists of instrumentation and process equipment for the WFL. A more detailed description is given later. Some of the equipment will be fixed on the WFL installation, as the process equipment. When it comes to the instruments, they are mostly flexible to be mounted as needed on other facilities.

Table 1: Technical specifications of the Well Flow Loop, before the infrastructure upgrades

Loop material	AISI 316, PVC
Liquids	Model oils, tap water
Gas	SF_6 due to density, gases not requiring special Ex/HSE needs as N_2
Pressure	Max. 10 bara
Temperature range	15 to 25°C
Test section	ID 100 mm, L= 47 m
Test pipe incl.	-1 to 90^o (15 m length), -0.5 to +5^o (47 m)
Superficial gas velocity range	0 - 10 m/s (400 Am^3/h)
Superficial liquid velocity range	0 - 2 m/s (100 Am^3/h)

2.2 Low Pressure Loop

The Low Pressure Loop (LPL) is used for studying 2- and 3-phase multiphase gas-liquid-particle flow in near horizontal pipes or in a rectangular channel, at atmospheric pressure. It is used to study phenomena in gas-liquid or liquid-particle flow, where the pressure is considered to be of minor importance. A picture is given in Figure 1.

Figure 1: Picture of the Low Pressure Loop

Examples of flow phenomena studied in the test facility are:

- Effects of drag reducers (DRA) in multiphase flow
- Mechanisms in suspension flow
- Slug flow in high viscosity liquid

The flow loop is permanently equipped with instrumentation necessary for basic multiphase flow experiments; flow meters, temperature sensors and pressure gauges that are used to monitor the flow conditions during an experiment. The gas flow rate is measured by a vortex meter. The liquid flow rate is measured with either a Coriolis meter or with an electro-magnetic flow meter.

Table 2: Technical specifications for the Low Pressure Loop

Loop material	PVC/Perspex/Latex
Liquids	Water or model oil w/flash point above 50^{o}C
Gas	Air
Pressure	Atmospheric
Temperature range	Ambient temperature
Test section	Circular pipes, D=27/60/100 mm Rectangular, HxW= 50x300 mm Length, 15-20 m
Test pipe incl.	-10 deg. to +10 deg.
Superficial gas velocity range	0 - 15 m/s, for ID=60mm (150 m^3/h)
Superficial liquid velocity range	0 - 6 m/s for ID=60mm (60 m^3/h)

Advanced scientific instruments can easily be mounted on this facility for commissioning, testing or even R&D purposes.

2.3 CO_2 – Flow Loop

IFE's CO_2 pipe flow loop is a closed loop designed to study situations where the CO_2 in transport pipelines (CCS) will enter the two-phase vapour-liquid region.

The test facility can also be used for testing of instruments and components.

The CO_2 flow loop is a semi-outdoor test rig designed and built to accommodate test campaigns related to long distance pipeline transport of pure CO_2 or CO_2 with impurities. Such pipelines are normally operated in the liquid or dense phase region. The test facility was built in 2011 in order to acquire experimental data for subsequent testing and validation of the CO_2 version of the transient multiphase flow simulator OLGA.

The loop design and performance make this loop a valuable and unique tool for studies of flow phenomena that occur if CO_2 rich pipelines should enter the multiphase flow region. The operating window goes from low pressure vapour flow to supercritical flow of CO_2 – and all conditions in between.

Table 3: Technical specifications of the CO_2 Flow Loop

Loop material	AISI 316
Fluids	Pure CO_2 and CO2 w/impurities, e.g. N_2, CH_4, H_2, O_2 (minor H_2S, SO_2 and H_2O)
Pressure	Max. 150 bara
Temperature range	-50 to +50°C in pump and gas booster -150 to +50°C for pressure discharge experiments
Test section	ID 44 mm, L= 13 m
Test pipe incl.	± 7 deg. + vertical
Superficial vapor velocity range	0 - 7 m/s (40 Am^3/h)
Superficial liquid velocity range	0 - 1 m/s (7 Am^3/h)

2.4 Waxy Crude Laboratory

Another experimental facility that was built in the last years is the Waxy Crude Laboratory for testing the restart conditions of a gelled oil. A 20 meter long test section is inbuilt in a controlled temperature box in order to cool down the test section.

The instrumentation consists of pressure and temperature sensors along the length (P) and through the vertical and horizontal profile (T). Visualization methods are also feasible in a test section built of transparent PVC.

Table 4: Technical specifications of the Waxy Crude Laboratory

Loop material	AISI 316, PVC
Fluids	Model oil, wax
Pressure	Max. 10 bara
Temperature range	0 to 50°C
Test section	Transparent PVC, ID 100 mm, L= 20 m
Test pipe incl.	Horizontal
Liquid pump capacity	4 - 50 m^3/h

2.5 Fluid Laboratory

The Fluid Laboratory is located at Department of PROTEK in IFE and has bench top equipment for characterization of colloidal systems like emulsions, suspensions, polymers etc. The laboratory holds following instrumentation

- Particle size measurements (from Malvern Instruments Inch.)
- Tensiometers for surface/interfacial tension and contact angle measurements at ambient and high pressure and temperature conditions (from Krüss and KSV instruments)
- Rheometer for flow characterizations of fluids and colloidal systems either ambient pressure and temperatures or high pressure and temperatures (from Anton Paar)

In this manner, the fluids used in the different flow loops and colloidal systems used for other research projects can be characterized in details in this laboratory.

3 Infrastructure

We have applied for funding from the NRC's infrastructure programme in several rounds starting back in 2009, when IFE received a one year pre-project to write an Infrastructure proposal. Since then, the plans for investments have been studied and adjusted with the restrictions of the process. The granted Infrastructure in 2013 was then a common project with SINTEF with a budget of MNOK 25 for each partner. In this report, only the IFE part is presented.

3.1 Plan for investments

The plan for investments was defined in the project proposal and has gone through some more adjustments through the project time. Statoil has been active in this process, following the project to ensure a successful progress in the investments.

3.1.1 Instrumentation

Investment in advanced instrumentation is the core of the strategy for the new infrastructure at IFE. At present there are no facilities, national or international, where a wide range of multiphase flow issues of industrial relevance can be studied in such detail that fundamental mechanisms can be adequately understood. In this national infrastructure, we proposed to enhance the following aspects of our measurement capabilities: phase distribution, velocity profile and turbulence characteristics, drop/bubble/ particle size and distribution, wall shear stress, flow development and rheology.

The original list of instrumentation in the plan for investments is presented in Table 5.

Table 5: List of instruments in the plan

	Instruments
Phase distribution	2nd generation X-ray CT and software
	Single-source X-ray
	Narrow g-densitometer
	Double wire-mesh sensor

Velocity profile and turbulence characteristics	Upgrade LDA to PDA
	UVP
Drop/bubble/particle size distribution	PVM probe
	Conductivity probe
Wall shear stress	Direct WSS sensor
Flow dev.	Cameras along the pipe

3.1.2 Process equipment

In the project description, the process equipment was defined as an upgrade of:

- Installation of a new low shear pump that can handle viscosities up to 1000 cP
- Installation of an inline electro-coalescer between the outlet of the test section and the inlet of the existing oil-water separator, as this will greatly increase the separation capacity
- Installation of a new centrifugal gas booster in order to avoid the drawback of liquid in the gas phase at high flow rates with the current gas booster (two-phase pump)

Already in the kick-off meeting of the project, the purchase of an electro-coalescer was discussed. The cost of this equipment would constitute a large percentage of the whole project, and the cost-benefit ratio of the equipment was not defined as sufficient to continue this plan. The wish was to be able to handle fluids with greater viscosity in the WFL and to improve the separation in the return system.

The list has therefore been significantly changed, keeping the objective of handling more viscous fluids in the WFL.

3.2 Budget and cost schedule

The total budget of MNOK 25 was distributed as given in Table 6.

Table 6: Total budget as given in the original description

Description	Cost	MNOK
Instruments	Direct Costs	15
	Personnel costs	4
Process equipment	Direct and personnel costs	6
TOTAL		**25**

For the cost schedule, the sponsors had different procedures. The NRC operated in terms of back payment, while Statoil operated with respect to milestones.

3.3 HSE

The project has been undertaken in accordance with HSE regulations and IFEs ISO certifications. New or modified process equipment installed on the Well Flow Loop has drawings, pressure certificates and tests in accordance with required documentation for this type of equipment. Instrumentation that will be used under pressurized conditions is also approved for this type of use by the manufacturer.

3.4 Conclusions

The final list of equipment that has been invested within the project is given in Table 7.

Table 7: Final list of investments in the Infrastructure project

		Instruments
Instruments	**Phase distribution**	Upgrade existing X-ray
		2nd generation X-ray CT and software
		Single-source X-ray
		Upgrade of gamma- densitometer
	Velocity profile and turbulence characteristics	LDA
	Drop/bubble/particle size distribution	PVM probe
	Wall shear stress	Direct WSS sensor
	Flow dev.	Cameras along the pipe
	Fluid characteristics	Interfacial tensiometer
		Densitometer
		Zeta potential upgrade
	Data acquisition & storage capacity	
Process equipment	**Gas booster**	
	Frequency converter	
	Gas flow meter	

	Pre-separator in the return system	
	Profile meter in the separator	
	Scrubber	
	Heat exchanger	
	Miscellaneous	
Other	**Administrative**	
	Miscellaneous	
	Travel expenses	

The financial status of the project has been presented through the expended budget available in the project as presented in Figure 2. At the moment of writing, there are still commitments of kNOK 870 of investments with delivery date in December 2015.

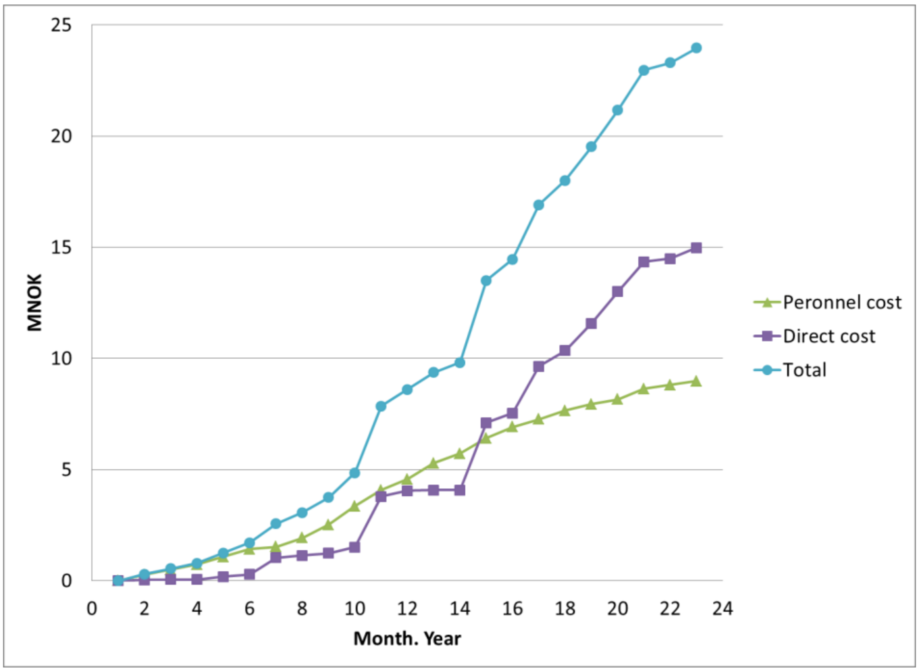


Figure 2: Economical status of in the project along the 24 month duration

4 Instrumentation

4.1 X-ray

4.1.1 Upgrade of the existing X-ray system

The original X-ray system at IFE, installed in 2008, consists of 2 sources and 2 detectors, positioned in horizontal and vertical orientation. It can be used to construct tomograms based on 2 projections. Each of its cameras can obtain up 300 images per second on a 64x2266 pixel CMOS detector chip, and the source voltage is up to 60 keV.

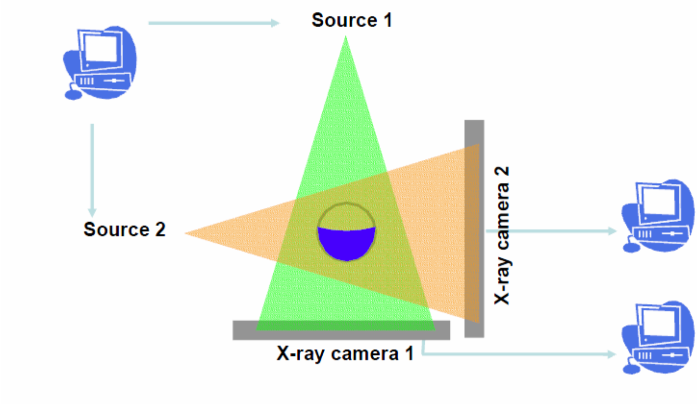


Figure 3: Schematic of the existing X-ray system

Data analysis of the system revealed that some aspects of the data recording were unreliable. In particular, the images were often not captured at the requested frame rate, nor were the two cameras properly synchronised. All combined, this strongly spoke in favour of an upgrade, seeing as the X-ray system provides useful flow measurements in a non-intrusive way.

The upgrade included extensive hardware and software changes implemented by the system provider, the Copenhagen-based company InnospeXion. The original AJAT cameras were kept, but new electronics for controlling and monitoring the system were installed in late 2014. After the upgrade, the timing accuracy for the system has been drastically improved, the two cameras operate in synchrony to within approximately 1 ms, and no individual image frames are lost during camera record intervals.

In addition to the work done by InnospeXion, significant work was done by IFE to make the data processing software more user-friendly and versatile, and with more routines for quality checking and monitoring data.

As the upgrade of the stereoscopic X-ray system demonstrated satisfactory behaviour, a set of entirely new X-ray systems were purchased from the same manufacturer, as described below.

4.1.2 1-D system

To extend our flexibility within X-ray measurements, a 1-camera X-ray system (including a point source) was purchased, with hardware specifics similar to that of the upgraded stereoscopic system. The 1-camera unit is moderately light weight, and can be shifted around on the rig with relative ease. It thus enables holdup profiles to be obtained at any available location along the pipe.

In addition to the AJAT standard X-ray camera in the new 1-camera system, a special purpose multi-energy camera was purchased. This camera can measure the X-ray intensity in 128 different X-ray energy (frequency) bands. It can thus be used to map the emitted spectrum from our various X-ray sources, and clear the way for the (near-future) usage of advanced conversion algorithms with improved accuracy, in particular in flow systems involving 3 phases (e.g.; gas, oil, water).

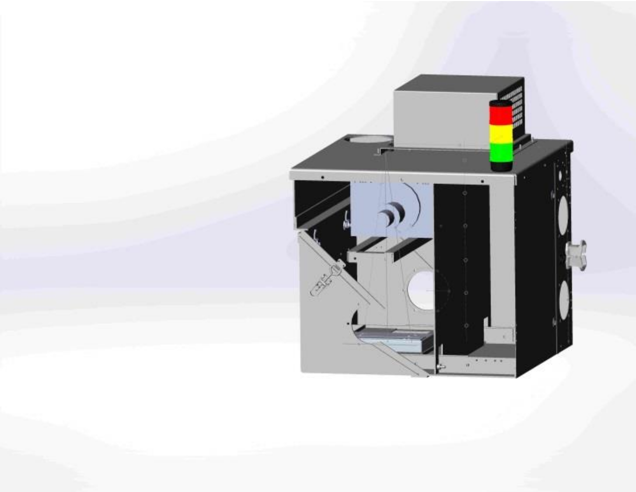


Figure 4: Simple one-dimensional X-ray source and detector system

4.1.3 Second generation X-ray tomography system

The so-called 3x2 system is the most advanced new X-ray hardware purchased through the IMF project is a system containing 6 different X-ray cameras, each equipped with its own X-ray point source. The cameras are located at two slightly different (and adjustable) positions along the pipe axis, with three cameras at each position. In one system, the cameras' azimuthal viewing angles are 90, 210 and 330 degrees (where 0 and 90 degrees correspond to horizontal and vertical X-rays, respectively), whereas in the other they are 0, 120, and 240 degrees. The two triangular systems can be used independently, or their six holdup projections can be combined in order to reconstruct the cross-sectional phase distribution. For general flows, the resulting tomograms are significantly sharper and more reliable than CTs obtained with only two viewing angles (as in the stereoscopic system). The hardware specifications for each camera in the 3x2 system are similar to that of the 1-camera system presented above.

In parallel with the installation and testing of the new 3x2 multi-camera system, IFE has developed a new CT software package which is highly versatile, and can give best-possible CTs once it is provided with a set of holdup projections together with certain user-defined parameters. The software can handle any number of projections (i.e., camera viewing angles), and once the necessary coefficients have been established for a given set of experimental data, tomograms can be produced very rapidly on a laptop computer.

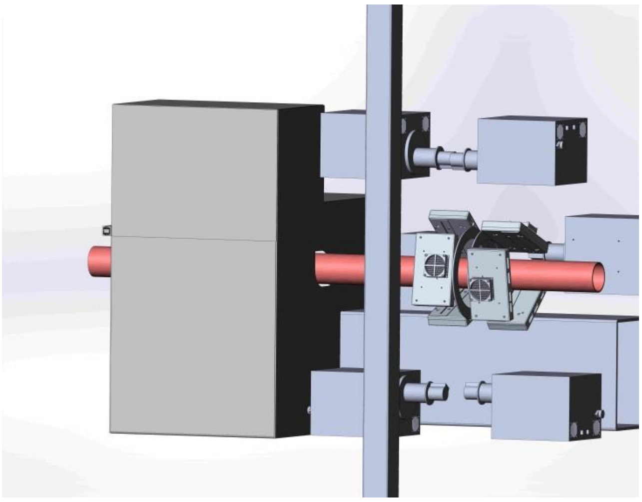


Figure 5: New generation X-ray tomography system with 2x3 detectors

4.2 Gamma densitometer

4.2.1 Background/motivation

IFE has three broad beam gamma densitometers for measuring liquid holdup. These are based on the so-called Fast-Volume-Weight-Meter (FVWM) design developed at IFE in the 1980's, see Figure 6. They have been, and to some extent still are, our workhorses for this kind of measurements. They are robust, easy to use and reasonably accurate, particularly if the flow is symmetric around the symmetry line for the instrument, which is often the case.

Two of the instruments are two-phase instruments, using the 60 keV energy in a 241-Am spectrum, and a NaI(TI)-detector with output to an IFE built Single Channel Analyser (SCA). The detectors are 20+ years old, which are more than twice the normal life time for such detectors. The detectors have become more unstable over the years, with frequent need for manual adjustment of the High Voltage and the counting windows. This means that the detector with its integrated PM tube needs to be renewed.

For the three-phase instrument, which has the same overall design as the two-phase instruments and that are also ~20 years old, the detector is overdue for renewal. The instrument uses two different ''windows'' of the energy spectrum from a 133-Ba source, with a half-life of 10.5 years. The count rates have therefore declined significantly over the years, which affect the count statistics negatively. Therefore, also the Ba-source should be renewed. Since the instrument was built nearly 20 years ago, relatively fast Multi-Channel-Analyzers (MCA) have come to the market. Since the old IFE-built SCA's are difficult to find spare parts for, it was also a wish to replace the two SCAs with a new MCA.

4.2.2 Requirements

The wish list for upgrade of the gamma densitometers therefore consists of:

1. 3x NaI(TI)-detectors with integrated PM-tubes and with new voltage dividers and pre-amplifiers. The detector diameter must be 5". The dead time for the unit must not exceed 2 μs. LaBr3 detectors were considered, but the price was beyond the available budget. IFE is partner in a NRC-funded project at University of Oslo, where part of the scope is to test a LaBr3 detector.
2. A Ba133-source with strength 1.11 GBq

3. An MCA. The requirement regarding count rates is 500 kcps, in order to be able to obtain reasonable accuracy for sampling frequencies of 50 Hz. To achieve this, the dead-time in the SCA/MCA must not exceed 1-2 µs.

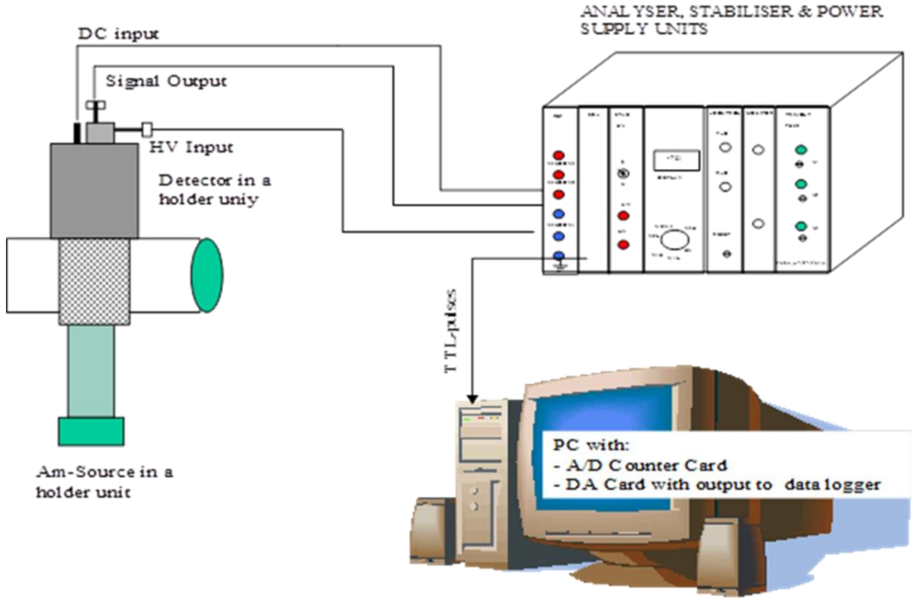


Figure 6: IFE FVWM broad beam gamma densitometers

4.2.3 Quotes

IFE's electronic group (Physics Dept.) is the one that have designed and built the broad beam gamma instruments and they were also engaged for the upgrade of the instruments. There are not many vendors/factories of such specialized components and for the components on the wish list we have related to:

Ba133-source, 1.11 GBq:	Eckert & Ziegler Nerlien Meszansky
NaI(TI)-detector w/voltage: splitter and pre-amplifier	Gammadata AB, representative of Saint-Gobain Crystals
Multi Channel Analyser:	Gammadata AB, representative of equipment from CAEN Itech Instruments

4.2.4 Evaluation/testing and challenges

4.2.4.1 Ba-source

The offer from Eckert & Ziegler was half the price of the offer from Nerlien Meszansky, which made the choice easy. The source was delivered in July 2015.

4.2.4.2 NaI(Tl)-detector

The challenge with the commercially available detectors are the overall throughput of pulses through the detector, the so-called dead time, a bottle-neck mainly related to the voltage splitter and the pre-amplifier. The pre-amplifier part of the offered equipment did not meet the dead-time requirement, since the specification said 7-9 μs. The pre-amplifiers from 20 years ago are no longer in production, which meant that we had to modify our old pre-amplifiers to fit the new detectors w/PM-tube. With poor documentation of the 14-pin connector, this proved to be a challenge for IFE's specialist (Sigurd Brattheim). Good support has all the time been given by Gammadata. It must be kept in mind that this is not off-the-shelves equipment, and also that IFE's dead-time requirement requires special solutions. IFE is a small customer and we cannot expect that Saint-Gobain Crystals, which is close to having a monopoly in this market, gives priority to our special requirements. A temporary solution has been found that works satisfactorily while a special adapter is about to be manufactured by Gammadata. The fact that IFE has received some laid-off equipment from SINTEF, including voltage splitter/pre-amplifier, has made this situation easier to handle.

4.2.4.3 Multi Channel Analyser – MCA

We received two MCAs for testing, one from Gammadata, a CAEN Model DT5780 and one from Itech Instruments, Itech Orion MCA. It proved that neither of them performed acceptably at high count rates. This means that we still have to rely on our two IFE built SCAs for the two-energy system. Amongst the laid-off SINTEF equipment was also a couple of SCAs, which have replaced the eldest of the SCAs that to date have been used in the current suite of broad beam gamma densitometers at IFE.

4.2.5 Current status

The status is that the two 2-phase instruments have been upgraded with new detectors and with 'refreshed' SCAs. They have been tested for stability and have been approved in this respect. A final performance test (calibration of measured holdup against a volumetric reference) will be carried out once the permanent pre-amplifier solution is implemented.

The two-energy three-phase gamma densitometer also performs well, but will need some further optimization, mainly related to the collimator; 1) make it curved (instead of the current rectangular shape) to account for wall-thickness variations, 2) use copper instead of lead to avoid fluorescent gamma rays, and 3) widen the collimator to increase the overall count rates. A comprehensive commissioning will be carried out once these modifications have been implemented. We have observed that the energy resolution with the new detector is better than with the old detector, which means that we can now distinguish the 30 keV peak from the rest of the ''surrounding energies'', which has previously been lumped into one large ''window'' (25-80 keV). This gives hope of establishing a simplified calibration for the instrument. The present calibration procedure consists in acquiring count rates for the two energy windows for a large number (120-150) of water-oil-gas fractions (static, stratified fluid layers) and use a curve-fit polynomial to the calibrations. This has recently been done for the upgraded instrument, with good results, see error bar example in the plot shown in Figure 7. In general the total holdup in three-phase flow is measured with an uncertainty of +/- 1.5%, while the distribution of holdup between the oil and water has moderately higher uncertainty. A comparison of holdup measured with the gamma densitometer and the X-ray system in dynamic situations is shown in Figure 8. The results are in good agreement.

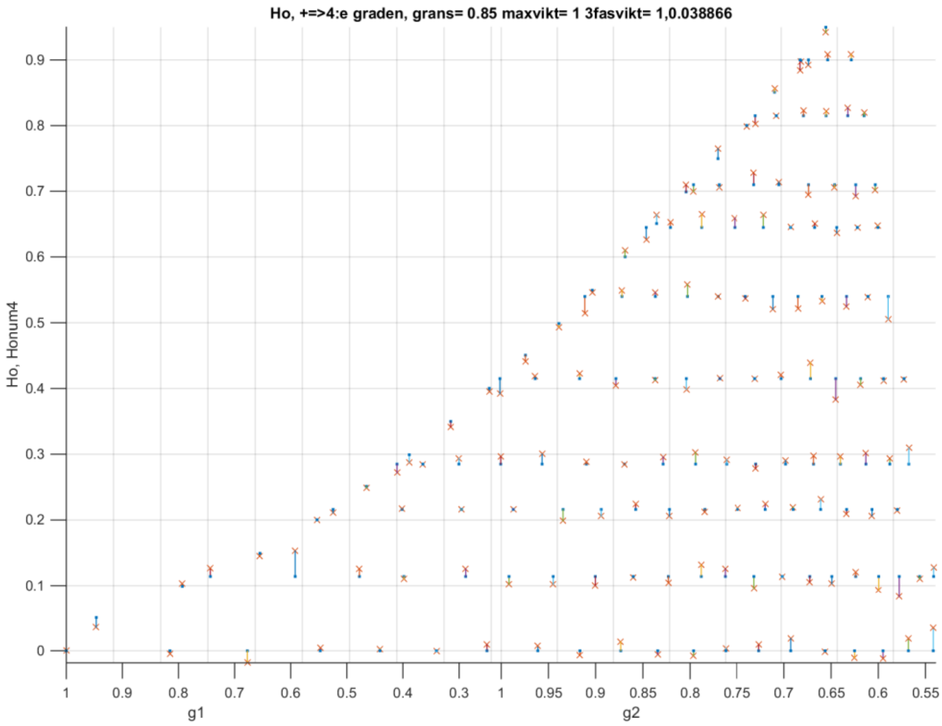


Figure 7: Typical error bars for water holdup – calibration data versus curve fit polynomial

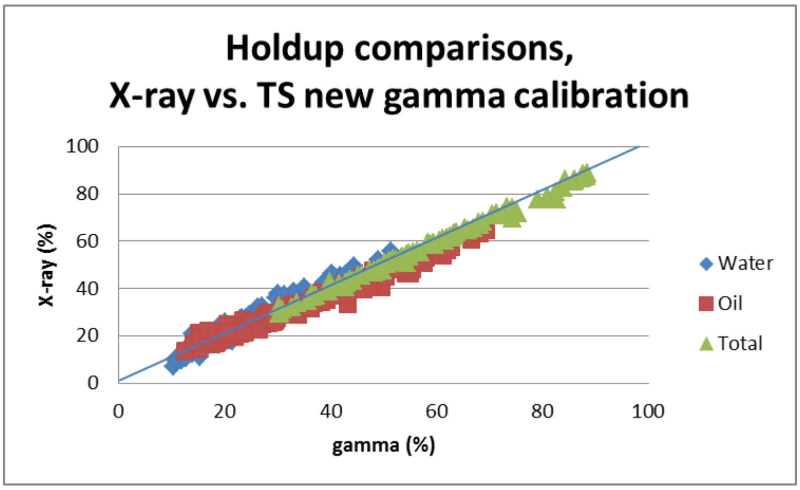


Figure 8: Comparison between holdup in three-phase flow measured with the gamma densitometer and the X-ray system

4.3 LDA-PDA

4.3.1 Background

Department PROSTEK at IFE has a 20 year old LDA system from Dantec, which has not been in working condition for the past 5 years, primarily due to laser failure. Also the burst signal analyser is old and out of date, which means that we were basically looking for a new system.

For measurement of mean velocity vectors and RMS-values, an LDA system is judged to be a complementary system to our PIV system for the following main reasons:

- Fast access to mean velocity components and the associated Reynolds stresses, although being point measurements, while PIV gives whole-field vector plots based on calibrations and interrogations. Both methods are optical.
- In dispersed flows, particularly suspensions (particle laden liquids), LDA has proved to tackle much higher particle concentrations than PIV.

4.3.2 Requirement specifications

The requirements for the LDA equipment were as follows:

- A 2 D system
- Solid State type laser, for robustness
- Minimum laser power 1 Watt per velocity component
- At least one water tight (8 bar) lens for insertion directly into a pressurised pipe
- A PDA system should an option in the offer

4.3.3 The quotes – evaluation

The two main providers of LDA-systems, TSI and Dantec, were contacted for quotes. The offers went through an iterative process, with respect to both technical specifications and costs. The two final offers were very competitive. The offer from Dantec was selected for the following main reasons:

- The re-use of parts of the fibre optics and the lenses from IFE's old LDA system favoured Dantec
- The fact that we have free access (''perpetual'' loan) to use Dantec PDA receiver optics, in good condition, from the Hydrodynamics lab at the University of Oslo, implied that we by choosing Dantec's offer got a state of the art LDA/PDA system for the price of an LDA system from TSI.
- IFE has very good experience with Dantec's technical support in Scandinavia

4.3.4 Technical specifications

The Dantec system consists of a Doppler Lite DPSS in a Fiber Flow LDA optical system as illustrated in Figure 9.

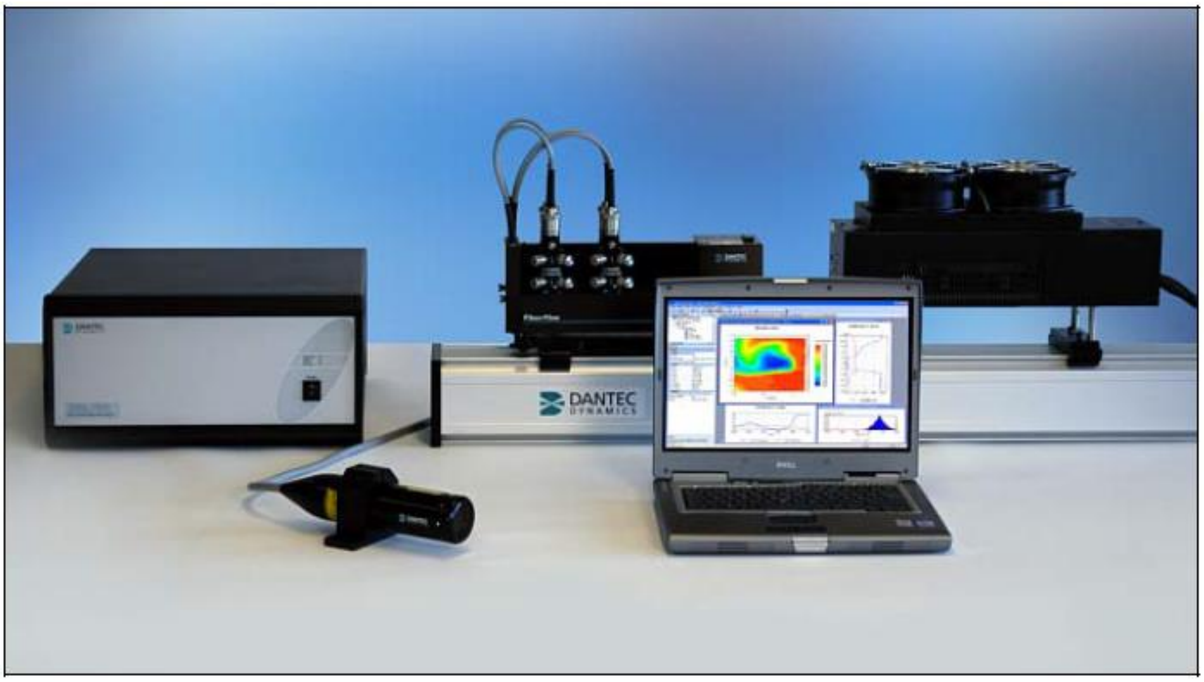
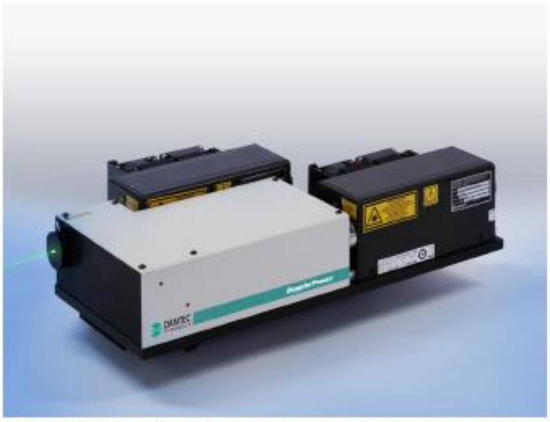


Figure 9. The main components in a typical Dantec LDA setup; From left: Burst analyser, probe/lens, alu-frame with laser, manipulators and fiber optics, and control PC with BSA Flow v5 software

4.3.4.1 The Laser

The laser is a DPSS (Diode Pulsed Solid State) laser with 2x1 Watt power, using the 514 nm and 488 nm wavelengths. The laser is from Doppler Power where the two lasers are built into one physical unit, see Figure *10*.



DopplerPower DPSS laser. 2 x 1W. 488 and 514 nm.

Figure 10. The DPSS laser

4.3.4.2 The fibre optics

We will re-use IFE's existing 2-component FiberFlow System, which also includes the Bragg cell for frequency shift. The arguments for using this unit in an upgraded system is that it is more or less identical to what Dantec offer as a new component today, and that this module mainly consists of optical parts that is not ageing. Prior to this decision, our existing

FiberFlow system was checked by Dantec and found to be in good order. Full service of existing FiberFlow is included in the quote.

4.3.4.3 PM tubes

Dantec also checked the PM-tubes in IFE's existing setup and concluded that these should be replaced. Dantec's solution to the challenges of measuring large and small particles simultaneously is an additional wavelength, 575 nm, from the colour separator.

4.3.4.4 Probes and optics

We will re-use our 60 mm probe with its two lenses. As additional probes and optical equipment, the upgraded LDA system includes:

1. A 27 mm probe with a f=60 mm stainless steel lens, adapted for pressure up to 8 bar
2. A 'Beam translator' for the 60 mm probe for moving laser beams to better cope with curved surfaces
3. A 'Beam expander' to reduce the size of the measurement volume, which makes the measurements more accurate and enables measurements closer to surfaces
4. 112 mm lenses for use with the beam translator and expander; f=310 mm and 500 mm.

4.3.4.5 The burst signal processor

The burst spectrum analyser is a BSA P60-2D with a maximum Doppler frequency of 160 MHz. The analyser is based on Ethernet. This BSA supports LDA probes as well as PDA receiver optics.

4.3.4.6 Software

The software is BSA Flow version 5 with advanced graphics add-on, supporting velocity and turbulence measurements with LDA as well as particle sizing and velocity with PDA. The main features include:

- Real time oscilloscope display of Doppler signals
- Time-saving data acquisition stop criteria with online confidence interval calculation
- Scripting capabilities and direct data access from third party software
- Automatic reporting tool
- Windows XP, Vista and 7 supported
- Export functionality to Excel and MatLab

4.3.4.7 PDA extension

Since IFE has the transmitting and receiving optics, the extension to a fully operating PDA system consists in an upgrade of the BSA from model F60 to B60 and two new photomultipliers with amplifiers. The standard software supports PDA.

4.4 PVM

A V819 Particle Vision Microscope (PVM), shown in Figure 11, has been acquired in the IMP framework. The supplier for the PVM system is Mettler-Toledo who is a multinational manufacturer of analytical instruments.

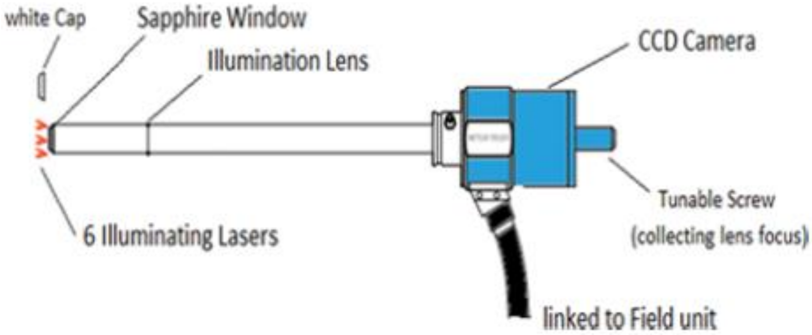


Figure 11: A PVM probe with six illuminating lasers and CCD camera.

The PVM provides in-situ digital greyscale images seen by the camera with the help of illuminating laser placed at the very end of the probe. The images taken by the camera can be used to measure droplet size, to obtain the shape of the droplets, particles or any other objects flowing in a fluid system.

The probe tip is separated from the camera by about 40 cm. The CCD camera has a resolution of 680 pixels x 512 pixels. Six independent laser light sources are located around the probe tip at each 60° angle. These strong light sources ensure good quality images in dark media. The field of view where the actual images are taken is 1075 µm x 850 µm. The physical resolution of the camera therefore is 1.6 µm / pixel. Droplets or particles larger than approximately 4 µm can easily be identified.

The PVM system requires extensive post-processing once the images are recorded in a computer disk. Droplet/particle counts and related statistics are obtained using a pattern recognition / image processing code. In certain cases manual checks are needed as well. Convergence of the statistics, i.e. droplet size and shape, depends on the number of images processed. It is therefore necessary to take a large number of images during each experiment. The sampling rate of the PVM is on the order of 1 image/second. Typical images which can be collected using the PVM system are shown in Figure 12. Using a real-time image analysis program, it is also possible to quantify particle dimensions and other characteristics as the images are recorded.

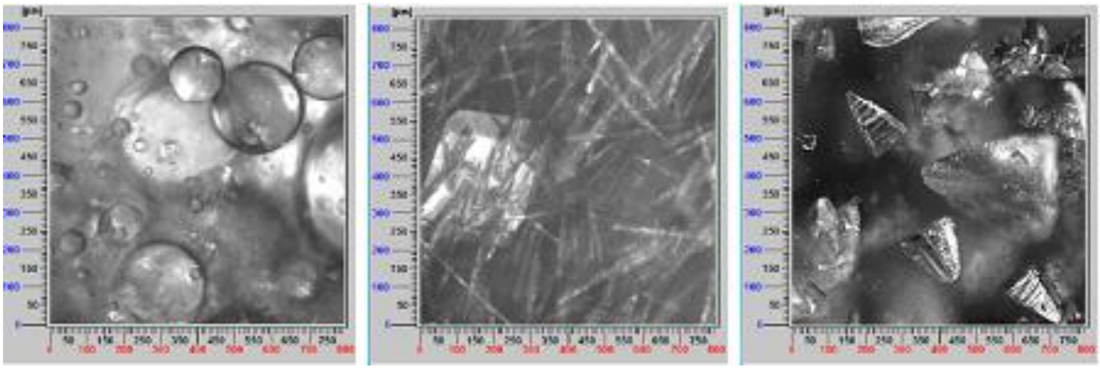


Figure 12: Typical images the PVM system can deliver in a fluid system. These pictures from left to right are droplets in an emulsion system, fibres and solid particles in fluid systems.

4.5 Direct Wall Shear Stress probe

Direct shear stress sensors based on optical resonance are commercialized by Lenterra USA. In the sensor, a floating element that is in direct contact with the fluid under testing, is attached to a cantilever beam which deflects in response to shear stress applied to the floating element surface, and transmits a force to a micro-optical resonator (see Figure 13). This resonator (typically made of silica glass) has an optical spectrum with peaks centered at particular light wavelengths. These resonances can be recorded by sending light to the resonator, and measuring the light that returns from it. When the cantilever deflects, the micro-optical resonator attached to the cantilever experiences strain, causing a shift ($\Delta\lambda$) in its resonant optical wavelength (see Figure 14). This shift is proportional to the shear stress.

Figure 13: Photo of the wall shear stress sensor (www.Lenterra.com)

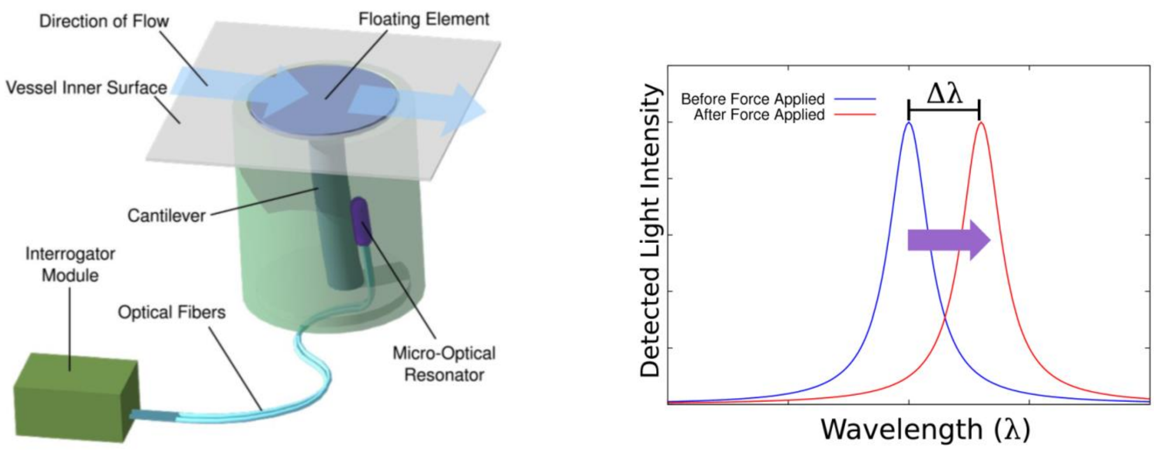


Figure 14: Diagram illustrating the Lenterra Shear Stress Sensor concept (left) and conceptual plot showing the shift (Δλ) of a resonance peak as a result of applied force on a micro-resonator (right) (www.Lenterra.com)

Two floating elements, RealShear^{TM} F-100 were purchased from Lenterra under the IMF project. The shear stress sensors were tested in the Well Flow Loop (WFL) in the summer of 2015. However, small particles (contamination) were trapped in the gaps of the sensors so that no good measurements were obtained. The sensors were then shipped back to the manufacture to repair. A filter system is planned to be installed in the WFL for further tests on the sensors.

4.6 Visualization

During the IMF program IFE has acquired a well-equipped visualization system with digital cameras and illuminating tools. Table 8 provides a brief listing of the items. Further details are provided in individual sections:

Table 8: List of high speed cameras and visualization systems acquired at IFE

No.	Product	Description
3	Photron FASTCAM Mini UX100	B/W camera
1	Photron FASTCAM Mini UX100	Color camera
2	Manfrotto tripod	Camera tripods
4	Manfrotto tripod	Adjustable tripod heads for easy mounting and adjustment
2	Photron trigger switch	Manual trigger of camera
1	Photron trigger box	Trigger box for controlling 4 cameras with one signal
1	LED panel 300x120mm 80W	White light LED panel
1	Oxford FireFly Laser	Laser light with optics

4.6.1 Cameras

As listed in Table 8, IFE has purchased 3 FastCam Mini UX100 high speed black & white cameras and 1 FastCam Mini UX100 high speed colour camera. These cameras are easy to use and synchronize with or without time delay between them. Individual properties together with the picture of cameras are as below.

FASTCAM Mini UX100 – B/W

- 16GB memory
- 1.3 Megapixel resolution (1280x1024 pixels) at frame rates up to 4,000fps frames per second
- 1 Megapixel resolution (1280x800 pixels) at 6,250fps

FASTCAM Mini UX100 - Color

- High-G single unit integrated processor
- Imager module with 1280 x 1024 pixel
- CMOS sensor with 12bit A/D output
- Interchangeable ‘C’ and Nikon F lens mount (compatible with 1“ format C mount lenses and Nikon manual focus and autofocus lenses with and without aperture ring)
- GigaBit Ethernet interface
- IRIG-B time code compatibility
- 100-240VAC power adapter
- Photron FASTCAM Viewer v3 system control software and support for MATLAB and LabVIEW

In order to extend our capabilities in placing the cameras along the flow loop, different tripod solutions were obtained. These are easy to use and save time during the setup. The precision of the positioning is high and meets our expectations. The Manfrotto Tripod and Manfrotto Camera Platform complete the set. Further details are provided along with the pictures as follow:

MANFROTTO TRIPOD	
	• Load Capacity: 26.5 lb • Max Height: 74" • Min Height: 16.9" • Folded Length: 31.5" • Leg Sections: 3 • Weight: 9.5 lb • Geared Center Column • Center Brace • Black Anodized Aluminum Construction

MANFROTTO CAMERA PLATFORM	
	• 3D head and smooth control on 3 axes. • Quick release hexagonal plate with secondary safety latch. • 3 built – in spirit levels for horizontal and vertical positioning • Good size control handles

4.6.2 Light sources for visualization

One of the most important aspects of good quality imaging and video recording is the quality and strength of the light sources. IFE therefore has purchased LED light panels to create right and high quality imaging. These are easy to use and adjust according to needs.

In addition, we have invested in a laser source which provides enough laser light for high-speed imaging. The laser can be triggered externally from a camera and operated in sync with analog and digital cameras. The laser can be operated in continuous or pulse mode according to the needs. Further technical details and pictures are given as follow:

LED PANEL LIGHT	
	• High energy efficiency 80W LED panel light Luminous update 5800Lm • High uniformity „ • Over-temperature protection • High quality light with a color rendering index of 80

OXFORD FIREFLY 10000 LASER	
	• 300W solid state pulsed laser. • Pulse repetition frequency up to 10 kHz • Pulse duration adjustable from 0.25 µs to 100 µs • Up to 200 pulses per burst • 0.5 µs minimum separation time within burst

4.7 Interfacial tensiometer

Surface tension and interfacial tension are essential parameters for multiphase flow modelling. As the EOR and CCS industry grows, a system which can measure the surface/interfacial tension under high pressure and temperature can be a very important and essential investment. There have been some discussions in the group on the necessity of having a state-of-the-art tensiometer with high pressure chamber (HPC) as part of our instrument portfolio.

Table 9: The tensiometer specification

	Krüss
Material	Hastelloy
Window	2x
Pressure	~517 bara

Temperature	~180°C
Chamber volume	20 ml
Pump	2x hand pump
Heating and Cooling system	Jacket of heating cable or tubing with coolant

Figure 15: Interfacial tensiometer with pressure chamber

4.8 Portable densitometer

Routine density measurements are essential in research laboratories to characterize the fluid samples. There have been some discussions to have portable densitometer in our research laboratory and thus the DMA 35 portable densitometer from Anton Paar was purchased. The instrument allows us density, specific gravity and temperature during on-site operations.

Figure 16: Portable densitometer (Picture from Anton Paar website)

4.9 Zeta potential upgrade

Zeta potential is one of essential parameters to investigate the stability of colloidal systems, such as suspensions and emulsions. The stability measurement of colloidal systems in industry is very important and thus a system that can measure the stability can be a very important and essential investment in our department. There have been some discussions in the group about the necessity of upgrading our Malvern Zetasizer NANO-Z as part of our instrument portfolio, thus the instrument was upgraded. The instrument has been used in ongoing research projects, such as NattBatt, in the department. Table 10 gives specification of the upgraded Malvern Zeta sizer Nano Z instrument, which is available in the fluid research laboratory at the PROTEK department in IFE.

Table 10: The Malvern zeta sizer Nano-ZS specification

	Malvern
Measurement range	3.8nm – 100 microns* (diameter)
Measurement principle	Electrophoretic Light Scattering
Minimum sample volume	150µL (20µL using diffusion barrier method).
Accuracy	0.12µm.cm/V.s for aqueous systems using NIST SRM1980 standard reference material.
Sensitivity	10mg/mL (BSA)
Temperature control range	0°C - 90°C +/-0.1**, 120°C option.
Light source	He-Ne laser 633nm, Max 4mW.
Power	100VA

Figure 17: Malvern zeta sizer NanoZ instrument (Picture from Malvern website)

5 Process equipment

5.1 Scrubber

A scrubber including advanced internals was chosen. A vane inlet dampens and distributes the flow. A mesh pad agglomerator both increases the droplet size at high rates and remove the liquid at low flow rates. At the top, the scrubber is equipped with demisting cyclones that are highly efficient at high gas flow rates. These may have reduced efficiency at very low flow rates.

The scrubber will be located upstream the new gas booster, see Section 5.1 to ensure dry gas flow from the source.

Figure 18: A schematic of the advanced scrubber

5.2 Gas booster

5.2.1 Background – motivation

Over its more than 20 years of operation, the gas booster in the Well Flow Loop has been a two-spindle screw pump from Bornemann. The flow rate capacity of the pump is 360 Am3/h. With its 65 kW motor, the lifting head has been more than 2.5 bara. The limitations and drawbacks with this gas booster have been:

- The maximum flow rate, which, for example, has been a limiting factor in studies of drop entrainment in gas flow and other gas-condensate and wet gas issues
- The fact that the screws are partly immersed in liquid means that liquid drops, at high rpm, are entrained in the gas phase. Since the downstream scrubber has not been working optimally, the gas phase has always carried some liquid when the gas flow rate is high, adding uncertainty to drop entrainment type of studies.

5.2.2 Requirements

The requirements for a new gas booster were as follows:

1. Minimum flow rate of 1000 Am3/h and a lifting head of 2.5 bar
2. Gas phase; SF6 and N2
3. 10 bar pressure rating
4. Preferably an axial blower
5. Impeller in stainless steel
6. Dry running

5.2.3 Vendors - quotes

A number of vendors of gas compressors and gas boosters were contacted. The list included:

Aerzen, Atlas Copco, Fuglesang, GE Oil and Gas, Howden, Nessco, Roots, Sulzer, Tuthill, RoTech Booster/Eagle Burgmann and Spencer Turbine.

We initially got two quotes:

1. From Roots, which was priced unreasonably high
2. From Eagle Burgmann (Nova Magnetics Burgmann) on their RoTech Booster, which could not meet the flow rate specification

After a new round with Eagle Burgmann and a new vendor, Spencer Turbine, we ended up with two offers for evaluation.

5.2.4 Evaluation

The two offers were based on two different technologies; the compact, magnetic driven centrifugal booster (RoTech) from Eagle Burgmann and the ''hermetic'' (pressure chamber) multistage centrifugal booster from Spencer Turbine, see Figure *19*.

Figure 19: Outlines of the two gas boosters; RoTech (left) and Spencer Turbine (right)

We know the RoTech booster technology well from the CO2-Loop, where a high pressure/low flow rate version of the offered booster is installed. We have been very satisfied with this booster, also with the follow-up from the vendor, Eagle Burgmann.

Spencer Turbine is a main US supplier of gas boosters, which includes equipment with specifications that are normally not found off-the shelf.

Drive line: The RoTech impeller is driven by magnets, which gives a compact design. The Spencer booster has a conventional drive line, but to cope with the high static pressure and avoid the leakage issue, the motor, axle and turbine is built into a pressure chamber (hermetic). This gives a slightly higher footprint compared to the RoTech booster. 2.1x2x1.5 m vs. 2.5x1.1x1.1 m. The RoTech Booster can be mounted vertically or horizontally, while the Spencer booster must be mounted with horizontal axle. In our case the horizontal versus vertical mounting is not vital for the installation.

Turbine/impeller: The RoTech has a one-stage radial compressor while Spencer's offer is a 3-stage turbine. The pump curves for the two machines are very much the same.

Connections/piping: The Spencer booster is delivered with 6'' flanges both on the suction and on the discharge side. The RoTech booster has 8'' connecting flange on the suction side and 4'' on the delivery side. This was not crucial for the choice.

Noise, dB: This is information that was not available at the time of placing the order.

Materials: Spencer offers casing, axle and internals in carbon steel and with the impeller in aluminium. The RoTech booster is offered in stainless steel.

Cost of installation: Judged to be more or less the same for both gas boosters.

Delivery time: Delivery time was 8-10 weeks shorter for the Spencer booster compared to the RoTech booster, 14-16 weeks versus 24 weeks.

Price: EagleBurgmann/RoTech gave a combined booster and demister (Innsep) package offer at a cost of 2 MNOK, including shipment and partly also the installation costs. The offer from Spencer, including a frequency converter, was 1.45 MNOK, including shipment, but not installation costs.

Conclusion: From a technical point of view the two gas boosters are judged to meet the specifications and we could find no serious drawback for one over the other. The materials and the compact design is a pre for the RoTech, while the con is that the Nova Magnetic-Burgmann factory in Nova Scotia has never previously delivered this type of booster for flow rates of 1000 m3/h. Spencer Turbine delivers proven technology at lower price and 4 months delivery time. In the end this became the decisive factor, and the offer from Spencer Turbine was accepted.

5.2.5 Status

The gas booster was delivered in late November and is about to be installed. The photos in Figure 20 show the booster next to the scrubber, on the concrete platform outside of the Well Flow Loop and one picture taken during assembly at the factory. The performance curves for the gas booster is included in Figure 21.

Figure 20: The Spencer Turbine

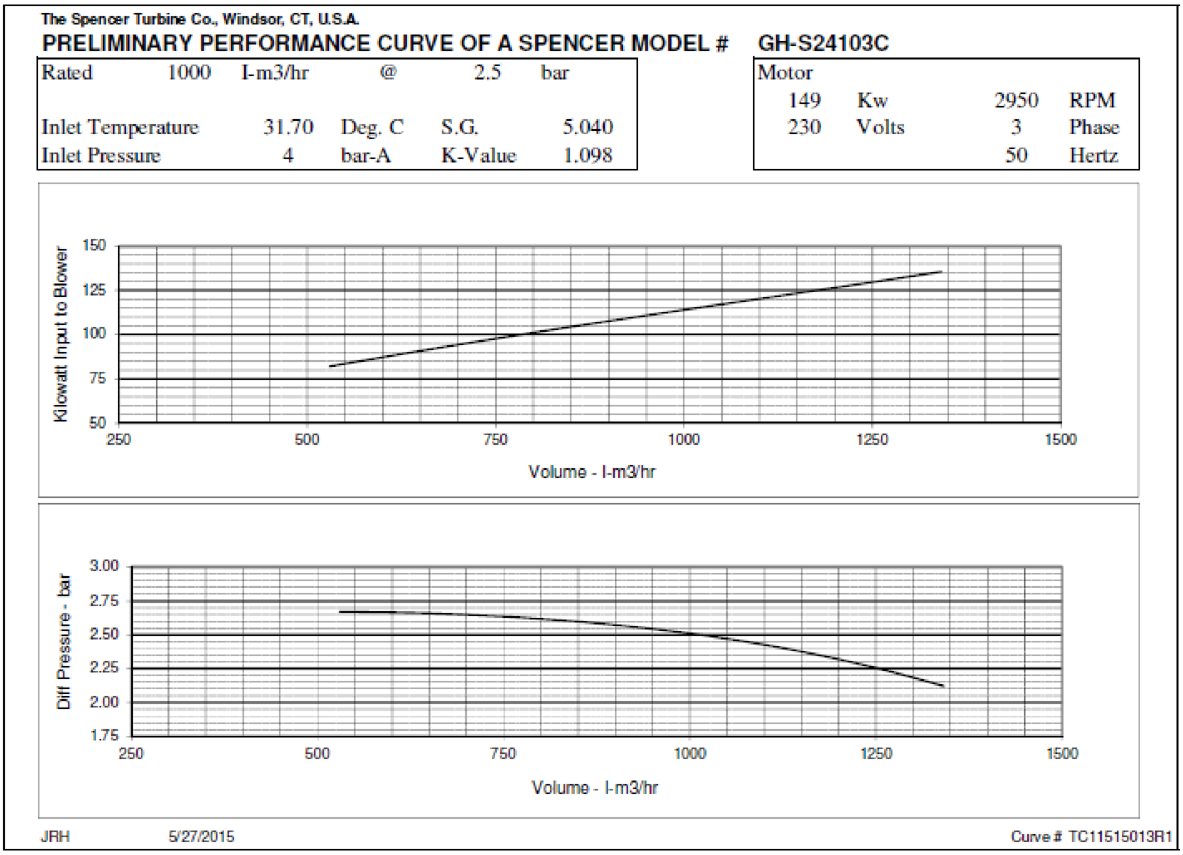


Figure 21: The performance curves for the gas booster

5.3 Gas flow rate meter

5.3.1 Background/motivation

The new gas booster gives flow rates beyond the maximum range of our current turbine meter, and a new gas meter was therefore required.

5.3.2 Requirements

The new gas meter should have a range of minimum 1000 Am3/h, with an accuracy better than 0.5% of reading, with a turn-down ratio of 1:20 and should be applicable for SF_6 as well as for other more conventional gases as for example nitrogen. Primarily, we wanted a flow meter without moving parts, and a multipath ultrasound meter was high up on the wish list. While turbine meters were the dominant fiscal meters 20 years ago, when the current turbine meter was purchased, multipath ultrasound meters have taken that position today.

5.3.3 Quotes – decision

We first got a quote from Sick for a 4-path ultrasound meter, which was also ordered. During the detailed engineering Sick realized that SF_6 had certain acoustic properties which challenged the engineers at Sick to such an extent that Sick withdrew their offer. After a new round with 5 different vendors where Coriolis meters, vortex meters and turbine meters were competing, vortex meters were quickly discarded due to relatively high pressure drop and lack of accuracy (1% at best). Coriolis meters for gas applications might work OK for the high density gas SF_6, but we doubt it is a good solution for nitrogen, for example. It must also be added that IFE has previous poor experience with Coriolis meters for SF_6, although this can be due to the fact that this particular meter was from a factory that we in retrospect understand have a poor reputation. We finally landed on a 6” turbine meter from Instromet, see Figure 22, for the following main reasons:

- Low price compared to top of the range Coriolis meters
- Lower pressure drop than Coriolis meters
- Turbines works equally well for SF_6 as for nitrogen
- Accuracy of 0.5% for a turn-down ratio of 1:20

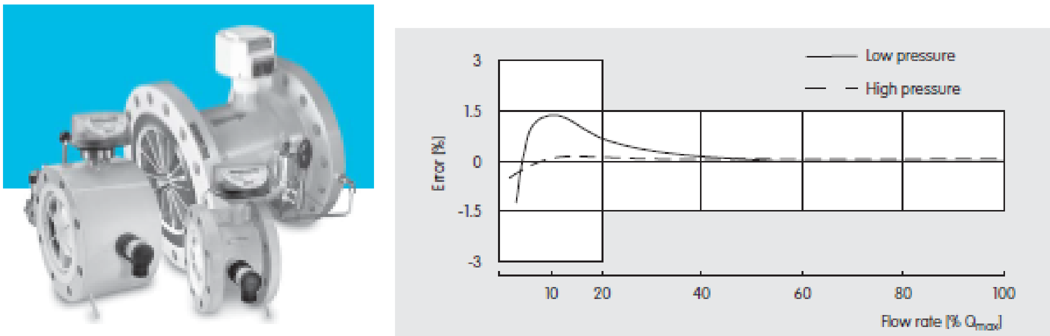


Figure 22: Design (left) and typical performance curve (right)

5.4 Heat exchanger

The increased capacity of the new gas booster requires a gas heat exchanger with increased capacity as well. The new scrubber, gas booster, heat exchanger and gas flow rate meter together constitute a completely new gas feed line, in parallel with the old gas feed line. The chosen heat exchanger is a water cooled plate heat exchanger from Alfa Laval, Model CB 300. This is similar to the plate heat exchanger mounted on the old gas feed line, but with increased capacity.

The key specifications for the heat exchanger are found in Figure 23 below, which also includes a photo of the unit.

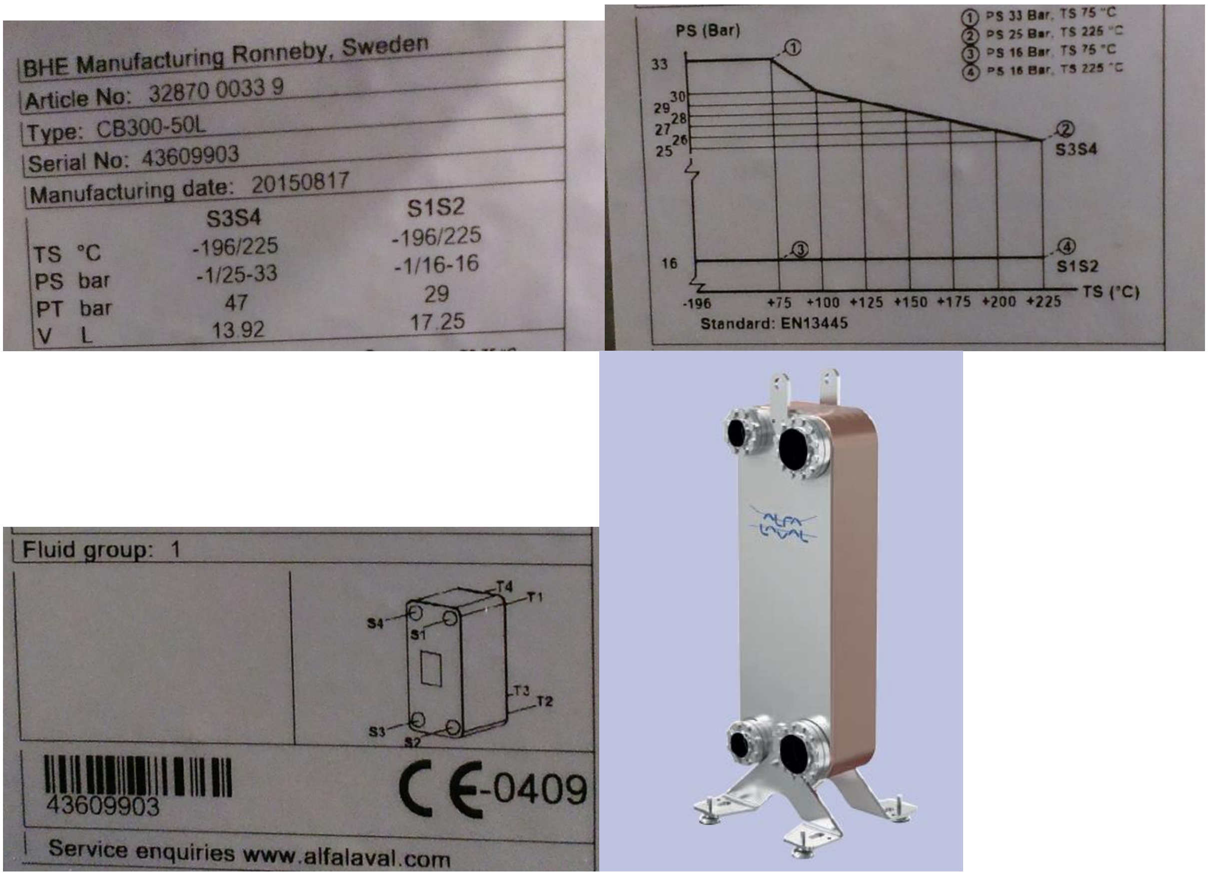


Figure 23: Details of the plate heat exchanger from Alfa Laval

5.5 Pre-separator

In experiments with viscous oils, the separation of the liquid phases has been a challenge in the Well Flow Loop. Now, a new pre-separator is installed in the pit under the extension of the test section.

It consists of an empty pipe with one inlet and 2 outlets for oil and water. The whole pre-separator is mounted on weight cells, and a PID control is installed to regulate the control valves on the water and oil outlets.

The return flow of the liquids in the test section is now controlled and handled in a much smoother manner, such that there is a minimum of mixing. Water and oil enters the liquid-liquid separator separately.

Figure 24: Picture of the pre-separator under the test section of the Well Flow Loop

The dimensions of the pre-separator are given in the following Table 11.

Table 11: Dimensions of the pre-separator

Length	11 meter
Diameter	0.5 meter
Volume	2200 litre

5.6 Profile meter

5.6.1 Background and motivation

The current possibilities for monitoring of the liquid inventory in the Well Flow Loop are through interface detection in three side wall mounted sight glasses and the liquid height in a transparent, outside mounted, vertical column. This monitoring has severe limitations and virtually no diagnostic capabilities. It has therefore been a desire - for a long time - to install a level profiler from Sentech AS (now part of Advantec Group) in the oil-water separator. The Sentech technology is acknowledged for being leading edge technology.

The offer from Advantec Group implies that the installation at IFE is regarded as a demo-installation where Advantec Group can take customers for demonstration. This is reflected in a favourable price.

5.6.2 Measurement principle

The operating principle for the instrument is the measurement of the dielectric constant, which has proved robust and accurate because of the large difference between water and hydrocarbon dielectric constants. Typically, the instrument is a rod with a number of individual ‘’sensor eyes’’ mounted, as illustrated in Figure 25.

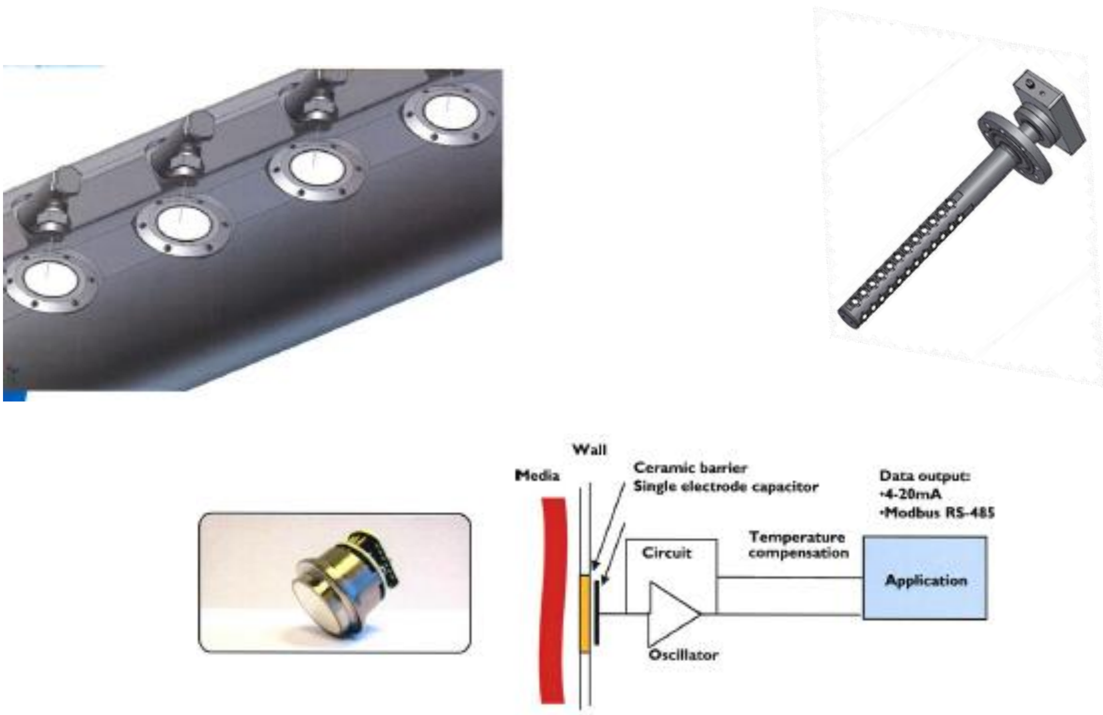


Figure 25: Illustration of the ‘’sensor eyes’’ and the rod mounting (top) and the sensor design (bottom)

Each single electrode capacitor is part of an electronic circuit, which oscillates with its resonance frequency. If the medium is changed, the capacitive properties of the capacitor are changed and the resonance frequency is changed accordingly. This change in frequency provides a high resolution measurement of the dielectric properties of the media. In this way the sensor can distinguish between pure liquids (water, hydrocarbons), emulsion layers and foams.

5.6.3 Specifications for the IFE installation

The instrument delivered to IFE has the following specifications:

- 80 mm diameter 316L stainless steel rod
- 1490 mm overall length
- Machined to hold 41 ceramic measurement probes
- Maximum operating temperature: 125°C
- Internal temperature sensors for each sensor
- Element and frequency oscillator
- ATEX and CSA approved [Ex ia] IIB T4
- Field mounted integral electronics junction box
- Sensor spacing at 60 mm
- Each sensor alternately located at 0 degrees and 180 degrees in the measurement area in a vertical orientation
- Approximately 1,230 mm of measurement area

The profile meter will be installed in the oil-water separator as illustrated in the drawings in Figure 20.

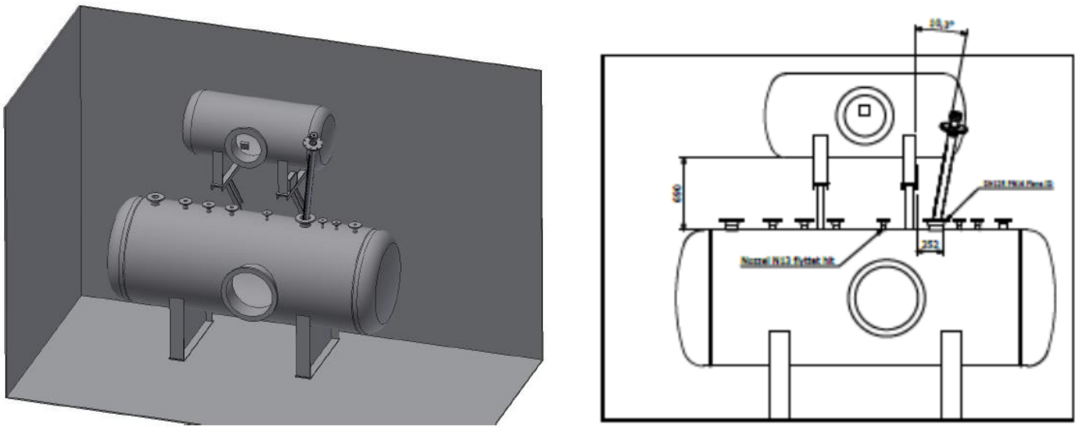


Figure 26: Schematic of the installation of the profile meter in the oil-water separator

5.7 The new Well Flow Loop

The Well Flow Loop that was described in Section 2.1 now has improved technical specifications when it comes to gas rates, control of humidity in the gas phase and use of more viscous oils.

The process equipment was described piecewise in section 5. The changes mainly consist of two major upgrades of the Well Flow Loop described in the following sections, the new gas feed and the liquid return.

5.7.1 The new gas feed

The new gas feed system is installed in parallel to the existing setup such that the gas feed can be chosen with respect to the need.

The new system will ensure a dry gas feed, with doubled capacities. Its installation is presented in the diagram in Figure 27.

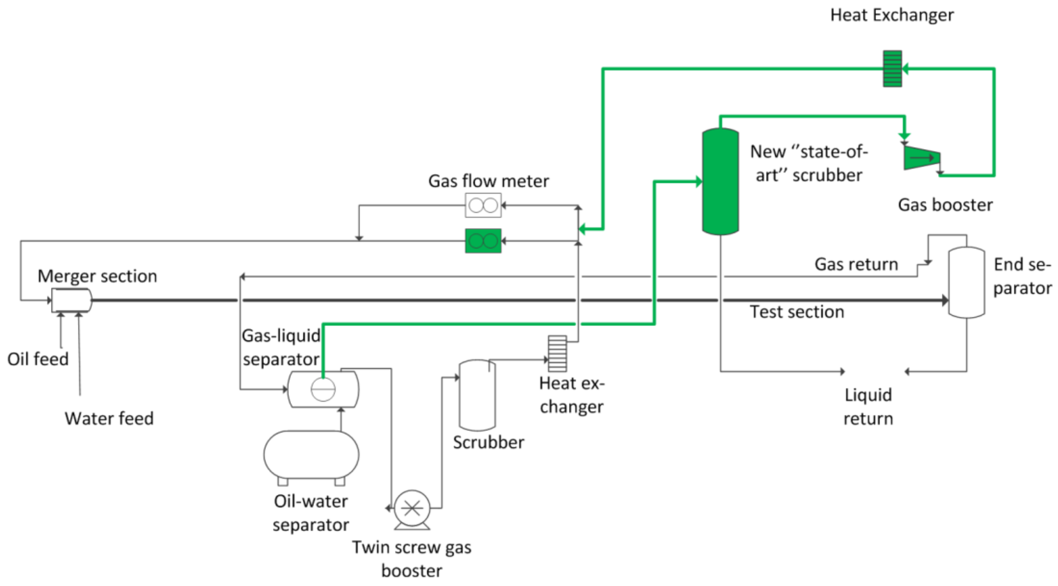


Figure 27: The new gas feed installation

5.7.2 The liquid return

The liquid return has also been significantly improved with several components described in section 5.5 and 5.6. In addition, modifications have been made on the liquid-liquid separator as a part of this system installation.

In Figure 28, a diagram of the Well Flow Loop is given. The liquid return system now consists of a separation of the liquids upstream of the liquid-liquid separator. The separator therefore has new incoming piping for this purpose which reduces the mixing previously observed. Additionally, gas is now removed from the liquid return system.

When the profile meter is installed in the liquid-liquid separator, the improved control of the separation of oil and water will be completed.

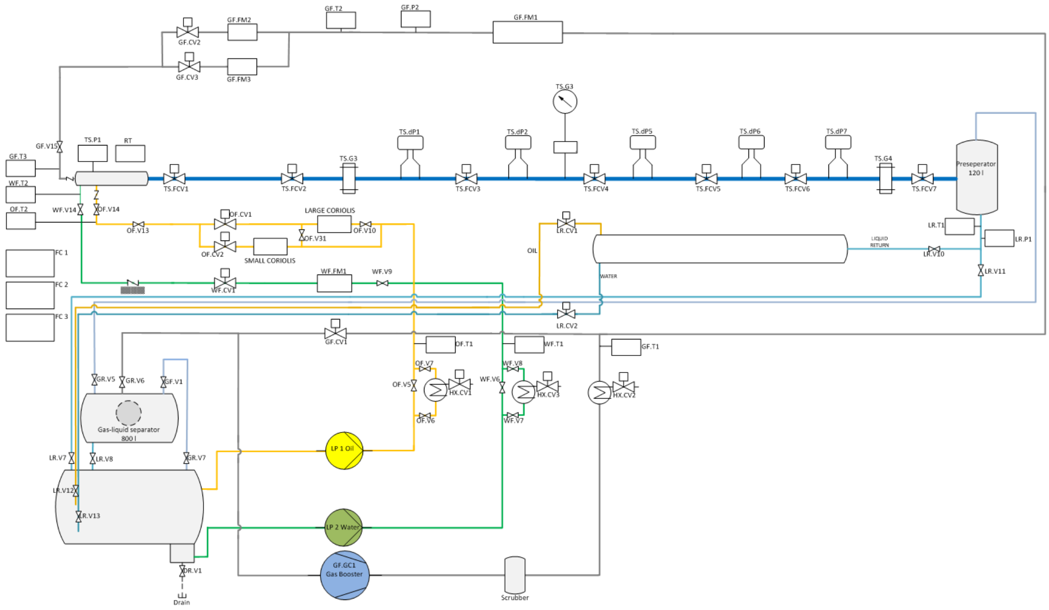


Figure 28: Process diagram of the WFL with new liquid return system

5.7.3 The test section

The test section was extended as part of an internal upgrade before the Infrastructure project. It consist now of a 47 m long transparent PVC tubing. When run at its full length, it can be inclined up to 5^{o}. The test section is mounted with flexibility such that the length can be shortened to reactivate the ability to run at higher inclinations. With a test section of 15 m, the possible inclinations are 0-90^{o} as before. Additionally, one can also mount a flexible hose in the middle of the test section and choose different inclinations starting with 25 m upstream and 22 m downstream or the contrary, as the original WFL and its extension are mounted on separate beams.

Figure 29 is a picture of the extended WFL with three X-ray systems and a gamma densitometer mounted.

Figure 29: Picture of the Well Flow Loop taken at the near end of the test section, equipped with X-ray tomography systems

5.7.4 Technical specification

Over the last years, new liquid pumps have also been purchased for different settings, allowing liquid flow feedings down to 10 kg/h with density measurement to ensure the liquid phase.

The new technical specifications of the Well Flow Loop are given in Table 12.

Table 12: Technical specification of the Well Flow Loop after the infrastructure upgrades

Loop material	AISI 316, PVC
Liquids	Model oils, tap water
Gas	SF_6 due to density, gases not requiring special Ex/HSE needs as N_2
Pressure	Max. 10 bara
Temperature range	15 to 25°C
Test section	ID 100 mm, L= 47 m
Test pipe incl.	-1 to 90^o (15 m length), -0.5 to +5^o (47 m)
Superficial gas velocity range	0 - 20 m/s (800 Am^3/h)
Superficial liquid velocity range	0 - 2 m/s (100 Am^3/h)

6 Summary

In addition to extension of the Well Flow Loop building and the test section of the facility performed respectively in 2012-2013 and 2013-2014, the Infrastructure project has given a unique possibility to upgrade the process equipment and purchase a large number of instruments. Additionally, the internal development in instrumentation and software for data analysis develops the experimental expertise of the group even further.

The Well Flow Loop will soon be able to circulate a dry gas phase, with a new scrubber installed upstream a new gas booster. Earlier, gas droplets could come from the gas compressor, but also from the gas-liquid separator depending on the flow conditions in the loop. Therefore, the scrubber has been installed downstream the gas-liquid separator, to feed the test section with an already dry gas.

The second process equipment improvement consists of the control and enhancement of the separation of the liquids in the return system. This consists of several steps and improvements on the loop resulting in a complete control of the separation. First, a large pre-separator is installed between the test section and the liquid-liquid separator. Containing only liquids, it is equipped with two outlets with regulator valves for water and oil. In this manner, the liquids can separate before coming to the liquid-liquid separator. The mixing previously observed in the separator is removed, and replaced with a controlled return system. In addition, a profile meter will be installed in the liquid-liquid separator, to indicate whether a mixing layer is present, increasing or decreasing in size.

Within instrumentation, X-ray has received the most attention in this round. Several X-ray systems have been purchased, both for simple profile holdup measurements, but also for complex tomography purposes with up to six projections. Since X-ray for multiphase flow still is under development it has received a great part of the personnel costs of the project.

The gamma densitometers of the WFL have also gone through a complete updating. Sources and detectors have been replaced.

In order to measure droplets and bubbles, the existing LDA system is upgraded to include a PDA system. In addition a PVM system is purchased which will be a nice extension of our FBRM.

Two Wall Shear Stress sensors have been acquired within the project. Their installation in the WFL requires a filtering system in order not to damage the sensors.

A tensiometer with pressure chamber has been purchased. This was not part of the original plans in the project, but the knowledge of the importance of the interfacial tension under pressure is increasing. With this instrument in the fluid laboratory, the fluid characteristics will be tested under real conditions of the WFL.

Visualization techniques are important also in multiphase flows, and several high speed cameras are invested in this project, in addition to different light sources; LED and laser.

The Well Flow Loop is now thoroughly equipped, both with process equipment and instrumentation for new detailed measurements within multiphase flows. We are looking forward to perform the next generation measurements in the following JIP MULTIFLOW starting in January 2016.

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