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"GAS-OIL PISTON-PROVER", A NEW CONCEPT TO REALIZE REFERENCE VALUES FOR HIGH-PRESSURE GAS-VOLUME IN THE NETHERLANDS

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SUMMARY

The paper describes the recently developed "GOPP" – Gas Oil Piston-Prover. This primary standard for high-pressure gas-volume is created to realize units of volume at various pressures for the Dutch National traceability-chain of high-pressure gas-flow measurements.
The paper presents the design, working principle, simulation calculations and first results to realize a calibrated rotary-piston gas-meter. Furthermore, the actual physical process is compared to simulation calculations, and temperature characteristics are discussed. With internal harmonization processes at NMi VSL with 'input' reference values from the three other primary standards, viz. DDD-conventional, DDD-extended pressure level and NMi TraSys, the aim of 0,1% uncertainty at 4.000 m^3/h and p = 60 bar is within reach. This will improve the uncertainty as well as the stability of the Dutch National reference values considerably.

The developed Gas-Oil Piston-Prover has the potential to become an important primary standard at NMi VSL, generating straight-forward Reference Values for high-pressure gas at a desired pressure. The gas can be of any nature, but the major aim is Natural Gas.
The paper presents describes the design, construction, working principle and features of a hydraulic driven piston-prover system. A 12 meter long, 600mm bore piston-prover is used for the realization of Reference Values for Gas-Volume at any pressure between 1 and 90 bar and any type of Gas.
The paper explains the coherence between the Gas-Oil Piston-Prover system and the other available traceability generators. Following the philosophy of NMi, a "tripartite" traceability-chain for high-pressure gas-flow Reference Values is created. GOPP is one of the current developments at NMi to reduce the uncertainty of its traceability-chain considerably.
The paper shows block diagrams, describing the coherence between physical equilibriums, simulation calculations and graphical simulations, compared to the results of full-scale experiments with a special duo-rotary piston-meter.
A method is described to demonstrate an absolute leak-free piston-seal operation. Also a special measuring method was designed for the determination of the average gas-temperature inside the expanding measuring-chamber during the movement of the piston.
Finally, real-time temperature and pressure readings, as well as the first calibration results of a duo-rotary gas-meter, established values for repeatability of the piston-prover system and first estimates of uncertainty budgets will be presented.

INTRODUCTION

In the past decades, efforts were made at NMi to generate, optimize, and recently to combine various sources of independently realized Reference Values for Volume of high-pressure Gas [1-5]. Today, the new Dynamic Displacement Device in 2000, "NMi TraSys" [6] assisted with "NMi Z/Z-meter" [7] and GOPP - Gas-Oil Piston-Prover complete together a triangle approach to the Dutch Traceability-Chain for high-pressure gas-flow measurements. These developments will, together with the applied concept of "Quadratic Weighing" [8, 9], ensure stable, reliable Reference Values with unprecedented uncertainty. The number as well as the values of the contributions of uncertainties due to 'copy-losses' and 'installation-effects' during traditional processes of boot-strapping for pressure and volume in the range of 5 to 120 m^3/h is completely short-cut. The developed primary standard will shorten the distance to the normal working standards. This means a considerable reduction in boot-strapping steps and uncertainty accumulation. The system is mobile and can be installed practically anywhere as long as it can be filled with approximately 5 m^3 of pressurized gas.

The modified, large piston-prover is in operation since December 2002.

Originally, the high-pressure piston-prover was designed as a primary standard for liquid flows and operated according to the dynamic 'double stroke' principle. Some 15 years ago the piston-prover was acquired and modified by Gasunie to an in-line, double acting piston-prover for Natural Gas. However, despite all efforts, satisfactory and acceptable results could not be obtained and Gasunie decided to put the piston-prover at rest.

In June 2000, during an open discussion with the two god-fathers of the test-facilities in Bergum and Westerbork, contemplating on pressure-balances, dynamic displacements, Gas-Oil separation, the idea was raised why not to use a piston-prover as a gas-oil displacement device with a piston as the defined separator between the two fluids. Quick search learned that the piston-prover of Gasunie was still available for its third change in live.
The piston-prover has been modified to operate according to the new concept. Tests at atmospheric conditions with Air showed promising results and tests at elevated pressures are planned for the next months. NMi GOPP is scheduled to be in full operation around November 2003 and its performance will be evaluated and cross-checked with the conventionally obtained sets of Reference Values of the Dutch traceability-chain for high-pressure gas-volume.

WORKING PRINCIPLE
The working principle is based on the displacement of a piston acting as a Gas-Oil separator. The piston travels at a relative low speed. A speed-controlled centrifugal pump generates an Oil flow-rate that moves the piston with a uniform velocity towards the left side of the cylinder, passing sensors indicating discrete volumes. The oil & gas container at the top-side of the configuration, works also like a displacement system and the gas is forced towards the open outlet of the container and flows into the cylinder.

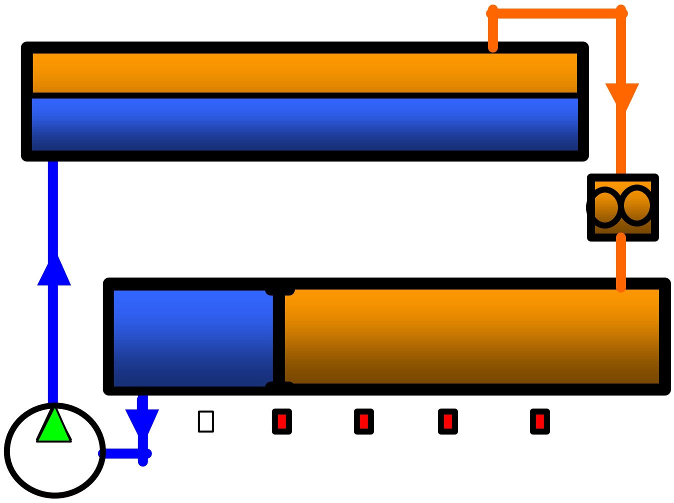


Figure 1,
Working principle of the Gas-Oil Piston-Prover

During the gas transport from the container to the cylinder, the mounted gas-meter will indicate a passed actual volume that is matched with the known volume of the displaced piston. Obviously it is a process with two strokes, after the active measuring stroke (piston moves to the left end) the pump will be stopped and the oil returns (caused by a slight over-pressure) to the cylinder and forces the piston back to its starting position. Proximity switches take care of the comparison process. The HF pulses coming from the Meter-under-Test (a Travelling Reference Meter) are compared with the reference LF pulses of the passed volumes of the primary cylinder.
In fact, the system is analogue to a Bell-Prover, with the moving piston as analogue to the liquid level inside the Bell-Prover, and the fixed cylinder as analogue to the moving Bell.
The advantage of this concept is the possibility to use high-pressure gas as the transported fluid.
The system includes a hydraulic oil flow-rate controller to maintain constant speed of the piston.

The developed primary standard has a flow-range of 5 till 120 m^3/h at actual gas flow-rates. The system is designed for calibrations of Travelling Reference Meters and has a direct relation to the "metre" and the "second". Consequently, "GOPP"-calibrated gas-meters are available with reference values at various pressures to disseminate traceability at junctions with similar conditions of the Dutch traceability-chain.
The CMC - Calibration and Measurement Capability of the system is expected to show results better than 0,05% (k=2, confidence level of ca. 95%).

"NMi GOPP" IN RELATION TO THREE, INDEPENDENT DUTCH TRACEABILITY CHAINS

In the next figure, three independent sets of reference values, or traceability chains, are presented together with their relations. First, the conventional Dutch traceability chain, with its over the years demonstrated CMC - Calibration and Measurement Capability of 0,18% at 100 m^3/h actual and 8 bar.
The second set is build around the new Dynamic Displacement Device - 2000. Its maximum flow-rate at 8 bar is 10 m^3/h. The uncertainty is estimated at 0,08% for 100 m^3/h, after boot-strapping in volume with 5 reference meters in two steps.
The third Dutch traceability-chain is built around GOPP. Its CMC is estimated at 0,05% at a flow-rate of 100 m^3/h and a pressure of 8 bar. GOPP is stand-alone and transportable.
Travelling Reference Meters (TRM) can be calibrated at any pressure with GOPP. Special efficient introduction of reference values by exchanging the ten cartridges of "NMi TraSys" in a TRM housing, permanently mounted on the GOPP for evaluation and comparison with reference values originating independently at NMi TraSys itself via boot-strapping processes.

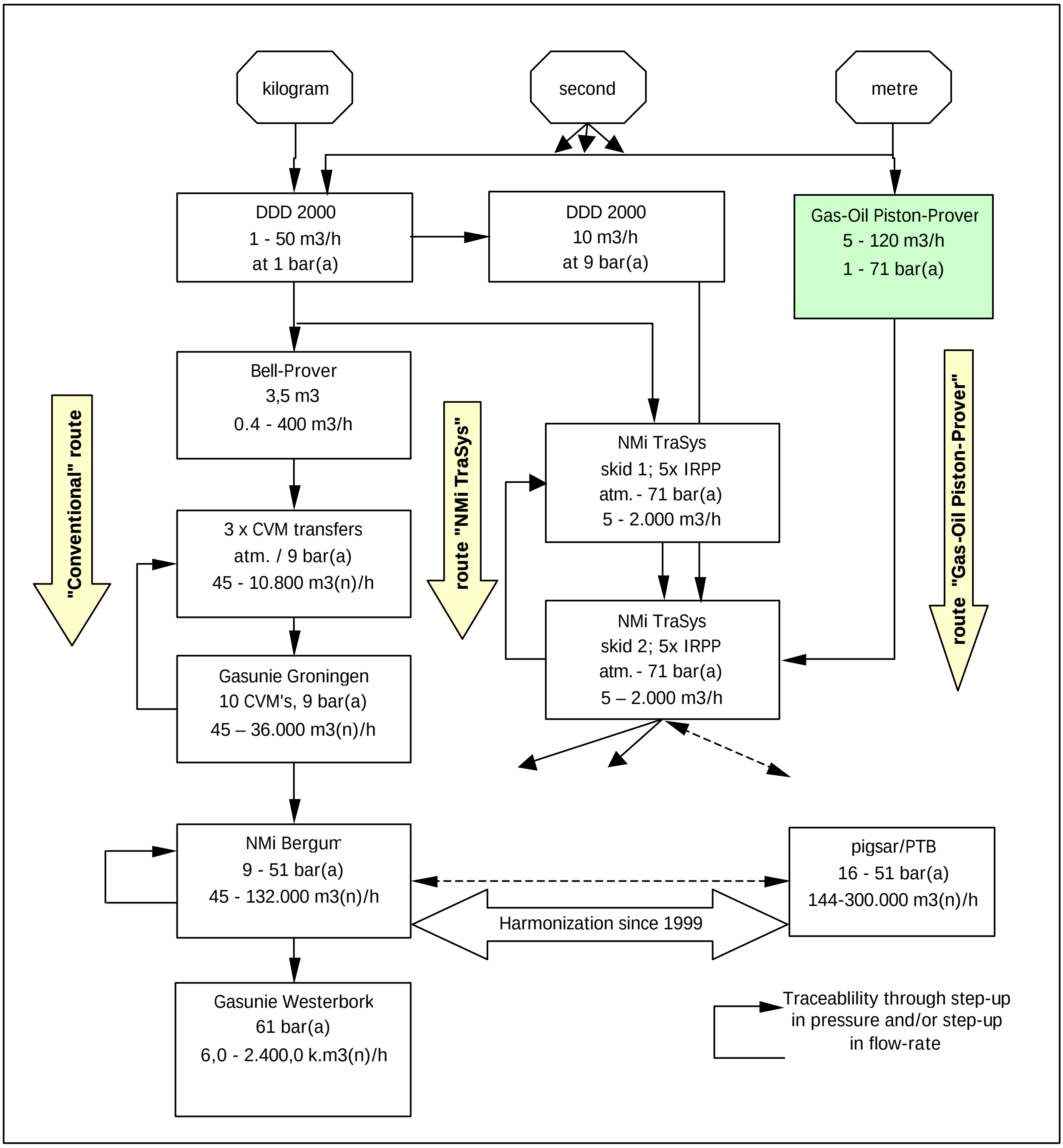


Figure 2, Three independent routes for traceability (sets of reference values)

The three sets of reference values can be harmonized on the basis of quadratic weighing, according to

$$u_{harmonized} = \sqrt{\sum_{i=1}^{n} u_i^2\ w_i^2} \quad \text{and} \quad w_j = \frac{1/u_j^2}{\sum_{i=1}^{n} 1/u_i^2} \quad \text{(see also [8-12])}$$

in which 'j' stands for the number of the laboratory

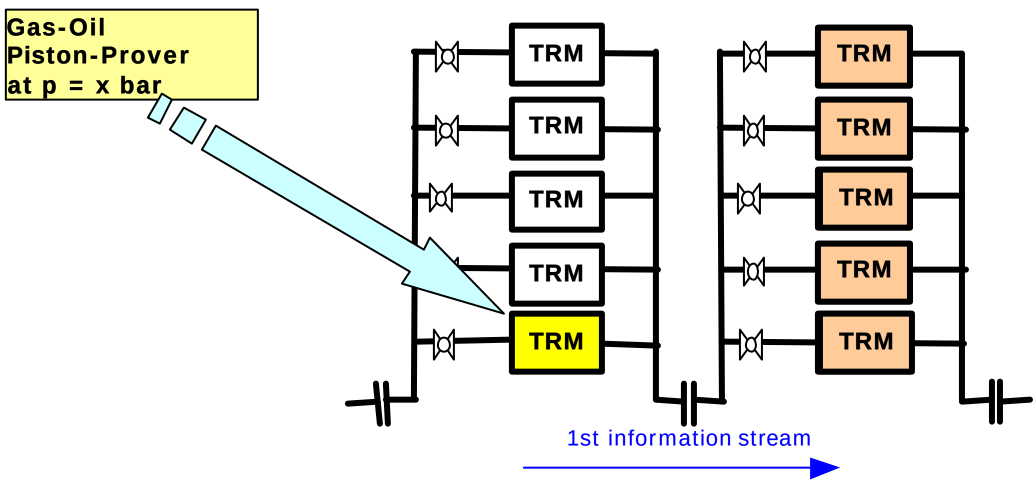
With n = 3 (total number of independent Dutch traceability-chains), u_1 = 0,18%, u_2 = 0,08% and u_3 = 0,05%, the weighing factors W_1, W_2 and W_3 are calculated to become 0,05 0,27 and 0,68 (if normalized to 1,00).
The crude harmonization uncertainty $u_{harmonized}$ = 0,04%. In the final CMC the long-term reproducibility of the particular chain as well as the uncertainty of the comparison has to be added.
Obviously, the uncertainty of the conventional chain (u = 0,18%) is hardly playing a role in the harmonized reference value (impact = 5%). However for the sake of redundancy and reliability, the more than 25 year operated conventional chain will be kept 'alive' as long as is needed to prove stability of the other two recently developed Dutch Traceability-Chains. "NMi TraSys" is intended to take over in time the function of the conventional chain.

DIRECT LINK TO "NMi TraSys"

General

While the maximum flow-rate of NMi GOPP is limited to 120 m^3/h, the step-up (boot-strapping) in flow-rate is a necessary additional step to create reference values at larger flow-rates. This could be done at suitable other test-facilities. In the Dutch situation however "NMi TraSys" is scheduled for this purpose as it is intended as a carrier & multiplier for the unit of volume for high-pressure Natural Gas. In only two boot-strapping steps, the volume flow-rate is enlarged in "NMi TraSys" to 2.000 m^3/h at any pressure between 1 and 70 bar.
Since NMi GOPP realizes reference values of gas volume at any desired pressure, theoretically no additional boot-strapping in pressure is required. One TRM of "NMi TraSys" is to be calibrated in one step directly at the desired pressure. However, in doing so, the 'physical connection' between the reference values at different pressure is lost, causing a source and contribution of uncertainty (by lack of information).
Thus, for the sake of redundancy and overlap in the traceability-chains, these pressure expansion-steps remain an essential element. The principles of boot-strapping and the consequences for uncertainty are extensively described elsewhere.

GOPP as source of independent information for boot-strapping in NMi TraSys



As can be seen in figure 3, with one TRM calibrated in GOPP, boot-strapping of volume to higher flow-rates is done in the parallel configuration of NMi TraSys.

Figure 3, Boot-strapping of volume with NMi TraSys

Each TRM can in turn be calibrated by GOPP (yellow TRM) and the data compared and evaluated against data obtained from previous boot-strapping processes of NMi TraSys itself. The operating efficiency of GOPP in relation to the advantages in reduced uncertainty will dictate what the final procedure will be.

SPECIFICATIONS OF THE SYSTEM

For the design of NMi GOPP, the following requirements have been specified

1. Straight-forward working principle, for transparent uncertainty analysis;
2. Smallest number of necessary boot-strapping steps afterwards in NMi TraSys;
3. Easy maintenance;
4. Transparent primary calibration method (realization of primary reference values);
5. Use of well-known principles or standardized methods;
6. Low risk of failure related to the working principle;
7. Acceptable cost;
8. Significant reduction of uncertainty at the high pressures.

The stainless steel-clad and precision-honed 600 mm cylinder / piston combination (length 12 meter) could be acquired with restricted initial investments. With respect to the requirement of limited risks in the projected development, NMi VSL-Flow is familiar to work with liquid flow control systems to maintain uniform piston velocities. The Micro-Flow installation in the low-pressure gas-flow facilities in Dordrecht, The Netherlands is equipped with a similar device.

Disadvantages of the conventional system, if compared to capabilities of GOPP

- Long traceability-chain. From the Basic Verification System to the facility in Bergum (50 bar) an uncertainty of 0,28% is accumulated;
- Re-calibration cycle is carried through three different facilities, causing in total a considerable amount of down-time;
- Handling a vast amount of different Travelling Reference Meters is time consuming (logistics, risks of accidents);
- Lots of steps leading to lots of labour and lots of data-handling;
- Complicated method, many possibilities to go wrong;
- Planning, scheduling to perform the re-calibration tasks is dependent on availability of each facility and personnel, and time lags during the projected cycle is at times difficult to avoid.

Technical features of NMi GOPP

The final design has the following specified features :

1. Minimum to maximum flow-rate at actual conditions : 5 m^3/h to 120 m^3/h;
2. Operating conditions : All types of gas at 1 to 90 bar, at ambient temperature conditions;
3. Easy exchange of Travelling Reference Meters (use of cartridges);
4. Easy to pressurize the closed circuit via a gas booster pump or from gas cylinders;
5. Flow control by means of both centrifugal speed control and Oil-flow control valve;
6. Smooth velocity control of the piston due to control of hydraulic flow;
7. Data-Acquisition System (DAS) reading : LF pulses from inductive proximity switches for the piston and HF pulses from the Meter under Test; temperature; p signals and delta-p signals;
8. A transportable system (ca. 20 tons, skid dimensions 12 * 2,5 * 2,5 metres);
9. Leak detection of piston-seals during travelling of the piston.

Before engineering of the modification, the following steps were carried out to minimize risks

- Evaluation and up-scaling of a comparable hydraulic flow-rate control system (Using data of NMi Micro-Flow installation, a primary standard working with flowing mercury and water);
- A simulation calculation programme was developed for the inventory of risks.

The complete technical design is described in the next sections.

GENERAL DESCRIPTION OF NMi GOPP

The Gas-Oil Piston-Prover is built on a 12 metre long transportable skid and weighs approximately 20 tons. The 12 metre long primary cylinder is positioned 2° out of the horizontal plane. The purpose of this angle is that possible piston seal leakage will soon become visible and can be quantified at both ends of the cylinder. The difference in height between the Gas & Oil container and the cylinder is chosen such that a passive return stroke of piston and oil is guaranteed. In this way expensive return flow-valves are avoided, further more, passive flow is advantageous for fast temperature equilibration after the measurement stroke is finished. It is advantageous to restrict the running time of hydraulic pump for reasons of heat generation by the pump. The worst case of oil heating due to the pump and electromotor heat generation is estimated at 0,01 °C per measurement run or piston stroke. Probably this drift in temperature cannot be observed due to the large surface of the container.

Figure 4, Side View

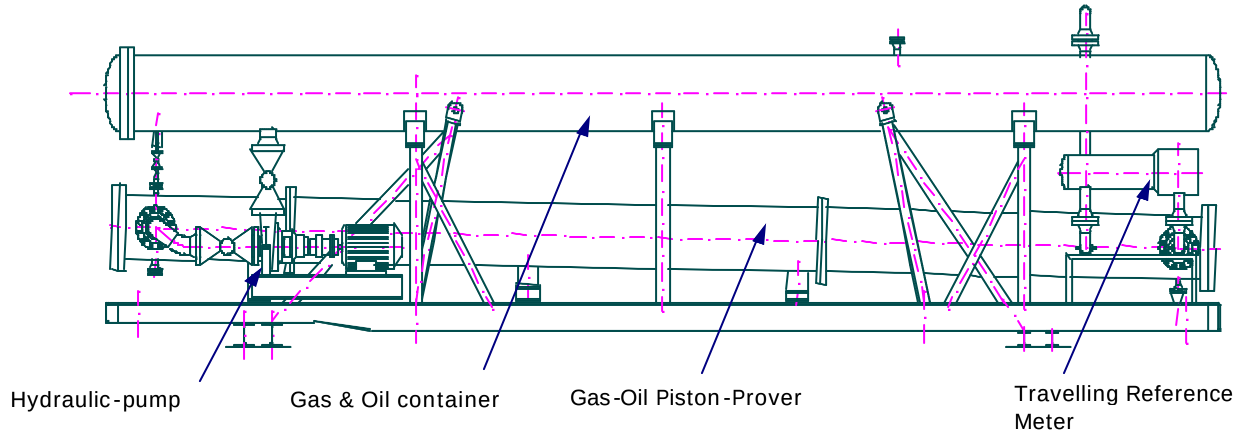
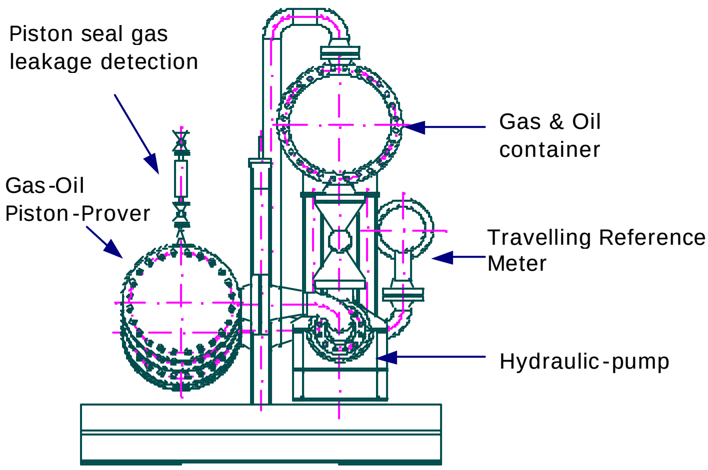


Figure 5, Front View, pump side



The hydraulic pump is specially designed for its purpose. Standard solutions were not available because at the suction side of the pump a line pressure up to 70 bar can be present. This requires a special seal around the pump shaft. To avoid possible pulsations of the pump, a centrifugal type was selected. The pump speed can be varied from 150 to 1.450 rpm.

The pump characteristics show a 1 bar pressure head at zero flow to about 0,3 bar at 120 m^3/h.

For hydraulic oil, a low viscous, low vapour-pressure mineral oil (Shell-Diala DX) is used.

A disadvantageous property of Oil is the solubility of Natural Gas (or hydro-carbon gases). When the system has to be depressurized, it has to be done very slowly to avoid foam generation caused by Natural Gas escaping from the Oil. At constant pressures the dissolved Natural Gas has no adverse effects on the uncertainty of the primary standard, but is of course taken into account. The oil-film that will appear after one travelling stroke of the piston is quantified at a thickness of 0,005 mm. The diameter of the cylinder will be corrected for this film dimension. The determination of this small amount of oil-film is done practically by weighing the mass of oil, collected on a clean cloth during cleaning of the inner wall of the measuring chamber.

PROCESS AND INSTRUMENTATION DIAGRAM AND FEATURES OF THE DATA-ACQUISITION SYSTEM

Simplified Process and Instrumentation Diagram is shown next

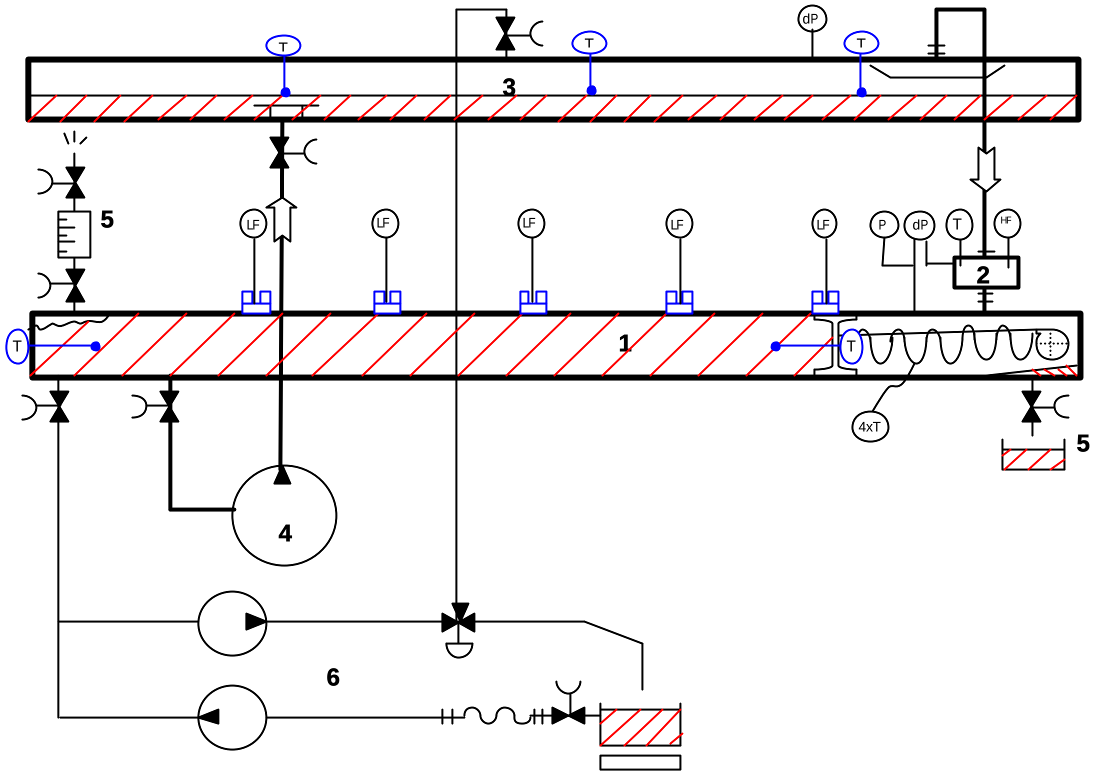


Figure 6 , GOPP - Process and Instrumentation Diagram

Legend at figure 6

1. Oil-side of the measuring cylinder
2. Travelling Reference Meter
3. Oil and Gas container
4. Hydraulic pump
5. Piston seal leak detection at Oil-side and Gas-side
6. Oil-draw setup for primary calibration of the reference volumes
7. Gas-side of the measuring cylinder. Equipped with equidistant temperature sensors

A Data-Acquisition System with sophisticated timing counter gates ensures proper collection of HF-pulses, LF-pulses, absolute pressure data, pressure difference signals and PT100 type of sensors. The timing and pulse counting of the HF signals will be carried out with a hard-ware gated counter-system to ensure proper interpolation between low and high frequent signals to avoid timing and pulse errors. As a result of this technique, in principal, no pulse round-off, or timing error is anticipated. The pressure difference between TRM and reference measuring chamber is not more than ca. 10 mbar so that differences in compressibility can be neglected.

Special attention was paid how to determine the average reference temperature of the measuring chamber. At four equidistant spots along the centre-line of the cylinder, temperature readings can be taken. Four light-weight fast-response temperature sensors are attached to a signal cable that slides along a flexible steel cable with smooth runners. The tension of the steel cable is controlled by a reel to ensure constant distance of the cable, and inherently of the temperature sensors, in relation to the inner wall of the cylinder.

Figure 8, Detail of the steel cable reel and one fixed temperature sensor

Figure 7, Detail of piston bottom, dampener legs, runner, signal cable and one fast temperature sensor

Figure 9, Overview of the naked piston, gas-sided piston-damper and temperature sensor moving configuration assembly

SPECIFIC ENGINEERING CONSIDERATIONS, SIMULATION PROGRAMME

Start and stop dynamics, expected stability of temperatures and pressures

In this section, the expected dynamic behaviour of the apparently simple system will be discussed. At first glance, the positive displacement meter, here a rotary piston gas-meter is coupled to a system that generates flow. From experience it is known that a free moving piston between two moving gas-masses will behave like a mass-spring system. At certain flows, depending on the smoothness of the contact between piston and cylinder, slip-stick effects and piston-mass inertia, etc., severe oscillations of the piston as well as in the Meter-under-Test could be generated. By filling one side of the cylinder with liquid, the stiffness of a hydraulic coupling between piston and flow generator is created. Unfortunately, nothing is for free, ("Law of Conservation of Misery") and the problem will now be focussed at another element of the system, viz. the rotating piston of the gas-meter. This element will behave exactly like the conventional translating piston in a cylinder, although the inertia of mass is smaller. A large effort was made to understand the expected dynamics of the system. The next diagram shows the flow-chart with expected dynamics that has been developed to realise a simulation program (see Figure 10).

Some specific results of the simulation assessment,

1. The smaller the (dead) gas-volume, the higher the oscillation frequencies;
2. Small diameter of gas lines improve the dynamics of the enclosed gas-volumes due to friction but gas pressure differences will increase and inherently restrict the maximum range of the flow-rate;
3. The inertia mass and cyclic volume ratio of the PD-meter have a direct relation with the oscillation frequency;
4. The impact of pressure loss of the PD-meter is negligible with respect to the dynamic behaviour;
5. The pump characteristics are decisive for the equilibrium response-time and the final flow-rate;
6. Impact of seal-friction and mass of the piston is negligible, so slip-stick effects do not play a significant role.

Other remarks are,

Three reference statements are valid during any time of the process-simulation i.e.,

1. Total mass of Gas in the system is constant;
2. Total mass of Oil in the system is constant;
3. In the whole system at any time : SUM (p * V) = Constant

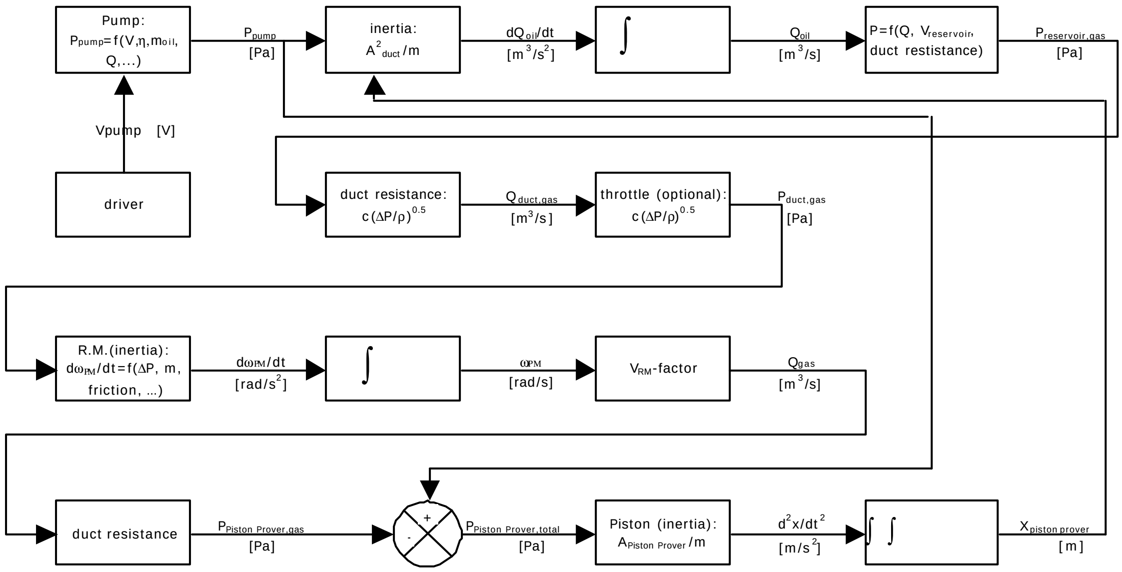


Figure 10

In the presented diagram, the relations between the various physical elements are shown. A detailed discussion will be published at a later moment in time. The purpose of the diagram is to give an idea of the several parameters and their impact on the dynamic behaviour of the prover.
In the diagram, the control loop is initiated with the start-up of the centrifugal pump (upper-left block). With real data of inertia of mass, cyclic volume of rotary gas-meter, static and dynamic friction, pressure-drop of the Meter-under-Test and the pump characteristics, the next situations were checked

1. Result when the pump is started in one time (step-controlled) at 32 Hz (Q = 72 m^3/h);
2. Result when the pump is started smoothly (ramp-controlled) from 14 to 32 Hz in 10 sec.

The next graph shows the behaviour of the rotary gas-meter. Oscillations are clearly present during the first part of the 120 seconds piston run.

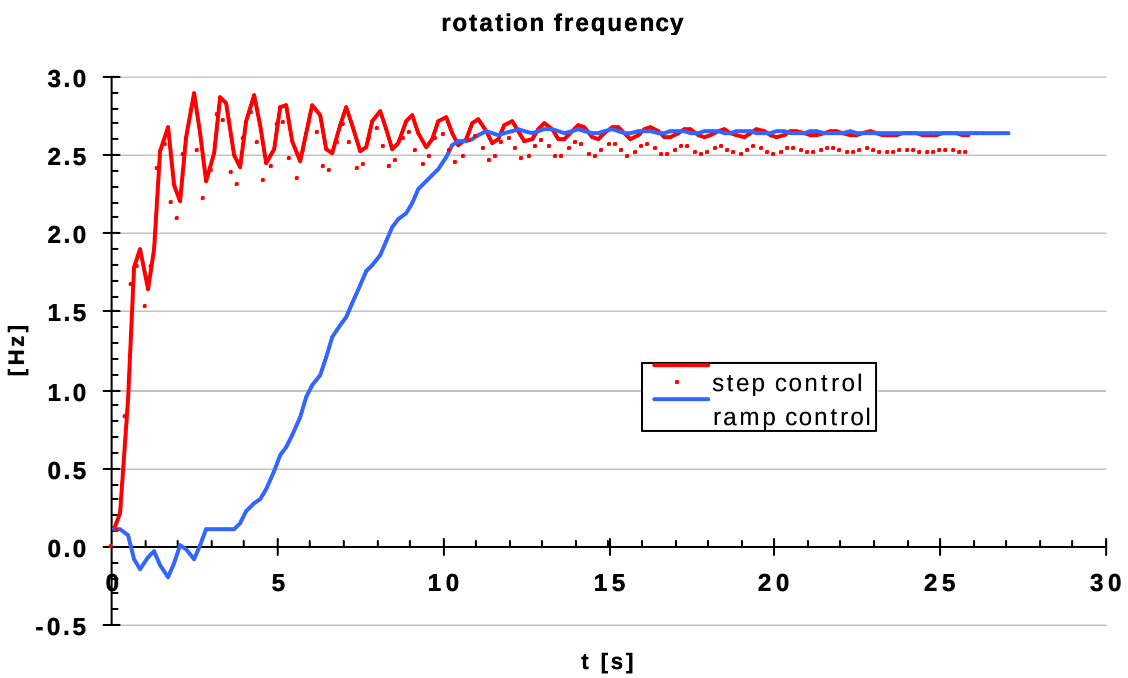


Figure 11, Simulated data of Rotary gas-meter dynamics at start-up

Obviously, a smooth start of the pump improves the dynamical behaviour after start-up considerably. Keep in mind that in the first 3 seconds of the ramp start-up, the oil is flushing back into the cylinder while at the same moment the pump head pressure is not yet able to compensate for the 2 meter pressure height of the oil, at the bottom level of the container.

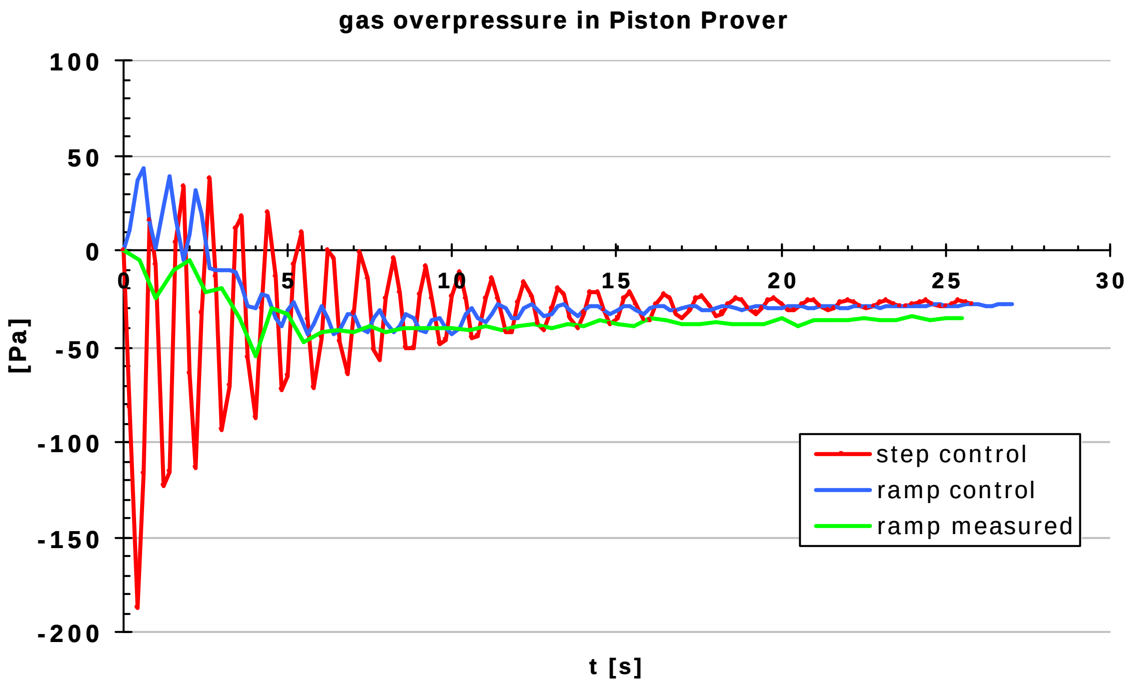


Figure 12, Simulated and measured data of cylinder gauge-pressure at Start-up

The graph shows the gauge-pressure inside the measuring chamber of the piston-prover. The smooth ramp start-up of the pump speed has a positive effect on the dynamic behaviour of the pressure as well.

Leak detector system for the piston seal

A general prerequisite for a piston-prover to operate properly is to prove an absolutely leakage-free performance of the seals. One advantage of using liquid as separator of gas is the possibility to quantify eventual present leakages of piston-seals during test-measurement runs. Up till now, with a Gas-Gas Piston-Prover it is complicated to prove an absolutely leak-free dynamic operation. Mostly, results of static leak-tests are accepted and an estimate of possible dynamic leaks will show-up in uncertainty budgets. In the Gas-Oil system however, possible oil leaks will accumulate at the lowest point in the gas measuring chamber, can be drained with a special valve, and be quantified.
At the highest point in the cylinder in the oil chamber, accumulated gas due to leaks can be quantified as well. A level-indicator is emptied and the change in level during flushing is measured.

FIRST MEASURING AND EVALUATION RESULTS

Set-up of the Test

In the periods September 2002 and March 2003, NMi GOPP has been tested in 'Dordrecht', the low-pressure gas test-facilities of NMi VSL-Flow. The goal of these tests was to evaluate the handling procedures, the performances in repeatability, temperature stabilisation times, velocities and movements of the piston, the flow-control system and the comparison with the results of the simulated dynamics. For practical reasons (dimensions and weight), GOPP was tested outside the laboratory under a shelter in the open Air. GOPP has been operated and tested at atmospheric conditions.

Reproducibility of test results with a duo-rotary piston meter at atmospheric conditions

The first evaluating tests focussed on the behaviour of the rotary gas-meter. Dozens of repeated piston-runs were made at several operating speeds and at different weather conditions. In the next figure, the standard deviation of accumulated pulse test data from the output of the rotary meter are shown. Each test was repeated over 10 times. The pulses were gated with the LF signals of the cylinder proximity switches at each 5 discrete reference volumes of the prover.

The readings are not corrected for possible dp and/or temperature differences between rotary meter and measuring chamber. From the results it can be concluded that the reproducibility of the system is excellent. When temperature and pressure corrections are applied and the timer/counter interpolation method is used, even smaller repeatability is expected.

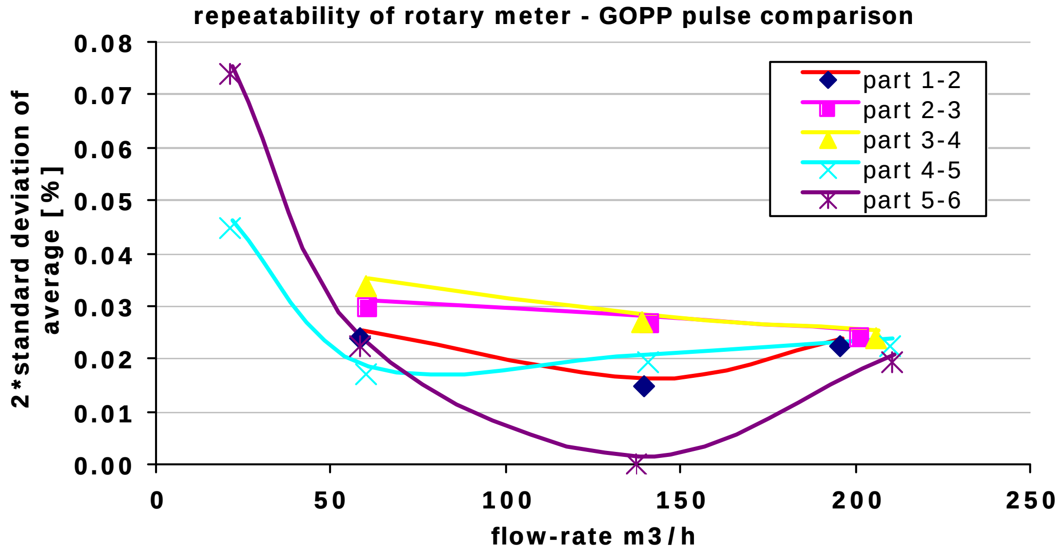


Figure 13, first tests of reproducibility

At low flow-rates, an increased repeatability is observed. Probably an impact of differences in temperature are observed while at the tests, pump speed was set to the maximum and the flow-rate was restricted with a regulating valve. Also the dead volume between partition 5 & 6 and the TRM has a maximum value in that condition.

Temperature stability

Set-up of the Test.

Five temperature sensors (fast response type) were used to demonstrate the temperature stability of the system during operation at atmospheric conditions. As mentioned before, the GOPP is placed in the open Air under a simple roof.

In the next figures, results of dynamic temperature measurements of the temperature inside the container, at the gas entrance, at a position of ca. 0,25 of the measuring chamber and at a position close to the piston, are given.

In the test-program a new test-run was started every 5 minutes while the test-run itself took 2 minutes to complete. The response of the temperature sensors during the 120 seconds (2 minutes) lasting piston stroke is shown.

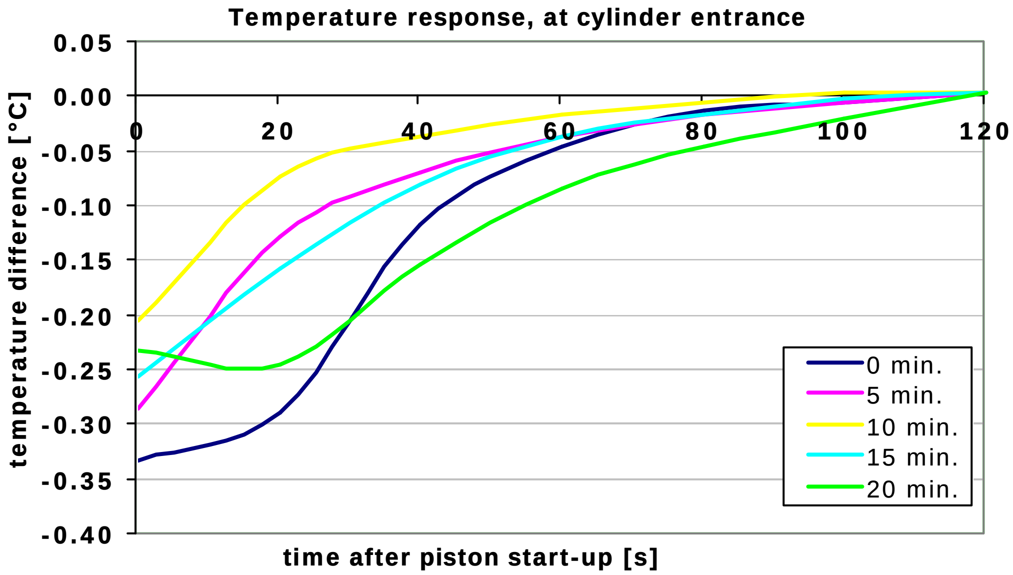


Figure 14

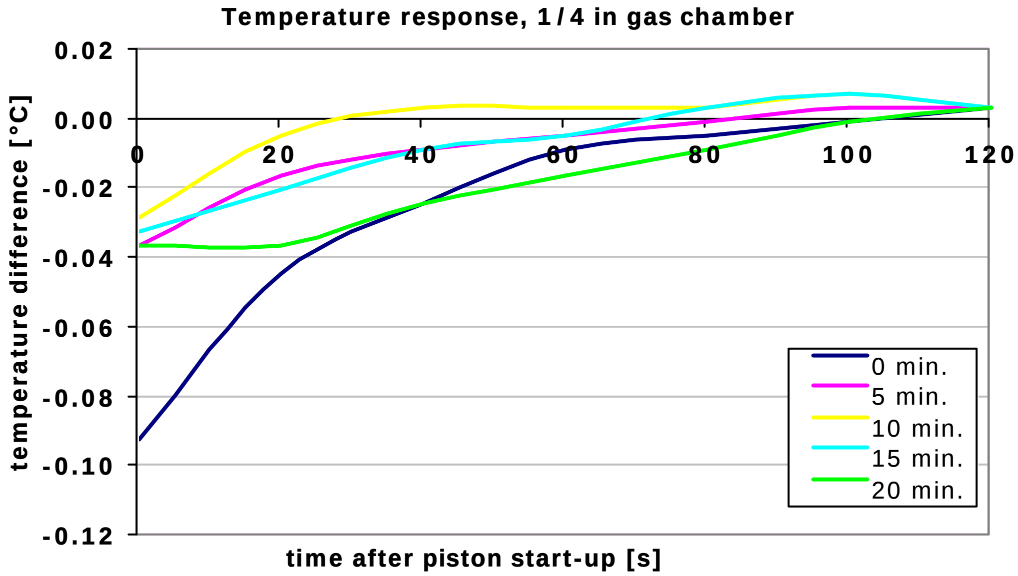


Figure 15

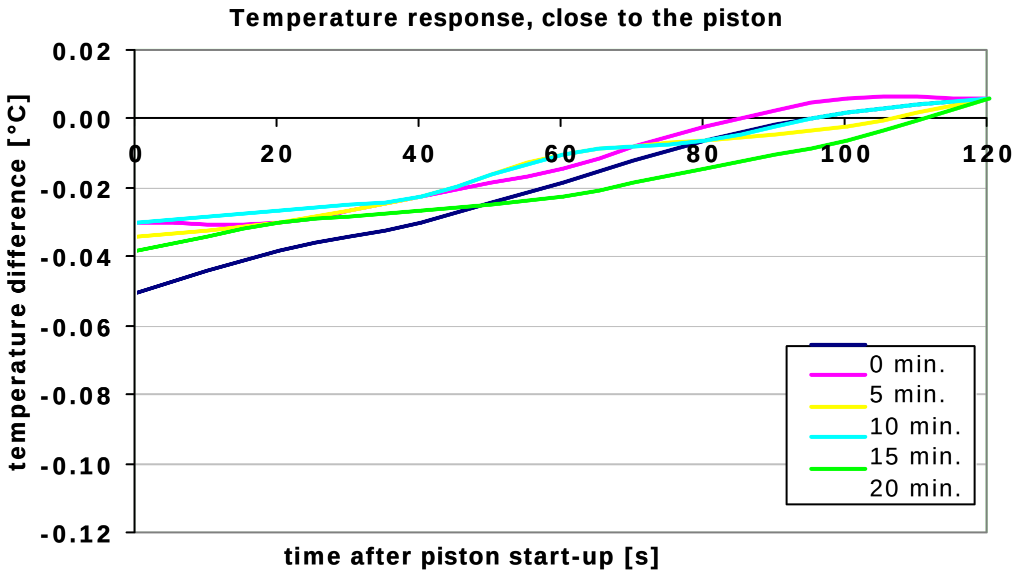


Figure 16

Comparison of the dynamic behaviour of the process with the results of simulation
In figure 12, the readings of a fast response pressure transmitter are compared with the forecast of the simulated dynamic response of the system. The indications of the gauge pressure inside the GOPP fits within 10-20% of the estimated values. Keep in mind that in real operation, the piston will not move in the opposite direction. This is prevented by the damper. The performance of the simulation program is accepted to be used for fine-tuning purposes, modifications or complete new designs of Gas-Oil Piston-Provers.

Conclusion
GOPP can probably be operated in open Air as long as temperature differences between container and cylinder can be kept as small as 0,2 °C. Temperature-differences can be minimized by isolating container, cylinder, Meter-under-Test and main piping from ambient temperatures. At this moment, no additional air-conditioning system is planned while meters will be tested at ambient temperatures. Maybe it would be advantageous in the future, to operate GOPP in a laboratory with strict temperature control in which no significant differences between temperatures of container and cylinder are present.

FUTURE WORK

NMi VSL-Flow is scheduling to repeat the tests shown in the previous sections at elevated pressures and to evaluate and to validate the long-term stability of the operation of GOPP. Furthermore, calibrations will be carried out to obtain reference values at selected pressures that give direct links to the conventional cycle (scheduled for November 2003). NMi VSL-Flow intends to keep the Flow-community informed about the measuring results and uncertainty analysis.

ACKNOWLEDGEMENTS

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