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An ultra high-pressure test rig for measurements of small flow rates with different viscosities

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ABSTRACT

Within the framework of a research project regarding investigations on a high-pressure Coriolis mass flow meter (CMF) a portable flow test rig for traceable calibration measurements of the flow rate (mass - and volume flow) in a range of 5 g min^{-1} to 500 g min^{-1} and in a pressure range of 0.1 MPa to 85 MPa was developed. The measurement principle of the flow test rig is based on the gravimetrical measuring procedure with flying-start-and-stop operating mode. Particular attention has been paid to the challenges of temperature stability during the measurements since the temperature has a direct influence on the viscosity and flow rate of the test medium. For that reason the pipes on the high-pressure side are double-walled and insulated and the device under test (DUT) has an enclosure with a separate temperature control. From the analysis of the first measurement with tap water at a temperature of 20 °C and a pressure of 82.7 MPa an extensive uncertainty analysis has been carried out. It was found that the diverter (mainly due to its asymmetric behaviour) is the largest influence factor on the total uncertainty budget. After a number of improvements, especially concerning the diverter, the flow test rig has currently an expanded measurement uncertainty of around 1.0% in the lower flow rate range (25 g min^{-1}) and 0.25% in the higher flow rate range (400 g min^{-1}) for the measurement of mass flow. Additional calibration measurements with the new, redesigned flow test rig and highly viscous base oils also indicated a good agreement with the theoretical behaviour of the flow meter according to the manufacturers' specifications with water as test medium. Further improvements are envisaged in the future in order to focus also on other areas of interest.

1. Introduction

In many complex applications regarding corrosion control and lubrication it is required to inject liquids, e.g. additives, with high accuracy into high-pressure lines. For instance drilling fluids [1–3] or additives with a wide range of viscosities are used for deep-sea drilling not only to lubricate [3–6] but also to improve the drilling performance [7–9] and the stability of the wellbore [10–17]. Especially for offshore oil drilling the additives need to be delivered at high pressures (e.g. 10 000 psi reservoir pressure or more) due to deep drilling depths. Typically the flow rates and quantities of additives are measured with a Coriolis mass flow meter (CMF). Special high-pressure CMF for this type of applications is available on the market [18–21] but there was – until recently – no suitable test facility for direct calibration available. Commonly the used CMF is calibrated on test facilities with known uncertainties but at low pressures and in water at ambient temperature as a test medium. Subsequently correction methods [22–25] based on theoretical considerations are used to adjust the calibration factor of the CMF to the expected process condition. This approach leads to a relative high uncertainty in the case of flow rate measurement. To improve the present situation and to enable high accuracy measurements SP *Measurement Technology* (MT) has built a unique test rig with which is now possible to calibrate flow meters directly under process conditions. A reliable and validated measurement uncertainty budget is to be developed. The main parameters of the test rig are shown in Table 1. Besides these specifications, measurements with e.g. higher viscosities are possible, but for reasons of temperature stability and allowing for pump limitations there are restrictions regarding higher flow rates and lower temperatures.

2. High-pressure test rig

The main idea was to build a portable flow test rig in order to have the possibility to perform also other essential tests, e.g. electromagnetic compatibility (EMC) tests, besides the flow

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Nomenclature

E (–)	error of the measurement
K (–)	the k-Factor of the DUT (pulse valence)
I (–)	scale value (display of the balance)
a (–)	coefficient
$m_{cont.}$ (kg)	collected mass (continuous measurement)
$\dot{m}_{cont.}$ (kg s^{-1})	mass flow rate (continuous measurement)
$m_{int.}$ (kg)	collected mass (interval measurement)
$\dot{m}_{int.}$ (kg s^{-1})	mass flow rate (interval measurement)
n (–)	number of diverter switchings
n_0 (–)	number of counted pulses
$t_{cont.}$ (s)	time of a continuous measurement
$t_{int.}$ (s)	time of an interval measurement
Δt (s)	time error of the diverter
δn_0 (–)	uncertainty of pulse counting
δI_{rep} (kg)	repeatability of the balance
δI_{cal} (kg)	calibration uncertainty of the balance
δI_{drift} (kg)	drift uncertainty of the balance
δI_{conv} (kg)	convection effect from the surrounding air
ρ_a (kg m^{-3})	density of air
ρ_{ref} (kg m^{-3})	density of reference weight
ρ_l (kg m^{-3})	density of test liquid (test medium)
δ_{repr} (kg)	the spread from five repeated samples
δ_{leak} (kg)	leakage and cavitation effects
δ_{div} (kg)	diverter asymmetry in certain situations
δ_{buff} (kg)	buffer effects due to temperature instabilities
δ_{loss} (kg)	losses due to evaporation and splashes
δ_{del} (kg)	completely emptying of delivery line
χ^2-test	chi-squared test
CMF	coriolis mass flow meter
CNG	compressed natural gas
DUT	device under test
EMC	electromagnetic compatibility
GUM	guide to the expression of uncertainty in measurement
MT	SP department of 'Measurement Technology'
SNR	signal-to-noise ratio
SP	Technical Research Institute of Sweden

calibration. A portable flow rig has also some advantages regarding manageability and space requirement.

2.1. Measurement principle

The measurement principle of the new high-pressure test rig is based on the gravimetric weighing principle according to the standard DIN EN 24185 [26] with flying-start-and-stop [27] as the mode of operation. This means that the determination of the volume - or mass flow rate by a meter, the device under test (DUT), is traceable by weighing. In the process, a fluid from the reservoir tank is delivered by a pump through the pipelines, the device under test (DUT), and returns via the switching device (diverter) back into the reservoir tank in a closed-loop cycle. After a certain time, when steady flow has been reached, the diverter will be switched. From now the medium does not flow back into the reservoir tank but fills a collecting vessel. When the collecting vessel has reached a certain level, the diverter will be switched back, the fluid is redirected back into the reservoir tank and the cycle is closed-loop again. After the equilibrium of the weighing scale has been reached (static weighing procedure) with respect to the measured time of the filling process and the mass, the density of the medium in the weighing container, the volume rate and the volume can be determined. Afterwards this volume will be compared with the volume from the accumulated volume pulses of the DUT. The deviation between these two values finally indicates the measurement error. In this application the major advantage of the CMF as mass flow device, is the possibility of direct comparison of the accumulated mass pulses from the DUT with the weighed weight, that means without having to consider the density and temperature as influence factors during the measurement.

Table 1
Overview of the specifications of the high-pressure test rig.

Parameter	Specification
Liquids	Water, water–glycol mixtures, base oils
Line pressures	Up to 85 MPa
Flow rates	5 g min^{-1} to 500 g min^{-1}
Temperatures	10 °C–40 °C
Viscosities	0.1×10^{-6} m^2 s^{-1} to 50×10^{-6} m^2 s^{-1}

According to the standard DIN EN 24185 [26] the flow measurement has to be traceable and linked to the *SI*-units such as mass, time, density, pressure and temperature. In this case only a complete traceability chain of the involved measurands ensures the accuracy of the calibration measurements. For that reason a comprehensive measurement uncertainty budget of the test facility is required. In order to avoid the adverse influence of the flow meter due to variations in pressure and above all temperature, or rather density and viscosity during the measurement, the stability of the test rig should be as high as possible. Changes of the external measurement conditions can lead to inaccurate measurement results and have consequently a significant influence on the calibration of a flow meter.

2.2. Operating principle

The operating principle of the high-pressure test rig including the used equipment is described in Fig. 1.

From the storage tank (1) the fluid is delivered to the high-pressure pump (3) passing a filter (2). The pressure level of the high-pressure pump is controlled by compressed air between 0 bar and 7 bar in the pneumatic part corresponding to 0 bar to 1000 bar in the liquid line. The device under test (DUT) (5) is installed and housed in a case on the high-pressure side. The line pressure is measured both before and behind the DUT by means of two pressure gauges (digital (4) and analogue (6) display). The flow rate is controlled by the use of two regulating valves (needle valves) (7) in series. Behind the valves the fluid flow is directed in either of two lines by the use of a diverter (8). In the first conception of the test rig the diverter was controlled by two valves driven by compressed air. In one direction, the return line, the fluid flows back to the storage tank, which means the fluid circulates in a closed-loop cycle. In the other direction (measurement situation) the fluid leaves the pipe system filling a sampling container. The mass pulses of the DUT are processed by a measuring converter (9) and counted by a pulse counter (10). A comparison between the accumulated mass pulses during the test and the collected mass of the fluid in the sampling container, including a number of corrections (e.g. buoyancy effect), results in the measurement error of the DUT. The temperature of the fluid can be controlled in a temperature range between −10 °C and 50 °C with a cooling and heating bath (11). A fan control (12) makes it possible to regulate the speed