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Investigations on pressure dependence of Coriolis Mass Flow Meters used at Hydrogen Refuelling Stations

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Abstract

In the framework of the ongoing EMPIR JRP 16ENG01 "Metrology for Hydrogen Vehicles" a main task is to investigate the influence of pressure on the measurement accuracy of Coriolis Mass Flow Meters (CFM) used at Hydrogen Refueling Stations (HRS). At HRS hydrogen is transferred at very high and changing pressures with simultaneously varying flow rates and temperatures. It is clearly very difficult for CMFs to achieve the later expected legal requirements in relation to the demand for accurate mass flow measurement at the measurement conditions at HRS. It was observed, mainly due to the very dynamic filling process, that the accuracy of mass flow measurement at different pressure ranges is too inaccurate. Particularly at higher pressures it was found out that especially short refuelling time causes significant measurement deviations. On this background it can be concluded that the medium pressure has a great impact on the mass flow measurement accuracy. To gain a deeper understanding of this matter RISE has built a unique high-pressure test facility. With the aid of this newly developed test rig it is possible to calibrate CFMs over a wide pressure and flow range with water and base oils as test medium. The test rig allows calibration measurements under the conditions prevailing at 70 MPa HRS regarding mass flows (up to 3.6 kg min^{-1}) and pressures (up to 87.5 MPa).

1. Introduction

To achieve the 2050 long-term goal of reduction of greenhouse gas emissions by 80-95% compared to the 1990 level, both the utilization of renewable and carbon-free energy carriers and the energy efficiency need to increase substantially over the next decades. This is particularly important for the transport sector which accounts at present for around 60% of the global oil consumption. To achieve these long-term climate objectives, the future of transport necessarily lies in the complete replacement of currently prevailing fossil fuels and electrification by renewables with zero emissions.

In general, electromobility is understood as electric drive with a power supply from a rechargeable battery. However, fuel cell electric vehicles (FCEV) are also used for electromobility, whereby the fuel cell (FC) is used as an energy converter and the energy store is a hydrogen tank. In a hydrogen-powered vehicle the compressed gaseous hydrogen (CGH2) is stored at high pressure (up to 70 MPa) in the tank. By separation of energy storage and energy converter significantly higher energy densities and thus ranges are possible.

The refuelling of a 70 MPa CGH2 vehicle at a hydrogen refuelling station (HRS) is completed within a few minutes. From high-pressure intermediate storages (e.g. 44 MPa and 95 MPa) the hydrogen is filled via pressure drop (overflow) into the vehicle tank. A passenger car with a typically tank capacity of around 5 kg can be filled in around 3 min according to SAE J2601. While refuelling, the hydrogen and thus the vehicle tank is heated significantly. To avoid this the so-called cold filling procedure is used. In this case the hydrogen is pre-cooled (down to -40 °C) before filling, e.g. with liquid nitrogen.

For monitoring the amount of hydrogen dispensed into the vehicle at an HRS, a robust and accurate flow meter is required that can operate over a variety of flow and temperature ranges and pressures up to 87.5 MPa. OIML R 139-1 provides accuracy requirements for flow measurement of GCH2. The measurement of mass flow is typically performed using Coriolis Mass Flow Meters (CFM). CFMs measure, in contrast to many other methods, directly the mass flow independent of fluid properties, and are generally not very sensitive to changes in viscosity, temperature, and pressure.

2. Scope of application

Almost all HRS meet the requirements according to the SAE J2601 fueling protocol (see **Table 1**). The SAE standardizes the fueling process by defining limits for the relevant refueling parameters.

Table 1: 70 MPa Hydrogen Fueling Specification

Parameter	Limit
Min. gas temperature (pre-cooling)	-40 °C
Max. gas temperature (tank)	+85 °C
Ambient temperature	-40 °C to +50 °C
Min. tank storage capacity	2 kg
Max. tank storage capacity	10 kg
Min. pressure (tank)	0.5 MPa
Max. pressure (tank) => 1.25 · 700 MPa	87.5 MPa
Max. flow rate	60 g/s (3.6 kg/min)

A typical 70 MPa HRS consists of high-pressure storage tanks at different pressure levels, a compressor (e.g. diaphragm compressor, ionic compressor) to fill the high-pressure storage tanks or directly the vehicle tank, a heat exchanger (pre-cooler, refrigeration unit) and a dispenser which controls the flow into the vehicle tank. At fast filling the dispenser controls the flow in such a way, that fast filling of 5 kg hydrogen in 3 min (or 7 kg in 5 min, respectively) can be achieved. To avoid tank overheating during the filling process, due to rapid compression of the gas, the pressurized hydrogen is cooled down to -40 °C by the heat exchanger on its way from the high-pressure storage tank to the dispenser. But that also means the pressure in the vehicle tank exceeds 70 MPa (up to 87.5 MPa) at the end of the fast fill process to ensure a filling at 70 MPa after cooling down.

2.1 Refueling process at HRS

The sequence of operation of a refueling process is standardized. SAE J2601 states requirements for temperatures and the speed of fueling, specified by Average Pressure Ramp Rate, APRR (comparable with Constant Pressure Ramp Rate, CPRR) during the hydrogen refueling process. Compliance with this standard ensures fast and safe refueling. Before the actual refueling, the connections, e.g. between dispenser nozzle and vehicle tank are automatically checked by the system. Subsequently, the pressure in the vehicle tank and its volume is determined by an initial pressure pulse (pressure surge). Based on these values the temperature curve (expected gas heating), the target pressure and the APRR for a complete filling are calculated. The APRR depends on the vehicles tank pressure and temperature, pre-cooling temperature and the ambient temperature. In accordance to SAE J2601 there are two ways to calculate the APRR. The classical way (lookup table method) is based on tables which specify the APRR for the given vehicle tank storage capacity, initial tank pressure, station type (station pressure and delivery temperature), ambient temperature and communication capability between vehicle and dispenser. The newly developed second way (MC formula method) works relatively similar. In contrast to the lookup table method the MC formula calculates a Dynamic Pressure Ramp Rate (DPRR) using adaptive feedforward control based on the measurement of pressure and temperature at the dispenser. Here, the pressure target is continuously and dynamically calculated in order to minimize the fueling time. For both methods all parameters are checked during refueling to monitor that they are consistent with the fueling protocol. When the vehicle is filled to the target pressure the refueling process is stopped and the nozzle can be disconnected from the vehicle.

2.2 Flow measurement at HRS

At HRS hydrogen is transferred at very high and changing pressures, varying flow velocities (very low to very high) and varying temperatures but the mass flow measurement must be extremely accurate. As it can be seen, these conditions are not trivial and not many flow meters are eligible. It is generally expected that CFMs are well suited for refuelling with continuously variable pressures and temperatures. The CFM measures the mass flow directly and the integrated value is used as basis for the billing of the H2 supplied. There are mainly two different approaches for the installation of the flow meter (CFM). The CFM can either be installed before or after the pre-cooler. This implies the CFM measures the hydrogen mass flow at ambient conditions (at around 20 °C) or at a temperature of around -40 °C. In both cases the zero-point of the CFM is set once, namely during commissioning at the planned operating temperature, e.g. at -40 °C.

3. High-pressure test facility

3.1 Measurement principle

The measurement principle (see **Figure 1**) of the flow facility is based on the master meter method with flying start-and-stop. In this context a pair of two CFMs measures simultaneously, where one CFM is installed, as device under test (DUT), at the high-

pressure site and the other CFM, as reference meter (master meter), at the low-pressure site.
Afterwards, the positions of the CFMs are exchanged. Both CFMs were previously calibrated at low-pressure using one of the national standard flow facilities at RISE (Research Institutes of Sweden).

3.2 Operating principle

From one of the selected storage tanks (200 L and 1000 L, filled with deionized and filtered water) the water is delivered to the high-pressure pump (PARKER AHL66-2D series) (passing two filters. The outlet pressure of the pressure pump (see **Figure 2**) is controlled by compressed air using a 1” pressure regulator in a range from 0 to 100 psi (0 to 7 bar) which corresponds to 0 to 13300 psi (0 to 913 bar) in the liquid line.

Figure 1: Measurement set-up (high-pressure test facility) equipped with two CFMs from HEINRICHS.

The compressed air is delivered by house connection but for higher pressures a diesel-powered air compressor (Ingersoll Rand 7/41+, air flow 4000 L/min at 7 bar, max. air pressure 8.6 bar) was used. A compressed air tank (volume 270 m^3, max. pressure 11 bar, TIDAN-VERKEN AB) is filled in order to provide a regular supply of compressed air for the high-pressure pump. Downstream the air passes an air dryer (HANKISON SPX series) and a compressed air filter (HANKISON HF series). The high-pressure pump is connected by an 800 mm long DN 10 high-pressure hose (spiralized steel reinforced polymer hose, CEJN) in order to prevent a possible vibration transmission from the pump to the high-pressure test facility.

By use of a needle valve the undesired fluctuations in pressure due to the piston movement are damped. Directly after the first elbow, another needle valve is installed using a tee connection (bypass line). At the beginning the bypass line is used to get rid of air bubbles in the first part of the high-pressure site. The pressure before the CFM at the high-pressure site (DUT) can be set by means of a pressure regulator (TESCOM 54-2000 series) in the range from 1500 to 15000 psi (100 to 1000 bar). The pressure before and after the DUT is measured by means of two pressure transmitters (KELLER Leo 3) in the range from 0 to 1000 bar.

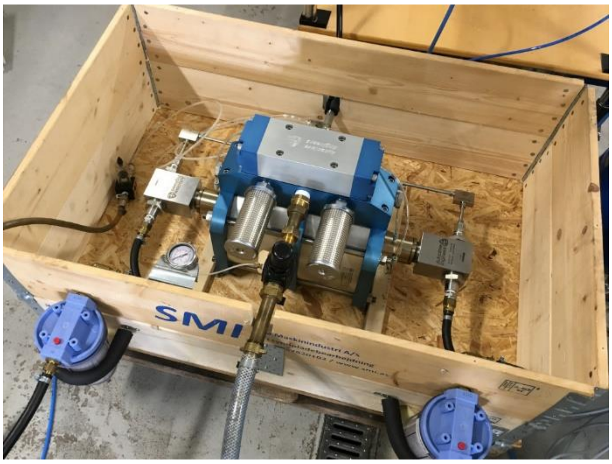

Figure 2: High-pressure pump PARKER AHL66-2D series.

To ensure an accurate detection of the zero-point, the DUT is installed between two completely leak-tight on-off ball valves, for symmetrical reasons, both with the same distance from the CFM. It is advisable to reduce the pressure in several steps to avoid an excessive pressure drop. For this reason, two further pressure regulators (TESCOM 54-2000 series) in the range from 1500 to 15000 psi (100 to 1000 bar) and 500 to 6000 psi (35 to 400 bar), respectively were installed. The pressure after these pressure regulators is measured by means of two pressure transmitters (KELLER Leo 3) in a range from 0 to 700 bar and 0 to 300 bar, respectively. The pressure upstream the reference meter (CFM at the low-pressure site) can be set by another pressure regulator (TESCOM 54-2000 series) in the range from 5 to 500 psi (0.35 to 35 bar) and measured by another pressure transmitter (KELLER Leo 3) in the range from 0 to 10 bara. In the normal case, the inlet pressure of the CFM used as reference meter is set to 5 bar, the pressure the CFM was calibrated at the national standard flow facilities. With the needle valve behind the reference CFM the flow rate is adjusted. All the pipework of the high-pressure facility has an outer diameter of 0.375" (9.5 mm) and an inner diameter of 0.203" (5.2 mm) using mainly 3/8" MP (medium pressure) C&T (cone and thread) connections. For the data acquisition a DAQ system developed by RISE (own hardware and software) has been used. The DAQ system provides four input channels for temperature, eight input channels for current and four input channels for pulse and frequency measurement (double-time chronometry). For each measurement point the line pressure was logged as 4-20 mA signal from the five pressure transmitters (KELLER Leo 3), the temperature from both CFMs as 4-20 mA passive current output and the finally the passive pulse/frequency output also from both CFMs.

4. Measurement results

4.1 Devices under test

There are not many high-pressure CFMs on the market. The devices (see **Table 2**) of the three leading manufacturers (outside Asia) will be investigated in the EMPIR project. For this reason, the manufacturers have provided some devices as in-kind contribution to the project.

Table 2: Overview of the investigated CFMs

Manufacturer	Sensor	Transmitter
RHEONIK	RHM04	RHE27
HEINRICHS	TM SH	UMC4
KEM KÜPPERS	TCHM0450	TCE8000

A higher line pressure leads in general to a stiffer measuring tube resulting in an underestimated mass flow rate. This effect is in general greater for larger size CFM and in theory negligible for very small flow meters. Also, most manufacturers state that the actual hydrogen temperature, and not the pressure, is one of the most important factors affecting the measurement accuracy. High pressures, however, present problems with the currently available flow meters. It is anticipated that CFMs do not achieve the necessary accuracies at higher pressures, and it can be assumed that particularly short refuelling time causes significant measurement deviations. Some manufacturers provide pressure compensation by manual input of the operating pressure (stable condition) or the possibility for real time compensation by adding an external pressure sensor to measure the actual pressure (unstable condition).

4.2 Measurements at low-pressure

Before the actual high-pressure measurements each individual CFM was separately calibrated with water as test medium at a temperature of 20 °C and an inlet pressure of around 5 bar by using one of the national standard flow facilities at RISE (Vattenmätbänk 7, VM7), see **Figure 3**.

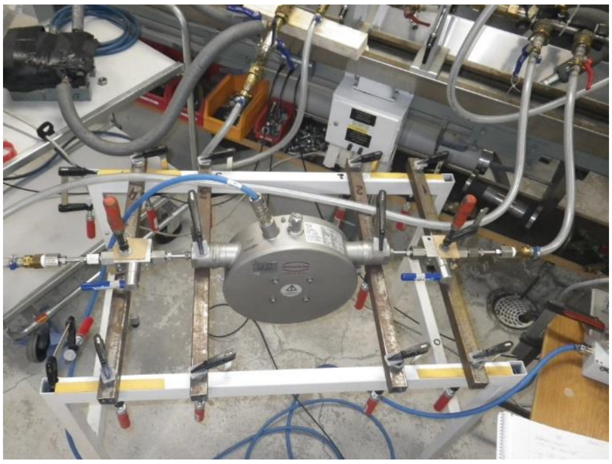

Figure 3: DUT calibrated at low pressure (HEINRICHS CFM).

For these measurements the (mass) frequency and pulse output was used. Before the flow calibration was performed, a zero-point adjustment of the DUT was carried out at the actual pressure (5 bar) and temperature (20 °C) conditions. After setting the new zero-point the pulses (while the low flow cut-off is shut off and without flow) were logged for 5 minutes to check how well the (automatic) zero-point setting performs.

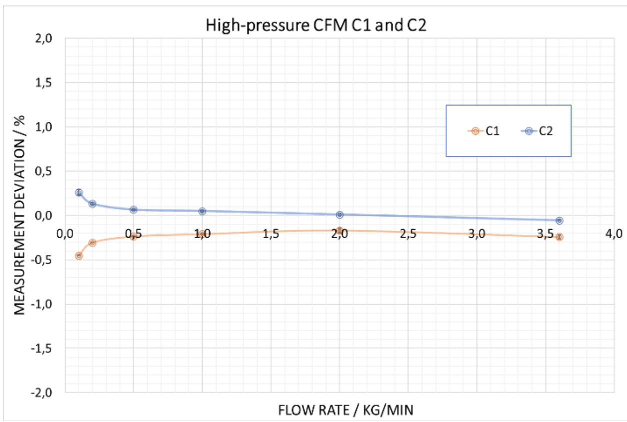

Figure 4: Measurement results for one of the three CFM pairs (C1 and C2) at low-pressure calibration.

The low-pressure calibration was performed at six different flow points (0.1 kg/min, 0.2 kg/min, 0.5 kg/min, 1.0 kg/min, 2.0 kg/min and 3.6 kg/min). For each flow point tested four repeated measurements were carried out, that means a total of 5 repetitions. The measurement results are shown in **Figure 4**.

4.3 Measurements at high-pressure

After the low-pressure calibration measurements were conducted in water (5 bar inlet pressure) one meter was used as reference meter at the low-pressure side (5 bar) and one meter as DUT at the high-pressure side (up to 850 bar). A generic test matrix regarding mass flow rates and pressures has been prepared. Initially, the mass flow rates were selected to cover the full operating range for a 70 MPa HRS (typically 3.6 kg/min). In sum, measurements were performed at the same six flow rates as for the low-pressure calibration at six different pressures (10 MPa, 25 MPa, 40 MPa, 55 MPa, 70 MPa and 85 MPa). Due to the limitations of the high-pressure pump the maximum mass flow rate at 55 MPa and 70 MPa (65 MPa) was 2.0 kg/min, and at 85 MPa (80 MPa) 1.0 kg/min respectively.

For the high-pressure testing we used the same zero-points as for the low-pressure calibrations. That means the flow meters were installed without setting a new zero-point. As it can be seen in **Figure 1**, the measurement setup the CFMs are installed in series with stiff metal pipe connections in between. In theory, vibrations from one CFM could be transferred to the other CFM via the pipework but also via the table. This would result in interference and erroneous mass flow rate measurements. To prevent vibration transmission through the table a wooden table was chosen, and shock absorbent rubber were placed under the CFMs connections. However, before the actual measurements were performed, we checked for crosstalk effects since we were not sure in all cases whether the CFMs worked at different driving frequencies. For this reason, the pulses obtain during zero flow (closed on-off ball valves upstream and downstream of each CFM) were compared for a certain period (e.g. 5 min) in case when both meters were supplied with power and in case when only one CFM was supplied with power. In addition, the same procedure was repeated at a constant flow rate. Here the totalized mass counter for one CFM was logged and compared for a certain period for the cases when the other CFM was switched on and off, respectively.

From the measurement result (see **Figure 5**) one could assume that there is a dependence of the flow rate measurement from the pressure. With increasing pressure, the measurement deviation is decreasing. However, attention should be drawn to the fact, not shown in **Figure 5**, that with increasing pressure also the temperature, especially for the reference meter at the low-pressure side, is increasing.

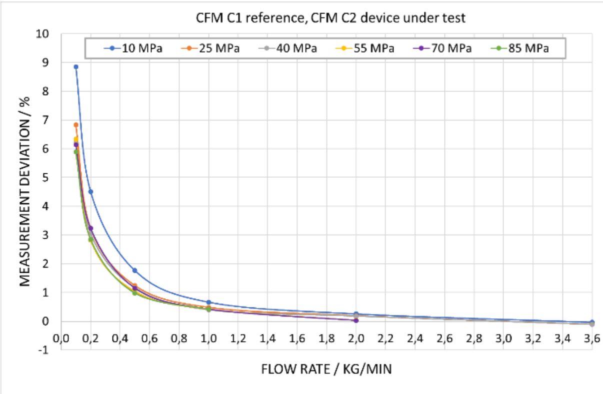

Figure 5: Measurement results at high-pressure for one of the flow meter pair (CFM C1 as reference, CFM C2 DUT).

It is particularly interesting to note that the temperature was quite stable at a certain pressure level during the measurements at different flow rates. But the temperature increased with increasing pressure values. Another effect was that the temperature at the place of the reference meter was depending on the compressed air supply. The compressed air supply was changed for higher pressures (usually after 400/550 MPa tests) from the house connection to the diesel-powered air compressor but some measurements (e.g. at 400 MPa) were performed with both configurations. Hereby it was established that the way of compressed air supply has an influence on the medium temperature at the place of the reference meter. The temperature measured at the place of the reference meter had, in some cases, a difference of up to 5 K depending on the compressed air was delivered by house connection or the diesel-powered air compressor (lower temperature). At the end in can be summarized that the temperature difference between 10 MPa and 85 MPa measurements was up to around 12 K (worst case) and that the measurement results need to be corrected regarding temperature to determine the pressure dependence of the mass flow rate. However, the desired correction regarding temperature requires more low-pressure calibrations in the temperature range of 20 °C to at least 30 °C.

5. Conclusion

A novel high-pressure flow test facility was built at RISE. With this facility it is possible to investigate the pressure dependence of Coriolis Mass Flow Meter (CFM) in a pressure range from 10 MPa to 85 MPa at flow rates in a range from 0.1 kg/min to 3.6 kg/min. Measurements were performed with CFMs from three different manufacturers. The achieved measurement results for one of in total three investigated pairs of high-pressure CFMs have been discussed. Summarized, it was shown that the conceived measurement setup works well. The only negative aspect is that the temperature at the place of the reference meter rises with increasing the inline pressure. Up to now low-pressure calibration were only performed at a temperature of 20 °C. However, it is possible to correct for the temperature effect and hence to separate the temperature and pressure effect, but this can only be achieved by additional traceable low-pressure calibration measurements at slightly elevated temperatures (e.g. up to 30 °C). In the next step additional low-pressure calibrations in a temperature range of 20 °C to 30 °C are planned for all CMFs. Afterwards, the obtained high-pressure data will be corrected regarding temperature. The overall objective is to publish a complete data set regarding the influence of pressure on the mass flow measurement accuracy for all three CFMs of the different brands.

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