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Air and Nitrogen Testing of Coriolis Flow Meters Designed for Hydrogen Refuelling Stations

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Abstract

The performance of Coriolis flow meters designed for use in hydrogen refuelling stations was evaluated in air and nitrogen by several National Metrology Institutes and Designated Institutes. Three meters were tested by members of the MetroHyVe consortium; NEL, METAS and CESAME EXADEBIT. A fourth meter was tested separately by KRISS and there was found to be a significant overlap in the test conditions and results from each experimental programme.

A wide range of conditions were tested overall, with gas flow rates ranging from 0.05 to 3.8 kg/min and pressures ranging from 10 to more than 40 bar. The densities encountered using air and nitrogen ranged from 11.5 to more than 52 kg/m^3 (equivalent to hydrogen at approximately 125 bar and 875 bar respectively). There was also some investigation of the influence of temperature on flow meter performance, with selected points tested at temperatures as low as -40°C. The effect of pressure was studied separately using water and is presented in another paper.

When the flow meters were operated within the manufacturer's recommended flow rate ranges, errors were generally within ±1%. For some of the meters tested, errors approached ±0.5%.

1. Introduction

To support its use as a low carbon transport fuel, an extensive infrastructure for hydrogen-powered vehicles is currently in development in many countries worldwide. However, the hydrogen industry cannot yet meet the measurement requirements of legislation surrounding the use of hydrogen fuel, due to a lack of methods and standards.

A European Metrology Programme for Innovation and Research (EMPIR) Joint Research Project was launched to address the metrological challenges associated with hydrogen vehicles and refuelling stations [1].

Work package 1 of the “Metrology for Hydrogen Vehicles” (MetroHyVe) JRP aims to establish a traceability chain for hydrogen flow metering in fuel cell vehicle refuelling applications.

The conditions which meters must operate at for this application are challenging from a flow metrology perspective. Hydrogen refuelling stations operate across a wide range of temperatures (-40°C to 85°C) and pressures (up to 875 bar) in accordance with the worldwide accepted standard SAE J2601 [2].

Researchers have previously addressed this challenge by developing primary and secondary flow standards for hydrogen at pressures of up to 350 bar [3][4]. Within the MetroHyVe project, several portable gravimetric standards have been developed for verifying the measurements at hydrogen refuelling stations at pressures of up to 700 bar.

These are all important steps in establishing a traceability chain for flow metrology in hydrogen vehicle refuelling. However in the longer term, it may prove more practical and cost effective to evaluate the flow measurements of hydrogen refuelling stations using a master meter.

Currently, there are no independent, traceable flow laboratories where flow meters can be calibrated with hydrogen across an appropriate range of pressures, temperatures and flow rates. An alternative approach is being investigated, which is the subject of this paper.

This involves using alternative fluids to hydrogen to perform type approval testing and to characterise the behaviour of mass flow meters under high pressure. If proven to be a success, flow laboratories will be able to use these new methods to perform type approval testing under safer conditions than using hydrogen at up to 875 bar.

The performance of three Coriolis mass flow meters developed for hydrogen refuelling applications was evaluated using air and nitrogen by three members of the MetroHyVe consortium; NEL, METAS and CESAME EXADEBIT. Test conditions were selected such that the densities and mass flow rates established in this test programme were broadly representative of those in field conditions.

The effect of temperature on meter performance was investigated by METAS during the same test programme. The effect of pressure on meter performance was studied separately using water and results will be presented in another paper.

Complementary research has been carried out by KRISS, who tested a fourth meter with air. The conditions tested by KRISS partially overlap with those tested by the MetroHyVe partners and extend the overall range of data collected to higher flow rates and lower pressures.

Results of the testing carried out by NEL, METAS, CESAME EXADEBIT and KRISS are presented in this paper.

2. Flow Meters Tested

A total of 4 flow meters were tested. All were Coriolis type flow meters currently used in hydrogen refuelling stations. Table 1 shows which flow meters were tested at each laboratory.

Meters A, B and C were loaned to the MetroHyVe project, each from a different manufacturer. Meters A and B were each tested by NEL, CESAME EXADEBIT and METAS. Meter C was tested by NEL only.

Meter D was purchased and tested by KRISS.

Table 1: Flow meters tested by each laboratory

	NEL	METAS	CESAME EXADEBIT	KRISS
Meter A	x	x	x	
Meter B	x	x	x	
Meter C	x			
Meter D				x

2. Test Matrices

2.1 MetroHyVe

A test matrix was devised by the MetroHyVe partners using mass flow rates representative of those encountered in a hydrogen refuelling station. Temperatures and pressures were selected so that tests could be conducted at densities of 23 and 46 kg/m^3, equivalent to hydrogen at 350 and 700 bar.

Table 2 shows the generic test matrix prepared for the nitrogen and air tests conducted by NEL, METAS and CESAME EXADEBIT. In practice, each laboratory deviated from this matrix to some extent.

Table 2: MetroHyVe Test Matrix.

Pressure (bar)	Temperature (°C)	Density (kg/m^3)	Mass Flow Rate (kg/min)
40	20	46.26	0.05
40	20	46.26	0.1
40	20	46.26	0.25
40	20	46.26	0.5
40	20	46.26	0.75
40	20	46.26	1
40	20	46.26	1.25
40	20	46.26	1.5
40	20	46.26	1.75
40	20	46.26	2
20	20	23.08	0.05
20	20	23.09	0.1
20	20	23.09	0.25
20	20	23.09	0.5
20	20	23.09	0.75
20	20	23.09	1

Flowrates were initially selected to cover the operating ranges of the tested flow meters up to 3.6 kg/min, the maximum flow rate specified by the SAE J2601 for light duty vehicles [2]. However, it was discovered that at this flow rate, pressure drop through each of the tested flow meters would be excessive.

At a meter inlet pressure of 40 bar and flow rate of 3.6 kg/min, the pressure drop with nitrogen would be more than 10 bar, or 25% of the inlet pressure. This would result in a significant density shift through the flow meter, which could not be considered representative of field conditions. Although the flow meters can incur large pressure drops in a hydrogen refuelling station, the ratio of differential pressure to meter inlet pressure would be much lower.

The flow meter manufacturers recommended a maximum flow rate of 2 kg/min for testing with air or nitrogen at 40 bar. This advice was followed and a maximum flow rate of 1 kg/min was selected for testing at 20 bar to achieve the same maximum velocity.

A minimum flow rate of 0.05 kg/min was selected. This was based on the lowest flow rate specified from the data sheets of all of the flow meters, although the meters loaned to the MetroHyVe project were previously calibrated by the manufacturers at higher minimum flow rates.

All three meters were calibrated by the manufacturers using water. Two of the meters were calibrated to a minimum flow rate of 0.2 kg/min, one meter was calibrated to a minimum of 0.5 kg/min.

2.2 NEL and CESAME EXADEBIT

Testing conducted by NEL and CESAME EXADEBIT followed the matrix shown in Table 2 with some minor deviations. Both NEL and CESAME EXADEBIT added test points to demonstrate consistency at the cross-over points of the reference flow devices used. CESAME EXADEBIT also added intermediate flow rates for the testing at 20 bar.

2.3 METAS

METAS tested at 20°C and -40°C to investigate the effect of temperature on meter performance. Flow rates were selected from the matrix shown in Table 2, but test conditions at 1.25 and 1.75 kg/min were skipped.

The heat exchangers used incurred a large pressure drop, so METAS were not able to test at the same pressures as NEL and CESAME EXADEBIT for every flow rate.

At low flow rates, the METAS tests were conducted at three pressures and two temperatures:

- 20°C, 34 bar up to 0.55 kg/min
- 20°C, 20 bar up to 0.55 kg/min
- -40°C, 31 bar up to 0.55 kg/min

To reach flow rates higher than 0.55 kg/min, the inlet pressure had to be increased. The maximum pressure tested was 88 bar.

2.4 KRISS

Table 3 shows the conditions tested by KRISS.

Compared to the ranges tested in the MetroHyVe project, KRISS tested at higher minimum and maximum flow rates and at lower minimum pressure and gas density.

The maximum flow rate tested was 3.76 kg/min at 40 bar, compared to 2 kg/min in the MetroHyVe project. The conditions tested by KRISS therefore included the maximum flowrate of 3.6 kg/min stipulated by the SAE J2601 standard [2], and higher velocities than those recommended by the flow meter manufacturers to the MetroHyVe partners.

Table 3: KRISS Test Matrix.

Pressure (bar)	Temperature (°C)	Density (kg/m^3)	Mass Flow Rate (kg/min)
10	20	11.53	0.23
10	20	11.53	0.23
10	20	11.53	0.23
10	20	11.53	0.45
10	20	11.53	0.45
10	20	11.53	0.45
10	20	11.53	0.92
10	20	11.53	0.92
10	20	11.53	0.92
20	20	23.09	0.44
20	20	23.09	0.44
20	20	23.09	0.44
20	20	23.09	0.89
20	20	23.09	0.89
20	20	23.09	0.89
20	20	23.09	1.82
20	20	23.09	1.82
20	20	23.09	1.82
30	20	34.67	0.66
30	20	34.67	0.66
30	20	34.67	0.66
30	20	34.67	1.36
30	20	34.67	1.36
30	20	34.67	1.36
30	20	34.67	2.75
30	20	34.67	2.75
30	20	34.67	2.75
40	20	46.26	0.87
40	20	46.26	0.87
40	20	46.26	0.87
40	20	46.26	1.78
40	20	46.26	1.78
40	20	46.26	1.78
40	20	46.26	3.76
40	20	46.26	3.76
40	20	46.26	3.76

3. Flow Laboratories

3.1 NEL

Meters A, B and C were tested in the NEL High Pressure Gas Flow Facility. They were installed in the 1" vent line of the flow facility. The large diameter piping upstream of the vent line served as a reservoir of pressurised nitrogen, which could be pre-heated to provide stable, near ambient temperatures at the meter under test.

An installation diagram is shown in Figure 1.

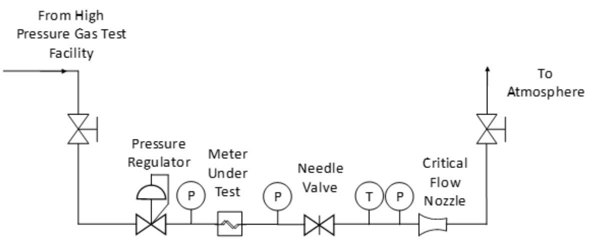

Figure 1: NEL Test Installation

The meter inlet pressure was set using a pressure regulator. Flow rates were controlled using a needle valve installed downstream of the test meter. Reference mass flowrates were determined using a range of critical flow nozzles installed further downstream and the nozzle outlet piping was open to atmosphere. The expanded uncertainty of the reference mass flow rate measurement is ±0.3% at 95% confidence.

No heat exchanger was installed in the test section. Gas was heated upstream of the test installation to compensate for temperature drop across the pressure regulator. The internal temperature measurements of the Coriolis meters were logged, and temperatures were close to ambient for the full range of test conditions.

A temperature probe and pressure transmitter with traceable calibrations were installed at the inlet to the critical flow nozzle holder. Test points were logged only once stability was achieved for these instruments. Pressure was also measured at the outlet of the test meter.

3.2 CESAME EXADEBIT

Meters A and B were tested in the CESAME EXADEBIT "M1" High Pressure Gas Flow Facility. The test rig uses dry air and operates at up to 45 bar. Very high volumetric flow rates can be achieved at low pressure, up to 5000 Nm³/hr. Critical flow nozzles are used for reference flow rate determination, these are traceable to the CESAME EXADEBIT primary standard PVTt test rig. The measurement uncertainty of the reference nozzles ranges from ±0.2 to ±0.3% at 95% confidence.

An installation diagram is shown in Figure 2. The test meters were installed upstream of the reference critical flow nozzles. Gas was supplied at high pressure from the M1 flow facility. Flow control valves upstream and downstream of the test meter were used to set the required pressure and flow rate.

No heat exchanger was installed. Gas was provided at ambient temperature. The internal temperature measurements of the Coriolis meters were logged and were always close to ambient.

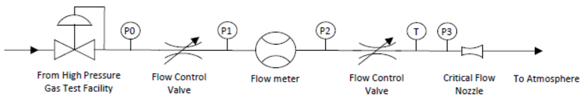

Figure 2: CESAME EXADEBIT Test Installation

3.3 METAS

Meters A and B were installed in the METAS "Mobile Normale" Gas Flow Facility. The test rig used nitrogen delivered from a 600 L bundle at 300 bar(a). A pressure-reducing valve reduced the pressure down to 100 bar(a). The installation diagram is shown in Figure 3.

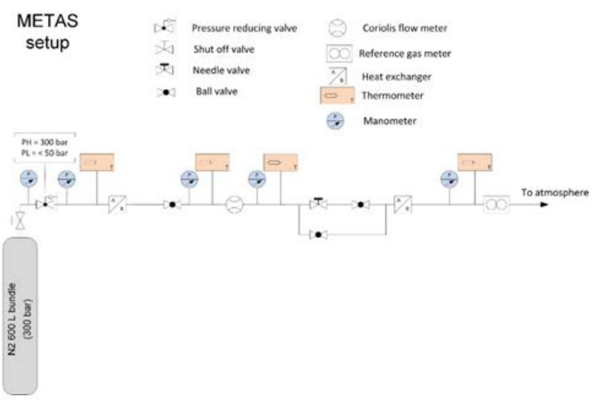

Figure 3: METAS "Mobile Normale" Gas Flow Facility

The test meters were installed between two heat exchangers. A heat exchanger upstream of the flow meter set the meter inlet temperature to either -40°C or 20°C. A heat exchanger downstream of the flow meter stabilised the gas temperature to ambient temperature conditions before the gas entered the METAS reference flow meters. These are rotary type flow meters with an expanded measurement uncertainty of ±0.3% at 95% confidence.

Flow rates were controlled using a needle valve installed downstream of the test meter. Temperature probes and pressure transmitters with traceable calibrations were installed at the inlet and outlet of the test meter and at the inlet of the reference gas meter. Test points were logged only once stability was achieved for these instruments.

3.4 KRISS

Meter D was tested at the high pressure gas flow standard system of KRISS. As shown in Figure 4, this is a blow-down type of flow facility, consisting of two compressors, a 52.4 m^3 storage tank, temperature control loop and two control valves. Steady air flows are generated at pressures ranging from 0.1 to 5 MPa.

The maximum flow rate achievable is 10 000 m^3/h at standard conditions (101 325 Pa and 293.15 K). Flow meters can be calibrated either against ISO 9300 sonic nozzles or the gravimetric primary standard consisting of a weighing tank and a fast-acting diverter. The expanded uncertainty of the primary standard is ±0.18% at 95% confidence.

The test meter was installed at the position between the 2nd pressure control valves and sonic nozzles. In this study, nozzles with throat diameters of 1.4 mm, 2mm and 2.9 mm were used for the calibration of the Coriolis flow meter depending on the working pressure and flow-range.

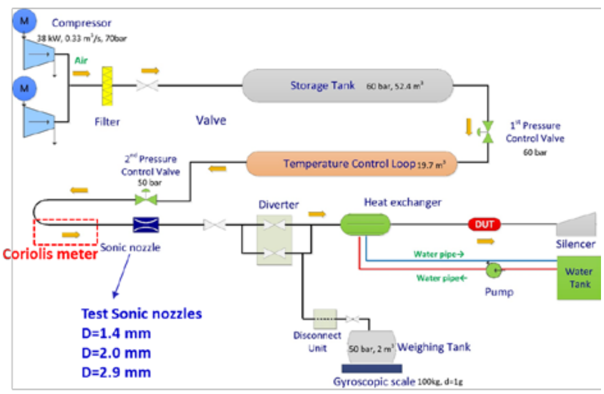

Figure 4: KRISS Test Installation

3. Test Results

2.1 NEL

Meters A, B and C were tested at NEL.

The results for Meter A are shown in Figure 5. Errors ranged from -1.26 to -0.09%. The largest error occurred at 39 bar(g) and 0.75 kg/min. All other results were within ±1%. The average error was -0.54% and average repeatability was ±0.024%.

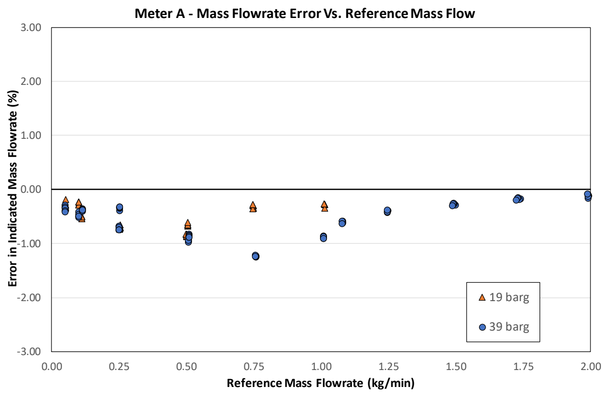

Figure 5: NEL Testing Meter A Results

The results for Meter B are shown in Figure 6. Errors ranged from -3.05 to 0.52%. The device performance was linear for most of the tested flow rates. Large negative errors occurred at low flow rates. At flow rates above 0.25 kg/min, errors were within ±1%, most were within ±0.5%. The average repeatability was ±0.06%.

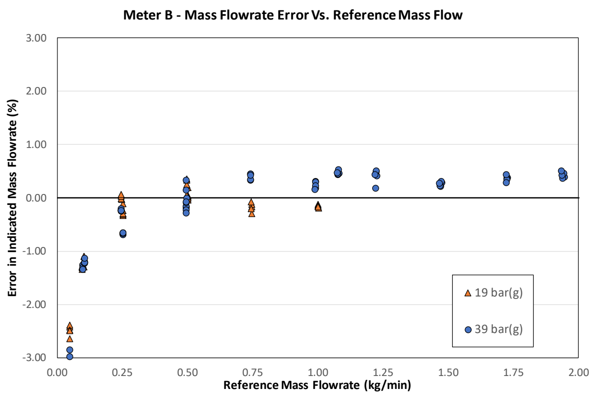

Figure 6: NEL Testing Meter B Results

The results for Meter C are shown in Figure 7. Errors ranged from -0.54 to 2.89%. The device performance was linear for most of the tested flow rates. Large positive errors occurred at low flow rates. At flow rates above 0.25 kg/min, errors were within ±1%, most were within ±0.5%. The average repeatability was ±0.065%.

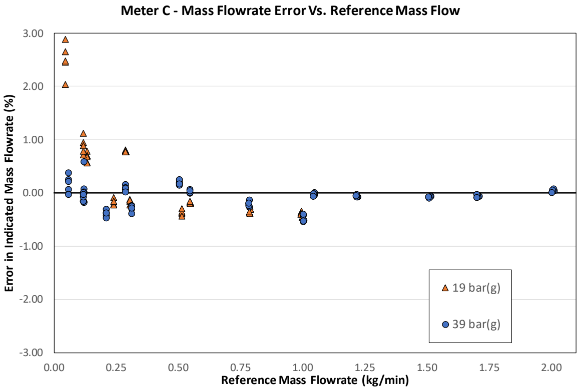

Figure 7: NEL Testing Meter C Results

2.2 CESAME EXADEBIT

Meter A and Meter B were tested at CESAME EXADEBIT.

The results for Meter A are shown in Figure 8. The performance of Meter A followed a similar trend to what was observed at NEL. Errors ranged from -1.18 to 0.41%. The largest error occurred at 39 bar(g) and 0.05 kg/min. The average error was -0.26% and average repeatability was ±0.04%.

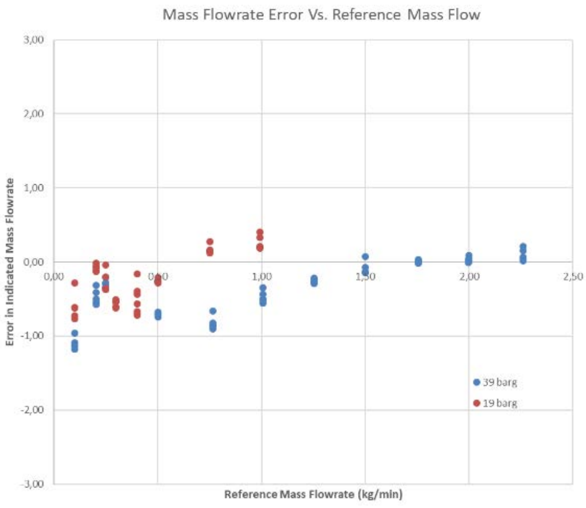

Figure 8: CESAME EXADEBIT Testing Meter A Results

The results for Meter B are shown in Figure 9. The performance of Meter B followed a similar trend to what was observed at NEL, but there appeared to be an overall offset of approximately -0.7%. Errors ranged from -2.16 to -0.49%. The device performance was linear for most of the tested flow rates. Errors were increasingly negative as flow rates decreased.

The largest error occurred at 39 bar(g) and 0.05 kg/min. The average error was -1.05% and average repeatability was ±0.06%.

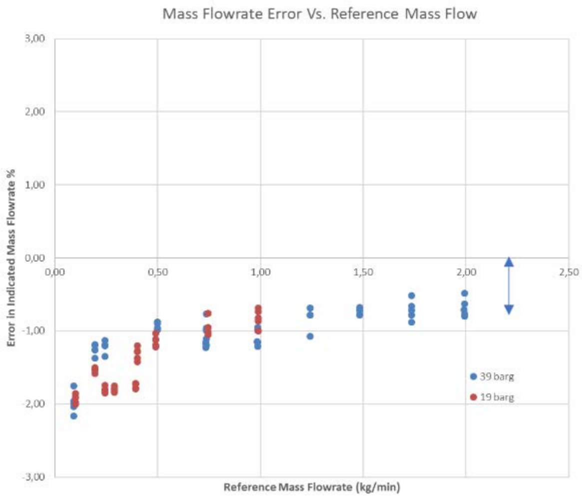

Figure 9: CESAME EXADEBIT Testing Meter B Results

2.3 METAS

Meter A and Meter B were tested at METAS.

The results for Meter A are shown in Figure 10. The largest errors occurred at flow rates of less than 0.2 kg/min. For flow rates above 0.4 kg/min, the average error was -0.8%.

Temperature appeared to have in influence on meter performance, but only at low flowrates. Larger errors and a greater spread of results occurred for the data collected at -40°C, but only at flow rates less than 0.4 kg/min. No clear inlet pressure dependence was observed.

At 20°C, repeatability was good, ±0.08% at the lowest flow rate.

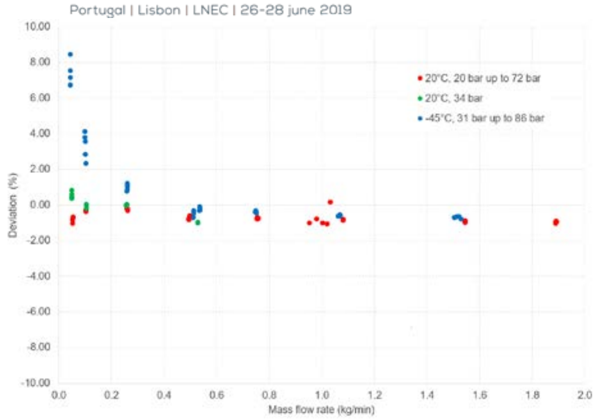

Figure 10: METAS Testing Meter A Results

The results for Meter B are shown in Figure 11.

Average error was 0.6% at flow rates less than 0.6 kg/min. Average errors decreased at higher flow rates to approximately 0.2% at 2 kg/min.

Larger errors occurred for the data collected at -40°C, errors were positive at flow rates less than 0.2 kg/min. Above 0.2 kg/min, errors for the low temperature data were negative, from -0.5% at 0.5 kg/min to -1% at 2 kg/min.

At 20°C, repeatability was good, ±0.1% at the lowest flow rate.

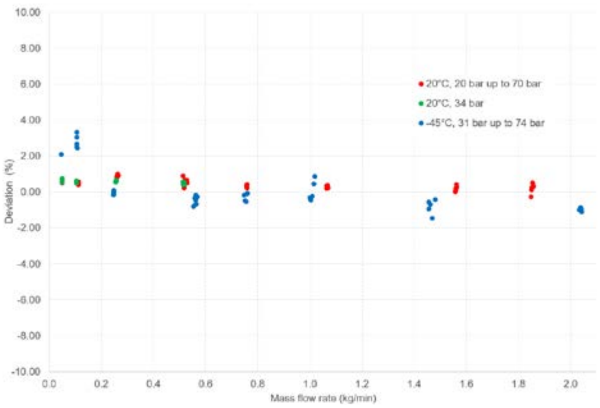

Figure 11: METAS Testing Meter B Results

2.4 KRISS

Meter D was tested at KRISS. The results are shown in Figure 12.

The meter was tested at four pressures, 10, 20, 30 and 40 bar. Errors ranged from -3.4 to 1.22 %. The largest errors occurred at flow rates below 0.5 kg/min. Above 0.5 kg/min, the meter performance was approximately linear and average error was 0.12%. Errors exceed ±1% for only a single data point in this range.

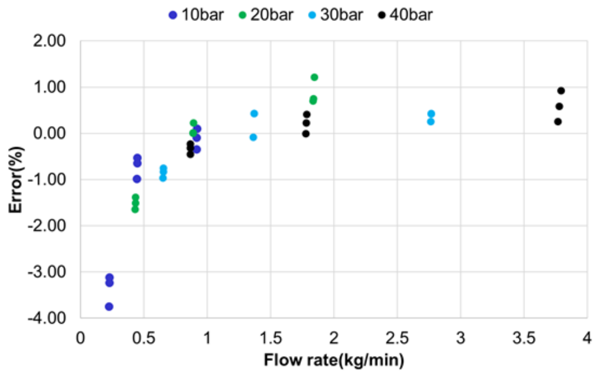

Figure 12: KRISS Testing Meter D Results

7. Conclusion

For most of the meters tested, the largest errors occurred at low flow rates. This is typical behaviour for Coriolis meters used at the low end of their operating range.

When the meters were operated at moderate to high flow rates, errors were typically within ±1%. Linearity in this range was typically within ±0.5%.

The meters tested were previously calibrated by their manufacturers with water. This shows the potential for calibrating meters with substitute fluids, considering the differences in density and viscosity between water and nitrogen, and the relatively low errors in the collected data.

One potential limitation of calibrating meters with substitute fluids such as nitrogen is that there will be a greater relative shift in density through the meter compared to operating with hydrogen at the same mass flow rate and inlet density. For this reason, the maximum flow rates tested in the MetroHyVe project were restricted. However, this restriction was not applied to the tests carried out at KRISS, and an influence of fluid velocity on meter performance was not observed.

An influence of temperature on meter performance was observed. Larger errors and a wider spread of results were observed when testing at -40°C. This effect was more pronounced at low flow rates.

For most of the data collected, pressure did not appear to have an influence on meter performance. At specific flowrates, differences were observed for data collected at different pressures, but an overall trend was not observed.

When installed in a hydrogen refuelling station, the meters will be subjected to a much wider range of pressures, so it is still necessary to investigate the influence of pressures up to 875 bar on meter performance. The effect of pressure up to 700 has been investigated separately within the MetroHyVe project using water.

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