Flow meter assessment (D2.3.3, D2.3.6, D2.3.7)

Dependency on several physical parameters (D2.3.3), Reynolds number interpolation (D2.3.6) and uncertainty estimation for calibrations in the field (D2.3.7)

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This document discusses the 'assessment of flow meters', which is part of MeDD (Metrology for Drug Delivery).

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1 Introduction

The aim of this task is to determine the influence of various physical parameters and operating conditions on the performance of various types of flow meters. The physical parameters and operating conditions for which the influence will be determined are those parameters and conditions that are most relevant for drug delivery applications and flow metering: viscosity, temperature, back pressure and pulsating flow.

The investigations on the performance of different flow meters influenced by changing physical parameters and operation conditions are reported.

It is worthwhile to mention at this point that only one of each flow meter type has been characterized by only one laboratory. Therefore, any conclusions should not be overestimated and stated as a general feature of the flow meter type. Nevertheless, general trends can be observed.

2 Flow meters, physical parameters and operating conditions

We test 3 different flow meter types:

- Coriolis flow meter
- Thermal flow meter
- Pressure drop flow meter

2.1 Coriolis flow meter

Type:	Mini Cori-flow M12
Serial number:	B10200983A
Manufacturer:	Bronkhorst High-Tech
Flow rate range:	3.3 g/min – 33.3 mg/min (100 % - 1 % Full Scale)
	200 g/h – 2.0 g/h (200 ml/h – 2 ml/h)
Accuracy:	± (0.2 + ZS / (flow rate in g/h) *100) %, ZS zero stability 0.1 g/h
Repeatability:	± (0.05 + 0.5* ZS / (flow rate in g/h) *100) %, ZS zero stability 0.1 g/h
Software download:	www.bronkhorst.com

2.2 Thermal flow meters

Type	SLI-0430
Serial number:	1305-00099
Manufacturer:	Sensirion AG
Flow rate range:	50.0 μl/min – 2.0 μl/min
	3.0 ml/h – 0.12 ml/h
Tubing:	1/8 inch
Accuracy:	± 5 %
Repeatability:	N/a
Software download:	http://www.sensirion.com

2.3 Pressure drop flow meter

Type	L-0.5CCM-D
Serial number:	100096
Manufacturer:	Alicat Scientific Inc. (Natec Sensors GmbH)
Flow rate range:	0.5 ml/min – 10 µl/min 30 ml/h – 0.6 ml/h
Tubing:	1/8 inch
Connections:	in the box, the direct connections to the flow meter have only to be hand-tighten
Temperature range	10 °C – 30 °C
Liquid	ultrapure water, deionized water
Accuracy:	± 2 %
Repeatability:	± 2 %
Software download:	METAS owned Software

2.4 Physical parameters and operating conditions

We investigate the following dependencies on the performance of the flow meters:

- Temperature (CETIAT)
- Pulsation (DTI)
- Back pressure (downstream of the flow meter; METAS)
- Viscosity (METAS)

3 Results and Discussion

In this section the results of the various laboratories on the influence of the physical parameters are summarized. Only one flow meter of each type has been tested for various conditions and therefore general conclusions have to be stated carefully as it might not fully represent the average behavior of these types of flow meters.

3.1 Temperature dependency (D2.3.3)

3.1.1 Description of the task

The flow meters (SLI-0430, SLI-1000, L-0.5CCM-D, M12) are tested using 3 different temperatures: 10, 20 and 30 degrees Celsius (water and ambient temperature). Flow rates starting from 0.5 ml/h up to 200 ml/h (depending on the flow rate range of the flow meter) are investigated by CETIAT.

The temperatures of water flowing through the flow meter and air around the flow meter have been set by changing the temperature setting of the climatic chambers in which the water reservoir and the flow meter are installed. A thermally regulated pipe links the two climatic chambers. Calibrated temperature probes are installed inline to monitor water and air temperatures.

3.1.2 Coriolis flow meter Mini Cori-flow M12 from Bronkhorst Cori-Tech

Measurements were done in the flow rate range from 1.3 g/h up to 200 g/h. The measured deviations are listed in Table 1 and the results are shown in Figure 1.

Table 1: Measured deviations of the Coriolis flow meter Mini Cori-flow M12 in the flow rate range from 1.3 g/h up to 200 g/h at temperatures of 10 °C, 20 °C and 30 °C.

Temperature (°C)	Reference flow rate (g/h)	Reference flow rate (mg/min)	Deviation (%)	Uncertainty (%)
10	1.34	22.33	-2.05	0.99
	1.82	30.33	1.03	0.94
	6.03	100.50	-0.77	0.63
	10.57	176.17	-0.19	0.15
	18.87	314.50	-0.19	0.12
	65.50	1091.67	-0.30	0.11
	194.07	3234.50	-0.36	0.11
20	1.36	22.67	1.10	0.96
	1.84	30.67	0.15	0.82
	6.19	103.17	-0.67	0.63
	10.75	179.17	-0.10	0.14
	19.20	320.00	-0.32	0.12
	65.42	1090.33	-0.20	0.11
	191.35	3189.17	-0.29	0.11
30	1.35	22.50	-0.47	0.96
	1.83	30.50	2.29	0.82
	6.17	102.83	-0.65	0.64
	10.89	181.50	-0.50	0.14
	19.45	324.17	-0.29	0.12
	65.45	1090.83	-0.23	0.11
	192.48	3208.00	-0.33	0.11

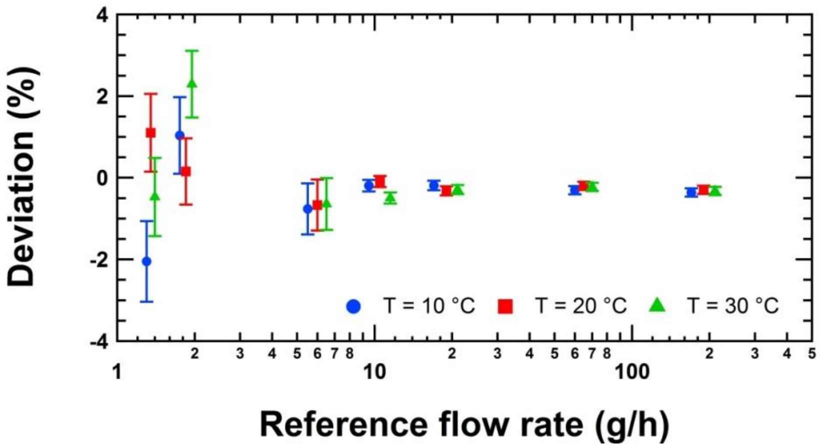

Figure 1: Measured deviations of the Coriolis flow meter Mini Cori-flow M12 in the flow rate range from 1.3 g/h up to 200 g/h at temperatures of 10 °C, 20 °C and 30 °C. The flow rates have been given an artificial off set in order to better visualize the results, for example the last 3 measurements are all for a flow rate of 200 g/h.

The Coriolis flow meter shows consistent results at all 3 temperatures down to the flow rate of 6 g/h. At the flow rates of 1.8 g/h and 1.3 g/h, the deviations are slightly temperature dependent, but inside the stated accuracy of the manufacturer. The lower limit of the stated flow range of the meter according to the specifications is 2 g/h and the flow rates of 1.3 g/h and 1.8 g/h are below the lower limit of the specifications of the manufacturer, hence large variations can be expected.

3.1.3 Thermal flow meter SLI-0430 from Sensirion

Measurements were done in the flow rate range from 0.4 ml/h up to 3 ml/h. The measured deviations are listed in Table 2 and the results are shown in Figure 2.

Table 2: Measured deviations of the thermal flow meter SLI-0430 in the flow rate range from 0.4 ml/h up to 3 ml/h at temperatures of 10 °C, 20 °C and 30 °C.

Temperature (°C)	Reference flow rate (ml/h)	Reference flow rate (µl/min)	Deviation (%)	Uncertainty (%)
10	1.25	20.83	0.35	1.02
	1.54	25.67	0.46	0.90
	1.87	31.17	-0.36	0.81
	2.35	39.17	-3.48	0.75
	2.86	47.67	-7.44	0.72
20	0.39	6.50	2.40	3.19
	0.78	13.00	3.01	1.42
	1.91	31.83	-1.11	1.26
	2.46	41.00	-6.52	0.81
	2.98	49.67	-10.52	0.75
30	1.22	20.33	1.22	1.03
	1.54	25.67	0.15	0.89
	1.86	31.00	-1.66	0.84
	2.37	39.50	-5.28	0.75
	2.87	47.83	-10.26	0.71

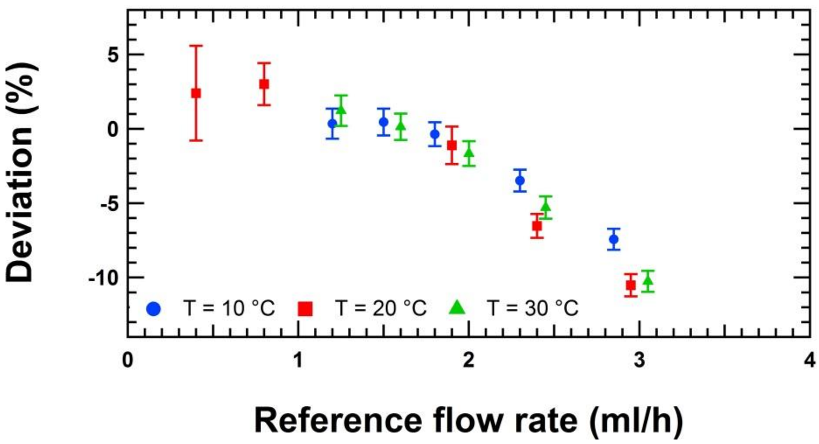

Figure 2: Measured deviations of the thermal flow meter SLI-0430 in the flow rate range from 0.4 ml/h up to 3 ml/h at temperatures of 10 °C, 20 °C and 30 °C. The flow rates have been given an artificial off set in order to better visualize the results, for example the last 3 measurements are all for a flow rate of 3 ml/h.

The Sensirion thermal flow sensor shows consistent results for all three temperatures in the flow rate range from 1 ml/h to 2 ml/h. Above 2 ml/h, the deviation measured at a water temperature of 10 °C is significantly different compared with the deviations measured at 20 °C and 30 °C.

This flow meter shows a non-linearity in the upper flow rate range above 2 ml/h, where the deviations are strongly increasing with increasing flow rate.

3.1.4 Pressure drop flow meter L-0.5CCM-D from Alicat Scientific Inc.

Measurements were done in the flow rate range from 1.2 ml/h up to 30 ml/h. The measured deviations are listed in Table 3 and the results are shown in Figure 4.

Table 3: Measured deviations of the pressure drop flow meter L-0.5CCM-D in the flow rate range from 1.2 ml/h up to 30 ml/h at temperatures of 10 °C, 20 °C and 30 °C.

Temperature (°C)	Reference flow rate (ml/h)	Reference flow rate (μl/min)	Deviation (%)	Uncertainty (%)
10	1.24	20.6525	-5.26	1.01
	2.03	33.76367	-1.36	0.79
	9.81	163.5005	0.46	0.14
	19.18	319.7217	1.28	0.12
	28.90	481.6433	0.73	0.45
20	1.20	19.99083	-3.14	1.03
	2.08	34.68867	-1.23	0.77
	9.87	164.5778	0.25	0.18
	19.30	321.7183	0.61	0.13
	29.00	483.395	0.58	0.11
30	1.21	20.16667	-2.46	1.04
	2.03	33.76733	-2.18	0.78
	9.90	164.919	0.09	0.19
	19.35	322.4183	0.68	0.12
	29.08	484.7033	0.88	0.11

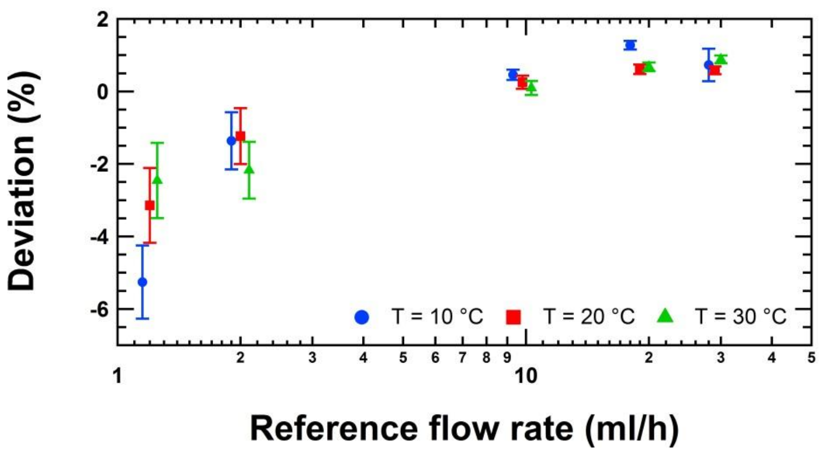

Figure 4: Measured deviations of the pressure drop flow meter L-0.5CCM-D in the flow rate range from 1.2 ml/h up to 30 ml/h at temperatures of 10 °C, 20 °C and 30 °C. The flow rates have been given an artificial off set in order to better visualize the results, for example the last 3 measurements are all for a flow rate of 30 ml/h.

The pressure drop flow meter shows consistent results at all 3 temperatures nearly over the whole flow rate range. At the flow rates of 1.2 ml/h and 20 ml/h, the deviations measured at a water temperature of 10 °C look like outliers as the deviations measured at 20 °C and 30 °C are consistent. As the flow meter is working in the temperature range from 10 °C to 30 °C according to the specifications, the dependency of the viscosity of water on temperature is probably corrected with the electronics.

3.1.5 Conclusion

The Coriolis flow meter is insensitive to different temperatures and shows consistent results for all 3 temperatures for flow rates above 2 g/h. Hence, the impact of temperature is not significant. It is recommended not to measure at the lowest flow rate limit where the deviations show some slight temperature dependency caused by the zero stability.

The Sensirion thermal flow sensor shows consistent results in the flow rate range from 1 ml/h to 2 ml/h for all three temperatures. Above 2 ml/h, the deviation measured at a water temperature of 10 °C is differing with the deviations measured at 20 °C and 30 °C. A possible explanation could be the temperature dependence of the specific heat capacity of water causing stronger deviations in the non-linear regime of the flow meter.

The pressure drop flow meter show consistent results at all 3 temperatures nearly over the whole flow rate range. At the flow rates of 1.2 ml/h and 20 ml/h, the deviations measured at a water temperature of 10 °C look like outliers as the deviations measured at 20 °C and 30 °C are consistent.

3.2 Pulsation dependency (D2.3.3)

3.2.1 Description of the task

The flow meters (SLI-0430, L-0.5CCM-D, M12) are tested using 2 different type of pulsating flow: standard syringe pump (Aladdin) and double syringe pump (Tecan). The following flow rates 0.5 mL/h, 2 mL/h and 10 mL/h are investigated by DTI.

The standard syringe pump (Aladdin) has a rotating spindle that presses the plunger in the plastic syringe forward in order to generate a flow. The spindle rotation causes the flow rate to pulsate with a periodicity equal to the revolutions of the spindle.

The double syringe pump (tecan) consist of two small glass syringes. The syringes works in an opposite manner, which means that one of the syringes is pumping (being emptied) while the other syringe is being filled. This allows for a continued flow although the volume of each syringe is very small. However, in order to make a continued flow the two syringes switch from filling to pumping with an overlapping session. This switching session causes a pulsation in the flow as the switching it is not very smooth.

The uncertainties of the facility for pulsating flow are described in Table 4.

Table 4: Uncertainties of the average reference flow rates for pulsating flow at DTI.

Flow rate Q (ml/h)	Uncertainty (%)
0.6	1.5
1	1.5
2	1
10	0.2

3.2.2 Coriolis flow meter Mini Cori-flow M12 from Bronkhorst Cori-Tech

In Figure 5 resp. 6, we show the flow rate data of the flow meter (black line) and the reference flow rate (red line) as a function of time, where the flow is generated by the Aladdin syringe pump resp. by the Tecan syringe pump. The slow pulsations from the motion of the plunger of the Aladdin syringe pump can be observed in Figure 5. The sharp peaks caused by the syringe change of the double syringe pump Tecan can be observed in Figure 6. Both flow meter and the balance detect these slow pulsations and the sharp peaks, although the reference flow rate determined by the gravimetric method is less sharp due to the relatively large time window of 3 s used to determine the flow rate.

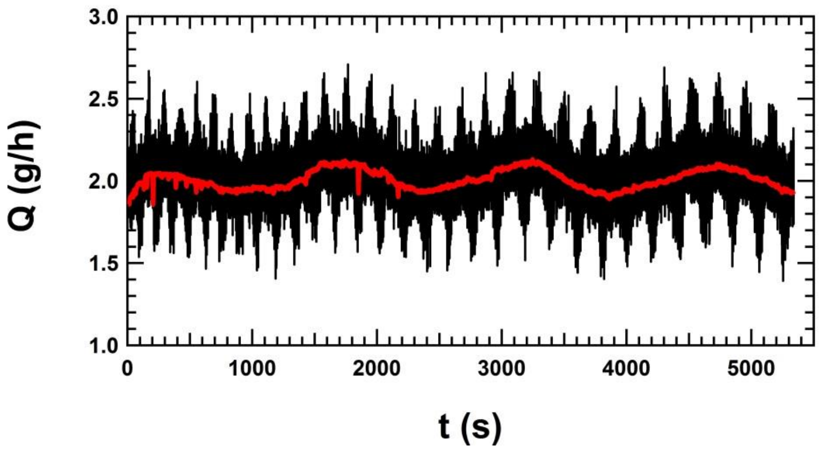

Figure 5: Flow rate data of the flow meter (raw data, black line) and the reference flow rate (red line) as a function of time, where the flow is generated by the Aladdin syringe pump.

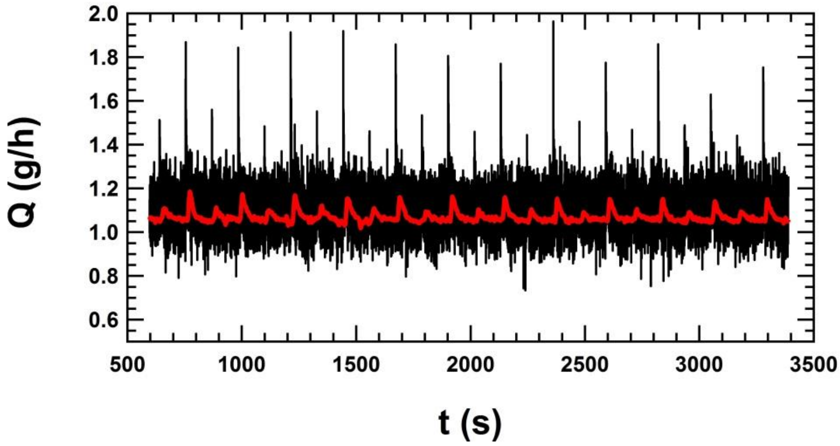

Figure 6: Flow rate data of the flow meter (raw data, black line) and the reference flow rate (red line) as a function of time, where the flow is generated by the Tecan syringe pump.

The measured deviations of the Coriolis flow meter Mini Cori-flow M12 in the flow rate range from 0.6 g/h up to 10 g/h for two different pulsating flows are consistent within the uncertainties (Table 5 and Figure 7).

Table 5: Measured deviations of the Coriolis flow meter Mini Cori-flow M12 in the flow rate range from 0.6 g/h up to 10 g/h for pulsating flow at ambient temperature.

Operation conditions	Reference flow rate (g/h)	Reference flow rate (mg/min)	Deviation (%)	Uncertainty (%)
Aladdin syringe pump	0.622	10.37	3.5	1.7
	2.001	33.35	1.8	1.1
	10.058	167.63	-0.0	0.3
Tecan syringe pump	1.106	18.43	4.1	1.7
	2.062	34.37	2.1	1.1
	9.829	163.82	-0.1	0.3

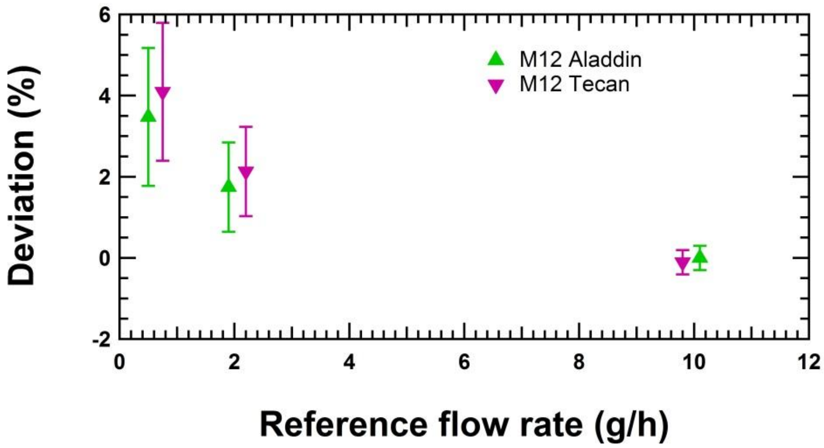

Figure 7: Measured deviations of the Coriolis flow meter Mini Cori-flow M12 in the flow rate range from 0.6 g/h up to 10 g/h for two different pulsating flows at ambient temperature. The flow rates have been given an artificial off set in order to better visualize the results, for example the last 2 measurements are all for a flow rate of 10 ml/h.

3.2.3 Thermal flow meter SLI-0430 from Sensirion

In Figure 8 resp. 9, we show the flow rate data of the flow meter (black line) and the reference flow rate (red line) as a function of time, where the flow is generated by the Aladdin syringe pump resp. by the Tecan syringe pump. The slow pulsations from the motion of the plunger of the Aladdin syringe pump can be observed in Figure 8. The sharp peaks caused by the syringe change of the double syringe pump Tecan can be observed in Figure 9. Both flow meter and the balance detect these slow pulsations and the sharp peaks, although the reference flow rate determined by the gravimetric method is less peaked due to the relatively large time window used to determine the flow rate.

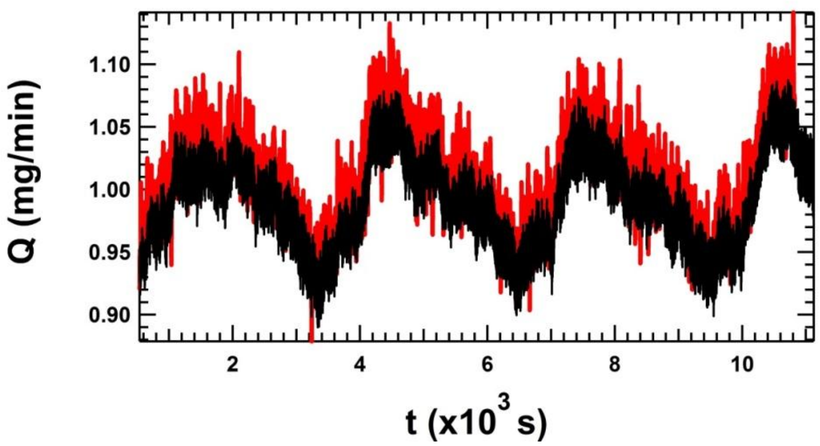

Figure 8: Flow rate data of the flow meter (raw data, black line) and the reference flow rate (red line) as a function of time, where the flow is generated by the Aladdin syringe pump.

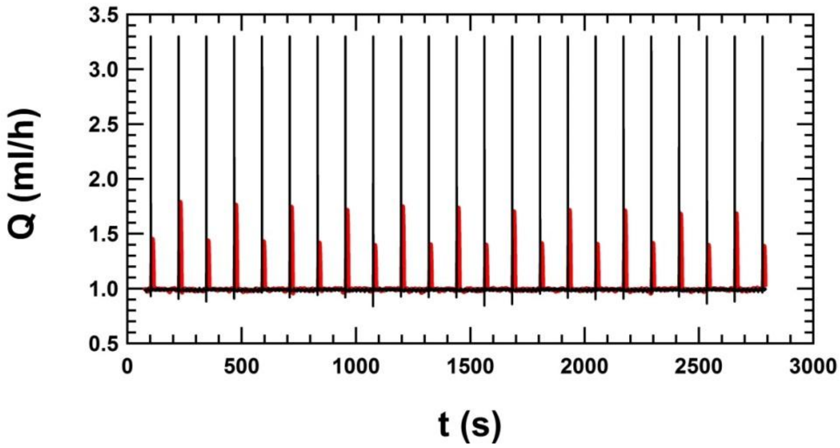

Figure 9: Flow rate data of the flow meter (raw data, black line) and the reference flow rate (red line) as a function of time, where the flow is generated by the Tecan syringe pump.

The measured deviations of the thermal flow meter SLI-0430 in the flow rate range from 1.0 ml/h up to 2.0 ml/h for two different pulsating flows are consistent within the uncertainties (Table 6 and Figure 10).

Table 6: Measured deviations of the thermal flow meter SLI-0430 in the flow rate range from 1.0 ml/h up to 2.0 ml/h for pulsating flow at ambient temperature.

Operation conditions	Reference flow rate (ml/h)	Reference flow rate (μl/min)	Deviation (%)	Uncertainty (%)
Aladdin syringe pump	0.993	16.55	-2.0	1.6
	1.941	32.35	-3.4	1.1
Tecan syringe pump	0.996	16.60	-2.0	1.6
	1.959	32.65	-3.9	1.1

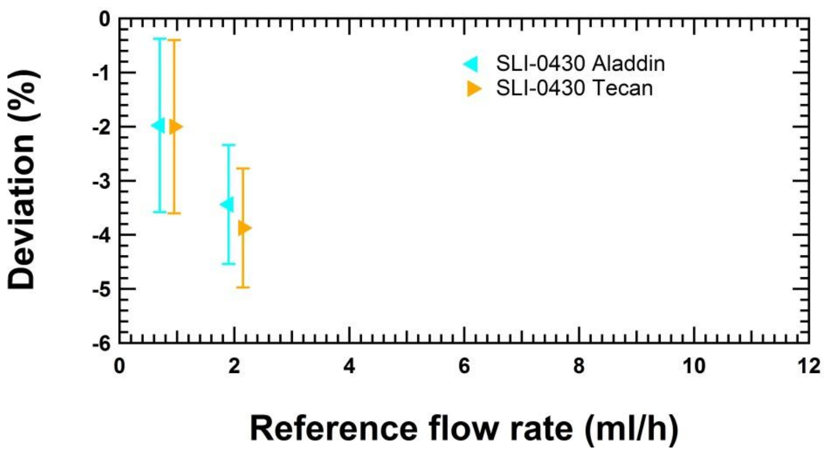

Figure 10: Measured deviations of the thermal flow meter SLI-0430 in the flow rate range from 1.0 ml/h up to 2.0 ml/h for two different pulsating flows at ambient temperature. The flow rates have been given an artificial off set in order to better visualize the results, for example the last 2 measurements are all for a flow rate of 2 ml/h

3.2.4 Pressure drop flow meter L-0.5CCM-D from Alicat Scientific Inc.

In Figure 11, we show the flow rate data of the flow meter (black line) and the reference flow rate (red line) as a function of time, where the flow is generated by the Aladdin syringe pump. The slow pulsations from the motion of the plunger of the Aladdin syringe pump can be observed in Figure 11. Both flow meter and the balance detect these slow pulsations.

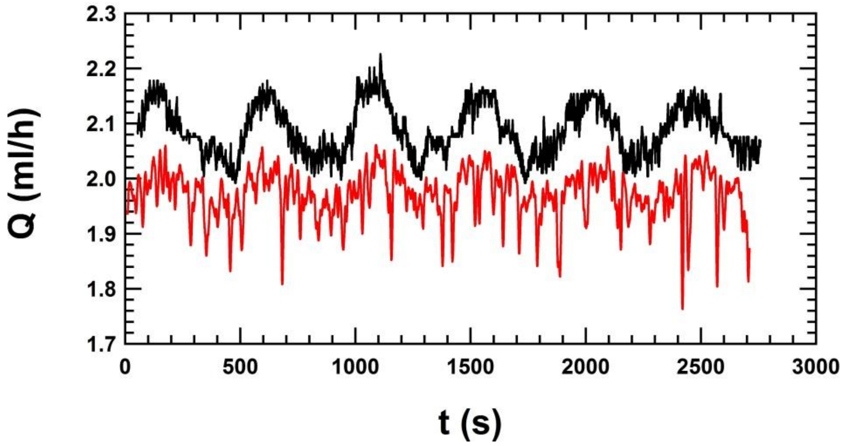

Figure 11: Flow rate data of the flow meter (raw data, black line) and the reference flow rate (red line) as a function of time, where the flow is generated by the Aladdin syringe pump.

Table 7: Measured deviations of the pressure drop flow meter L-0.5CCM-D in the flow rate range from 0.7 ml/h up to 11.0 ml/h for pulsating flow at ambient temperature.

Operation conditions	Reference flow rate (ml/h)	Reference flow rate (μl/min)	Deviation (%)	Uncertainty (%)
Aladdin syringe pump	0.494	8.23	6.1	1.9
	1.974	32.90	6.3	1.1
	9.885	164.75	6.5	0.4

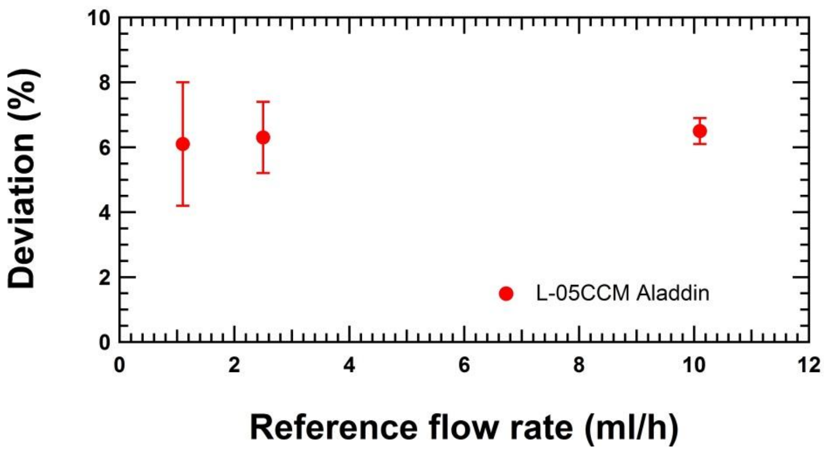

Figure 12: Measured deviations of the pressure drop flow meter L-0.5CCM-D in the flow rate range from 0.7 ml/h up to 11.0 ml/h for two different pulsating flows at ambient temperature.

3.2.5 Conclusion

The measured deviations of the Coriolis flow meter Mini Cori-flow M12 and the thermal flow meter SLI-0430 for two different pulsating flows are consistent within the uncertainties. The results of the pressure drop flow meter L-0.5CCM-D cannot be used for a conclusion as only one flow generator was used for the measurements.

3.3 Back pressure dependency (D2.3.3)

3.3.1 Description of the task

The flow meters (SLI-0430, L-0.5CCM-D, M12) are tested using 2 different back pressures by METAS. The facility already generates a backpressure in the range from 10 mbar to 30 mbar depending on the flow rate. This backpressure corresponds to the order of magnitude of the standard patient back pressure of roughly 17 mbar. Therefore, only one additional back pressure of 170 mbar (10 times patient pressure) is investigated at the following flow rates 0.5 mL/h, 2 mL/h and 10 mL/h.

The back pressure has been created by a pressure reducing valve installed downstream of the device under test.

3.3.2 Coriolis flow meter Mini Cori-flow M12 from Bronkhorst Cori-Tech

The measured deviations are listed in Table 8 and the results are shown in Figure 13. The Coriolis flow meter seems not to be sensitive to any change in backpressure.

Table 8: Measured deviations of the Coriolis flow meter Mini Cori-flow M12 in the flow rate range from 2.0 g/h up to 10 g/h for two different back pressures at a temperature of 22 °C.

Operation conditions	Reference flow rate (g/h)	Reference flow rate (mg/min)	Deviation (%)	Uncertainty (%)
Liquid water Back pressure 0 mbar	9.7902	163.17	-0.55	0.18
	1.9692	32.82	0.04	0.59
Liquid water Back pressure 170 mbar	9.7308	162.18	-0.50	0.21
	1.9524	32.54	0.19	0.30

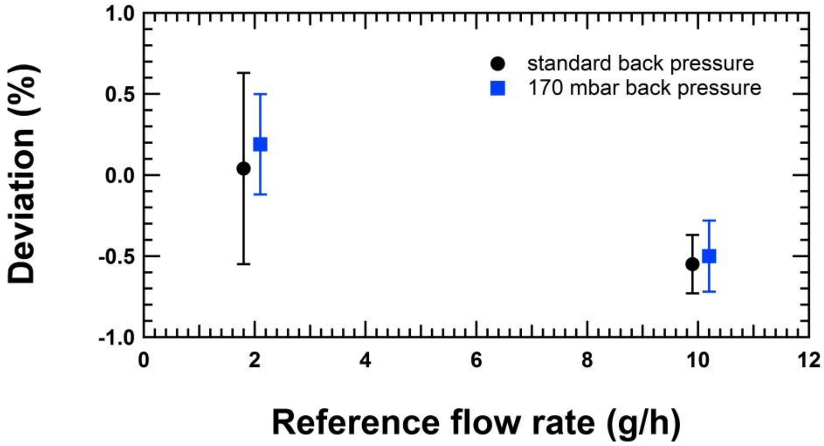

Figure 13: Measured deviations of the Coriolis flow meter Mini Cori-flow M12 in the flow rate range from 2.0 g/h up to 10 g/h for two different back pressures at a temperature of 22 °C.

The flow rates have been given an artificial off set in order to better visualize the results, for example the last 2 measurements are all for a flow rate of 10 ml/h

3.3.3 Thermal flow meter SLI-0430 from Sensirion

Only the flow rates 0.5 ml/h and 2.0 ml/h are investigated as the flow rate range is from 0.5 ml/h to 3 ml/h according to the technical specifications of the manufacturer. The measured deviations are listed in Table 9 and the results are shown in Figure 14. The thermal flow meter seem not to be sensitive to any change in backpressure.

Table 9: Measured deviations of the thermal flow meter SLI-0430 in the flow rate range from 0.5 ml/h to 2.0 ml/h for two different back pressures at a temperature of 22 °C.

Operation conditions	Reference flow rate (ml/h)	Reference flow rate (μl/min)	Deviation (%)	Uncertainty (%)
Liquid water Back pressure 0 mbar	2.09	34.84	-3.04	0.25
	0.52	8.66	-0.29	0.23
Liquid water Back pressure 170 mbar	2.10	34.93	-2.91	0.21
	0.53	8.84	-0.49	0.21

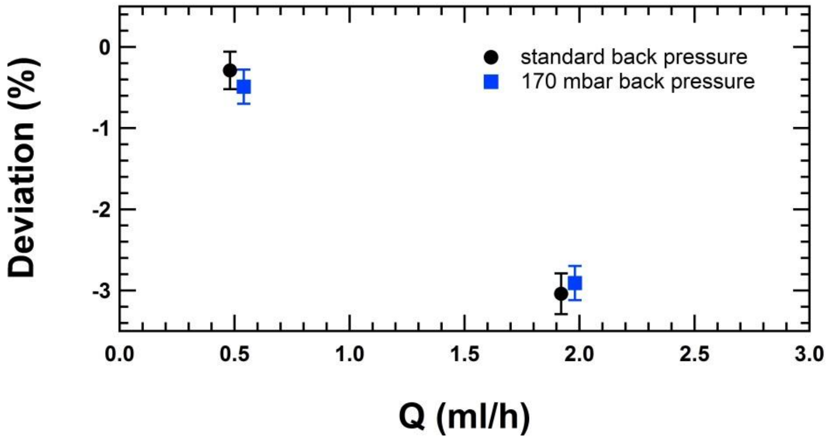

Figure 14: Measured deviations of the thermal flow meter SLI-0430 in the flow rate range from 0.5 ml/h to 2.0 ml/h for two different back pressures at a temperature of 22 °C. The flow rates have been given an artificial off set in order to better visualize the results, for example the last 2 measurements are all for a flow rate of 2 ml/h

3.3.4 Pressure drop flow meter L-0.5CCM-D from Alicat Scientific Inc.

According to the technical specifications of the manufacturer the maximum flow rate is 30 ml/h (500 μl/min) with a range of 1:50, which leads to a minimum flow rate of 0.6 ml/h (10 μl/min). Measurements were done in the flow rate range from 0.75 ml/h up to 10 ml/h. The measured deviations are listed in Table 10 and the results are shown in Figure 15.

Table 10: Measured deviations of the pressure drop flow meter L-0.5CCM-D in the flow rate range from 0.75 ml/h up to 10 ml/h at temperature of 22 °C.

Operation conditions	Reference flow rate (ml/h)	Reference flow rate (μl/min)	Deviation (%)	Uncertainty (%)
Liquid water Back pressure 0 mbar	9.71	161.91	2.39	0.21
	1.95	32.48	1.54	0.50
	0.75	12.56	-1.77	0.50
Liquid water Back pressure 170 mbar	9.82	163.72	2.87	0.45
	1.89	31.56	2.55	0.36
	0.76	12.67	1.23	0.73

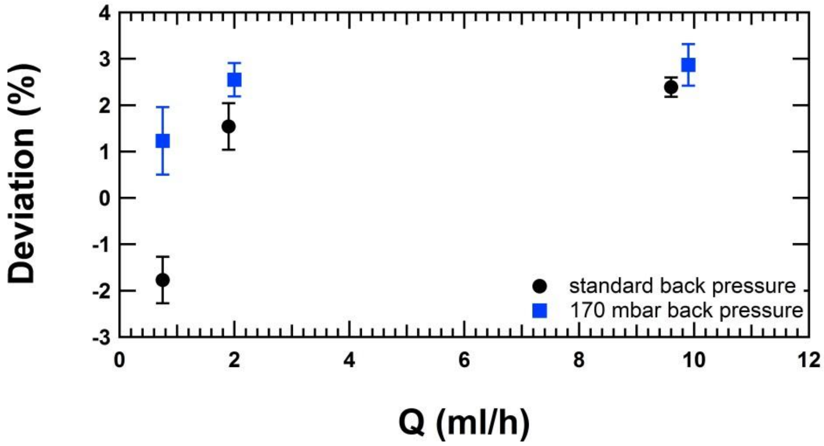

Figure 15: Measured deviations of the pressure drop flow meter L-0.5CCM-D in the flow rate range from 0.75 ml/h up to 10 ml/h for two different back pressures at a temperature of 22 C. The flow rates have been given an artificial off set in order to better visualize the results, for example the last 2 measurements are all for a flow rate of 10 ml/h

At the two lowest flow rates the measurements for different back pressures are not consistent. However, according to the technical specifications of the manufacturer the accuracy of the flow meter is ± 2 %. The measured deviations are still within the stated accuracy of the flow meter. This could be verified by reproducibility measurements of the flow meter. Unfortunately, these measurements have not been done due to lack of time.

3.3.5 Conclusion

As expected, the Coriolis flow meter and the thermal flow meter are not sensitive to any change in back pressure. The pressure drop flow sensor shows at the two lowest flow rates not consistent results for different back pressures. However, the measured deviations at the flow rate of 0.75 ml/h are still within the stated accuracy of the flow meter.

3.4 Viscosity dependency (D2.3.3)

3.4.1 Description of the task

The flow meters (SLI-0430, L-0.5CCM-D, M12) are tested using 3 different liquids: water, water-glucose mixture with viscosities of 2 times and 4 times of water. The following flow rates 0.5 mL/h, 2 mL/h and 10 mL/h are investigated by METAS.

The flow has been generated by means of a syringe pump, which is easy to handle with the different liquids and can be easily connected to the weighing system at METAS.

3.4.2 Coriolis flow meter Mini Cori-flow M12 from Bronkhorst Cori-Tech

Only the flow rates 2 g/h and 10 g/h are investigated as the flow rate range is from 200 g/h to 2 g/h according to the technical specifications of the manufacturer. The measured deviations are listed in Table 11 and the results are shown in Figure 16. The data of the back pressure measurements are shown as references for the measurements with the liquid water. As it is expected that the Coriolis flow meter is not sensitive to any change in viscosity, only the water-glucose mixture with viscosities of 4 mPa·s is used to confirm this.

Table 11: Measured deviations of the Coriolis flow meter Mini Cori-flow M12 in the flow rate range from 2.0 g/h up to 10 g/h using water and a water-glucose mixture with the viscosity of 4 mPa·s at a temperature of 22 °C.

Operation conditions	Reference flow rate (g/h)	Reference flow rate (mg/min)	Deviation (%)	Uncertainty (%)
Liquid water Back pressure 0 mbar	9.7902	163.17	-0.55	0.18
	1.9692	32.82	0.04	0.59
Liquid water Back pressure 170 mbar	9.7308	162.18	-0.50	0.21
	1.9524	32.54	0.19	0.30
Liquid water-glucose Viscosity 4 mPa·s Back pressure 0 mbar	11.3166	188.61	-0.63	0.23
	2.2596	37.66	-0.23	0.26

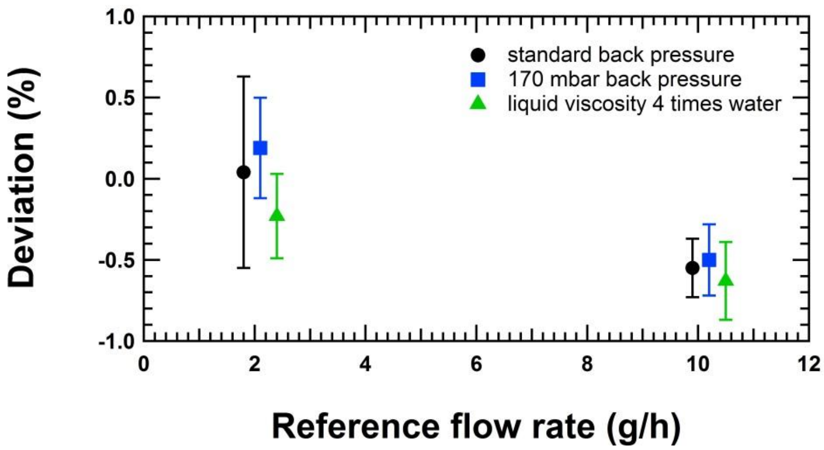

Figure 16: Measured deviations of the Coriolis flow meter Mini Cori-flow M12 in the flow rate range from 2.0 g/h up to 10 g/h using water and a water-glucose mixture with the viscosity of 4 mPa·s at a temperature of 22 °C. The flow rates have been given an artificial off set in order to better visualize the results, for example the last 3 measurements are all for a flow rate of 10 ml/h.

The measured deviations with the liquid water and the liquid water-glucose mixture are consistent. This confirms the fact that the Coriolis flow meter measures mass flow rate which is independent of the viscosity and the density of the liquid (Table 11 and Figure 16).

3.4.3 Thermal flow meter SLI-0430 from Sensirion

Only the flow rates 0.5 ml/h and 2.0 ml/h are investigated as the flow rate range is from 0.5 ml/h to 3 ml/h according to the technical specifications of the manufacturer. The measured deviations are listed in Table 12 and the results are shown in Figure 17. The data of the back pressure measurements are shown as references for the measurements with the pure water.

Table 12: Measured deviations of the thermal flow meter SLI-0430 in the flow rate range from 0.5 ml/h to 2.0 ml/h using water and water-glucose mixtures with the viscosity of 2 mPa·s and 4 mPa·s at a temperature of 22 °C.

Operation conditions	Reference flow rate (ml/h)	Reference flow rate (µl/min)	Deviation (%)	Uncertainty (%)
Liquid water Back pressure 0 mbar	2.09	34.84	-3.04	0.25
	0.52	8.66	-0.29	0.23
Liquid water Back pressure 170 mbar	2.10	34.93	-2.91	0.21
	0.53	8.84	-0.49	0.21
Liquid water-glucose Viscosity 2 mPa·s Back pressure 0 mbar	1.99	33.20	-3.69	0.62
	0.60	10.00	-1.11	0.63
Liquid water-glucose Viscosity 4 mPa·s Back pressure 0 mbar	1.99	33.09	-4.19	0.62
	0.60	9.95	-0.51	0.61

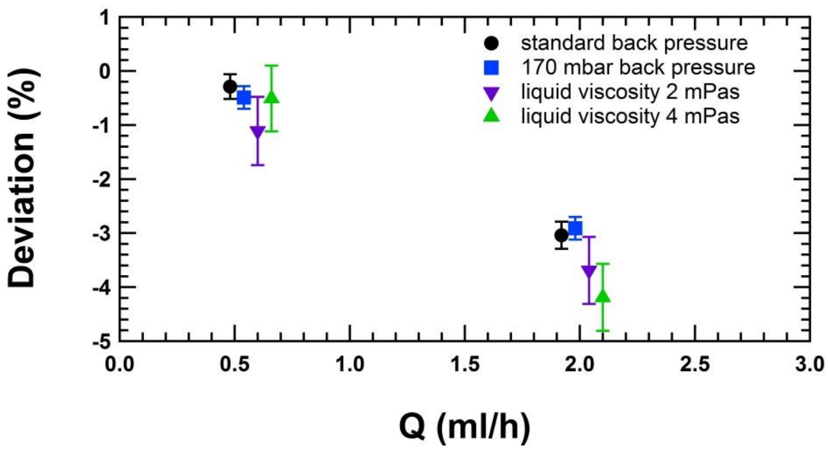

Figure 17: Measured deviations of the thermal flow meter SLI-0430 in the flow rate range from 0.5 ml/h to 2.0 ml/h using water and water-glucose mixtures with the viscosity of 2 mPa·s and 4 mPa·s at a temperature of 22 °C. The flow rates have been given an artificial off set in order to better visualize the results, for example the last 4 measurements are all for a flow rate of 2 ml/h

The water-glucose mixtures have different specific heat capicities (c_p) and conductivity as water. The conductivity of the liquids is not known. The specific heat capacities can be calculated according the following equation, if the mass fraction of glucose and water is known (Table 13).

$$c_{p,mix} = \frac{\sum_{i=1}^{2} m_i \cdot c_{p,i}}{\sum_{i=1}^{2} m_i}$$

Table 13: Glucose aqueous solutions produced at IPQ

Fluid	Mass fraction of mixture (cg/g)	viscosity	Specific heat capacity (J/kg/K)	Density at 20 °C (kg/m3)
Water	-	~ 1 mPa·s	4182.0	-
Certificate IPQ 211.35/1441988	21.208	~ 2 mPa·s	3552.8	1077.334
Certificate IPQ 211.35/1441986	35.211	~ 4 mPa·s	3137.3	1136.380
Saccharose	-	-	1215.6	-

We clearly see that the specific heat capacities of the different liquids are changing. Intuitively, a decreasing heat capacity would increases the flow rate indication as it is easier to heat up the liquid and the resulting temperature difference would be smaller. However, we observe a decreasing flow rate with decreasing specific heat capacity. The conductivity of the liquids is not known and has not been determined experimentally.

3.4.4 Pressure drop flow meter L-0.5CCM-D from Alicat Scientific Inc.

As this flow meter is set for ultrapure or deionized water, the manufacturer reminded that other liquids could damage the flow meter. Cleaning the flow meter with the Isopropanol alcohol was also not recommended due to the high risk of damage. Therefore, this flow meter was not tested with the water-glucose mixtures.

3.4.5 Conclusion

As expected, the Coriolis flow meter is not sensitive to any change in viscosity. However, we observe a decreasing flow rate with increasing viscosities and decreasing specific heat capacity of the liquids for the thermal flow meter. The change in the indications of the flow rates is probably not due to different viscosities, but results from the different specific heat capacities.

These measurements were not performed with the pressure drop flow meter as the manufacturer reminded that other liquids than ultrapure or deionized water could damage the flow meter.

4 Consistency check on similar measurements

Several measurements performed with similar environmental conditions should lead to consistent results between the different laboratories.

- (A) the measurements performed at 20 °C at CETIAT
- (B) the measurements performed at 22 °C with slow pulsating flow at DTI
- (C) the measurements performed at 22 °C with no back pressure at METAS

The measurements performed by the different laboratories are not consistent as can be seen by the DoE (Degree of Equivalence) larger than 1 (Table 14).

The reference value has been calculated according to

$$\varepsilon_{RV} = \sum_{i=1}^{n} \frac{\varepsilon_{lab-i}/U^2(\varepsilon_{lab-i})}{1/U^2(\varepsilon_{lab-i})}$$

where *n* is the number of participating labs. The uncertainty of the RV follows from:

$$u(\varepsilon_{RV}) = \frac{1}{\sqrt{\sum_{i=1}^{n} 1/U^2(\varepsilon_{lab-i})}}$$

Table 14: Degree of equivalence of the measurements at similar environmental conditions.

Type	Lab	Q (g/h, ml/h)	Dev (%)	U (%)	DoE	ε_{RV} (%)	U_{RV} (%)
Coriolis	(A)	10.75	-0.1	0.14	0.79	-0.24	0.10
	(B)	10.06	0.0	0.30	0.75		
	(C)	9.79	-0.55	0.18	1.50		
	(A)	1.84	0.15	0.82	0.22	0.35	0.44
	(B)	2.00	1.8	1.10	1.22		
	(C)	1.97	0.04	0.59	0.42		
Thermal	(A)	1.91	-1.11	1.26	1.46	-2.99	0.24
	(B)	1.94	-3.4	1.1	0.37		
	(C)	2.09	-3.04	0.25	0.15		
Pressure drop	(A)	9.87	0.25	0.18	6.61	1.71	0.13
	(B)	9.89	6.5	0.4	11.38		
	(C)	9.71	2.39	0.21	2.74		
	(A)	2.08	-1.23	0.77	3.07	1.43	0.39
	(B)	1.97	6.3	1.1	4.17		
	(C)	1.95	1.54	0.5	0.18		

Therefore, we remind the reader that only one flow meter of each type has been tested for various conditions and therefore general conclusions have to be stated carefully as it might not fully represent the average behavior of these types of flow meters. Nevertheless, general trends can be observed.

5 Reynolds interpolation

In general, flow meters can be quite sensitive to changes in the Reynolds number and velocity profile. However, the results of Section 3 show that the temperature, viscosity and back pressure do not have a significant impact on the metering accuracy (for the ranges tested). Hence, the obtained results indicate the Reynolds number is not relevant for these flows.

This can actually be shown by looking at the velocity profile of a Poiseuille flow, given by:

$$u(y) = \frac{1}{2\mu}\left(\frac{dp}{dx}\right)(y^2 - Dy)$$

where y is the distance perpendicular to the wall, $\frac{dp}{dx}$ is the horizontal pressure gradient (driving force) and μ is the dynamic viscosity.

A Poiseuille is defined as a fully developed laminar flow and exists between two infinite parallel plates. Because of the very small dimensions of the capillaries and tubing used in the microfluidic applications and flow meters, a fully developed laminar flow is a very good assumption. Consequently, for the same flow rate, one will have the same velocity profile. In case the viscosity changes (either directly or through temperature), the pressure gradient will have to compensate.

6 Uncertainty estimation for calibration in the field

The aim of this task is to estimate the uncertainty of the flow meter used for calibration in the field. The results of the measurements performed for the flow meter assessment (D2.3.3) are used for the estimation of several contributions to the final uncertainty.

6.1 Uncertainty contributions

The uncertainty contributions are the following:

- uncertainty of the flow meter calibration by a primary standard
- uncertainty of the indication (resolution) of the flow meter
- uncertainty due to the possible drift of the flow meter
- uncertainty due to the repeatability of the flow meter
- uncertainty due to different liquid used as the one during the calibration
- uncertainty due to different pressure and temperature as the one during the calibration

6.1.1 Uncertainty of the flow meter calibration by a primary standard

We assume that 0.2 % is a reasonable value for the calibration of flow meters in the upper flow rate range. At the lower flow rate range the uncertainty might be larger than 0.2 %. Flow rates covering this assumption are in general above 10 μl/min, but depend on the primary standard used to calibrate the flow meter.

6.1.2 Uncertainty of the indication (resolution) of the flow meter

The flow meters are read out by means of the analog output or the software provided by the manufacturer. The worst case of the resolution is given by the analog output, where we assume a resolution of 0.005 V on a 0-5 V output and a resolution of 0.01 mA on a 4-20 mA output. This gives us a value of 0.1 %.

6.1.3 Uncertainty due to the possible drift of the flow meter

For the drift of the flow meter we assume an uncertainty contribution of 0.3 % based on various measurements of Coriolis and thermal flow meter. The reproducibility measurements of the flow meters are well covered by this conservative estimate as the Coriolis and thermal flow meters reproduce very well in the upper flow rate range. The lowest flow rate range has to be avoided if possible.

6.1.4 Uncertainty due to the repeatability of the flow meter

The uncertainty of the repeatability of the flow meter is estimated to 0.2 % based on various measurements of Coriolis and thermal flow meter.

6.1.5 Uncertainty due to different liquid used as the one during the calibration

To estimate the influence of the different liquids on the calibration curve we take into account the measurements performed for the viscosity dependency of the flow meters. We consider the largest difference «ε» in the obtained deviations for one flow rate to calculate a contribution which is distributed rectangular (Table 15).

$$u_{Viscosity} = \frac{\varepsilon}{2\sqrt{3}}$$

Table 15: Largest difference «ε» in the obtained deviations for one flow rate of the «viscosity dependence» to calculate a contribution which is distributed rectangular.

Type flow meter	Flow rate (ml/h)	ε (%)	U (%)
Coriolis	1.8	0.42	0.25
Coriolis	10.0	0.13	0.08
Thermal	0.6	0.82	0.48
Thermal	2.0	1.28	0.74

As the liquids used are water Glucose mixtures the viscosity and the heat capacity as well as the heat transfer rate are different than the one of water. Therefore a significant deviation is observed for the thermal flow meter which results of the different heat capacity and the heat transfer rate of the liquids. It is more than correct to estimate this contribution to 0.3 % for all types of flow meters.

6.1.6 Uncertainty due to different pressure and temperature as the one during the calibration

To estimate the influence of the different pressure and temperature on the calibration curve we take into account the measurements performed for the pressure and temperature dependency of the flow meters. We consider the largest difference «ε» in the obtained deviations for one flow rate to calculate a contribution which is distributed rectangular (Table 16).

$$u_{Viscosity} = \frac{\varepsilon}{2\sqrt{3}}$$

Table 16: Largest difference «ε» in the obtained deviations for one flow rate of the «back pressure and temperature dependence» to calculate a contribution which is distributed rectangular.

Type flow meter	Flow rate (ml/h)	ε_P (%)	U_P (%)	ε_T (%)	U_T (%)
Coriolis	1.8	0.15	0.09	2.14	1.24
Coriolis	10.0	0.05	0.03	0.40	0.24
Thermal	0.6	0.20	0.12	0.87	0.51
Thermal	2.0	0.13	0.08	1.3	0.76
Pressure drop	1.0	3.0	1.74	2.80	1.62
Pressure drop	2.0	1.01	0.59	0.95	0.55
Pressure drop	10.0	0.48	0.28	0.37	0.22

We have to point out that the temperature dependence measurements of the thermal flow meter and the back pressure measurements of the Coriolis measurements were not consistent with the other measurements. The measurements of the pressure drop flow meter were not consistent for all measurements. Moreover, only one flow meter per type has been investigated. For reasonable statistics at least 10 flow meters of each type should have been tested.

However we can state that for the Coriolis flow meter the uncertainty component due to different pressure and temperature is of the order of 0.3 % and 0.5 % for the other types of flow meter in the upper flow rate range.

6.2 Final uncertainty

The different components are now be summarized in Table 17 and 18, where the final uncertainties for Coriolis and the other types of flow meters are determined.

Table 17: Uncertainty calculation for a Coriolis flow meter used for calibration in the field.

Uncertainty component i	Uncertainty (%)	Distribution	Standard uncertainty	Sensitivity coefficient	u_i (%)
Calibration	0.2	Rect, $k = \sqrt{3}$	0.12	1	0.12
Resolution	0.1	Rect, $k = \sqrt{3}$	0.06	1	0.06
Drift	0.3	Rect, $k = \sqrt{3}$	0.18	1	0.18
Repeatability	0.2	Norm, $k = 2$	0.10	1	0.10
Liquid	0.3	Rect, $k = \sqrt{3}$	0.18	1	0.18
Pressure, Temperature	0.3	Rect, $k = \sqrt{3}$	0.18	1	0.18

Total uncertainty k=1	0.36 %
Total uncertainty k=2	0.72 %

Table 18: Uncertainty calculation for other types of flow meter used for calibration in the field.

Uncertainty component i	Uncertainty (%)	Distribution	Standard uncertainty	Sensitivity coefficient	u_i (%)
Calibration	0.2	Rect, $k = \sqrt{3}$	0.12	1	0.12
Resolution	0.1	Rect, $k = \sqrt{3}$	0.06	1	0.06
Drift	0.3	Rect, $k = \sqrt{3}$	0.18	1	0.18
Repeatability	0.2	Norm, $k = 2$	0.10	1	0.10
Liquid	0.3	Rect, $k = \sqrt{3}$	0.18	1	0.18
Pressure, Temperature	0.5	Rect, $k = \sqrt{3}$	0.29	1	0.29

Total uncertainty k=1	0.43 %
Total uncertainty k=2	0.86 %

These uncertainties of 0.72 % for the Coriolis flow meter and 0.86 % for the other types of flow meters are conservative estimations and these values might be improved by an investigation of a large batch of flow meters or by the calibration of a single flow meter under various influence conditions of these physical parameters.

7 General conclusions

The design of the Coriolis, thermal and pressure drop flow meters plays an important role for the application of various physical influence parameters and different liquids. The Coriolis flow meter and the thermal flow meter have only tubing, which is in contact with the liquids and the sensors are mounted outside or on the tubing. The pressure drop flow sensor has two pressure sensors that are in contact with the liquid.

These measurements confirmed that the Coriolis flow meter is not influenced by temperature changes, back pressure changes or even different liquids. The reason is that the mass and the density of a liquid are measured by means of the Coriolis principle.

These results also confirmed that the thermal flow meter is sensitive to any change in the specific heat capacity of the liquid as the initial calibration is done with water. Other liquids with different specific heat capacities will lead to different calibration curves. However, the temperature and the back pressure changes are not influencing the thermal flow meter significantly.

The pressure drop flow meter revealed a slight dependency on the back pressure at the lower limit of the flow rate range. However, all the measured deviations are within the specifications of the flow meter.

The uncertainty of the flow meter for the calibration in the field has been estimated to be 0.72 % for the Coriolis flow meter and 0.86 % for the other types of flow meters. These values are conservative estimations and they might be improved by the calibration of a single flow meter under various influence conditions of these physical parameters.