Characterisation of flow meters for fuel consumption measurements in realistic drive cycle tests

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Abstract

Type approval testing of vehicles on chassis dynamometers, or experiments at the engine tests bench, require a precise measurement of the time-dependent fuel consumption, that is usually carried out by means of flow meters. However, the performance of these instruments can be jeopardized considering both the range of flow rate and its high dynamicity. In addition, the adoption of innovative fuels, such as biofuels and synthetic fuels, is nowadays of increasing interest thanks to their potential in pollutant emission reduction. Therefore, flow meters should depend as little as possible on the selected fuel, e.g. density and viscosity, and fuel temperature, guaranteeing high measurement accuracy in each test condition. In this context, the scope of the ongoing EMPIR Joint Research Project 20IND13 "SAFEST" is to investigate the measurement accuracy of flow meters considering different fuels and different highly dynamic operating conditions. More specifically, in this paper the analysis on a Coriolis flow meter is presented. Flow measurements were carried out using different fuels in a wide density and viscosity range along with a broad temperature range.

1. Introduction

The sector that contributes one of the most to air pollutant emissions in Europe is transport. The road transport sector was not only the largest contributor to total nitrogen oxide (NOx) emissions in the EU-28 in 2018 [1], accounting for 47 % (39 % road transport and 8 % non-road transport) but was also the source for 27 % of Europe's CO_2 emissions in 2019 [2]. For this reason, various measures were discussed and taken to reduce this emission contribution. Here it is significant, that a few years ago, a new mandatory measurement procedure called Worldwide harmonized Light vehicle Test Procedure (WLTP) and a new driving test cycle, Worldwide harmonized Light vehicles Test Cycle (WLTC) were introduced. The WLTC was implemented, because it is more realistic than the previous New European Driving Cycle (NEDC), i.e. the fuel consumption values measured during type approval were generally lower than the values occurring in real driving conditions. Discrepancies between laboratory and road values for vehicles were as high as 20 % to 40 % depending on the type of vehicle.

The procedure and the obtained consumption values in the WLTP are closer to the real world, because the WLTP is based on real-driving data gathered from 14 countries (some EU countries plus Switzerland, USA, India, South Korea and Japan), resulting in average driving profiles.

In contrast to the NEDC, acceleration and braking are more frequent and more intensive in the WLTP, and there is less idling. A major difference is that testing is also carried out at higher speeds and that the test time is significantly longer. In addition, driving resistances such as mass, rolling resistance and air resistance are taken into account to a greater extent than in the outdated NEDC. From 1 September 2018, WLTP is obligatory for the initial registration of every new car. This means that fuel consumption and emissions will be tested using this procedure during the type-approval of all new passenger car models in the EU.

The situation is similar for heavy-duty vehicles, such as trucks. However, the tests here are not carried out on a chassis dynamometer but on an engine dynamometer (engine test bench). The WHTC (World Harmonised Transient Cycle) is the test cycle for the certification of engines and was adopted from the Euro VI emissions regulation for heavy-duty vehicles. Like the WLTC, the WHTC is a transient test of 1800 s duration, with several motoring segments. In contrast to the WLTC, three driving conditions are represented in the WHTC including urban, rural and motorway driving.

In the scope of the EU strategy for low-emission mobility the use of alternative fuels and engine efficiency improvements play an essential role. Even though European Parliament lawmakers voted beginning of June 2022 to support an effective EU ban on the sale of new petrol and diesel cars from 2035, this does not mean that there will be no more vehicles with combustion engines on the roads from that point on. For economic, resource-specific and technical reasons, a complete transformation of technologies or replacement of vehicles is not feasible on a short- to mid-term timeframe. It is therefore to be expected that a larger fleet of vehicles with combustion engines will still be on the roads for some time to come which cannot be ignored in terms of their contribution to emissions and global warming.

2. Background

Concerning fuel consumption measurements, there is a need for metrological action in several aspects: Regarding the measuring performance of flow meters there are no reliable quantitative insights into how fuel flow meters perform under (i) dynamic load changes as they are calibrated at static flow rates and infrastructure for dynamic calibrations needs to be established first. Moreover, (ii) the performance of flow meters deployed in fuel consumption measurement at zero flow or low flow rates of a few 100 ml/h is not known. In addition to this (iii), there is no reasonable estimate of the effects of operation conditions such as density, viscosity, and fluid temperature on flow meter performance and the associated uncertainty. In sum, engine developers and test bench operators need and are demanding precise fuel consumption flow meters that provide highly accurate measurement results with various fuels in a wide flow rate range even during cyclic tests. The current state of knowledge is not sufficient for this.

Within the EMPIR Joint Research Project 20IND13 “SAFEST” different flow meters are investigated for their suitability as fuel consumption flow meters. The work in the project is divided in such a way that PTB (Physikalisch-Technische Bundesanstalt) addresses dynamic fuel consumption measurements of small to medium-sized passenger cars (current consumptions less equal 25 l/h) and smaller trucks (current consumptions less equal 100 l/h) with input data, i.e. theoretical background from IB-HAWE (Ingenieurbüro Hagemann) and real consumption data recorded at engine test benches from UniPG (University of Perugia) and PoliTO (Polytechnic University of Turin). Here, a special focus will be placed on the idling consumption in the range of some 100 ml/h.

RISE (Research Institutes of Sweden) is concerned with the influence of different fuels on the measurement accuracy of fuel flow meters at steady flow rates. The focus is on the widest possible density and viscosity range. The flow range is from 3 l/h to 400 l/h, which corresponds, for example, to the current consumptions of petrol/gasoline passenger cars up to 600 kW and diesel trucks up to about 800 kW. The flow range was specified in this way to investigate a wide flow range at the same time within the scope of the project.

The development of a metrological infrastructure to be able to investigate the measurement performance of flow meters for dynamic flow changes consists of two parts. On the one hand, the provision of test profiles that reflect flow variations occurring in fuel consumptions in road transport, and on the other hand a measuring infrastructure that is capable to realise these profiles and to capture the measurement performance in a traceable manner.

The test profiles for vehicles were derived following several steps. The WLTC comprises four phases with different speed distributions, during which fuel consumption is measured and exhaust emissions are sampled (Figure 1). The duration of the entire WLTC is 1800 s and the cycle is composed of low speed, medium speed, high speed, and extra high speed phases. From the WLTC for passenger car engines and the World Harmonised Transient Cycle (WHTC) for truck engines the equivalent turndown ratios were derived.

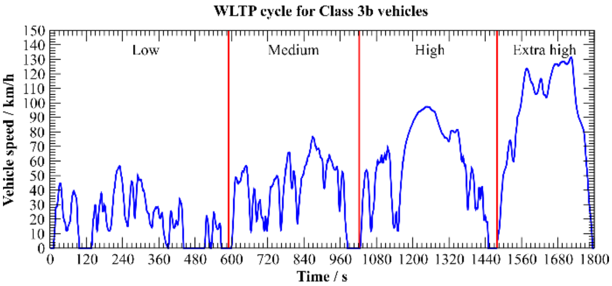
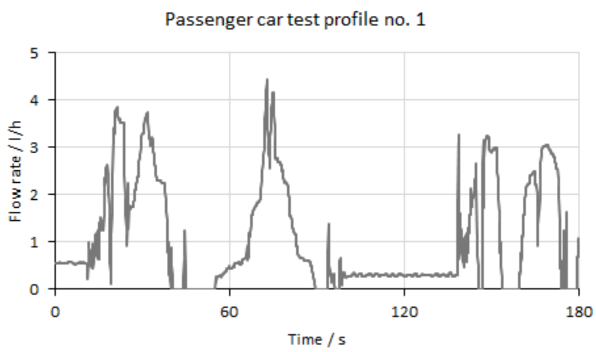


Figure 1: WLTP/WLTC for class 3b vehicles. Class 3 (highest power-to-mass ratio) is representative of vehicles driven in Europe.

Based on real test runs, the fuel demands from the engine control units (ECUs) were determined and correlated to the dynamic response of the test equipment applied. From these, test profiles for passenger cars and trucks were derived which take up characteristic sequences of the harmonized test cycles. Broad applicability is made possible by the fact that the test profiles can be simply scaled to reflect different engine sizes. In addition to closeness to reality attention was paid in the profile development to suitability for practical implementation. For this reason, profile sequences were derived for each application. Figure 2 and Figure 3 show the principle test profiles obtained for passenger cars and trucks.



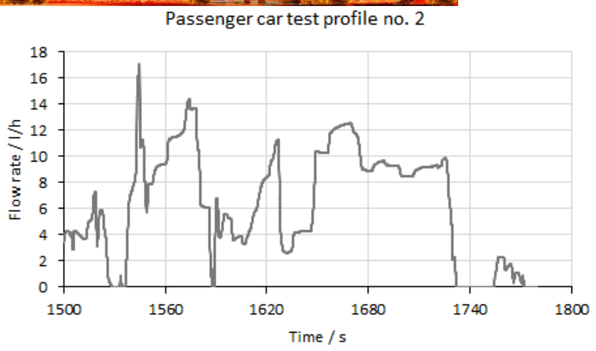


Figure 2: Test profiles derived for a petrol/gasoline passenger car with a 97 kW engine; Car test profile no. 1 is derived from the “low phase” and car test profile no. 2 from the “extra high phase” in the WLTC (see **Figure 1**); please note the different scaling of the y-axis.

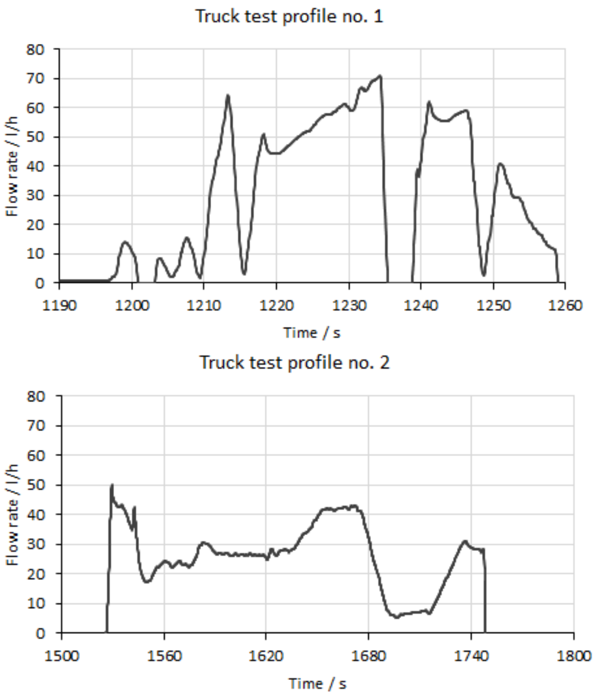


Figure 3: Test profiles derived for a diesel truck with a 263 kW engine; Truck test profile no. 1 is derived from the “rural phase” in the WHTC and truck profile no.2 from the “motorway phase” in the WHTC.

The test profiles serve as basis for the development of test rigs capable to realize dynamic flow changes with these characteristics.

3. Method

3.1 Procedure at PTB

PTB’s approach for a technical realization of the vehicle profiles consists of using a set of cavitation nozzles and orifices of different sizes which can be individually controlled and combined. Preliminary tests have shown very promising results. However, further measurements and validations are still required, among other things to get a better grasp of influencing factors.

Not only the wide dynamic range and the dynamic flow changes are a challenge for every flow meter, but the wide range of fuels with their different physical (viscosity, density) and chemical properties (composition, proportion of biofuels) play a role. None should significantly affect the accuracy of the fuel flow meter.

3.2 Procedure at RISE

Two main principles of flow measurement are used in fuel consumption measurement. One is realized as positive displacement (DP) flow meter, as a volume flow meter and the other one as Coriolis flow meter (CFM), as a mass flow meter.

For the measurements at RISE, a Proline Promass A 500 CFM from Endress+Hauser (E+H) was investigated (Figure 4). CFMs are known to be almost insensitive to the physical properties (density, viscosity) of the liquid and are suitable for dynamic flow measurements [3].

Figure 4: DUT – Endress+Hauser Proline Promass A 500.

As given in Table 1, the mass flow rate and volume flow rate can be measured using the pulse or the frequency output. For all measurements shown in the following, the high frequency outputs (10 kHz) were used for the mass flow signal and the volume flow signal. In addition, the density and temperature were logged via the analogue signals (4 mA-20 mA).

Table 1: Specifications by the manufacturer and settings of the DN4 (1/8”) Endress+Hauser Proline Promass A 500 CFM for the measurements for liquids.

Specification	Value
Flow rate range	0 to 450 kg/h
Max. measurement error flow rate	± 0.1 % mass flow ± 0.1 % volume flow
Max. measurement error density	± 0.0005 g/cm^3
Pressure range	Up to 430 bar
Temperature range	-50 °C to 205 °C
Signal outputs (configuration during measurements)	Mass flow and volume flow: pulse/frequency (10 kHz) Density: analog 4-20 mA Temperature: analog 4-20 mA

3.2.2 Test liquids

The Proline Promass A 500 was calibrated with water (as baseline measurement), Exxsol D40, Exxsol D120, HVO100 and RME100 in a flow rate range from 3 l/h to 400 l/h each in a temperature range from 15 °C to 30 °C. A zero point adjustment at 20 °C was carried out for each new test liquid. However, this zero point was not changed during the temperature measurements.

Exxsol D40 is a substitute for petrol/gasoline and Exxsol D120 represents a slightly heavier diesel. In general, Exxsol D80 is considered to be a substitute for diesel. Exxsol D120 with a higher viscosity was used to widen the viscosity range. RME100 is a first-generation biodiesel and is produced from crops grown directly in the fields. HVO100 is a second-generation biodiesel, also called “advanced biofuel”. Second-generation biofuels are produced from residual and waste products from, for example, industry and households. Large quantities of used cooking oil and offal are also used. The use of biodiesel has several advantages and can also help reduce CO_2 emissions. For example, there are assumptions that RME100 minimises CO2 emissions by 70 % [4] and HVO100 by 70 % to 90 % [5] compared to conventional diesel.

Table 2: Density and viscosity values of the test liquids at a temperature of 20 °C. The measurements were performed at RISE’s Chemistry Laboratory.

No.	Test liquid	Temp. °C	Viscosity mm^2/s	Density g/ml
1	Exxsol D120	20	5.35	0.8231
2	Exxsol D40	20	1.54	0.7711
3	RME100	20	6.90	0.8770
4	HVO100	20	5.31	0.7868

The density and viscosity values of the four test liquids were determined at a temperature of 20 °C at RISE’s Chemistry laboratory (Table 2).

5. Measurements results

5.1 Water calibration facility

For the baseline measurements with water, one of the primary standard water flow calibration facilities (VM7) at RISE [3] was used (Figure 5). VM7 consists of a high and a low pressure tank. The pressure is kept constant in both tanks. Flow is the generated by means of a pressure difference between both tanks.

Figure 5: Calibration facility VM7 used for the measurements with water and temperatures between 10 °C and 30 °C.

The desired flow rate is set using digital valves with different opening scenarios depending on the flow rate. The measurements were carried out in flying start-and-stop using a piston prover with two calibrated test volumes of 1 L and 5 L as reference. The expanded measurement uncertainty of the calibration facility is U(*k=2*) ≤ 0.1 %.

5.2 Measurement results (water)

Before the measurements with the actual fuels, a baseline measurement with water was carried out at eight flow rates with five repetitions each. An additional heating jacket for the CFM was used for temperature stability.

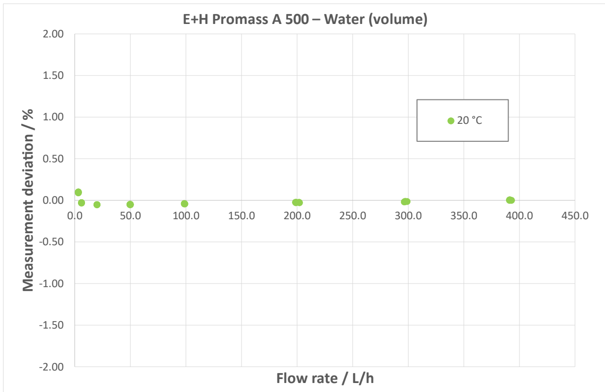


Figure 6: Within the project, calibration measurements were carried out with water in a temperature range from 15 °C to 30 °C. The figure shows the measurement results for the measurements at 20 °C.

As can be seen in Figure 6, the CFM has a very good repeatability and reproducibility for the measurements with water. The maximum spreading within a flow rate value is 0.14 % and the standard deviation is better than 0.05 % for all flow rates.

For the temperature-dependent flow measurements in the temperature range from 15 °C to 30 °C, which are not shown here, the CFM indicates the same measurement deviation at the higher flow rates regardless of temperature. At lower flow rates the influence of the zero point is noticeable. Here, the flow meter tends to go into the minus range for temperatures below 20 °C and into the plus range for temperatures above 20 °C. To evaluate the possible influence of the heating jacket on the measurement accuracy of the CFM, measurements were carried out at 20 °C with and without the heating jacket. However, an influence on measurement accuracy of the CFM could not be determined.

5.3 "Hydrocarbon" calibration facility OM2

The measurements with the different alternative and synthetic fuels were carried out using a commercially available calibration facility. The TriFlow TF series primary liquid flowmeter calibration system is a compact, hydraulically operated system, closed-loop system, based on the positive displacement (DP) principle. The flow rate is generated by using a precisely honed, chrome-plated stainless-steel piston, which is inserted into a liquid container and displaces a known volume as a reference. By means of a linear encoder, the movement of the piston generates a continuous sequence of electrical pulses. Double-time chronometry and quadrature-time methods according to ISO 7278-3 are used to eliminate timing errors and improve overall accuracy. The displacement calibrator is practically insensitive to viscosity, density, and compressibility effects of the test liquid. The specifications of the calibration facility can be found in Table 3. The expanded measurement uncertainty of the calibration facility is U($k=2$) ≤ 0.1 %.

Table 3: Specifications of the TriFlow Low Flow Liquid Calibrator System TF030 (OM2)

Specification	Value
Standard flow ranges	0.900 l/h to 1800 l/h
Minimum achievable flow	0.030 l/h
Accuracy	± 0.03 % of reading
Repeatability	± 0.02 % of reading
Pressure range	Up to 12 bar
Temperature range	10 °C to 50 °C
Viscosity range	Up to 10'000 mm^2/s
Signal inputs	Frequency (10+ kHz) Analog 0/4-20 mA Analog 0-5/0-10 VDC Visual

5.4 Measurement results (test fuels)

For stable temperature measurements with OM2, the system was equipped with an additional heat exchanger in the return line and a construction that can keep the area around the piston temperature stable. Furthermore, the actual measuring section was equipped with an additional temperature conditioning and enclosure. The constructional changes have ensured that the temperature can be kept stable over the entire temperature range. In the worst case (lowest flow rate at 15 °C), the temperature stability was ± 0.20 K over a period of five repeat measurements. As for the water measurements, only the results obtained from the volume flow signal of the CFM at a temperature of 20 °C are shown in the following.

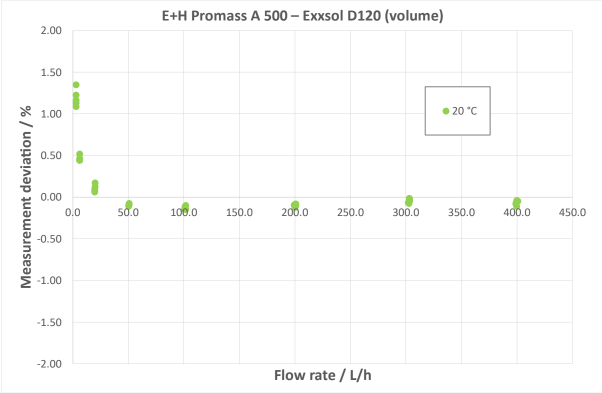


Figure 7: Calibration measurements with Exxsol D120 at a temperature of 20 °C.

As can be seen in Figure 7, the CFM has a very good repeatability and reproducibility for the measurements with Exxsol D120. The maximum spreading at 20 °C within a flow point is 0.26 % and the standard deviation is better than 0.10 % for all flow rates. The influence from the zero point is perhaps more noticeable in these measurements than in the other test fuels.

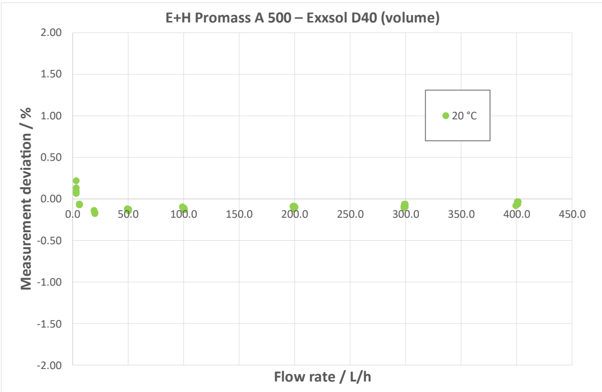


Figure 8: Calibration measurements with Exxsol D40 at a temperature of 20 °C.

The measurements with Exxsol D40 show a similar characteristic as the measurements with water (Figure 8). The maximum spreading at 20 °C within a flow point is 0.14 % and the standard deviation is better than 0.06 % for all flow rates.

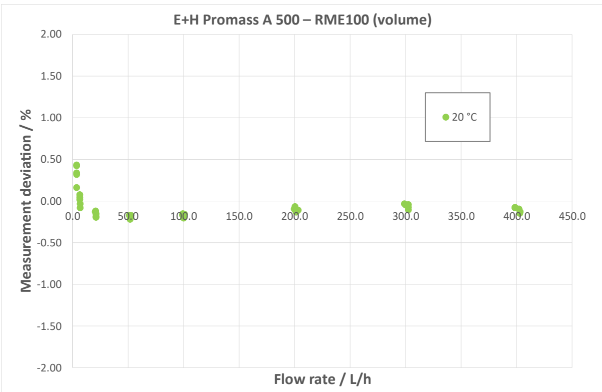


Figure 9: Calibration measurements with RME100 at a temperature of 20 °C.

The RME100 measurement results are very similar to the measurements with Exxsol D120 (Figure 9). The maximum spreading within a flow rate is 0.27 % and the standard deviation is better than 0.11 % for all flow rates.

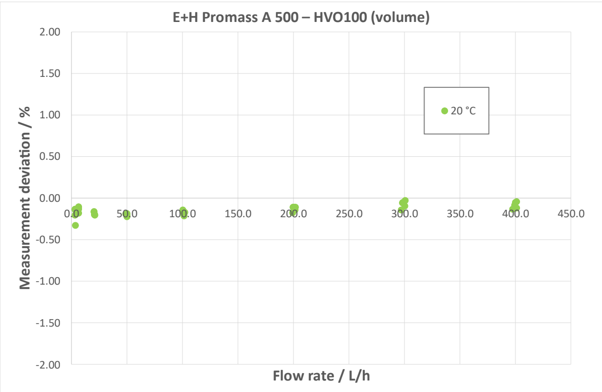


Figure 10: Calibration measurements with HVO100 at a temperature of 20 °C.

The CFM also performs very well in the measurements with HVO100. The measurement results are very similar to RME100 and Exxsol D120 (Figure 10). The maximum spreading within a flow rate value is 0.20 % and the standard deviation is better than 0.08 % for all flow rates.

In summary, it can be stated that the CFM performs well over the entire flow range investigated. At higher flow rates, the measurement deviation is close to zero. The measurement deviation of the CFM at lower flow rates is, as expected, dependent on the zero point. Overall, the CFM appears to be suitable for measuring the fuel consumption of different fuels in large engine test benches over the entire flow range studied.

6. Conclusion

As part of the EMPIR Joint Research Project 20IND13 "SAFEST", investigations on the measuring accuracy of fuel consumption meters were carried out. The focus here is on the one hand on dynamic flow tests typical for driving cycles and fuel consumption driving. Here, special attention is paid to the very low idling flow rates that occur in the range of a few 100 ml/h, especially in smaller, fuel-efficient vehicles. Currently, PTB and other project partners are working closely together to establish the infrastructure to carry out such tests. Two sets of consumption profiles, one for passenger cars and one for trucks, derived from real consumption measurements are presented here. Both sets are intended to provide the basis for the later dynamic measurements.

Due to the power range of the vehicles, the instantaneous fuel consumption of the vehicles can vary from around 0.5 l/h (and less) for small vehicles at idle to more than 300 l/h for super sport cars, large sport utility vehicles and trucks when accelerating. This means that, depending on the engine power of the vehicle, the fuel consumption is in a different flow range. A Coriolis flow meter (CFM) was investigated at RISE for use as fuel consumption meter in high-power chassis dynamometers with flow rates up to 400 l/h. In contrast to smaller passenger cars, the idle flow rates here are already significantly above 1 l/h. For this reason, the range from 3 l/h to 400 l/h is particularly interesting. The aim of this activity was to investigate the influence of different types of fuels (conventional, alternative and synthetic), i.e. different densities and viscosities, and temperature on the measurement accuracy of the CFM. Here the measurement results at 20 °C obtained with four different fuels that have a very wide density and viscosity range are presented for the first time. Altogether the CFM performs very well with all test fuels in the flow rate range investigated.

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