# Metrology for reliable fuel consumption measurements

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**Abstract**

Reliable fuel consumption measurements play an essential role in developments to increase engine efficiency and the transformation to e-fuels or emission determination. A verification of the performance of flow meters used for the fuel consumption measurements under real-world conditions compared to laboratory conditions is thus of great interest since often the measurement technology must be an order of magnitude better than the targeted improvements. Apart from the influence of the pressure- and temperature-dependent transport properties of the fuels and the ambient conditions, a characterization of the measurement performance under dynamic fuel consumption and at low or zero consumption is of particular relevance. Traceable metrological infrastructures and procedures, which will enable an evaluation of the measurement performance of flow meters in this regard, are currently being developed within the scope of the EMPIR-project "Safest" (20IND13). Test profiles based on the demand of the engine control unit were derived for passenger cars and trucks which take up characteristic sequences of the harmonized test cycles WLTC and WHTC. The profiles can simply be scaled to reflect different engine sizes. Based on a profile from a ferry navigating in a harbour the performance of flow meters used in the maritime sector is investigated. In addition to the measurement accuracy under dynamic conditions, the performance of flow meters is analysed related to ambient conditions and different transport properties of the fuels. The investigations show influencing factors that should be considered when determining emissions by means of flow measurements of the fuel supply to the engine.

## 1. Introduction

Fuel consumption measurements play an essential role in many areas, such as developments to increase engine efficiency, the transformation to the use of e-fuels or emission determination. Tightened emission requirements and stricter fuel consumption limits (e.g. Regulations (EU) 2015/757, (EU) 2019/631) have resulted in reliable fuel consumption measurements becoming a hot topic for vehicles and ships. However, the quality of the fuel consumption measurement is directly linked to the quality of the fuel flow measurement, and via this, to the measurement performance of the flow meter. Thus, to assess the measurement quality of the flow meters used for fuel consumption measurements under close to real-world conditions compared to the usually used laboratory conditions with constant flows is of great interest. In many cases, the measurement technology must be an order of magnitude better than the targeted improvements in, for example, fuel economy or emission determination. Consequently, it is necessary to know the measuring performance of the flow meters in more detail. Besides the influence of the pressure- and temperature-dependent transport properties of the fuels and the ambient conditions, insights into the measurement performance under dynamic fuel consumption and at low or zero consumption are of particular relevance. Traceable metrological infrastructures and procedures, which will enable corresponding evaluations of the performance of flow meters deployed in vehicles and ships for consumption measurements, are currently being developed in the EMPIR-project "SAFEST" (20IND13). In addition to dedicated guidelines regarding e.g. the impact of ambient conditions and fuel properties the project outputs will make it possible to calibrate flow meters not only statically but also dynamically in the future. This paper presents the first results of work on the issues in the marine sector.

## 2. Dynamic characterizations

The development of a metrological infrastructure to be able to investigate the measurement performance of flow meters for dynamic flow changes consists of two key components

1. test profiles that reflect flow variations occurring in fuel consumptions in road and maritime transport
2. a test rig that is capable to realize these profiles and to capture the measurement performance in a traceable manner.

*2.1 Derivation of the test profile*

When travelling on the open sea, fuel consumption is not subject to large fluctuations. Nevertheless, there is still potential for fuel savings here. In coastal areas or harbours the situation is different. Due to the greater manoeuvring required here, fuel consumption is variable. In many regions, emission limits are specified for these areas, non-compliance with which can result in severe fines. Therefore, fuel consumption measurements in these areas are of particular importance, as they are used to calculate emissions. This was why the fuel consumption of a ferry navigating in a harbour was used as basis for the derivation of the maritime test profile shown in Figure 1. It could be demonstrated that by a simple scaling the profile can be adapted to different engine sizes.

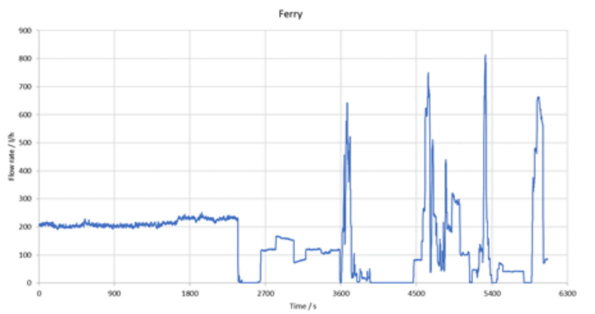


**Figure 1:** Test profile based on fuel consumption of a ferry navigating in a harbour.

*2.2 Development of measurement infrastructure*

Test profiles such as the one shown in Figure 1 serve as basis for the development of test rigs capable to realize dynamic flow changes with these characteristics.

For realizing the flow changes related to the ferry profile a needle valve (DN4) was integrated in a conventional test rig at PTB. Figure 2 shows a section of the measurement results obtained with a Coriolis flow meter on PTB's hydro-carbon test rig "MÖZ". White spirit 180/210 (at 20 °C: density: 784.813 kg/m³, kinematic viscosity: 1.72 mm²/s) was used as test liquid. Similar results were obtained using a turbine. The profile realization is basically very good. All flow changes from small to large as well as zero flows are present. However, some of the peak amplitudes are not fully captured yet.

A prerequisite for any eventual future dynamic calibrations of flow meters is that the quality with which the test profiles are realised on a test rig can be verified and quantified. One essential requirement is the measurement against a sufficiently accurate reference that is traceable. However, this alone is not sufficient to assess the quality of a profile implementation on a test rig, because the quality with which the individual flow changes are realised also plays an essential role here.

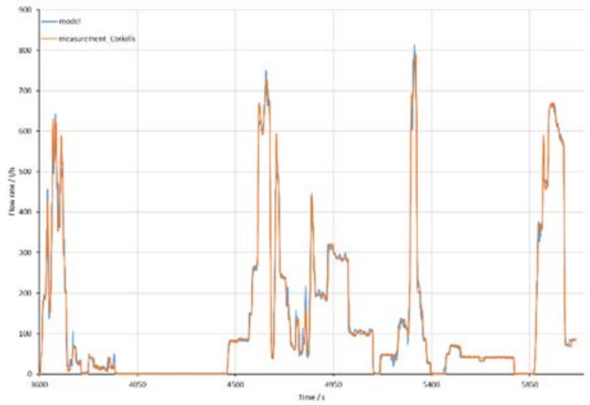


**Figure 2:** Realization of the maritime test profile of Figure 3 on PTB's test rig MÖZ. Only the section with major flow rate changes is drawn. Measurements were carried out with a Coriolis flow meter.

Further evaluation criteria are therefore needed based on the consideration of the residuals, time until a stable flow rate is achieved, repeatability etc. The feasibility of these criteria was demonstrated in the EMPIR-project "Metrowamet" (17IND13) [1][2]. For the evaluation of flow meter performance regarding dynamic flow changes a similar approach should be followed. In one of the next steps the realization of the test profile shown in Figure 2 will be analysed based on the aforementioned evaluation criteria. First, however, work will be done on further optimising the realisation of the profile.

## 3. Characterisations with regard to test medium

The scope of investigation on the influence of the test medium on the measuring performance of flow meters covers a flow range up to 8000 l/h. Measurements will be carried out using at least three different types of flow meters with different measuring principles that are typically deployed for consumption measurements in the maritime sector. Furthermore, measurements are to be carried out with at least three different hydrocarbon liquids at different temperatures and thus different viscosity/density ranges, which correspond to alternative and synthetic fuels that are seen as promising future replacements for conventional fuels. The temperature range of interest in this investigation extends from 15 °C to 30 °C. It is clear that it is not feasible to measure an arbitrarily high number of flow meters or a very wide range of fuels and media temperatures with reasonable effort. The aim is to create a sufficiently broad database with which it will be possible to quantify the suitability of conversions via the Reynolds number for different transport properties of liquids. In this way, it should also be clarified or indications found as to whether there is also a direct interaction between the liquid and the flow meter. In the following, a first set of measurement results is presented and discussed.

*3.1 Characterization of screw spindle flow meters*

The KRAL volume flow meter is a robust flow meter for liquids and offers laboratory accuracy even in harsh, industrial applications. KRAL was the first company to launch a complete flow meter series based on the screw spindle principle. They are frequently used for fuel consumption monitoring for diesel fuels according to EN 590 and especially on ships for heavy fuel oils (HFO) and marine fuels according to ISO 8217. Fuel consumption measurement can be carried out with single-line and differential method. For the more common method, differential method, two flow meters are required, one in the engine's supply line, the other in the return line. The difference between the supply and return lines represents the actual fuel consumption. To calculate the net fuel consumption with an assumed accuracy of better than 2 %, each individual flow meter must have a high measurement accuracy. As a rule, the circulation flow rate for this type of installation is about three to four times as high as the net fuel consumption. According to manufacturer, KRAL volume flow meters can measure with a high accuracy of ±0.1 % regardless of the chemical and physical properties of the fuel.

The positive displacement (DP) flow meter operates with the screw spindle principle and measures independently from the velocity flow profile. That means, flow disturbances such as pipe bends, elbows and T-junctions, and also pulsating flow have no influence on the measurement accuracy. This flow meter type typically requires some lubrication of the pumped medium to reduce friction, especially at high flow rates and high pressure. If lubrication is too low, there is a risk of fuel pump failure, resulting in repair costs and downtime. On 1 January 2020, the new International Maritime Organization (IMO) regulations on the sulphur content of marine fuels [3] came into force. The new regulations stipulate that only marine fuels with a sulphur content of less than 0.5 % may be used on ships worldwide, even if they are on the high seas or outside coastal environmental protection zones. The largest challenge is the fact that low-sulphur fuels have a low viscosity and lower lubricating properties due to desulphurisation.

The two most common KRAL flow meter types for marine fuel consumption measurements, which mainly include diesel and heavy fuel oil, are the OMG and OMP series. RISE has a number of OMG-20, OMG-32 and OMG-68, OMG-100 and OMG-140 flow meters. Their technical data are summarized in Table 1.

Due to the flow specification, a KRAL OMG-32 was selected as the Device Under Test (DUT) at RISE. According to the manufacturer, the flow sensor already operates at a viscosity of 1 mm$^2$/s. Practical experience has shown that this flow sensor type works better with higher viscosities of at least some mm²/s, especially at high flow rates roughly above 600 l/h, which corresponds to a dynamic ratio of 1:10.

**Table 1:** Specifications of the KRAL OMG flow meters.

| Technical data | OMG-020 | OMG-032 | OMG-068 | OMG-100 | OMG-140 |
|---|---|---|---|---|---|
| Nominal Diameter DN / mm | 20 | 25 / 32 | 50 | 100 | 150 |
| Flow rate / l/h $Q_{max}$ | 2,700 | 9,000 | 63,000 | 180,000 | 450,000 |
| $Q_{nom}$ | 1,800 | 6,000 | 42,000 | 120,000 | 300,000 |
| $Q_{min}$ | 18 | 60 | 420 | 1,200 | 3,000 |
| Max. pressure / bar | 250 | 250 | 100 | 40 | 40 |
| Temperature / °C | -20 to +200 | -20 to +200 | -20 to +200 | -20 to +200 | -20 to +200 |
| Viscosity / mm²/s | 1 to $1x10^6$ | 1 to $1x10^6$ | 1 to $1x10^6$ | 1 to $1x10^6$ | 1 to $1x10^6$ |
| Precision / % | ±0.1 | ±0.1 | ±0.1 | ±0.1 | ±0.1 |


**Figure 3:** DUTs - top KRAL OMG-032 flow meter with stainless steel housing (Meter 1); bottom KRAL OMG-032 flow meter with carbon steel housing (Meter 2).

Two KRAL OMG-032 flow meters (Figure 3) were characterized in-depth. One flow meter (Meter 1) has a stainless steel housing and the other one (Meter 2) a housing made of carbon steel. The inner workings are the same for both flow meters.

**Table 1:** Density and kinematic viscosity values of the test liquids at different temperatures. The measurements were performed at the RISE Chemistry Laboratory.

| | | 20°C | 40°C | 70°C |
|---|---|---|---|---|
| **Mobiltherm 605** | Viscosity / mm²/s | 82.3 | 31.2 | 10.9 |
| | Density / kg/m³ | 868.0 | 855.2 | 836.1 |
| | | | | |
| | | **10°C** | **20°C** | **30°C** |
| **Exxsol D40** | Viscosity / mm²/s | 1.79 | 1.54 | 1.29 |
| | Density / kg/m³ | 778.5 | 771.1 | 763.6 |
| **Exxsol D120** | Viscosity / mm²/s | 7.20 | 5.35 | 4.16 |
| | Density / kg/m³ | 830.0 | 823.1 | 816.3 |

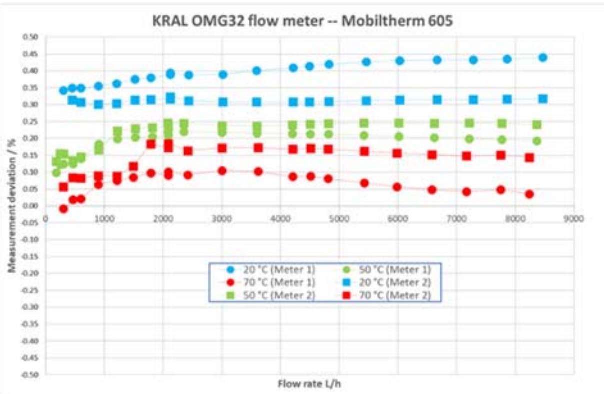


**Figure 4:** Measurement results of the two KRAL OMG-32 flow meters (Meter 1 and Meter 2) during calibration with Mobiltherm 605 as test liquid at 20 °C, 50 °C, and 70 °C.

The fluids selected are Mobiltherm 605, which has a wide range of viscosities depending on the temperature, Exxsol D40, which is a substitute for petrol, and Exxsol D120, which represents a slightly heavier diesel. Prior to the flow measurements, the kinematic viscosity (according to ISO 3104:2020) and density (according to ASTM D 4052:2018) of the three test liquids were determined at the RISE Chemistry Laboratory (Table 2). All flow measurements were carried out on a test rig at RISE using a 12" Brooks Compact Prover (BCP12) as reference. The measurement uncertainty U($k=2$) of the test rig is 0.10 % for flow rates < 1000 l/h and 0.08 % for flow rates ≥ 1000 l/h.

Both flow meters perform well at relatively high viscosities. In the measurements with Mobiltherm 605 and at different temperatures, both flow meters demonstrate a very good performance at the relatively high viscosities. From a flow rate of about 200 l/h, for both flow meters an almost linear, horizontal trend is obtained, regardless of the temperature or viscosity. With increasing temperature, the measurement deviation is decreasing. With 0.4 % Meter 1 has a much wider spread than Meter 2 with just 0.15 % for a viscosity decrease by a factor of 7.5 and a temperature increase by a factor 3.5.

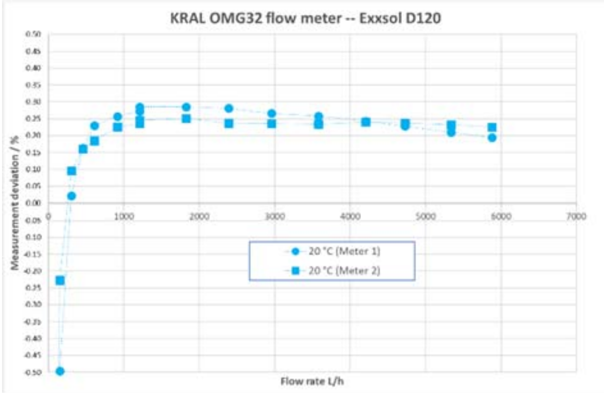


**Figure 5:** Measurement results of the two KRAL OMG-32 flow meters (Meter 1 and Meter 2) during calibration with Exxsol D120 as test liquid at 20 °C.

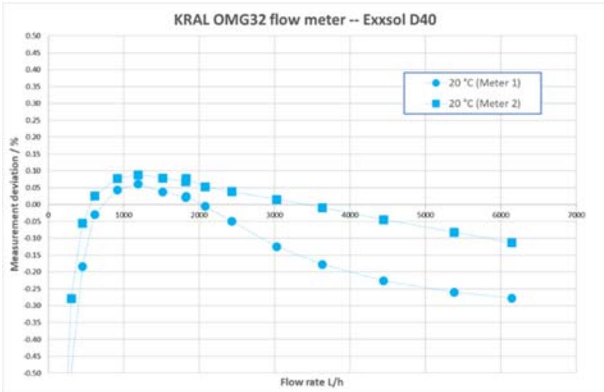


**Figure 6:** Measurement results of the two KRAL OMG-32 flow meters (Meter 1 and Meter 2) during calibration with Exxsol D40 as test liquid at 20 °C.

It can be assumed that the change in the error curve is mainly due to the thermal expansion of the meter housing, i.e. the thermal expansion coefficient since the thermal expansion coefficient of stainless steel is (about 1.5 times) greater than that of carbon steel.

Exxsol D40 is the test medium with the lowest viscosity value. As is known, a low viscosity particularly has an effect at higher flow rates. As can be seen in Figure 5, the KRAL flow meter has the typical start-up behaviour of a DP meter without an auxiliary motor, which is due to the bearing resistance. However, even in this range, the repeatability and reproducibility of the flow meter is exemplary. For higher flow rates, the calibration curve is no longer horizontal compared to the measurements with Mobiltherm 605 and higher viscosities but decreases approximately linearly. At higher flow rates, especially with liquids of lower viscosity, leakage occurs between the screw and the housing. The leakage value is greater for the stainless steel flow meter than for the carbon steel flow meter. The higher the flow rate, the higher the bearing friction, which leads to a greater pressure drop and

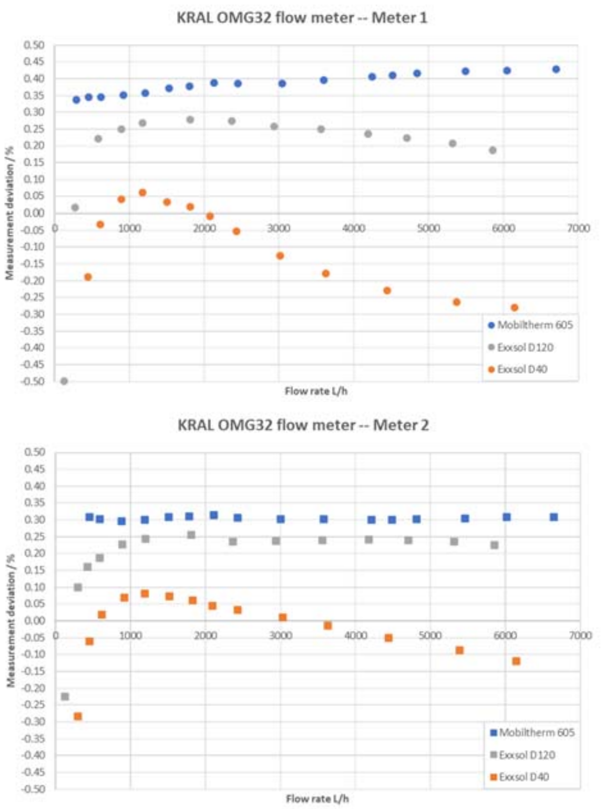


**Figure 7:** Measurement deviations of Meter 1 (top) and Meter 2 (bottom) obtained for three different test liquids at 20 °C.

greater leakage. The leakage flow is not an issue. The meter has a repeatability and reproducibility of high quality with the same test liquid and temperature at the higher flow rates.

As can be seen in Figure 6, the start-up behaviour starts earlier compared to Exxsol D40, while the approximate linear decrease of the calibration curve is slower, as expected. Compared to Exxsol D40, there are also smaller differences between the KRAL flow meter with the stainless steel housing and the KRAL flow meter with the carbon steel housing.

For flow rates of 3000 l/h and above the measurement deviations between the two flow meters differ by about 0.17 % for Exxsol D40 which is slightly larger than the difference obtained for Mobiltherm 605 at 20 °C and significantly larger than the one for Exxsol D120.

Figure 7 shows exemplarily the measurement deviations of the two meters obtained for the three test liquids at 20 °C. Not unexpectedly the measurement deviations vary considerably in the entire flow range when moving from a low to a high viscosity liquid. Both, Figure 4 and Figure 7 once more illustrate the significance which the consideration of the transport properties of the liquid to be measured requires.

All in all both investigated KRAL OMG-032 flow meters have a good performance for all three test liquids. However, it is evident that the flow meters operate better at higher viscosities. This can be determined on the basis of the calibration errors, which no longer vary above a certain (lower) flow value. This means that as soon as a certain flow rate is exceeded when testing liquids with a higher viscosity, the measurement deviation of the meter remains almost constant over the entire flow range. This means up to a flow rate of approximately 600 l/h (dynamic ratio 1:10) there is some start-up behaviour with these flow meters.

The measurement deviations at different temperatures seem to depend only or mainly on the material of the housing respectively the coefficient of expansion. The KRAL flow meter with the carbon steel housing apparently performs slightly better at low flow rates and test fluids with lower viscosity than the KRAL flow meter with the stainless housing.

## 4. Conclusion

Within the EMPIR-project “SAFEST” (20IND13), metrological infrastructure is being developed to characterise the measurement performance of flow meters used for fuel consumption measurements close to the real operating conditions. In the scope of the project, a test profile was derived that reflects fuel consumption characteristics and associated flow changes for ships in coastal areas and which can be used for flow meter testing purposes in calibration laboratories. The technical implementation on a conventional test stand has begun. Moreover, criteria for the evaluation of the test rig performance and flow meters (at a later stage) were defined.

Initial measurements to investigate the influence of the transport properties of the test medium on the measurement performance of flow meters used in the maritime sector have been started. The example of two KRAL flow meters shows that for kinematic viscosities of several mm²/s and more, these meters exhibit an approximately stable measurement deviation in the flow rate range considered in this paper (~300 l/h to ~7000 l/h). The smaller the viscosity values become, the more the measurement deviations vary, especially for flow rates smaller than 600 l/h. At very low flow rates, a measurement accuracy of ±0.1% is no longer necessarily guaranteed. This underlines the importance of an adequate calibration of flowmeters also in the maritime sector, especially against the background that fuels with a lower viscosity than in the past are to be used.

## Acknowledgements

This project 20IND13 SAFEST has received funding from the EMPIR programme co-financed by the Participating States and from the European Union's Horizon 2020 research and innovation programme.


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