Metrology for reliable fuel consumption measurements in the maritime sector

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A B S T R A C T

Reliable fuel consumption measurements play an essential role in the maritime sector whether for emission determinations or the use of novel fuels. A verification of the performance of flow meters used for fuel consumption determination under realistic conditions is thus of interest. Apart from the influence of the pressure- and temperature-dependent transport properties of the fuels, a characterization of the measurement performance under dynamic fuel consumption is of relevance. Traceable metrological infrastructure and procedures, which will enable an evaluation of the measurement performance of flow meters in this regard, are being developed in the scope of the EMPIR project "Safest" (20IND13). A consumption profile of a ferry navigating in a harbour serves as basis. In addition to the measurement accuracy under dynamic conditions, first investigations of the performance of flow meters are carried out in terms of fluid temperature and fuel transport properties for the example of spindle screw meters.

1. Introduction

The European and international efforts to decarbonise maritime transport, combined with successively stricter requirements, are presenting the industry with new challenges. Among other things, the Carbon Intensity Indicator (CII) was introduced [1]. This prescribes the recording of the CO_2 emissions actually emitted by ships in circulation with a gross tonnage of 5,000 GT and more [2]. The CII is the responsibility of ship operators. A five-point scale from "A" to "E" is used to determine how cleanly the ship was operated in the past 12 months. If ships are rated "D" in three consecutive years or "E" in one year, a catalogue of measures for CO_2 reduction must be developed in order to achieve at least a "C" rating.

Furthermore, CO_2 emissions trading will take effect in Europe from 2024: At the end of November 2022, EU legislators agreed to include maritime transport in the Emissions Trading Scheme (ETS) [3]. Ship operators will thus be obliged to pay for the CO_2 emissions of their ships. The EU ETS is a system where a limited amount of emission allowances (cap) is put on the market and can be traded. The cap is reduced every year to ensure that the EU's 2030 emissions target of a 55 % reduction

compared to 1990 can be met and that the EU becomes climate neutral by 2050. The EU emissions trading scheme for industry has been in place since 2005, but this is the first time in the world that shipping has been included in such an emissions trading scheme. The project is part of the "Fit for 55″" package under the European Green Deal.

From 2024, the ETS will apply to ships over 5,000 GT carrying cargo or passengers for commercial purposes. Emissions will be reported and verified through the EU's existing Monitoring, Reporting and Verification (MRV) system. The EU MRV system will be extended to offshore vessels over 400 GT and general cargo vessels between 400 and 5,000 GT carrying cargo for commercial purposes from 2025. Off-shore vessels above 5,000 GT will be included in the ETS from 2027. By 2026, the European Commission will consider whether general cargo and offshore vessels between 400 and 5,000 GT should also be included in the ETS. Ships that fail to comply with the EU MRV requirements for two or more consecutive periods may be expelled and denied trading in the EU. Companies that fail to surrender allowances are liable to an excess emissions penalty of €100/t CO_2 and are still liable for the surrendering of the required allowances.

Fuel consumption is a key factor in emission determinations.

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Moreover, the value of the CII is significantly influenced by the type of fuel used, the efficiency of the ship, operating parameters such as ship speed, cargo carried, weather conditions and by the general condition of the ship. Two means to lower the CII value are to reduce fuel consumption and/or to change the fuel type partly or full to a "greener" one.

The "Guidance/Best practices document on monitoring and reporting of fuel consumption, CO_2 emissions and other relevant parameters pursuant to Regulation 2015/757 on monitoring, reporting and verification emissions from maritime transport" [4] provides information on the determination of total measurement uncertainties as well as guideline values with regard to the methods selected for CO_2 determination in the monitoring concept. A maximum value of 10 % is set for the total measurement uncertainty for the amount of consumed fuel, irrespective of the method of determination. Beyond this, there are no further requirements or recommendations.

The measurement uncertainty associated with the amount of consumed fuel, like all other variables, affects the value of the CII, simply put, with what certainty a ship lies in one of the classes. The measurement uncertainty of the fuel consumption measurement alone results in an uncertainty of a comparable magnitude for the CII. For a reliable CII value, the standard value for the measurement uncertainty of the fuel consumption measurement is usually too high. For example, the class range for the "C" rating is in the single-digit percentage range. The same applies for a reliable proof of a fuel consumption reduction, as required for compliance with or improvement of the emission class.

Against this background, it is of interest to assess the measurement performance of the flow meters used for fuel consumption measurements under close to realistic conditions compared to laboratory conditions with constant flows. 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. Calibrations are often carried out with a fluid that is not the same as the fluid used under operating or laboratory conditions, which is why it may be necessary to adapt the calibration to the fuel used and under operating conditions. 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. The research project 20IND13 "Sustainable advanced flow meter calibration for the transport sector" (Safest) [5] of the European Metrology Programme for Innovation and Research (EMPIR) of the European Association of National Metrology Institutes (EURAMET) addresses some of the issues mentioned above. 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.

2. Dynamic characterisation

At present, flow meters are calibrated at discreet test points and constant flow rates covering either the whole measuring range or a part of it. By this the static measurement performance of the meters is characterized. However, in many applications including fuel consumption measurements flow meters are exposed to variable, often rapidly changing flows. Thus, it is of interest to learn, how flow meters perform under these dynamic conditions.

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

This must be supplemented by an appropriate validation strategy.

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 e. g. by weather routing or optimization of ballast distribution. In coastal areas or harbours greater manoeuvring is required and fuel consumption becomes more variable. Furthermore, emission limits are specified for these areas in many regions. Non-compliance can result in severe fines. 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 Fig. 1. About 16 % of the flow rates of the 6064 s long profile which has a temporal resolution of 1 s are below 10 l/h. Several amplitude changes in the range of 600 l/h up to 800 l/h in a time span of 80 s to 90 s occur which are interrupted by intermittent flow variations. It could be demonstrated that by a simple scaling the profile can be adapted to different engine sizes. The cumulated volume of the profile amounts to 260.3 l.

2.2. Development of measurement infrastructure

Test profiles such as the one shown in Fig. 1 serve as basis for the development of test infrastructure capable to generate and measure dynamic flow changes with these characteristics.

For realizing the flow changes of the ferry profile a needle valve (DN4) operated with a step motor was integrated in a conventional test rig (expanded measurement uncertainty U ($k = 2$) = 0.05 %) at PTB with a weighing system as reference (Mettler-Toledo IT3, measuring bridge with TBRICK 15 strain gauge load cell, measuring range 0 – 1000 kg, resolution 10 g, drift 0.021 g/min ± 0.01 g/min). The scheme of the test rig is shown in Fig. 2. The gravimetric reference is calibrated in the classic way using weights. For the experiments changes in the weighing signal were recorded with a sampling interval of up to 0.2 s. The data were corrected for buoyancy and instrumental drift. The test rig runs with white spirit 180/210 (at 20 °C: density: 784.813 kg/m^3, kinematic viscosity: 1.72 mm^2/s) as test fluid. The accumulated volume of the profile corresponds to a mass of 204.3 kg when white spirit is considered.

The valve performance and control as well as the performance of a Coriolis flow meter DN8 (max. mass flow of 2 t/h) and the weighing system were evaluated by step responses. The pulse output of the Coriolis flow meter was used in all investigations. Any cut off or data filtering was switched off and auto zero set.
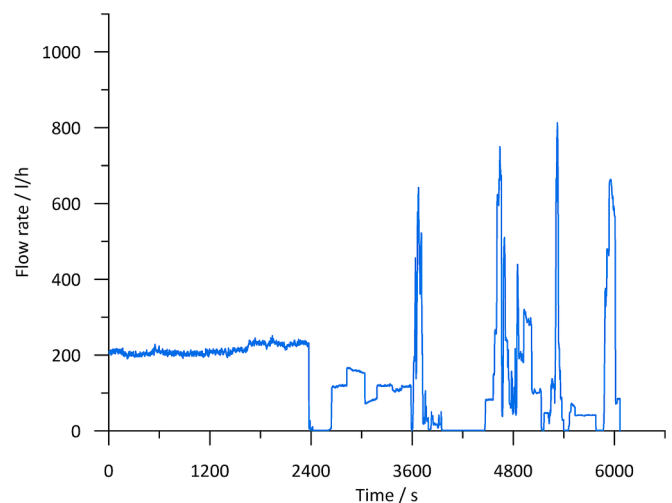

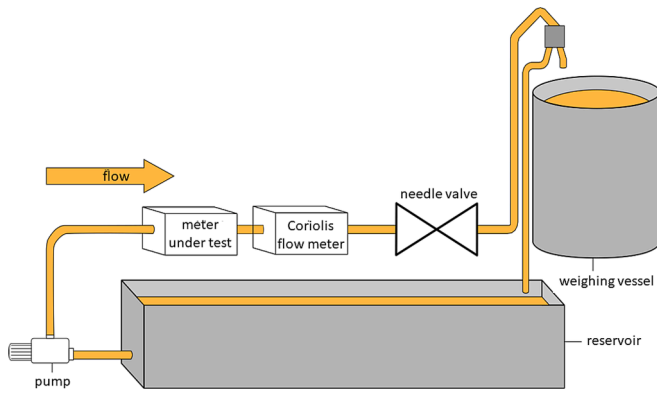**Fig. 1.** Test profile based on fuel consumption of a ferry navigating in a harbour.

Fig. 2. Scheme of the test rig used for dynamic flow generation.

Fig. 3 shows an example from the early investigations. The response to a 2-step decreasing flow change was investigated here. The first step from 200 l/h to 10 l/h is well reproduced, albeit with a time delay. However, the second step from 10 l/h to 0 l/h is not visible in the recording of the Coriolis flow meter and also not in the recording of the weighing system. The difference in the total mass captured by both was below 0.12 % which means the issue was related to the flow change realization itself. Subsequently, the control of the valve was refined, and a hardware solution implemented which completely closes the valve for flow rates below 15 l/h. In consequence, the profile sections with low flow rates are improved now.

An example of a profile realization is given in Fig. 4. A first visual inspection shows that the realization seems to be good. All flow changes from low to large as well as zero flows are present. 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 appropriately assessed and quantified. One essential requirement is the measurement against a sufficiently accurate reference that is traceable. However, this alone is not enough, because the quality with which the individual flow changes are realized also plays an essential role for dynamic calibrations. Further evaluation criteria are therefore needed based on the consideration of the residuals, time until a stable flow rate is achieved, repeatability and given total mass versus measured mass. The feasibility of these criteria was demonstrated in the EMPIR-project "Metrowamet" (17IND13) [67]. A similar approach will be followed for evaluating the performance of flow meters in dynamic flow changes.

Before the criteria were applied the measured data were filtered to a 1 s sampling interval corresponding to the interval of the test profile
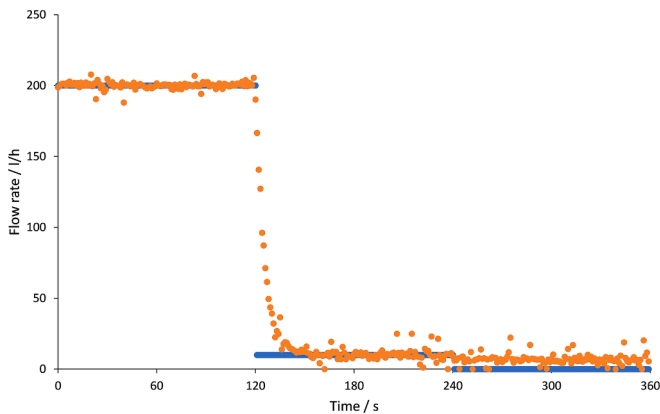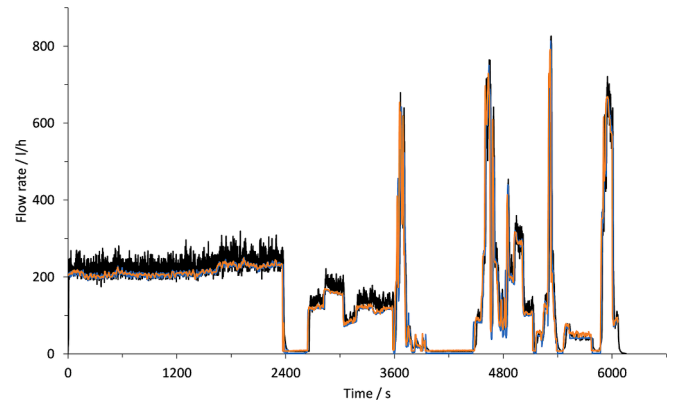

Fig. 4. Example for the realization of the test profile shown in Fig. 1; – test profile, – Coriolis flow meter DN8, – weighing system.

(Fig. 1). Based on four repeated measurements an average total mass of 204.8 kg (± 0.17 %) was measured by the weighing system which corresponds to a surplus mass of 0.5 kg compared to the theoretical mass of the test profile (deviation of 0.26 %). The Coriolis flow meter systematically records about 3 kg more than the weighing system. The reason for this is that the meter systematically measured larger flow rates for flows below 20 l/h than actually occur. This could be confirmed by additional step response experiments. Moreover, the reduced performance quality of Coriolis flow meters below a certain flow rate level is also the reason why a cut off flow rate can be set for this meter type. A flawed auto zero setting as cause (which would be rather unrealistically large) could be excluded by dedicated experiments in which auto zero was systematically changed and the measurements redone.

In order to calculate the standard deviation of the actual profile realization first the standard deviation of each profile realization point was determined. In a second step the average over all 6064 values was computed and then referred to the average flow rate determined from the average of the actually measured flow profiles. By this a metric is available to assess the overall repeatability of the profile realizations. The thus determined average standard deviation for the measurements of the Coriolis flow meter is 5.2 %. The cross-correlation coefficient between the averaged flow series and the given profile is 0.998. The average standard deviation of the weighing time series is 5.4 % and a comparable correlation with the model.

The averaged residual determined from the difference between the average measured profile and the test profile amounts to + 2.8 l/h. Fig. 5 shows that the largest residuals occur at the largest flow rate changes. The fundamentally good overall agreement is nevertheless evident when looking at the histogram of the residuals shown in Fig. 6 (top). 85 % of

Fig. 3. Example for the evaluation of the performance and control of the needle valve DN4 based on a 2-step response and a Coriolis flow meter (DN8) recording in preparation of the implementation of the profile in Fig. 1; – model, – Coriolis flow meter DN8.
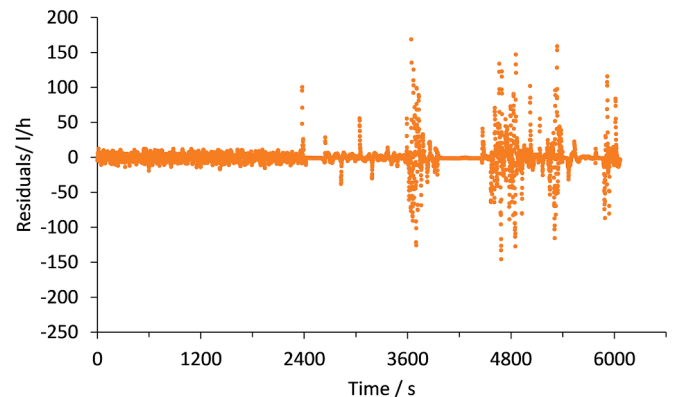

Fig. 5. Average residuals of the test profile measured with a Coriolis flow meter DN8.
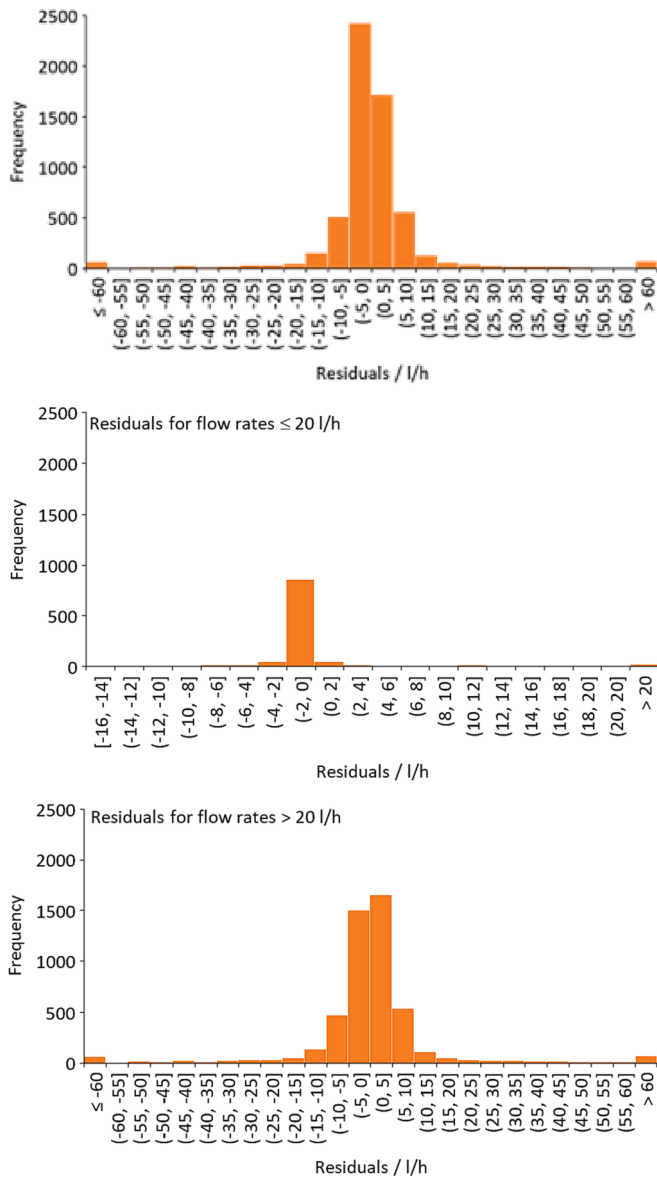
Fig. 6. Histogram of the residuals shown in Fig. 5; top: residuals of the entire time series; middle: residuals for given flow rates ≤ 20 l/h and bottom: residuals for given flow rates > 20 l/h.

the residuals that means the differences between measured and given values at each point in time are in the range of ± 10 l/h. A separate analysis of the residuals at flow rates ≤ 20 l/h (Fig. 6 middle) and > 20 l/h (Fig. 6 bottom) shows that the main deviations occur at larger flow rates and are not significantly caused by the performance of the Coriolis flow meter in the low flow rate range. Such deviations, in this case related to large flow rate changes, are to be expected since every measurement device has its own instrument response. Flow meter and weighing system thus respond delayed on flow rate changes, on the one hand due to finite (instrument-specific) reaction times and on the other hand due to different path lengths. By changing the distance between valve & Coriolis flow meter and the weighing system by a few meters potential associated effects on the delay times were investigated. None were found.

In Fig. 7 a section of the test profile (Fig. 1) with a decreasing and an increasing flow rate change is shown as well as the flow variations as captured by the Coriolis flow meter and the weighing system. All three data sets were synchronized. Nonetheless some small delays of some seconds remain which are linked to the different transfer functions of the
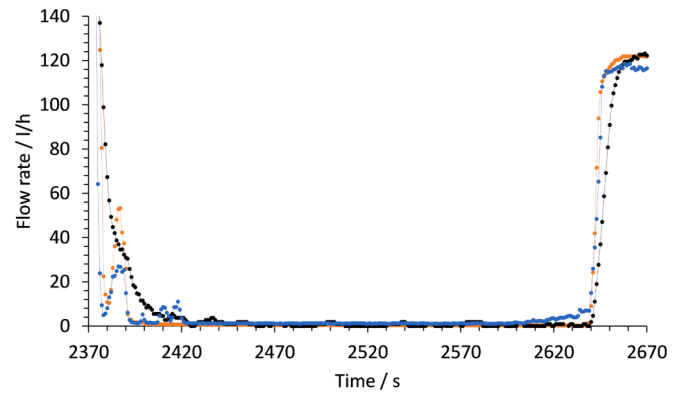

Fig. 7. Example of a decreasing and an increasing flow rate change and the response of the Coriolis flow meter and the weighing system: − test profile and averaged data: − Coriolis flow meter DN8, − weighing system. The data sets were synchronized beforehand. For eye guidance the markings are connected by a line.

devices. The 'smeared' response caused by the inertia of the weighing system is clearly visible. It is also visible that decreasing and increasing flow rates lead to slightly different responses.

3. Characterisation of flow meters with regard to the test medium and its temperature

The scope of the investigations on the influence of the test medium on the measuring performance of flow meters covers a flow range up to 8,000 l/h. Measurements are carried out using different types of flow meters that are typically deployed for consumption measurements in the maritime sector. Three different hydrocarbon fluids and different temperatures and thus different viscosity/density ranges are considered. 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 large database with which it will become possible to quantify the suitability of Reynolds number (Re) based conversions for different fluid transport properties and to determine where the limits are. A first set of measurement results is presented and discussed in the following.

3.1. Characterization of screw spindle flow meters

The KRAL volume flow meter is a robust flow meter for liquids and is targeted at harsh, industrial applications. The flow meters are frequently used for fuel consumption monitoring for diesel fuels according to EN 590 and especially on ships which use heavy fuel oils (HFO) and marine fuels according to ISO 8217. According to the manufacturer, KRAL volume flow meters can measure with an accuracy of ± 0.1 % regardless of the chemical and physical properties of the fuel.

The positive displacement (PD) flow meter operates with the screw spindle principle and measures independently from the velocity flow profile. It uses two equal-sized screws that rotate against each other to generate known volumes of fluid that can be measured per revolution. Flow disturbances such as pipe bends, elbows and T-junctions, and also pulsating flow should have no influence on the measurement accuracy. A weak dependence in performance of this meter type on kinematic viscosity and temperature (due to thermal expansion of the pipe diameter) was discussed in the frame of the bilateral comparison APMP.M.FF-K2 [8].

This flow meter type typically requires some lubrication of the pumped medium to reduce friction, especially at high flow rates. 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) regu-lations on the sulphur content of

marine fuels [9] came into force. The new regulations stipulate that only marine fuels with a sulphur content of less than 0.5 % are to be used on ships worldwide, even if they are on the high seas or outside coastal environmental protection zones. Due to the desulphurisation low-sulphur fuels have a low viscosity and lower lubrica-ting properties. This raises the question how the meters perform under these conditions.

For the study two KRAL OMG-32 flow meters (Fig. 8) belonging to RISE were extensively characterized. Their technical data are summarized in Table 1. 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. 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 at higher kinematic viscosities of at least a few mm^2/s. The spread is greater at low viscosity fluids at high flow rates compared to higher viscosity fluids.

The fluids selected for the measurements 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 fluids were determined at the RISE Chemistry Laboratory (Table 2). The flow measurements at RISE were carried out at three different test rigs, with a 12″ Brooks Compact Prover (BCP12) as reference. The measurement uncertainty U($k = 2$) of the test rigs is 0.10 % for flow rates < 1,000 l/h and 0.08 % for flow rates greater than 1,000 l/h.

In the measurements with the three test fluids and at different temperatures (Figs. 9 - 12), both meters demonstrate a very good performance at the relatively high viscosities. Standard deviations are in the order of 0.1 % up to some percents for flow rates below 200 l/h. From Figs. 9 to 12 an impression of the variation in the standard deviations depending on meter, temperature and viscosity can be gained. Typically,

Table 1
Specifications of the KRAL OMG-32 flow meter.

Nominal Diameter DN / mm	25 / 32
Flow rate / l/h	9,000
	6,000
Q_{max}	60
Q_{nom}	
Q_{min}	
Max. pressure / bar	250
Temperature / °C	- 20 to + 200
Viscosity / mm^2/s	1 to 1x10^6
Precision / %	± 0.1

Table 2
Density and kinematic viscosity values of the test fluids at different temperatures. The measurements were performed at the RISE Chemistry Laboratory.

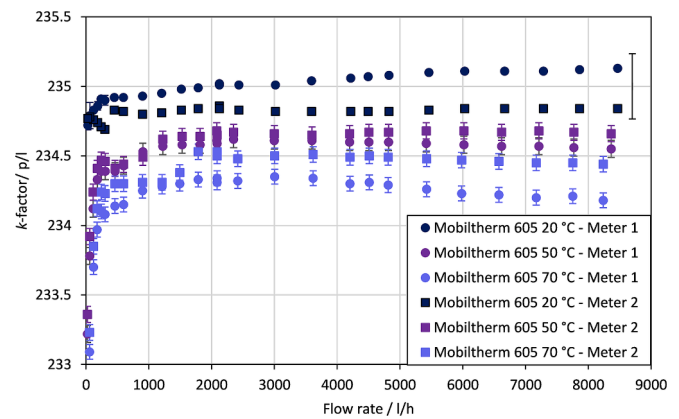|		20 °C	40 °C	70 °C
Mobiltherm 605	Viscosity / mm^2/s	82.3	31.2	10.9
	Density / kg/m^3	868.0	855.2	836.1
		10 °C	20 °C	30 °C
Exxsol D40	Viscosity / mm^2/s	1.79	1.54	1.29
	Density / kg/m^3	778.5	771.1	763.6
Exxsol D120	Viscosity / mm^2/s	7.20	5.35	4.16
	Density / kg/m^3	830.0	823.1	816.3

Fig. 9. Measurement results of the two KRAL OMG-32 flow meters for a calibration with Mobiltherm 605 as test fluid at 20 °C, 50 °C, and 70 °C (change in viscosity: factor of 7.5); the bar indicates U ($k = 2$) = ± 0.1 % of the test rig.

Meter 1 shows somewhat larger standard deviations compared to Meter 2. With decreasing viscosity standard deviations increase by roughly an order of magnitude. From a flow rate of about 200 l/h, for both flow meters an almost linear, horizontal trend is obtained for Mobiltherm 605, regardless of the temperature or viscosity. Basically, there is a trend that with decreasing viscosity/increasing temperature, the calibration curve shifts downwards. Various factors come together as explanation for this behaviour.

With 0.4 % Meter 1 has a much wider overall spread in its curves than Meter 2 with just 0.15 % for a viscosity decrease by a factor of 7.5 and a temperature increase by 50 K. As mentioned previously, the two meters differ only with regard to their housings, the inner workings are the same. As the thermal expansion coefficient of stainless steel is 1.6 × 10^{-5} m/m/K and therefore higher than the one of carbon steel with 1.1 × 10^{-5} m/m/K the different curves can be explained by the different thermal expansions of the housings and associated slight changes in geometry relative to the inner workings of the meters. The two screws in both flow meters are made of carbon steel. Therefore, when the housing
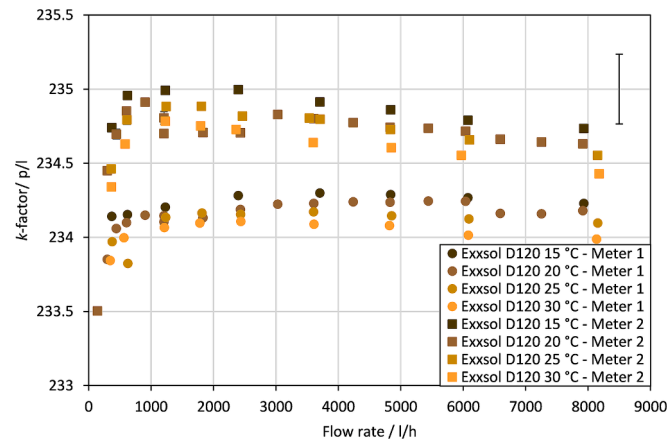

Fig. 8. DUTs - top KRAL OMG-32 flow meter with stainless steel housing (Meter 1); bottom KRAL OMG-32 flow meter with carbon steel housing (Meter 2).

Fig. 10. Measurement results of the two KRAL OMG-32 flow meters for a calibration with Exxsol D120 as test fluid at 15 °C, 20 °C, 25 °C, and 30 °C (change in viscosity: factor of 1.7); the bar indicates U ($k = 2$) = ± 0.1 % of the test rig.
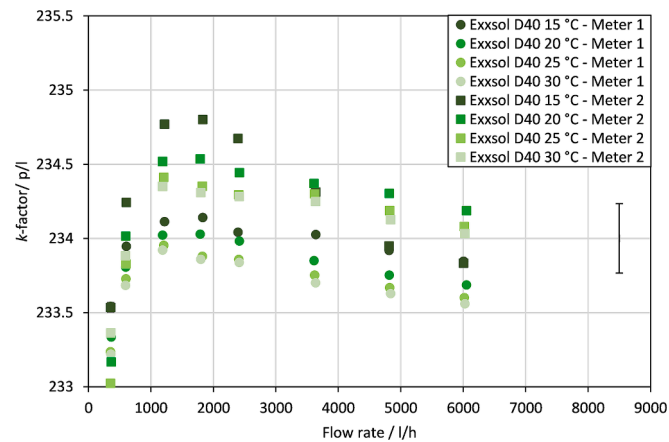

Fig. 11. Measurement results of the two KRAL OMG-32 flow meters for a calibration with Exxsol D40 as test fluid at 15 °C, 20 °C, 25 °C, and 30 °C (change in viscosity: factor of ∼ 1); the bar indicates U ($k = 2$) = ± 0.1 % of the test rig.

Fig. 12. Measurement results of the two KRAL OMG-32 flow meters for a calibration with three different test fluids at 20 °C (change in viscosity: factor of 50), top: Meter 1, bottom: Meter 2.

is made of stainless steel, the gap between the screws and the housing increases as the temperature rises, as stainless steel has the greater co-efficient of thermal expansion compared to carbon steel. The situation is different when the housing is also made of carbon steel.

Exxsol D40 is the test fluid with the lowest viscosity value. As is known, a low viscosity particularly has an effect at higher flow rates. As can be seen in Fig. 11, the KRAL flow meter has the typical starting behaviour of a PD meter without an auxiliary motor, which is due to the bearing resistance. However, even in this range, a good repeatability and reproducibility of the flow meter is given. For flow rates of 3,000 l/h and above the k-factors 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. In the higher flow rate range, the calibration curve is no longer horizontal compared to the measurements with Mobiltherm 605 and higher viscosities but decreases approximately linearly. Here, especially with liquids of lower viscosity, leakage occurs between the screws and the housing. The leakage value is greater for the stainless steel flow meter (Meter 1) than for the carbon steel flow meter (Meter 2). The higher the flow rate, the higher the bearing friction, which leads to a greater pressure drop and greater leakage. Nevertheless, the leakage flow is not an issue. Meter 1 has a repeatability and reproducibility of
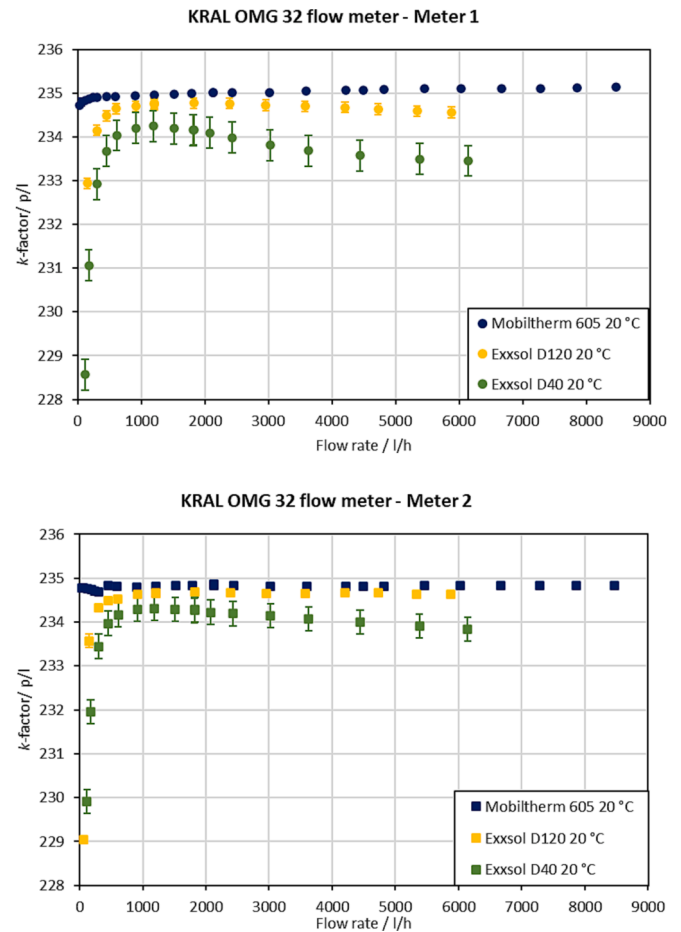
high quality with the same test fluid and temperature at the higher flow rates.

Figs. 9 to 12 once more illustrate the significance which the consideration of the transport properties of the liquid to be measured requires. Plotting the calibration curves of Fig. 12 against the Reynolds number (Fig. 13) emphasizes this and exemplifies how an additional influencing factor might affect the calibra-tion curves, in this case introducing gradients in the curves of Meter in the curves of Meter 1.

All in all, both investigated KRAL OMG-32 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 fluids with a higher viscosity, the k-factor of the meter remains almost constant over the entire flow range. The starting behaviour of the KRAL meter depends strongly on the viscosity. The lower the fluid viscosity, the starting behaviour shifts towards higher flow rates. For highly viscous fluids, the starting behaviour shifts to-wards low flow rates or is not visible at all (cp. Figs. 9, 12). For the fluids investigated here, the starting behaviour at all temperatures occurred below 600 l/h, (which corresponds to a dynamic ratio of 1:10).

The k-factors at different temperatures of the two flow meters investigated here depend mainly on the material of the housing respectively the coefficient of expansion. A weak viscosity dependence of the k-factor exists in addition. The dependencies are in a similar order of magnitude as found by [8]. 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
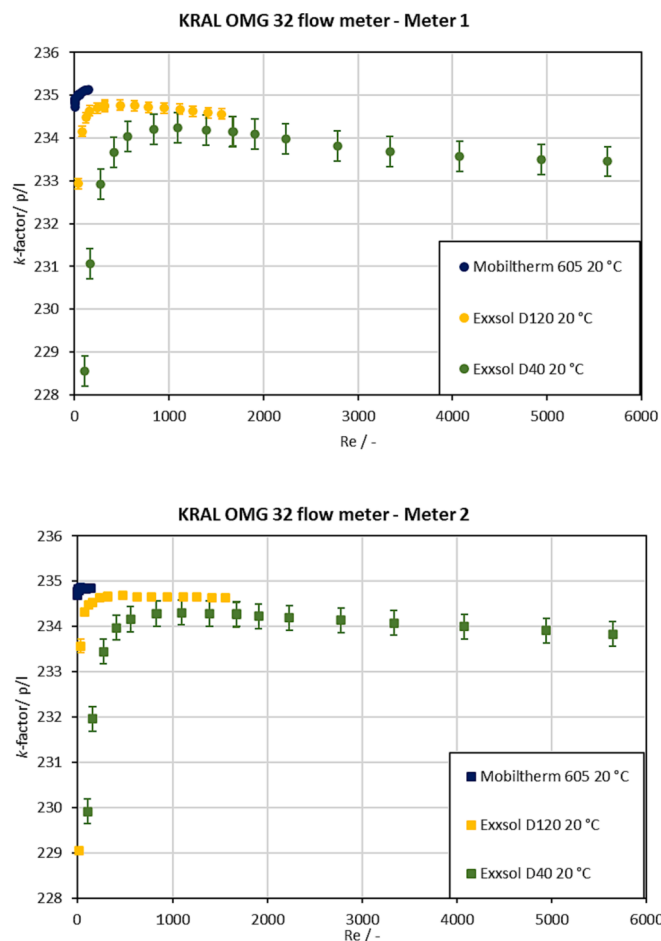
KRAL OMG 32 flow meter - Meter 1

KRAL OMG 32 flow meter - Meter 2

Fig. 13. Measurement results of the two KRAL OMG-32 flow meters for a calibration with three different test fluids at 20 °C (change in viscosity: factor of 50) against Reynolds number, top: Meter 1, bottom: Meter 2.

stainless steel housing.

4. Conclusion

Within the EMPIR project "SAFEST" metrological infrastructure is being developed to enable a characterization of the measurement performance of flow meters used for fuel consumption measurements close to 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. A technical implementation on a conventional test rig using a needle valve was successfully demonstrated. Currently, investigations are carried out to further optimize the implementation with a focus on quantifying the impact the distance between meter under test and reference has. Moreover, criteria for the evaluation of the test rig performance and flow meters were defined and tested regarding their suitability. First results look promising, but there is still room for improvement e.g. regarding the relative position of meter under test and reference.

First measurements to investigate the influence of the transport properties of the test fluid on the measurement performance of flow meters used in the maritime sector have been finalized. The example of two KRAL flowmeters shows that for kinematic viscosities of several mm^2/s and more, these devices exhibit an approximately stable k-factor in the flow rate range considered in this paper ($\sim$300 l/h to $\sim$ 7,000 l/h). The lower the viscosity values become, the more the k-factor varies, especially for flow rates below 1,000 l/h. An accuracy of $\pm$ 0.1 % is no longer easily guaranteed here. This underlines the importance of an adequate calibration of flow meters also in the maritime sector, especially against the background that fuels with a lower viscosity than in the past are to be used. To put the investigations on a broader basis, measurements with other flow meter types which are performed in the scope of SAFEST will prove helpful.

CRediT authorship contribution statement

Corinna Kroner: . **Heiko Warnecke:** Investigation, Methodology, Writing – review & editing. **Oliver Büker:** Investigation, Methodology, Writing – original draft, Writing – review & editing. **Krister Stolt:** Investigation. **Per Wennergren:** Investigation, Writing – review & editing. **Günter Hagemann:** Resources. **Manfred Werner:** Resources.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

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