

Publishable Summary for 20IND13 SAFEST

Sustainable advanced flow meter calibration for the transport sector

Overview

Greenhouse gas emissions produced by the road and maritime transport sector contribute to climate change, therefore these emissions need to be reduced. Recent measures to achieve this have focused on alternative fuels, improvements in engine testing and setting up tight emission standards. However, advances also need to be made in flow metrology as these new measures directly depend on the quality of these measurements for determining engine efficiency through fuel consumption and emissions measurements. The purpose of this project is to provide the foundation for advanced flow metrology in this sector, leading to reliable fuel consumption measurements. The characterisation of flow meters, at close to operational conditions, and an improved understanding of how the fuel's properties effect flow measurements will foster innovation in the transport sector and it will increase the deployment of sustainable alternative transport fuels. Moreover, the results will contribute to appropriate emissions calculations.

Need

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.

Metrological engagement in the transport sector is needed in a number of ways. So far, there are no reliable quantitative insights into how flow meters perform under real-world fuel flow changes because they are calibrated at steady flow rates. Therefore, a metrological infrastructure, suitable for testing flow meters under variable flow conditions needs to be developed. [Objective 1] There is also a lack of sufficient quantitative information on the effect of operating conditions, such as ambient and fuel temperatures, on the performance of flow meters. [Objective 2] This information will be important as the calibration and operating conditions of the flow meters are significantly different. In addition, this information will be of relevance when looking at in-use fuel consumption measurements for vehicles. [Objective 1] Fuel properties have a direct impact on engine performance. Thus, the adoption of new fuels and efficient engine development will only happen if the fuel's properties are well known. There is, therefore, a need for sufficient information on the viscosity and density of alternative and synthetic fuels. [Objective 3] The effects of changes in viscosity and density fuel properties, and how they affect flow meter performance, also needs to be assessed. This is particularly relevant for the maritime sector as quite a diverse range of fuels are used. [Objective 2] As knowledge of the density and viscosity of a fuel are crucial for both flow measurement and efficient engine operation, there is a clear need for the advanced inline measurement of these parameters. [Objective 3] Furthermore, there is a need to have this metrological information available in a concise and easily accessible way for stakeholders. It will be used for state-of-the-art recommendations for advancements in fuel consumption measurements and as input for the regulations that are needed to reliably monitor and determine fuel consumption and emissions in the transport sector at a European level. [Objective 4]

Objectives

The overall objective of this project is to develop a metrological infrastructure for use in performing advanced flow measurements in the transport sector.

The specific objectives of the project are:

1. To develop the infrastructure required for evaluating the accuracy of the flow meters and other systems (e.g. flow meters integrated in conditioning systems), which are used in cars and trucks to measure the consumption of fuel, under the New European Driving Cycle, the Worldwide harmonised Light vehicles Test Cycle, or the World Harmonised Transient Cycle. Test liquids should include e.g. water and

hydrocarbons, with densities $> 400 \text{ kg/m}^3$, viscosities $> 0.01 \text{ mPa}\cdot\text{s}$, pressures $\leq 300 \text{ bar}$, and flow rates $0.0001 \text{ m}^3/\text{h} - 8 \text{ m}^3/\text{h}$.

2. To develop the infrastructure and procedures required for evaluating the accuracy of flow meters, which have potential for measuring the consumption of alternative fuels in the maritime sector, under close to real world conditions. The selected alternative fuels should have the same range of densities, viscosities, pressures and flow rates as specified in objective 1. This objective should address measurements of dynamic flow and en route fuel consumption, with uncertainties.
3. To prepare a fuel property matrix of the transport properties of alternative fuels e.g. bio-diesel (FAME), bio-alcohol and synthetic fuels. This should enable the transfer of calibrations between fuels and extrapolation to higher temperatures and pressures. The selected fuels should have densities $> 400 \text{ kg/m}^3$, viscosities $> 0.01 \text{ mPa}\cdot\text{s}$, temperatures $\leq 620 \text{ K}$, pressures $\leq 300 \text{ bar}$ and flow rates $\leq 2 \text{ m}^3/\text{h}$. Sensors should also be developed for traceably measuring density and viscosity in situ.
4. To provide metrological input, and pre-normative research, for the further development of international standards with a focus on close to real-world flow calibrations in the transport sector. In addition, to contribute to the development of a pan-European harmonised framework, which will enable the emission targets set by the International Maritime Organization, the European Conference of Ministers of Transport and the Fédération Internationale de l'Automobile to be met and controlled.
5. To facilitate the take up of the technology and measurement infrastructure developed in the project by the measurement supply chain (accredited laboratories, instrumentation manufacturers), standards developing organisations (IMO, ISO) and end users (transport sector).

Progress beyond the state of the art

This project aims at establishing a metrological infrastructure and providing recommendations for an integral characterisation of flow meters ensuring reliable fuel consumption measurements in road and maritime transport.

Currently, exhaust emissions and the fuel consumption of motor vehicles are determined based on the Worldwide harmonized Light vehicles Test Procedure (WLTP) or the New European Driving Cycle. For the evaluation of fuel consumption, the regulation UN ECE.R49 only recommends the performance specification for the measurement instruments and not the complete measurement system. Further contributions to the measurement results, such as from the environment, are also not clearly required to be taken into consideration. Thus, the measurement errors caused by the dynamic execution of the test cycles are almost unknown.

In this project, test rigs, which are used for flow meter calibrations, will be realised that will be capable of generating and measuring dynamic flow changes based on test cycles. This novel metrological infrastructure will go beyond the current state of the art and will be evaluated in an inter-comparison; with the results used for setting up an appropriate uncertainty assessment. The consortium will also develop the protocols required for the new dynamic test regime and will closely work together with standards bodies to enable a timely transfer to practical application. By evaluating the impact that operating conditions, and the transport properties of the fuel, have on flow meter performance, an innovative integral uncertainty assessment of the flow measurement will be possible. In addition, a numerical tool will be provided that will enable the investigation of different operating conditions and parametric analyses to be performed, which are currently difficult to carry out experimentally. (Objective 1)

Recent changes in the regulations for the emission control of ships, and in order to support alternative fuels and endeavours in increasing engine efficiency, have resulted in a key role for fuel consumption measurements. As in the automotive sector, the characterisation of flow meters in the maritime sector has not developed further in recent years: flow meters are calibrated at test points with steady flows, with one test liquid and at standard conditions. The measurement uncertainty also applies to these conditions, which are far removed from actual operating conditions.

In this project, infrastructure and procedures will be developed, as required, for the evaluation of the accuracy of the flow meters deployed in fuel consumption measurements in the maritime sector. New insights will be provided into the impact of the operating conditions of the flow meters and on the transport properties of the fuels on flow meter performance. The focus will be on the properties of alternative liquid fuels which are considered promising for future uses such as biodiesel, methanol or synthetic fuels. Furthermore, flow meter performance under dynamic loads, as occurring e.g. in Emission Control Areas (ECA), will be addressed and

the results will be summarised in a comprehensive uncertainty budget. For road transport, a validated numerical tool will be provided as support for experiments to address the impact of the operating conditions and the test liquid on flow meter performance. (Objective 2)

Fuel properties have a direct impact on engine performance and hence any negative impacts will affect the acceptance and adoption of new fuels. Furthermore, the measurement performance of a flow meter depends on the transport properties of the liquid and it therefore affects the correctness and reliability of the fuel consumption measurement. In all cases reliable liquid properties data is essential. As current operating conditions generally vary, the transport properties must be known in relation to pressure and temperature. This situation results in the need for up-to-date and accurate density and viscosity data and data on how these transport properties change under different operating conditions. In addition, sensors or sensor systems are required for traceably measuring both parameters in situ and this will contribute to an improved on-board fuel consumption measurement.

This project will provide a fuel property matrix of the transport properties of current and up-coming alternative and synthetic fuels for the temperature and pressure range relevant to road transport and the maritime sector. This will improve the transfer of flow meter calibrations between different fuels and it will enable an appropriate determination of the measurement uncertainty of flow meters especially under actual operating conditions. Thermophysical property models for alternative fuels will also be made available which can then be used to extrapolate the fuel properties to operating conditions, (i.e. conditions which cannot be easily realised in labs). The thermophysical property models will represent a useful ready-to-use tool for manufacturers and end users. Further progress will be achieved by the project by addressing the in-line measurement of density and viscosity, which are important for both an improved en-route fuel consumption determination and to ensure engine performance and efficiency. In addition, sensor systems based on commercially available components will be addressed and a prototype ultrasonic densimeter will be developed. (Objective 3)

Currently only standards and recommendations exist for the evaluation of flow meters at single test points with steady flows and for meter stress tests based on switch-on/switch-off procedures which are independent of the specific application area. This means that, it is difficult to quantify the uncertainty associated with transferring the calibration for one liquid to another because the measurements required for this are not sufficiently available. If taxation and emission determination are based on fuel consumption measurements and the amount of fuel consumption is a major selling point, the quality of the fuel consumption measurement becomes much more important and with it the associated measurement uncertainty. The problem has been partly recognised e.g. the new ISO development of an evaluation method for transient flow rates, but progress is currently very slow.

This project will develop guidelines for the evaluation of the flow meters deployed in the transport sector, with a view to real-world operating conditions, including recommendations for the determination of uncertainty budgets. Further input will be provided by the project to metrological technical committees such as EURAMET TC Flow (TC-F) or BIPM CCM WG Fluid Flow (WGFF) and relevant national committees as they also provide guidelines on flow measurements which are used by end users. At present there are no specific stakeholder bodies in the transport sector with clear links to flow metrology. However, various competence centres, clusters and alliances of interest exist at the national or European level and relevant conferences will be targeted for dissemination of the project's results. (Objective 4, 5)

Results

To develop the infrastructure required for evaluating the accuracy of the flow meters and other systems (e.g. the conditioning system around the flow meter), which are used in cars and trucks to measure the consumption of fuel, under the New European Driving Cycle, the Worldwide harmonised Light vehicles Test Cycle (WLTC), or the World Harmonised Transient Cycle (WHTC). Test liquids should include e.g. water and hydrocarbons, with densities $> 400 \text{ kg/m}^3$, viscosities $> 0.01 \text{ mPa}\cdot\text{s}$, pressures $\leq 300 \text{ bar}$, and flow rates $0.0001 \text{ m}^3/\text{h} - 8 \text{ m}^3/\text{h}$. (Objective 1)

The equivalent turndown ratios were derived from the WLTC for passenger car engines and from the WHTC for truck engines. Based on real test executions, the fuel demands from the engine control units (ECUs) were determined and correlated to the dynamic response of the test equipment applied. Based on this information, test profiles for passenger cars and trucks were derived which take up characteristic sequences of the harmonized test cycles. In particular, fuel consumption at idle and zero consumption phases were included. These are critical in consumption measurements as the flow meters deployed are not calibrated in this range. Different engine sizes can be addressed by simply scaling the profiles. The test profiles serve as the basis for

the development of test rigs, at the partners facilities, which are capable of realising dynamic flow changes with these characteristics. Attention was paid to the fact that the profiles are suitable for practicable implementation at the stakeholders, for eventual dynamic calibrations of flow meters.

One approach for the technical realisation of vehicle-related profiles on a test rig consists of a combination of cavitation nozzles and orifices, other ones or on/off valves, proportional valves and fuel injectors. It is essential that the measurement is against a sufficiently accurate reference that is traceable. However, this alone is not sufficient to assess the quality of a profile implementation on the test rig as e.g. the realisation of the individual flow rate changes is also of importance. 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 17IND13 "Metrowamet" [1][2]. Concerning the evaluation of flow meter performance with regard to dynamic flow changes, a recommendation was drafted for a procedure, protocol and evaluation.

A prerequisite for any development towards 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. On the one hand, the aforementioned evaluation criteria come into play, and on the other hand, the quality and comparability of the technical implementations needs to be determined by means of an intercomparison employing a well-characterised transfer standard.

Furthermore, measurements of different types of flow meters, at room temperature, using different test liquids have begun. Likewise, flow meter characterisations for different liquid and ambient temperatures have started. At present, it is still too early to draw conclusions. Furthermore, a literature review is underway on the state of the art of fluid flow simulations and on the interaction between the test liquid and the performance of the flow meter.

To develop the infrastructure and procedures required for evaluating the accuracy of flow meters, which have potential for measuring the consumption of alternative fuels in the maritime sector, under close to real world conditions. The selected alternative fuels should have the same range of densities, viscosities, pressures and flow rates as specified in objective 1. This objective should address measurements of dynamic flow and en route fuel consumption, with uncertainties. (Objective 2)

The test liquids and the first devices to be measured were selected and the measurements have started. The selected types of flow meter comprise among others Coriolis flow meters, differential pressure (dp) sensors and piston meters. Concerning the development of a test cycle for the maritime sector the fuel consumption of a ferry navigating in a harbour was considered. As for vehicles, it could be shown that the fuel consumption can be scaled to different sizes of ship engine. Based on the measurement, a test profile was derived. Tests were started regarding the technical realisation of the flow changes on a test rig. By using a needle valve very good realisation results could be obtained.

Flow measurements using at least three different types of flow meters (measuring principle (e.g. Coriolis, turbine, dp) / manufacturer) that are used in the maritime sector for different liquid temperatures and using different hydrocarbon liquids have begun. These will lead to insights into the influencing factors which might need to be taken into account when using these flow meters.

To prepare a fuel property matrix of the transport properties of alternative fuels e.g. bio-diesel (FAME), bio-alcohol and synthetic fuels. This should enable the transfer of calibrations between fuels and extrapolation to higher temperatures and pressures. The selected fuels should have densities $> 400 \text{ kg/m}^3$, viscosities $> 0.01 \text{ mPa}\cdot\text{s}$, temperatures $\leq 620 \text{ K}$, pressures $\leq 300 \text{ bar}$ and flow rates $\leq 2 \text{ m}^3/\text{h}$. Sensors should also be developed for traceably measuring density and viscosity in situ. (Objective 3)

A survey of alternative and synthetic fuels was carried out and a number of relevant current and upcoming fuels were identified. Four fuel classes were defined for which further studies and measurements will be carried out: Biodiesel (FAME), Hydrotreated Vegetable Oil (HVO), Oxymethylether (OME), E10. For the quality assurance of the density and viscosity measurements it was decided to carry out a laboratory comparison using a N4 standard before starting with the actual measuring program. The materials and design details of a prototype ultrasonic densimeter to fit the required working conditions are under evaluation. The design of a new test rig for in-line density and viscosity measurements, hosting the prototype ultrasonic densimeter and a piezoelectric viscometer is in progress. Discussions on the improvements of the in line measurements of commercially available density and viscosity devices have started.

To provide metrological input, and pre-normative research, for the further development of international standards with a focus on close to real-world flow calibrations in the transport sector. In addition, to contribute to the development of a pan-European harmonised framework, which will enable the emission targets set by the International Maritime Organization, the European Conference of Ministers of Transport and the Fédération Internationale de l'Automobile to be met and controlled. To facilitate the take up of the technology and measurement infrastructure developed in the project by the measurement supply chain (accredited laboratories, instrumentation manufacturers), standards developing organisations (IMO, ISO) and end users (transport sector). (Objectives 4, 5)

The outputs associated with objectives 1-3 will be used to prepare guidelines for the evaluation of the flow meters used in the transport sector, with a view to real world operating conditions, including recommendations for the determination of uncertainty budgets. This means this part of the project gains relevance at a later stage of the project. In the meantime, the focus is on technical discussions and information from various stakeholder communities.

Impact

A stakeholder advisory board was set up comprised of representatives of manufacturers of flow meters and test rig technologies for the transport sector, a maritime association, a national metrological institute and standardisation bodies. It has the responsibility for keeping the project aligned with industry's needs and for informing end users about project findings as they emerge. NMIJ, the University of Torino and AVL GmbH joined the project as collaborators and will provide insights based on their long-term and diverse experience. To foster impact the project has a dedicated website. Presentations were given by project partners at workshops and meetings hosted by industry.

Impact on industrial and other user communities

The outputs of this project will create impact by enabling stakeholders who depend on fuel consumption measurements in the road transport and maritime sectors, such as vehicle manufacturers, freight forwarders, ship owners, and regulatory authorities, to have access to reliable fuel consumption data.

One key project output will be advanced calibration capabilities. These will generate impact by enabling flow meter performance to be assessed under the dynamic flows that are associated with test cycles such as the World Harmonized Stationary Cycle (WHSC) or the World Harmonized Transient Cycle (WHTC). The project's associated technical guide and the design for a secondary test rig, which will be capable of generating dynamic loads, will help to facilitate practical take-up. In addition, efforts towards downsizing vehicle engines will be supported by the project's improved fuel consumption measurements.

By providing a fuel property matrix of alternative and synthetic fuels, companies will be supported in their endeavours to develop engines which work efficiently with alternative or synthetic fuels. The provision of a validated numerical tool for investigating the interaction between test liquid and flow meter performance will enable companies to replace experimental setups with simulations with known uncertainties, in particular in the case where experimental conditions are costly or dangerous to realise. Likewise, the provision of two well-characterised synthetic test liquids for use as substitute fuels for flow meter characterisations will support the work of companies that are active in the development of drive systems and testing technology.

The project's technical guides for the comprehensive uncertainty assessment of the flow meters that are used for the fuel consumption measurement of cars and trucks and in the maritime sector will create impact by helping manufacturers of these devices to supply their customers with more reliable information about the performance quality of their products. The project's outputs will also help to create impact by paving the way towards a realistic uncertainty determination for fuel consumption measurements.

The project will contribute to improving the measurement capabilities of the fuel transport properties under operating conditions through its advancement of in-line measurements of the density and viscosity of alternative and synthetic fuels, by developing a sophisticated system combining standardised calibration procedures. This will in turn support an improved fuel consumption determination as the flow meter performance for the real-time transport properties will be taken into consideration in the flow measurement.

To foster the take up of the project's findings by a wider community in flow metrology from NMIs/DIs, industry and academia, all outputs with direct links to flow measurements and measurement quality will be compiled in a PTB-Report, which will be made freely available to end users via the project's website.

Impact on the metrology and scientific communities

Based on the outputs of this project, such as the assessment of the measurement performance of flow meters under dynamic loads, the project partners will develop novel measurement capabilities and procedures which will allow them to perform a more detailed and profound characterisation of the devices than was previously possible. The technical guides, for the comprehensive uncertainty assessment of flow meters, as well as the PTB-Report, are especially relevant to flow metrology and they are intended to serve as a basis for broader knowledge dissemination to the scientific community.

The technical guide for the assessment of flow meter performance under dynamic load changes will contribute towards future dynamic calibrations by providing, (i) guidance on requirements for the realisation of a test rig that is able to generate and measure dynamic loads, and (ii) recommendations for a measurement procedure and for the analysis of the results.

Stakeholders in the metrology and scientific communities will be further supported by establishing new capabilities at project partners to measure the transport properties of liquids at significantly higher pressure ranges than available at present. For density, the range covered will be up to 170 °C and 1000 bar. For viscosity, the ranges covered will be up to 350 °C and 40 bar, as well as up to 150 °C and 700 bar. The knowledge, primarily residing at universities in this area, will be transferred to NMIs/DIs via this project.

The project will also support research linked to alternative and synthetic fuels as a more comprehensive data base on the density and viscosity of these liquids will be available in the fuel property matrix. The provision of two extensively characterised synthetic test liquids, which will be useable as fuel substitutes, will further support the use of alternative and synthetic fuels.

Furthermore, the project's results, obtained with different fuels, will improve the scientific community's understanding of the influence of the liquid on the flow meter itself as well as the effects that are due to changes in the flow profile. This deeper understanding will help with the quality assessments that are undertaken when different liquids are used for calibration and under operating conditions.

Impact on relevant standards

This project will provide input to a number of national and international committees dealing with flow measurements. Among others, input will be provided to EURAMET TC-F and to the BIPM CCM WGFF. The technical guides on the assessment of the measurement uncertainty of flow meters, prepared in this project, as well as the PTB-Report on the advancements in flow metrology, will be used as inputs for new guides and for revisions to existing guides. The project also intends to support EURAMET TC Mass and Related Quantities (TC- M) and the BIPM CCM WG on Density and Viscosity (WGDV) in their aim to provide guidance on density and viscosity determinations. At a national level, calibration service providers will be informed on a regular basis about the project's activities and results so that these can be taken into account in the revision of standards, recommendations and guidelines. Among these are the DIN NA152-04-02AA "Flow rate and Amount" and the DKD TC "Flow Measurands".

Longer-term economic, social and environmental impacts

The transport sector has been identified as one of the main sources of greenhouse gas emissions. This has led to major efforts to shift towards a climate-neutral mobility. Advanced flow metrology is a key factor in this move towards low-emission mobility, as increasing engine innovation, or validated emission determinations for ships and vehicles, rely on appropriate fuel consumption measurements. Reliable data and measurements of the transport properties of these fuels are also required and both will be fostered by the outcomes of this project.

CO₂ standards for heavy duty vehicles and ECA in the maritime sector are further means towards a low and zero emission mobility. The capabilities and knowhow developed in the project will help determine the relevant parameters with sufficient accuracy.

Standards and frameworks in liquid flow metrology will be advanced by the project's results which is a precondition to realising the long-lasting goal of a European harmonised approach for the evaluation of fuel flow measurements which are closer to real-world conditions. In the longer-term the project will also support stakeholders in their endeavours to comply with Europe's shift towards low-emission mobility whilst maintaining competitiveness.

Project start date and duration:		01 September 2021, 36 months
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Internal Funded Partners:	External Funded Partners:	Unfunded Partners:
1. PTB, Germany	6. IB-HAWE, Germany	-
2. INRIM, Italy	7. IC, United Kingdom	
3. RISE, Sweden	8. TU-Ch, Germany	
4. TUBITAK, Turkey	9. UNICAS, Italy	
5. VTT, Finland	10. UNIPG, Italy	
RMG: -		

References

[1] 17IND13 Metrowamet – Metrology for real-world domestic water metering; <https://www.ptb.de/empir2018/metrowamet/the-project/>

[2] Warnecke, H., Kroner, C., Ogheard, F., Kondrup, J.B., Christoffersen, N., Benková, M., Büker, O., Haack, S., Huovinen, M., Unsal, B, 2022. New metrological capabilities for measurements of dynamic liquid flows. Metrologia, <https://doi.org/10.1088/1681-7575/ac566e>