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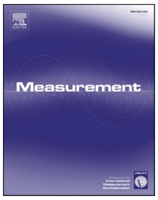

Dynamic calibration of flow meters using reference flow rate profiles generated by injectors

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ABSTRACT

A new method to calibrate flow meters under dynamic conditions has been developed, based on the generation of variable reference flow rates using an automotive injection system.

The method was tested with different flow profiles, including both idealized flow time-histories (sinusoidal and sawtooth waves) and actual fuel flow rate profiles recorded during WLTP (Worldwide harmonized Light vehicles Test Procedure) automotive type-approval tests. To demonstrate the effectiveness of the method, some results obtained with a Coriolis flow meter are presented. Compared with other methods such as those based on valves or volumetric pistons, the reference flow rate profiles obtained by the proposed approach feature dynamic characteristics (mainly flow oscillation time and gradients) that can be easily tailored to specific applications. The method has a high potential in evaluating the dynamic response of flow meters, which can be very different from that obtained with constant flow calibration.

1. Introduction

The response of flow meters, as is normally the case for many measuring instruments, depends on the working conditions. One of the main measurement problems with flow meters concerns the unsteady flow conditions, as many applications show a strong flow rate variation over time. In general, in case of unsteady condition, the metrological traceability of the instrument cannot be limited to knowing the sensitivity of the instrument, which is obtained in the steady-state regime, but it is necessary to know the dynamic behavior that is the frequency-dependent response of the instrument [1]. However, it is only since a few decades that the metrology community has made the necessary support to provide traceability through dynamic calibrations. An important initial contribution was achieved with research program EMRP from the European Association of National Metrology Institutes (EURAMET) “IND09 – Traceable Dynamic Measurement of Mechanical Quantities” [2], which had the objective of establishing traceability for dynamic mechanical quantities, in particular: force, torque and pressure.

The need to obtain information on dynamic response is also of great interest for the flow meters, already in the 1990 s the first studies began [3], and several studies have modeled the dynamic response of different flow meter technologies [4,5]. Although these works represent a first approach to dynamic calibration, from a metrological point of view they are lacking of the uncertainty evaluation.

However, a first metrological approach to dynamic calibrations of flow meters is quite recent, the first project at European level between NMIs was in 2018 with the EMPIR (European Metrology Programme for Innovation and Research) project 17IND13 “Metrology for real-world domestic water metering – MetroWaMet” [6]. An aspect of this project dealt with the calibration of domestic water meters in conditions close to real-world. In this framework, several NMIs set up calibration facilities capable to realize flow profiles similar to those of domestic meters. Such calibration systems were realized using fast-acting valves, fast piston position changes and cavitation nozzles [7,8]. The metrological consistency concerning dynamic flow profile capability of the dynamic test rigs was assessed by a comparison [9].

However, interest in the field of dynamic flow measurement is very wide and there are applications where the dynamic flow rate is much more significant than water meters. Among the most challenging applications, where it is important to know the flow rate with very rapid variations, there is the fuel delivery in internal combustion engines, both for direct and in-direct fuel injection configurations. The study of the fuel flow profile, which describes the variation in the mean fuel mass

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flow over time, is of considerable interest, as it potentially influences the engine performance, consumption and emissions during the engine operating point transients.

To control the vehicles emission, the type-approval tests, in terms of both emission and fuel consumption, are required. The European legislation has introduced the WLTP (Worldwide harmonized Light vehicles Test Procedure) and more recently the RDE (Real Drive Emissions), which are representatives of the vehicle actual on-road operation [10]. These new tests lead to problems in terms of measuring fuel flow, being characterized by relatively abrupt powertrain load and fuel rate transients, which are flow conditions far different from the constant fuel flow conditions in which flow meters are normally calibrated.

In this regard, the recent EMPIR project 20IND13 "Sustainable advanced flow meter calibration for the transport sector – SAFEST" [11] focused on establishing a traceable metrology infrastructure and procedures to evaluate the measurement performance of fuel flow meters under dynamic condition.

Many of the laboratories involved in this project had already participated in the MetroWaMet project. Thus, they used the same techniques as those used for the dynamic calibration of water meters to create the reference flow profiles for calibration, adapting the facilities so as to reduce the minimum flow rates.

For the SAFEST project a new method for generating reference flow profiles has been proposed by the University of Perugia and Istituto Nazionale di Ricerca Metrologica (INRIM), based on the use of automotive fuel injectors. This allows the control of the rail pressure and, by controlling the injectors actuation frequency and duration, the amount of fuel, to reproduce the assigned test flow rate profile to be used for the flow meters calibration.

The new method to generate dynamic profiles by the use of injectors for flow meter dynamic calibration is described. Following details of this approach are provided along with examples of different profiles generated. Moreover, the analysis of the results is reported describing the advantages obtained with the injectors, e.g. better repeatability, faster response, compared with the other methods.

2. The use of injectors to generate reference flow rates

As the fuel injection rate is essential for improving engine performance, and controlling emissions, several studies on the hydraulic characterization of injectors can be found in the literature: a recent review can be found in the paper of Mata et al. [12].

From the steady Bernoulli equation, the basic model for an injector nozzle, in steady flow conditions the mass flow rate q_m flowing through the injector can be evaluated by:

$$q_m = C_d A \sqrt{2\rho \Delta p} \tag{1}$$

where A is the cross-sectional area of the orifice, C_d is the dimensionless discharge coefficient, ρ is the liquid density, Δp the pressure drop across the injector.

The injected fuel mass can be obtained by multiplication of the mass flow rate q_m and the effective injection time T_{inj}.

However, the model (1) is difficult to characterize, as:

- the parameter C_d depends on many factors, among which the details of the needle and its seat design, the effective pressure drop, the eventual trigger of cavitation phenomena [13];
- the effective injection time T_{inj} does not correspond exactly to the energizing timing T_e of the coil;
- the flow rate q_m is not constant for the whole energizing time T_e.

Currently, there are two main types of injectors commonly used in fuel injection systems for internal combustion engines: electromagnetic and piezoelectric. The study was carried out with electromagnetic injectors, which are high speed on/off solenoid valves consisting of a needle-controlled nozzle that is opened by energizing a coil.

For a more precise model, the dynamic of the high speed solenoid valve could be divided into the electrical circuit model, the magnetic circuit model and the of mechanical components and of the hydraulic flow, resulting in the so called 0-D1D lumped parameter approach. In this context various physical models have been developed [14–16], however very often modeling based on experimental measurements, is enough [17].

The proposed methodology to generate flow profiles consists in dynamically driving an adequate number of injectors at a constant frequency using a PWM (Pulse Width Modulation) strategy to obtain the desired flow rate. While in a normal engine control system the injector actuation strategy (single or multiple actuation depending on the engine type and operating condition) is repeated once per engine cycle and hence at variable frequency, in the present application the actuation frequency could be in principle arbitrary. Hence, the frequency can be chosen so as to minimize flow pulsations as much as possible. Further, for the present laboratory application all the influencing parameters such as fluid pressure and temperature can be easily controlled. Consequently, the generation of an assigned flow rate relies on the hydraulic characterization of each of the used injectors in terms of energizing time vs. flow in the prescribed operating conditions defined by the constant actuation frequency, fluid temperature and pressure.

In such a way, the key point for the characterization of the injector in flow rate is the energizing time T_e and the difference between the energizing time T_e and the actual injection duration T_{inj} and how this difference is affected by the working conditions.

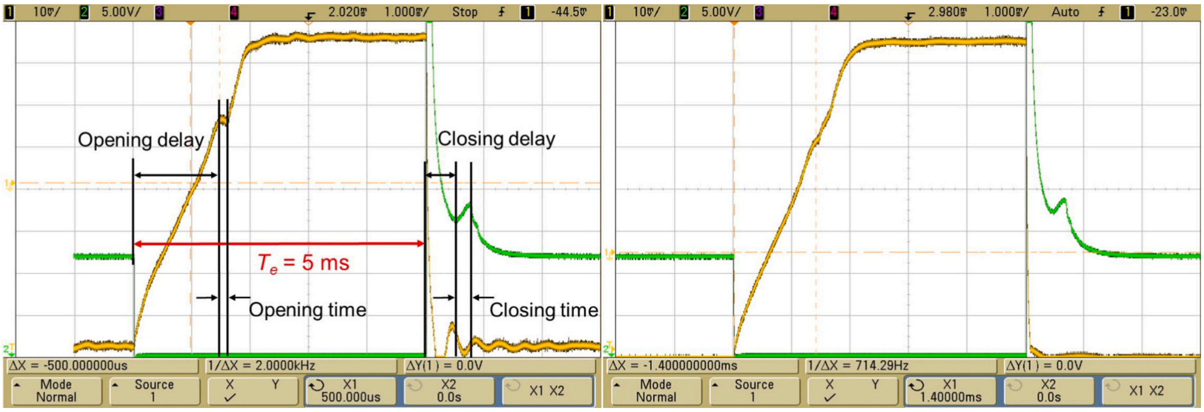
A study to estimate the injector opening and closing delay times with respect to the energizing and de-energizing time of the coil was performed by using the method proposed in [18]. Based on the analysis of the control current of the injector and the voltage at the terminals of the transistor that drives the injector, it is possible to evaluate the opening and closing time of the needle: an example is shown in Fig. 1, showing the current and voltage waveform where the time base is 1 ms, the y-axis resolution is 5 V for the voltage and 100 mA for the current.

The electric circuit of the injector can be schematized as a RL circuit and the movement of the needle produces a change in the inductance. By observing the change in the derivative of the current waveform (yellow curve in Fig. 1), the actual opening timing of the injector can be determined. In addition, the analysis of voltage decay (green curve in Fig. 1) allows to observe that the change in the derivative of the waveform defines the actual point of the closing movement. In particular, the first change of derivative of the current curve defines the moment at which the needle begins to rise, evidencing the opening delay with respect to the start of the logic command. While the second change of derivative defines the moment of maximum opening of the needle, the difference of this time with the opening delay defines the valve opening time. Similarly, from the derivative of the tension, the timings of start of closure (valve closing delay) and end of closure of the needle (the valve closing time) are observed.

Since the flow rate transition during the opening time is similar but opposite to the flow rate transition during the closing time, the injection time T_{inj}, defined as the time in which the flow rate is constant, can be approximately considered as the difference between the closing start time and the opening start time. For example from Fig. 1 a) it is observed that the energizing time is 5 ms, the valve opening delay is about 1.4 ms and the valve closing delay is about 0.5 ms.

The characteristics of the injectors can be verified from these measurements. For example, it can be seen that injectors of the same model have different dynamic response. Fig. 1 b) shows the curves obtained for another injector nominally identical to the one of Fig. 1 a) at the same working conditions. It is noted that the injector in Fig. 1 b) has the opening and closing delay shorter than the injector in Fig. 1a), as it is also evident in the opening and closing times.

In addition, the opening and closing delays are not constant under different working conditions, for example:



a) b)

Fig. 1. Example of current waveform (yellow) and voltage at the terminals of the transistor (green), for two nominally identical injectors a) and b) respectively.

- the increase in supply voltage reduces the opening delay Since the achievement of the current level producing the needle lift is faster;
- the effect of upstream pressure is also observable, increasing the pressure the opening delay increases and the closing delay decreases;
- as indicated in [14], the fluid viscosity and consequently the temperature affect opening and closing times.

These mentioned are effects that can be controlled by keeping constant the working conditions of the supply voltage and the fluid temperatures and pressures.

Having defined the working conditions, the calibration of the injectors is done by correlating the injected quantity with the energizing time. The test can be performed by keeping the supply frequency constant and changing the duty cycle to obtain the desired energizing time. The mass (or volume) injected can be measured using a flow meter or, for more accurate measurements, using a balance.

Fig. 2 shows a typical calibration curve of the quantity delivered in terms of flow rate for different energizing times T_e, obtained with a solenoid injector used in a medium-sized car, which is driven with a frequency of 20 Hz, temperature of 20 °C and $\Delta p = 0.4$ MPa. These calibration curves can also be obtained for several injectors controlled in parallel. From these calibration curves, which express the injected quantity as a function of energizing time, it would be possible to calculate the number of injectors to be used and their energizing time as a function of the required flow rate.

The calibration curves (e.g. Fig. 2, blue dots) show a two-zone operation, corresponding to the so-called ballistic and linear operation of the injector, that differs in the slope variation: the one for small T_e, and a linear zone in which the injected quantity becomes linearly proportional to the T_e [10]. This behavior can be clearly observed from the voltage and current curves of the injector. From Fig. 3 a), the opening of the injector is achieved with $T_\mathrm{e} = 1.6$ ms, in which the needle starts to move, but does not reach the maximum opening, and $T_\mathrm{inj} = 0.3$ ms (Fig. 2 red dots). By increasing the energizing time, the opening delay is kept constant, while the needle stroke and thus the injection time increases. In Fig. 3 b) at the energizing $T_\mathrm{e} = 1.75$ ms, the valve reaches the maximum opening, with about $T_\mathrm{inj} = 0.75$ ms. Starting from this energizing time, the opening and closing times reach the maximum value and are held constant, consequently, the difference between T_e and T_inj remains constant, of about 1 ms, therefore the linearity zone between T_e and the mass flow rate is reached.

Another effect observed is that the current in the coil depends on the resistance of the coil, which depends on its temperature. Consequently, as the coils have a non-negligible maximum electrical power, of about 12 W, the injector heats up depending on the duration of the energizing time and the control frequency. It is evident that equivalent excitation duration T_e, but different frequencies, results in different currents, as increasing the frequency increases the temperature of the coil and thus reduces the current. For example, from Fig. 4, with frequencies of 20 Hz (Fig. 4a)) and 80 Hz (Fig. 4b)), both with a $T_\mathrm{e} = 2.5$ ms, a decrease of

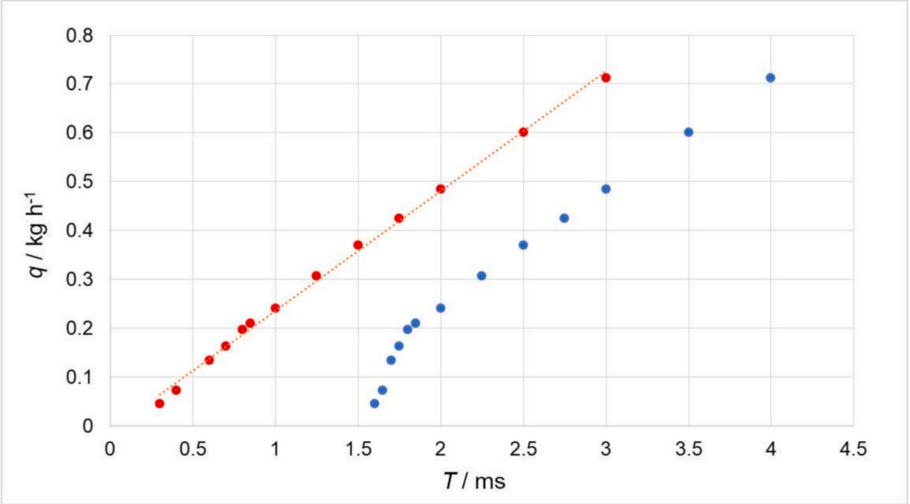
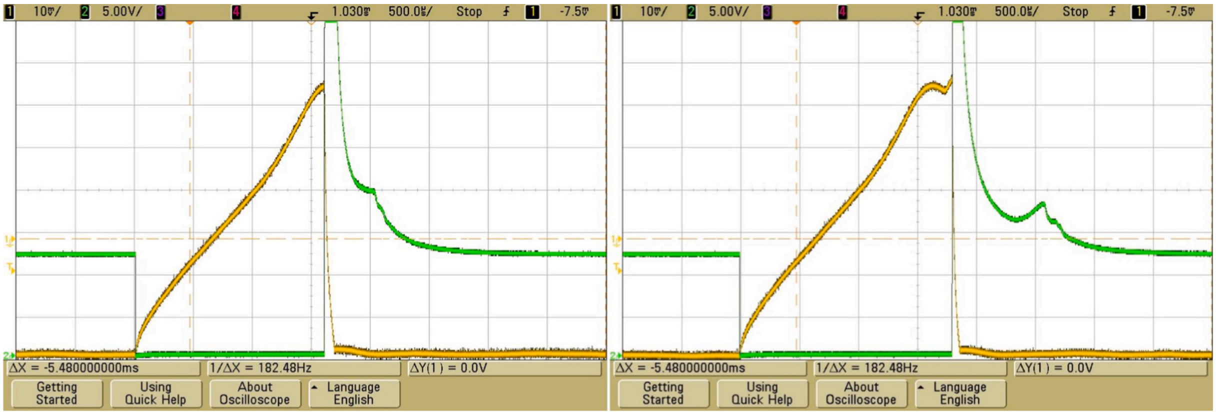
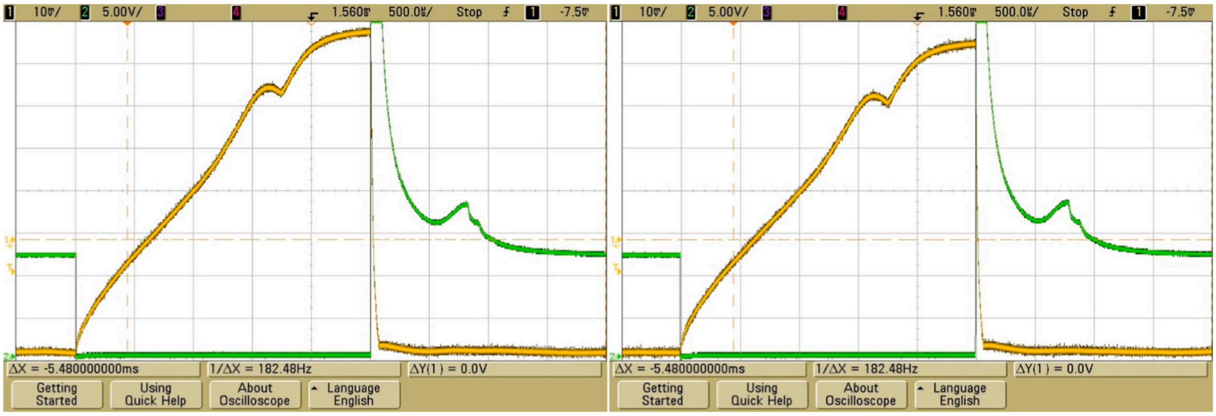


Fig. 2. Example of characterization of an injector: flow rate q as a function of times T_e (blue dots) and T_inj (red dots).



a) b)

Fig. 3. Waveforms at the time at which the injector: a) starts to open, $T_e = 1.6$ ms; b) reaches maximum opening, $T_e = 1.75$ ms.



a) b)

Fig. 4. Waveforms with $T_e = 2.5$ ms, at different frequencies: a) 20 Hz and b) 80 Hz.

about 40 mA can be observed. Moreover, the current value at which the valve opens decreases with increasing temperature, and the difference in the opening delay is approximately 0.02 ms. Probably the injector temperature affects the fluid temperature, which changes the response characteristics of the needle, due to the reduction of the liquid viscosity. This effect is also evident, with similar behavior, for short energizing times, when the needle is not completely open. As a result, the variation in temperature due to self-heating, causes relative differences in the injection times that become negligible as energizing times increase. This effect has to be taken into account, as the calibration of the injectors is performed at constant energizing times, consequently the temperature and resistance of the injectors are constant, whereas in the process of generating the test flow profile, the energizing times are variable.

3. Generation of the flow rate profiles

As shown in Section 2, keeping the pressure drop constant, at different flow rates, by means of a regulating valve, it is possible to determine the flow rate in mass injected as a function of time T_e. The calibration curves can be obtained for single or several injectors controlled simultaneously or in a phase-shifted way so as to reduce flow pulsations and pressure in the upstream common rail. From these calibration curves, which express the injected quantity, or the flow rate as a function of energizing time at a given pressure drop, it would be possible to calculate the number of injectors to be used and their energizing time as a function of the required flow rate for the calibration of the flow meter. However, this approach would be impractical, since in the case of the generation of extreme variations in flow rate, it would not be possible to keep the pressure drop of the injectors constant. For this reason, the approach is not to calibrate the injectors alone, but in series with the flow meter to be calibrated. In this way, only the upstream pressure is kept constant and the calibration also considers the pressure drop due to the flow meter.

Fig. 5 shows the hydraulic scheme adopted for the tests at INRIM, where the flow meter is placed upstream of the injectors, which have the outlet at atmospheric pressure. With this approach, the pressure variations are easily controlled, even for abrupt variations in flow rate, as the pressure downstream of the injectors is constant at atmospheric pressure and the upstream pressure will vary, but only slightly if a pressure tank with a sufficiently large volume and a fast regulation control is used. With this method, however, it is necessary to calibrate the injectors every time a new flow meter is to be calibrated, as the calibration of the injectors will depend on the pressure drop on the flow, which depends on the type of flow meter.

For the realization of the flow rate profile, the energizing time can be modified either by changing the frequency or the duty cycle. However, the frequency should not be too low in order to achieve flow rates that are not too fluctuating. Although there is no limit for high flow rates, as it would be sufficient to increase the number of injectors, there is a limit for the minimum flow rate. The latest, for a given pressure drop, depends on the type of injector, the minimum duration of injection time, and the minimum drive frequency, which must be adequate to not generate excessive pulsation and to operate outside the ballistic zone. Minimum values of about 10 Hz can be considered adequate. Another limitation of

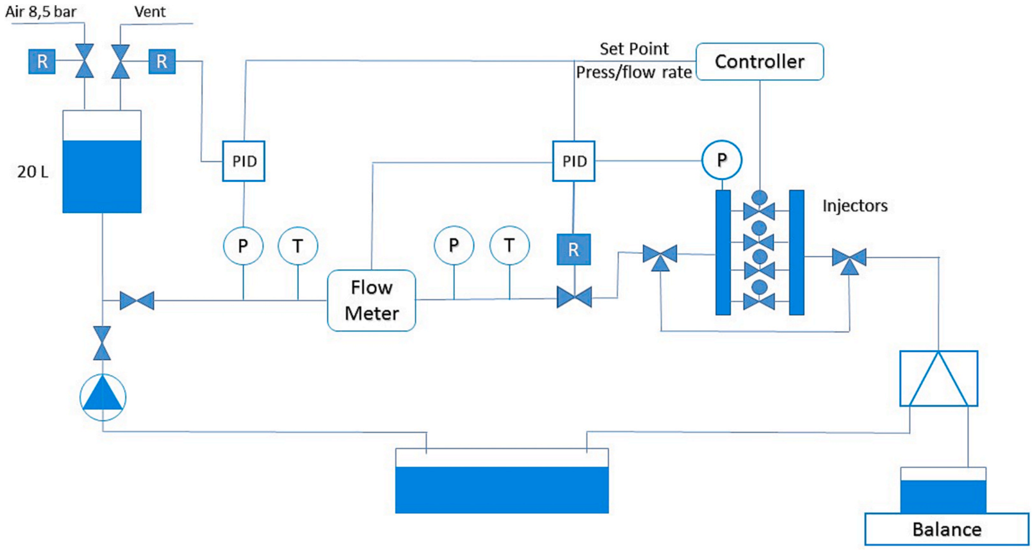


Fig. 5. Scheme of the INRIM bench for dynamic flow meters calibration.

the use of injectors is due to their construction characteristics, for which their use with lubricating liquids, such as fuels or oils, is preferable.

In practice, the approach of using injectors to generate variable flow profiles is as follows:

- define the profile to be implemented, and establish the timing, that is the time resolution for the profile;
- set the working conditions, i.e., temperature and fluid pressure;
- define the frequency range of the injector drive;
- depending on the characteristics of the injectors, set the flow rate ranges and for each, the number of injectors to be operated;
- carry out the calibration of the injectors (together with the flow meter) at constant flow rates to determine for each defined flow rate range, the duty cycle as a function of drive frequency and flow rate;
- in case of calibration with flow rate requiring many injectors, their calibration must be carry out by controlling all the injectors, fixing an even phase shift among them to obtain a flow rate as constant as possible.

The reference flow rate for the injectors calibration can be measured gravimetrically by weighing the totalized liquid for a certain test time at a constant flow rate. The reference flow rate can also be determined by means of the flow meter to be dynamically calibrated, in which case the flow meter must first be calibrated at a constant flow rate. This approach can be adopted by checking in advance that the constant-frequency injector drive does not affect the flow meter measurement.

For the dynamic calibration of the flow meter:

- according to the required flow rate, calculate the frequency and duty cycle of each injector for each command pulse according to the calibration curves and establish the timing;
- start the test by driving the injectors dynamically with the calculated frequency and duty cycle.

In the case of flow profiles in which the flow rate at the beginning or at the end is non-zero, it is preferable to install a diverter valve in order to minimize the transients.

4. The experimental apparatus

At INRIM in the framework of the SAFEST project, a new calibration bench has been developed in order to calibrate flow meters in static and dynamic operating conditions, with liquids different from water. The liquid used is the oil FUCHS VISCOR1487 AW-2, which is in conformity with the standard Calibration liquid ISO 4113 [19]. The bench calibration is based on the gravimetric method. In Fig. 5 the bench layout is schematically illustrated. The pressure is generated using a pressure vessel of 20 L, which pressure is kept constant through compressed air regulated by a control valve, from 0.3 MPa up to0.6 MPa. In addition, a regulating valve located downstream of the flow meter can be used to keep the oil pressure constant upstream of the injectors, or to control the flow rate, e.g. during the calibration at constant flow rate. Downstream of the regulating valve there are four gasoline injectors (coil supply 12 V), used to generate the dynamic flow rate profiles, shown in Fig. 6. The injectors can be bypassed allowing to calibrate the flow meter at a constant flow rate, by modulating the valve downstream of the flow meter. The bench can operate in two different methods, by the “standing start and stop method” and the “flying start and stop method” defined from the use of the diverter valve. The system is equipped with a balance with a capacity of 10 kg and a resolution of 1 mg, which allows the

Fig. 6. Photograph of the injectors system.

calibration of both flow meters and injectors at a constant flow rate. The bench is as well equipped with thermostated bath, thermometers and pressure transducers to measure the temperature and pressures with uncertainty of 0.05 °C and within0.0001 MPa, respectively. The control is performed by a National Instrument (NI) system, and the software was developed in LabVIEW environment.

The injectors are driven with a NI module 9401, which provides the adjustment of the frequency and duty cycle of the four injectors, independently; the outputs of this card control the mosfet transistors that drive the injectors. The injectors installed are typical for a medium-sized car, the maximum flow rate achievable for each injector with an upstream pressure of 0.4 MPa is around 8 kg/h.

The tests shown in this work were performed using a constant control frequency of 20 Hz. With such a frequency, by selecting the injector with the shortest opening time, the minimum flow rate was about 0.03 kg/h. The programming of the sequence of pulses to be generated to realize the required profile is done by means of a software that allows a dynamic variation of the duty cycle of each injector with the desired timing. The tests presented in the paper were performed with a time resolution of 100 ms, which was the same time resolution of the profile to be generated. In order to smooth out the pulsations, the injectors are controlled in sequence with an equispaced delay between them. To achieve the desired flow rate, one or more injectors and different duty cycles can be used. The measurements obtained for a single injector and for multiple injectors define different flow rate ranges. For the tests of this work, one injector was used for flow rates up to 1 kg/h and two injectors between 1 kg/h and 5 kg/h.

For the calibration, the test time at constant duty cycle must be long enough so that the relative weighing uncertainty is negligible compared to the required uncertainty. The reference of the flow rate can be determined by measuring the mass totalized in the test, by using the balance, or from the flow meter, provided that its calibration was previously performed at constant flow rate. With the latter mode, the uncertainty is slightly higher than with the balance, but it is considerably faster, as it is made by recording the average flow rate of the test period.

For each flow rate range the measurements are fitted with a polynomial to obtain the duty cycle value as a function of the flow rate. For low flow rates a third-degree polynomial is normally used, for the higher flow rate zone a straight line is sufficient. In order to generate the flow rate profile for the dynamic calibration of the flow meter, the parameters of the polynomials are then introduced into the software, which, depending on the profile to be generated, calculates for each injector all the duty cycle values to be sent to the injectors, at each instant of time defined by the timing.

Since, as already shown in section 2, it is important to keep the injector at a temperature as constant as possible. For this reason even when an injector has to be kept closed, it is still energized, but with a duty cycle such that it does not cause it to open.

In the case where the start flow rate of the profile is non-zero, the injectors are controlled to generate the initial flow rate before the start of the test. At the start of the test, the diverter is switched to the balance, and the injectors begin to be controlled with the specified timing. At the end of the test, the injectors are switched off and the diverter is switched to the storage tank.

5. Calibration results and uncertainty evaluation

The proposed method and the calibration facility have been validated with the measurement comparison carried out by the partners of the EMPIR SAFEST project [20] and with additional tests with different flow rate profiles: some results are shown in this paper. The comparison of the results obtained using different types of systems for the realization of dynamic flow profiles, showed that the system realized by INRIM, with injectors, has achieved better results than the other methods [21,22]. This is a consequence of the fast response time of the injectors and their extremely high repeatability in the timing control, which cannot be achieved with the other systems that use for example sonic nozzles with valves or piston devices. However, at present, the system is limited to the maximum flow rate of approximately 30 kg/h.

The main objectives of the tests were to verify:

- the response of the flow meters with different profiles, comparing the results obtained with constant flow rate;
- The agreement among the actual profile produced by the injector and the target one.

All profiles were generated with a timing of $\Delta T = 100$ ms, so the function generated is discrete and is represented by a series of flow rate values $Q_{\mathrm{prof},\,i}$, with $i = 1..n$, where $n = T/\Delta T$ and T defines the duration of the test. During the tests, the instantaneous flow rates Q_j at the time t_j, recorded by the analog output of the flow meter, were acquired with a timing of $\Delta t = 20$ ms.

Initially the flow meter is calibrated at constant flow rate, determining the relative error of the flow meter E_{DUT} for different flow rates:

$$E_{\mathrm{DUT}} = \frac{m_{\mathrm{DUT}} - m_{\mathrm{REF}}}{m_{\mathrm{REF}}} \tag{2}$$

where m_{DUT} is the mass totalized by the flow meter and m_{REF} is the reference value determined from the balance over the duration of the test.

For the dynamic calibration, the profile with variable flow rates of a defined duration is generated, and the parameters analyzed have been:

1) The relative dynamic error E'_{DUT} of each test, as defined in equation (2), which provides an estimate of the dynamic response of the flow meter.
2) The relative error E_{REF} determined by:

$$E_{\mathrm{REF}} = \frac{m_{\mathrm{REF}} - m_{\mathrm{PROF}}}{m_{\mathrm{PROF}}} \tag{3}$$

which provides an estimate of the goodness of the flow profile generation, where m_{REF} is the mass determined by the balance, and m_{PROF} the reference mass calculated from the reference profile, determined by the integral of the theoretical flow rate profile defined from the values $Q_{\mathrm{prof},i}$. The authors are aware that E_{REF} is not a rigorous estimate of goodness of the flow profile generation, since, being based on the total mass generated, there is certainly some compensation for errors in the generated profile, in the sense that errors in defect in the upward flow rate phases could be compensated for by errors in excess in the downward flow rate phases. However, by running tests with different profiles, a reasonable estimate of the goodness of the flow profile generation can be obtained.

Both the uncertainties $u(E'_{\mathrm{DUT}})$ and $u(E_{\mathrm{REF}})$ depend on the uncertainty $u(m_{\mathrm{REF}})$, which depends on the flow profile generation method. The description of the evaluation is given in section 5.1. The uncertainty contribution $u(m_{\mathrm{DUT}})$ is evaluated by the resolution r of the output pulse generation of the flow meter $(r/2\sqrt{3})$. Since the value m_{PROF} is the reference value, the associated uncertainty is null.

3) The estimation of errors $E_{Q,j}$ is carried out evaluating the response delay Δd, between the reference flow rate $Q_{\mathrm{prof},j}$ and the recorded flow rate Q_j, so that $k = \Delta d/\Delta t$. The errors $E_{Q,j}$ of the instantaneous measured flow rate Q_j, at the time t_j, determined by:

$$E_{Q,j} = Q_j - Q_{\mathrm{prof},j+k} \tag{4}$$

from which the mean value E_Q of the values $E_{Q,j}$ and the associated standard deviation $s(E_Q)$ are determined.

In general, the value Δd depends on effects due to the flow meter under test and partly also on the generation method used, the hydraulic circuit, and the acquisition of the flow rates Q_j. Regarding the flow meter, the delay may be due to the type of measuring principle used and also to the necessary filters used on the signal of the sensor. Other delays are due to the flow rate calculation and the subsequent generation of the output signal. These delays consist of a constant part depending on the data process and a variable part depending on the frequency spectrum of the measured flow rate, the latter being certainly less significant.

By testing different flow meters, it was observed that this delay Δd is highly dependent on the type of flow meter, differences can exceed times of 0.5 s. In addition, as this delay depends on many factors, it is complicated to estimate the different contributions to the delay value Δd. As a first approximation, the results shown were determined by considering the Δd value constant for the whole duration of the test, the value was determined so as to obtain the minimum value of $s(E_Q)$.

5.1. Uncertainty ofm_{REF}

The uncertainty of the reference value $u(m_{\mathrm{REF}})$ depends on the response of the injectors used to generate the flow profile and the method used to calibrate them.

In the case where the injectors are calibrated by means of the flow meter, which is the method used in the tests shown, the uncertainty contributions are:

- Uncertainty calibration of the flow meter at constant flow rate (u_{FCAL}).

The errors E_{DUT} are used to correct the analog output, the associated uncertainties $u(E_{\mathrm{DUT}})$ are therefore considered. An additional uncertainty is also considered as the errors are not constant over the entire flow rate range, and it is therefore necessary to interpolate the error values.

- Uncertainty of the analog output (u_{AN}).

The injector calibration curve that provides the duty cycle values as a function of flow rates is obtained from the analogue output. The uncertainty u_{AN} considers the stability of the analogue output of the flow meter, but also that of the acquisition card.

- Uncertainty of the calibration curve of the injectors (u_{ICAL}).

Injector calibration curves are obtained by fitting the values of flow rate and duty cycle. This uncertainty considers the uncertainty of the fit and its repeatability.

Since, as described in the previous sections, the conditions of use of the injectors do not correspond exactly to those of calibration, the following additional contributions of uncertainty must be taken into account:

- Uncertainty due to the temperature and pressure of the fluid (u_{F}).

The injectors are calibrated with constant duty cycles and the fluid temperature and pressure are constant. In the profile generation the temperature and pressure are no longer perfectly constant, and no corrections are applied to the calibration curves, so that additional uncertainties are taken into account, in particular for the variations of Δp and ρ of Equation (1).

- Uncertainty due to the self-heating of injectors (u_{SH}).

Since the calibration of the injectors is performed at a constant duty cycle, the injector temperature is constant. When used for the profile generation, as described in Section 2, the self-heating of the injector causes a change in the injector response. An uncertainty is taken into account for this effect.

From the above contributions, the overall calibration uncertainty of the flow rate due to the injectors $u_{\mathrm{I}}(Q_{\mathrm{prof}})$ is determined as:

$$u_{\mathrm{I}}(Q_{\mathrm{prof}}) = \sqrt{u_{\mathrm{FCAL}}^2 + u_{\mathrm{AN}}^2 + u_{\mathrm{ICAL}}^2 + u_{\mathrm{F}}^2 + u_{\mathrm{SH}}^2} \tag{5}$$

Associating with each flow rate $Q_{\mathrm{prof},i}$ value of the profile to be generated is the corresponding calibration uncertainty $u_{\mathrm{I}}(Q_{\mathrm{prof},i})$. The total uncertainty of the mass totalized in the test, associated to the injectors, u_{IT}, can be obtained as mean of the values $u_{\mathrm{I}}(Q_{\mathrm{prof},i})$ (neglecting the uncertainty of the test time).

The uncertainty of the totalized reference mass $u(m_{\mathrm{REF}})$ also depends on contributions that are not related to the calibration of the injectors:

- Delays due to injector opening and closing times (u_{D}).

The delays limit the dynamic response of the injectors. It follows that an uncertainty has to be considered in relation to the frequency spectrum of the profile to be realized. This value was experimentally evaluated so that the error value E_{REF} was consistent with its associated expanded uncertainty $U(E_{\mathrm{REF}})$.

- Weighing uncertainty (u_{W}).

The total mass of each test is measured using a balance. The main contribution depends on the synchronization of the diverter with the test time duration and the dripping at the end of the test.

- Repeatability uncertainty (u_{R}).

The uncertainty u_{R} is determined by the standard deviation s of the error E_{REF} obtained by repeating the test several times.

In conclusion, the uncertainty $u(m_{\mathrm{REF}})$ is given by

$$u(m_{\mathrm{REF}}) = \sqrt{u_{\mathrm{IT}}^2 + u_{\mathrm{D}}^2 + u_{\mathrm{W}}^2 + u_{\mathrm{R}}^2} \tag{6}$$

6. Test profiles and results

The results presented are related to four different profiles:

- The profile “Car n1”, which was used in the comparison carried out in activity A4.1.3 of the EMPIR SAFEST, representing a flow rate profile obtained in WTLP tests [20], with variations up to about 4 kg/h.
- Two sine wave profiles, where the amplitude of the variation is between 1 kg/h to 5 kg/h with frequencies of 0.1 Hz and 0.3 Hz.
- One sawtooth profile, where the amplitude of the variation is between 0 kg/h to 5 kg/h with a ramp duration of 18 s.

The profiles are shown in Figs. 8, 9 and 10. The values of m_{PROF} and the duration T for the four profiles are shown in Table 1.

A Siemens Coriolis flow meter DN 1.5, with measurement range of 0–30 kg/h was used to perform the tests with all four profiles. In the tests, the pulse digital output and the 4–20 mA analogue output were acquired to record the total mass m_{DUT} and the instantaneous flow rate Q_j, respectively. As the digital output was set at 2 mg/pulse, the uncertainty $u(m_{\mathrm{DUT}})$ is negligible for all profiles. The tests were carried out with an upstream pressure of 0.4 MPa and at a temperature of about 23 °C. Test results were obtained with 5 repetitions.

6.1. Results at constant flow rate

At constant flow rate the results for the relative error E_{DUT}, obtained with pulse digital output, are shown in Fig. 7, where the error bars are the expanded uncertainties. The calibration uncertainty $u(E_{\mathrm{DUT}})$ ranges

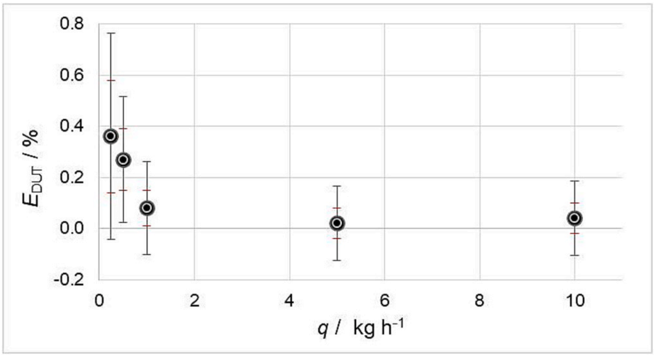


Fig. 7. Results of the flow meter calibration at constant flow rate from 0.2 kg/h to 10 kg/h. Error bars in red are the expanded uncertainty $U(E_{\mathrm{DUT}}) = 2u(E_{\mathrm{DUT}})$, and error bars in black are the expanded uncertainty $U_I(Q_{\mathrm{prof}}) = 2u_I(Q_{\mathrm{prof}})$.

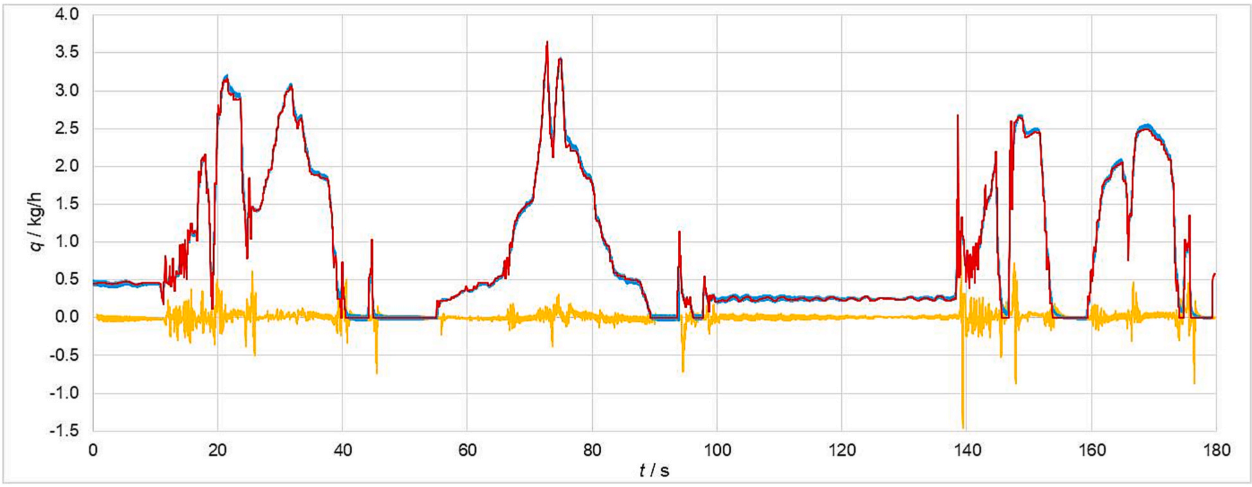


Fig. 8. Flow rate for “Car 1” profile: reference profile (red line), measurements (blue line) and residuals (yellow line).

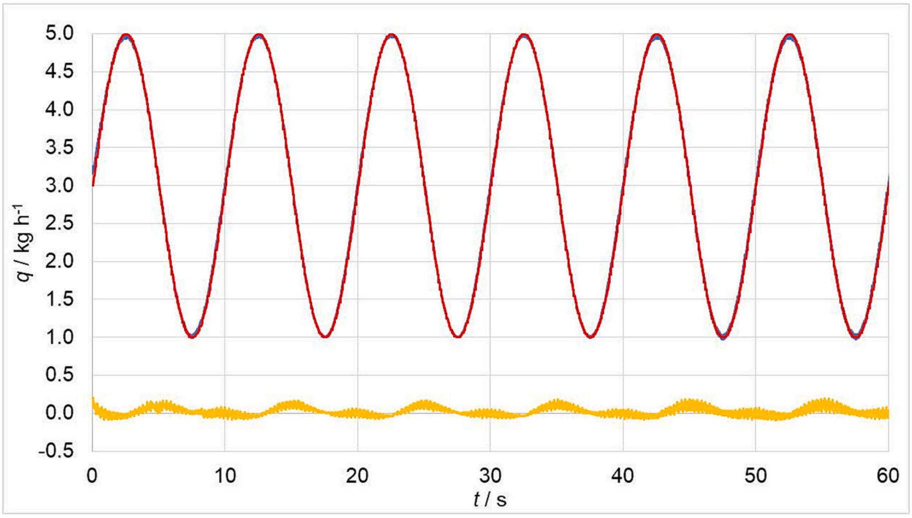


Fig. 9. Flow rate for “Sine 0.1 Hz” profile: reference profile (red line), measurements (blue line), and residuals (yellow line). For reason of visual clarity the plot reports only 60 s.

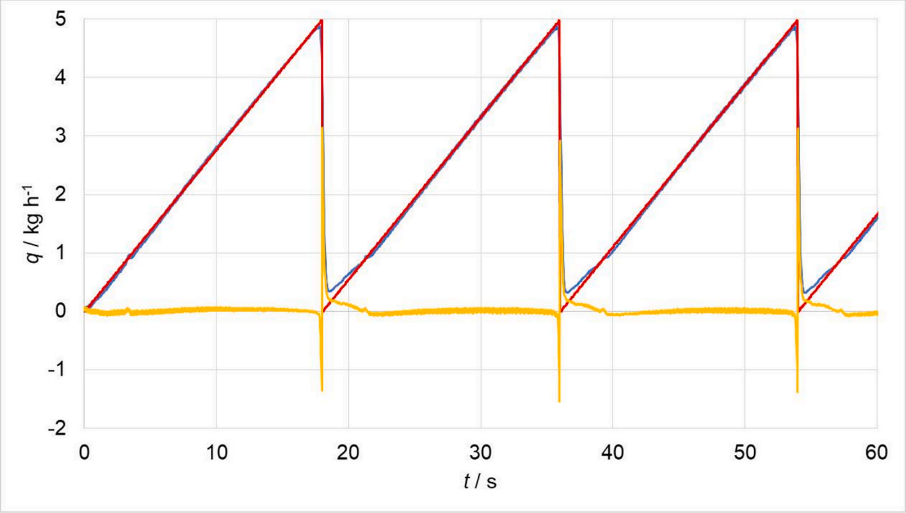


Fig. 10. Flow rate for “Sawtooth” profile: reference profile (red line), measurements (blue line) and residuals (yellow line).

Table 1
Definition of profiles with values of total reference mass m_{PROF} and test time T.

Profile	m_{PROF}/ g	T / s
Car 1	43.55	179.81
Sine 0.1 Hz	147.68	175.01
Sine 0.3 Hz	146.50	175.01
Sawtooth	124.17	180.01

from 0.11 % to 0.03 %, considering the interpolation, the uncertainty u_{FCAL} ranges between 0.04 % and 0.02 %.

The analogue output was adjusted so that the value was aligned with the flow rate value obtained from the pulse digital output. Thus, at the same flow rate, the error of the analogue output can be considered similar to that calculated with the pulse output. However, to account for the adjustment and the repeatability of the analogue output, the uncertainty of the analogue flow rate was $u_{\mathrm{AN}} = 0.05$ %, and the contribution u_{ICAL} was estimated between 0.04 % and 0.03 %. The contribution for u_{F} depends on the different conditions of the fluid during calibration and using of the injectors and also on the stability on the working condition. Considering that the pressure variations are within 0.003 MPa and the temperature variations are within 0.5 °C, which have effects on the density, from Equation (1) the value $u_{\mathrm{F}} = 0.02$ % was estimated. As described in Section 2, the contribution for u_{SH} is more significant for the very low value of the duty cycle. From the experimental measurements, it was observed that the maximum current variation during the test was less than 10 mA, according to section 2 could produce an injection time variation of less than 5 µs. The contribution for u_{SH} was estimated to be variable from 0.15 % at 0.2 kg/h to 0.02 % at 10 kg/h. From Equation (5), the values for $u_{\mathrm{I}}(Q_{\mathrm{prof}})$ ranges from 0.2 % to 0.08 %, the values are shown in Fig. 7. The contribution associated to the weighing uncertainty was$u_{\mathrm{W}} = 0.035$ g.

6.2. Results under dynamic conditions

The results obtained for the dynamic profiles introduced in Section 6 are following analyzed. For all profiles, it was observed that the delay Δd was approximately between 540 ms and 560 ms. After this correction due to the shift, the errors $E_{Q,j}$ were evaluated.

Profile "Car 1".

For "Car 1" profile, $u_{\mathrm{IT}} = 0.12$ % and, as $m_{\mathrm{PROF}} = 43.55$ g, the relative contribution for the weighing is $u_{\mathrm{W}} = 0.08$ %. This profile presents considerable flow variations, so the uncertainty due to the dynamic response of the injectors was$u_{\mathrm{D}} = 0.1$ %, and the repeatability of E_{REF} was$u_{\mathrm{R}} = 0.15$ %, it therefore results that $U(m_{\mathrm{REF}}) = 0.40$ %. For this test, the u_{R} and u_{W} contributions are not so negligible due to the small totalized mass, thus for profiles with quantities above 100 g would be less than 0.3 %.

Fig. 8 shows an example of the errors $E_{Q,j}$ detected, it can be seen that the negative errors are more pronounced, which is due to the fact that the injectors are unable to generate extreme peaks or that the analogue output is damped and cannot measure the extreme changes in flow rate. The results obtained are shown in Table 2. The measured total mass is quite consistent with the theoretical one, $E_{\mathrm{REF}} = 0.44$ % and $U(E_{\mathrm{REF}}) = 0.40$ %.

Considering the errors E_{DUT}, obtained in the constant flow rate calibration, according to the reference profile the error should have been 0.02 % with an expanded uncertainty of 0.11 %, as $E'_{\mathrm{DUT}} = 0.2$ %, the difference between static and dynamic calibration is therefore approximately 0.2 %.

Profile "Sine 0.1 Hz" and "Sine 0.3 Hz".

For the two sine profiles $u_{\mathrm{IT}} = 0.08$ %, as approximately $m_{\mathrm{PROF}} = 147$ g the relative contribution for the weighing is $u_{\mathrm{W}} = 0.03$ %. For these profiles the flow rate variations are quite smooth, the uncertainty due to the dynamic response of the injector is $u_{\mathrm{D}} = 0.025$ % at 0.1 Hz and 0.05 % at 0.3 Hz. As a result $U(m_{\mathrm{REF}}) = 0.23$ % at 0.1 Hz and$U(m_{\mathrm{REF}}) = 0.25$ % at 0.3 Hz.

Fig. 9 shows an example of the errors $E_{Q,j}$ detected. The results obtained are shown in Table 3 and 4. As expected, increasing the frequency an increase of the standard deviation of the residuals is noted. The time shift of the residual is likely to be due to the volumes upstream and downstream the injectors. Their sizing is the result of a trade-off between the required dynamic response of the system and the stability during constant flow operation. The measured total mass is consistent with the theoretical one, E_{REF} is about -0.1 % and $U(E_{\mathrm{REF}}) = 0.25$ %, for both the profiles.

For both the profiles, considering the errors E_{DUT} obtained in the constant flow rate calibration, the error should have been 0.02 % with an expanded uncertainty of 0.10 %. Since E'_{DUT} is between 0.10 % and 0.16 %, the difference between static and dynamic calibration is therefore less than the case of the "Car 1" profile. However, as in "Car 1", the dynamic error is higher than the one would be obtained by considering only the static calibration. It is also noted that compared to the "Car 1" profile the repeatability of the dynamic error E'_{DUT} is significantly improved (less than 0.03 %), which demonstrates the excellent accuracy of the injectors control.

Profile "Sawtooth".

For the "Sawtooth" profile $u_{\mathrm{IT}} = 0.09$ %, as approximately $m_{\mathrm{PROF}} = 124$ g the relative contribution for the weighing is $u_{\mathrm{W}} = 0.03$ %. For this profile for the uncertainty due to the dynamic response of the injector a contribution $u_{\mathrm{D}} = 0.075$ % was associated. Therefore the uncertainty results $U(m_{\mathrm{REF}}) = 0.33$ %. The measured total mass is consistent with the theoretical one, $E_{\mathrm{REF}} = 0.26$ % and $U(E_{\mathrm{REF}}) = 0.33$ %. The results are summarized in Table 5.

As with the "Car 1" profile, there is an increase in the error E_{REF}, this is probably due to the fact that for both the "Car 1" and "Sawtooth" profiles there are extreme variations in flow rate, so the injectors have more difficulty generating the profile, particularly during the closing phases.

Fig. 10 shows that the measurement (blue line) is unable to accurately reproduce the falling edge of the sawtooth waveform (red line). The spike of the residuals (yellow line) is due to flow rate inertia (depending on the volume of liquid between the injectors and the sensor) and also to the analogue flow rate output of the flow meter, which are normally filtered to dampen the noise of the measurement. For this reason there are positive peaks on the errors E_Q (yellow line of Fig. 10), corresponding to the zero flow rate. This effect is also clear by considering the value of E_{REF} which is higher than the values obtained for the other profiles.

Considering the errors E_{DUT}, obtained in the constant flow rate calibration, according to the reference profile, the error should have been 0.06 % with an expanded uncertainty of 0.11 %. In contrast to the results obtained in the other tests, the dynamic calibration error is negative $E'_{\mathrm{DUT}} = -0.17$ %, and the difference from previous values is up to about 0.4 %, which exceeds the expanded uncertainty. This effect could be due to a different response of the flow meter caused by the

Table 2
Results obtained with profile "Car 1", mean values and standard deviation s are shown.

	m_{DUT}/ g	m_{REF}/ g	T/s	E'_{DUT}/ %	$U(E'_{\mathrm{DUT}})$/ %	E_{REF}/ %	$U(E_{\mathrm{REF}})$ / %	E_Q/kg h^{-1}	$s(E_Q)$/ kg h^{-1}
Mean value	43.826	43.740	179.812	0.20	0.40	0.44	0.40	0.007	0.08
S	0.071	0.105	0.001	0.12		0.15		0.001	

Table 3
Results obtained with profile “Sine 0.1 Hz”, mean values and standard deviation *s* are shown.

	m_{DUT}/ g	m_{REF} / g	T / s	E'_{DUT}/ %	$U(E'_{\mathrm{DUT}})$ / %	E_{REF}/ %	$U(E_{\mathrm{REF}})$ / %	E_Q/kg h^{-1}	$s(E_Q)$/ kg h^{-1}
Mean value	147.830	147.587	175.013	0.16	0.23	−0.06	0.23	0.020	0.05
S	0.080	0.119	0.003	0.02		0.08		0.002	

Table 4
Results obtained with profile “Sine 0.3 Hz”, mean values and standard deviation *s* are shown.

	m_{DUT}/ g	m_{REF}/ g	T / s	E'_{DUT}/ %	$U(E'_{\mathrm{DUT}})$ / %	E_{REF}/ %	$U(E_{\mathrm{REF}})$ / %	E_Q/kg h^{-1}	$s(E_Q)$/ kg h^{-1}
Mean value	146.499	146.359	175.010	0.10	0.25	−0.10	0.25	0.048	0.17
S	0.114	0.097	0.001	0.03		0.07		0.003	

Table 5
Results obtained with profile “Sawtooth”, mean values and standard deviation *s* are shown.

	m_{DUT}/ g	m_{REF}/ g	T / s	E'_{DUT}/ %	$U(E'_{\mathrm{DUT}})$ / %	E_{REF}/ %	$U(E_{\mathrm{REF}})$ / %	E_Q/kg h^{-1}	$s(E_Q)$/ kg h^{-1}
Mean value	124.278	124.490	180.010	−0.17	0.33	0.26	0.33	0.025	0.22
s	0.037	0.175	0.001	0.12		0.12		0.005	

falling edge of the sawtooth. This behavior deserves future investigation.

7. Conclusions

A new method for the realization of variable flow rate profiles for the dynamic calibration of flow meters was presented. The method is based on the calibration of injectors, which in turn are used to generate reference flow rates. The method provides traceable reference standard profiles, to which an uncertainty is associated. The evaluation method is described. Thanks to the fast response time of the injectors and the excellent control accuracy, the results obtained are better than other systems that use for example sonic nozzles with valves or piston devices. Examples of calibration with different flow rate profiles were presented. The analyzed profiles were a typical flow rate profile of WTLP tests, two sine waves with different frequency, and a sawtooth waveform. The uncertainty achieved is about 0.3 % independently of the profile realized, with test repeatability values less than 0.05 %. Performing tests on a Coriolis type flow meter with different flow rate profiles, it was shown that the results of dynamic calibration are different from static calibration and also depend on the type of flow rate profile. At present the method is implemented with a calibration bench, specifically equipped with four injectors, able to obtain flow rates up to 30 kg/h. Future developments will aim to extend the flow rate range and improve the uncertainty, for example through the use of piezoelectric type injectors, which are less affected by temperature variations due to self-heating compared to injectors with solenoids.

CRediT authorship contribution statement

Raffaella Romeo: Writing – original draft, Investigation, Data curation, Conceptualization. **Lucio Postrioti:** Writing – review & editing, Methodology, Conceptualization. **Davide Torchio:** Methodology, Investigation. **Manuel Martino:** Methodology, Conceptualization. **Andrea Malengo:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Formal analysis, Conceptualization.

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.

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Data availability

Data will be made available on request.

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