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Turbine flowmeter response to transitional flow regimes

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ABSTRACT

In this paper, acceleration and deceleration performance of turbine flowmeters was investigated in transitional flow regimes. Different flow meters and peak gas flow rates were used, with a step flow transition induced by rapid closing and reopening of the pipeline valve. Hotwire anemometry was employed as a reference method to assess the dynamic response of turbine flowmeters. Results of this study suggest a good dynamic response of turbine flowmeters in accelerating flows, with only a slight delay of the turbine rotation. However, in decelerating flows, the response of the flowmeter turbine was found to be slow, with characteristic time constants up to 35 s and large resulting over-registration of transferred gas volume. Our findings were quantified by multiple regression models for flowmeter response times and over-registered volumes, which were both find to drop with Reynolds number and increase with the flowmeter size. Understanding dynamic response is essential to evaluate dynamic errors and evaluate overall measurement uncertainty.

1. Introduction

Despite the constant development of novel flow measurement methods, the turbine-type meters remain widely used in volume measurement of natural gas due to their accuracy and reliability. A well calibrated and properly installed turbine flow meter is capable of measurements with less that ± 0.25% error (Tang [1]). Several publications have so far dealt with turbine flowmeter calibration and measurement uncertainty analysis (Van der Grinten [2], Ruiz et al. [3], Nerijus et al. [4]), as well as with numerical modeling of the flowmeter operation (Osiadacz and Witos [5], Guo et al. [6]).

The majority of existing studies was focused on steady-state operation of the flowmeter where the flow rate of gas is constant or changes at a very slow rate. While such a uniform transport of natural gas is certainly desired, flow conditions in the pipelines are often far from constant due to fluctuations in gas supply and demand, which are closely linked to unpredictable environmental conditions (Geršak et al. [7]). The two main types of time dependent flows are pulsating and intermittent flows (Cascetta and Rotondo [8]), but the actual gas flow may be a combination of both, especially over longer periods of time. Pulsating flows are typically generated by pulsating devices such as compressors and regulators and are characterized by harmonic oscillations of the gas flow rate about its mean value, constantly resulting in excessive volume readouts by gas meter, known as over-registration or overestimation (Lee et al. [9]). The effect of flow pulsations on the measurement uncertainty of turbine flowmeters was investigated and modeled by Cheesewright et al. [10] and Lee et al. [9] as a function of pulsation frequency and amplitude, as well as flow meter size and flow rate. As shown by Stoltenkamp et al. [11], acoustic perturbations (e.g. due to standing waves in the system) may also cause substantial oscillations of the gas flow rate, leading to significant measurement errors due to the poor dynamic response of turbine flowmeters.

The effect of pulsating flow disturbances can be partly reduced by a proper installation of the flowmeter, including a sufficient length of straight pipe sections and the application of flow settling devices such as tube bundles and flow conditioning plates (Mattingley and Yeh [12], Miller [13]). However, even a properly installed turbine flow meter will still be affected by intermittent flow transitions, which cannot be sufficiently reduced in the system. These are mostly induced by quick changes in the flow rate of gas, usually due to opening or closing of a pipeline valve or sudden changes in gas demand. The rotational speed of a flowmeter turbine typically follows the flow acceleration well, but exhibits a significant delay when slowing in a decelerating flow (Cascetta and Rotondo [8], Tonkonogij et al. [14], Tonkonogij and Tonkonogovas [15]) resulting in over-registration of gas volume. Despite the exponential reduction of the turbine rotational speed [14,15], the meter response duration may be relatively long compared to the duration of the flow transition (especially if the flow is completely stopped), leading to significant over-registration of gas volume. According to Cascetta and Rotondo [8], a typical medium-sized turbine flowmeter may experience as much as 10,000 on/off cycles or other significant step changes in flow rate per year, consequently

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overestimating the gas volume by more than 1%. In [14] and [15], response characteristics and corresponding dynamic measurement errors of turbine gas meters are discussed in dimensionless form.

The flow rate variability presents an additional source of measurement uncertainty in operation of turbine flowmeters besides the measurement uncertainty in steady flows. During exploitation of a gas distribution system, flow disturbances can cause a significant dynamic error in the registered volume of natural gas. This is becoming an increasingly important issue due to the increasing natural gas prices and consumption as well as more rigorous gas metering regulations. Therefore, the present paper aims to assess the effect of transitional flow phenomena on the dynamic measurement error of turbine flowmeters. The error (i.e over-registered gas volume) will be presented as a function of flow meter size, flow rate and duration of the intermittent step flow disturbance.

2. Experimental methodology

2.1. Experimental set-up

Experimental work presented in this paper was performed at the Laboratory for testing and calibration of gas meters at the company Sarajevogas in Sarajevo, Bosnia and Herzegovina. The laboratory is situated in the Institute SAGALAB officially designated by the National Institute of Metrology of Bosnia and Herzegovina and has successfully participated on EURAMET project 1296 of inter-laboratory calibration comparison in the range of flow rates from 20 m^3/h to 1000 m^3/h, having approved calibration and measurement capabilities.

SAGALAB facility operates on the master meter principle where the meter under test (transfer standard) is located downstream from the standard meters. Ambient air is sucked by a blower and the flow rate is adjusted by regulation of the blower and electromotive valve. Testing procedure is software controlled.

Characteristics of the SAGALAB facility:

Range of flow rates:	(0.5–4000) m^3/h
Operating temperature:	(21 ± 2) °C
Operating pressure:	Atmospheric conditions
Measurement uncertainty (k = 2):	0.31%

Intermittent flow performance of three different turbine flowmeters was evaluated in a specially adapted test rig – consider measurement setup shown in Fig. 1. The test installation consisted of an open pipeline filled with air (at 1 bar absolute pressure and approximately 20 °C temperature), a centrifugal blower for producing the desired volumetric flow rate Q, a turbine flowmeter to be tested, and a valve behind the inlet flow straightener. Each of the three different flowmeters to be tested (G250, G1000 and G2500) required a pipeline with a different size (DN80, DN200 and DN300, respectively), to which the same flow measurement equipment was installed prior to the start of the particular set of experiments. During the measurements, the air flow was first stabilized at the desired nominal value Q. The pipeline valve was then rapidly closed and later (after approximately one minute) reopened to induce an intermittent step disturbance of flow deceleration and acceleration, respectively.

Table 1
Turbine flowmeters used in experiments. Ranges of Q and Re are provided for unrestricted flow (fully opened valve).

#	Type	D (m)	$Q_{\max}$ (m^3/h)	Q range (m^3/h)	Re range ($\cdot 10^3$)
1	G250	0.1	400	50–250	11.8–58.9
2	G1000	0.2	1600	300–1100	35.4–130
3	G2500	0.25	4000	1100–3000	104–283

Flow rate, i.e. rotational speed of the flowmeter turbine was measured by a high frequency (HF) pulse signal $p(t)$, for flowmeters of three different sizes (diameter D, Table 1) with respective maximum flow rates $Q_{\max}$ (basically, the volume of gas flown through the meter is proportional to the number of pulses). Additionally, the velocity of circulating air at the pipe centerline was measured by a hotwire (HW) anemometer (Dantec MiniCTA 55P11 [16]) as a measure of the instantaneous air flow rate. The main advantage of HW anemometry is its very good dynamic response to changing flow conditions, making it well suited for evaluation of other methods' performance in transitional flows. Both the flowmeter signal and the HW anemometer signal were sampled at 5000 Hz and acquired to a computer using National Instruments measurement cards and LabVIEW software.

2.2. Calculation of experimental variables

In the first step in the post processing of measurement data, turbine rotational speed ω (unit: Hz) was calculated from the pulse signal $p(t)$ as $\omega(t) = 1/\Delta t(t)$, where Δt is the time between neighboring peaks of $p(t)$ at time t. Then, the normalized rotational speed was calculated as $\omega_{\mathrm{n}} = \omega/\omega_{\max}$, where $\omega_{\max}$ is the value of ω at nominal (100%) gas flow rate. Besides, the centerline flow velocity v was calculated from the hotwire voltage signal $U(t)$ by equation $v = (U^2/0.741–2.651)^{2.036}$, which was obtained from HW calibration data.

For the purpose of comparison to the turbine rotational speed, HW-measured velocity was also normalized as $v_{\mathrm{n}} = v/v_{\mathrm{m}}$. However, due to the fact that the HW signal exhibited significant turbulence-induced oscillations, the signal v(t) was smoothed and down sampled to 100 Hz sampling rate. Then, v_{m} was computed as the time-averaged velocity after the flow rate through the meter has been fully resumed following the valve reopening. Finally, both ω_{n} and v_{n} were plotted as a function of time (a sample diagram is shown in Fig. 2). Note that since v_{n} was computed from measurements conducted at the pipe centerline, it is linearly proportional to the maximum flow velocity of a velocity profile, but not to the mean flow velocity $\overline{v} = Q/A$ (Q is the gas volumetric flow rate and A is the pipe cross-section area) as the profile shape changes with Reynolds number (Eq. (1)). In Eq. (1), ν_{a} is the kinematic viscosity of air.

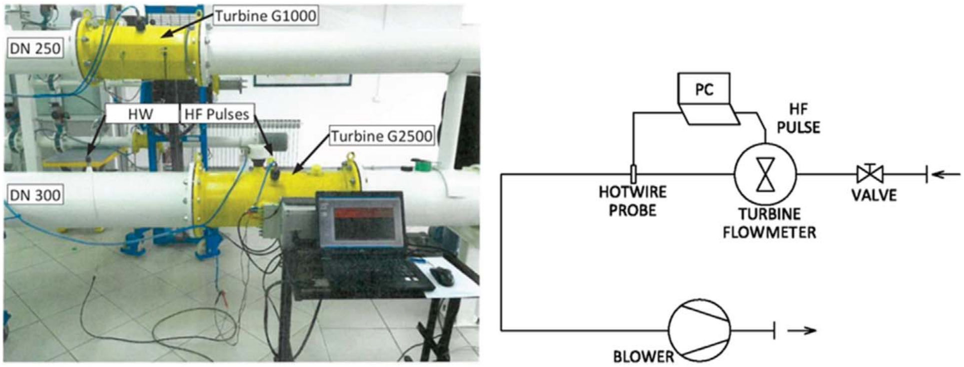

Fig. 1. Measurement setup for testing the turbine flowmeter dynamic response.