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TRACEABILITY OF GAS FLOW MEASUREMENTS IN COMPLEX DISTRIBUTION SYSTEMS – UNCERTAINTY APPROACH VS ERROR APPROACH

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Abstract

The objective of the paper is to analyse traceability issues in real-life gas flow measurements in complex distribution systems. The initial aim is to provide complete and traceable measurement results and calibration certificates of gas-flow meters, which correspond to specific installation conditions. Extensive work has been done to enable a more credible decision on how to deal in particular situations with the measurement uncertainty which is always subject of a flow meter's calibration as a quantitative parameter value obtained in laboratory, and with the qualitative statement about the error of an outdoor meter. The laboratory simulation of a complex, real-life distributed system has been designed to achieve the initial aim. As an extension of standardized procedures that refer to the laboratory conditions, the proposed methods introduce additional "installation-specific" error sources. These sources could be either corrected (if identified) or considered as an additional "installation-specific" uncertainty contribution otherwise. The analysis and the results of the experimental work will contribute to more precise and accurate measurement results, thus assuring proper measurements with a known/estimated uncertainty for a specific gas flow installation. Also, the analysis will improve the existing normative documents by here presented findings, as well as fair trade in one of the most important and growing energy consumption areas regarding the legal metrology aspects. These facts will enable comparing the entire quantity of gas at the input of a complex distributed system with the cumulative sum of all individual gas meters in a specific installation.

Keywords: calibration, energy efficiency, error analyses, measurement uncertainty, traceability.

1. Introduction

Traceability of measurement results provides information needed for reliable measurements of gas flow. Another important aspect is the accurate measurement of gas flow where the accuracy of a measurement method is described by trueness and precision [1]. The accurate measurement is an essential requirement given in Directives [2–4] and relevant for many applications. There are many issues affecting the accuracy of measurement, such as: comparability of measurement results of gas quantities of considerable values, demanding and sometimes not realistic requirements

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and expectations for uncertainties regarding required errors, difficulties in determining realistic measurement uncertainties for on-site flow-meters compared with those obtained in laboratories, and many others. There is still lack of knowledge concerning traceability of measurement results, as well as their contribution to measurement uncertainties and their exact influence.

It is necessary to continually explore the sources of measurement uncertainty to attain a better insight into the factors affecting the measurement process [5]. It will lead to an increased measurement uncertainty value. Underestimation of uncertainties might cause too much trust to be placed in the obtained results, with sometimes embarrassing or even disastrous consequences [6]. A number of international normative documents and standards define measurement procedures, analysis and evaluation of measurement uncertainty, means for establishing measurement traceability and on-site calibration of gas flow. However, additional considerable research is still necessary in order to improve the relevance of these documents in real-life applications regarding scientific, industrial and legal metrology aspects. The existing deficiency becomes obvious when certain assumptions or requirements of the written standards [7] and regulations [8–10] are analysed and compared taking into account feasible and realistic needs [4]. What can be done in such situations? Before providing an answer to this question, all results that could be corrected (based on calibration results) as well as the uncertainty budget of the measurement results (thorough evaluation of uncertainty sources/contributions) need to be identified. There are two different standardized approaches to the evaluation of uncertainty which will be outlined below. The collected results and considerations are strengthened through the analyses of these two approaches to evaluation of measurement uncertainty which should be taken into consideration when setting up a model of measurements. An instrument is usually calibrated for specified service conditions. Nevertheless, calibration of flow meters in the laboratory conditions does not match that in the real working conditions. Therefore, the calibration procedures as well as the final results should be reviewed from this point of view [11]. If calibration is performed in the laboratory conditions, then specific flow measurement and measurement results will be supported by referring the traceability to the International System of Units. There is a significant number of laboratories that deal with scientific, industrial and legal metrology requirements. But, on the other hand, there is a limited number of laboratories and bodies that are actively involved in both (industrial and legal) processes. Such laboratories would considerably strengthen their capabilities by merging these two processes. The metrological impact on the quality of generated results due to their dependence on instrument and installation should be constantly studied. Regarding this, the identification and characterization of the traceability issues in real-life gas measurements carried out in complex distribution systems in terms of "installation-specific" error sources is the main objective of this paper.

2. Zero hypothesis and practical background of research

The principal requirements and guidelines given by the directive [3] ("to ensure that final customers for natural gas are provided with individual meters that accurately reflect the final customer's actual energy consumption") and by the standard [5] ("to calibrate gas meters under real conditions") are set for real conditions but they can be satisfied only in ideal situations. By comparing the possibilities of the existing calibration/verification installations for flow meters with the requirements given by these relevant documents, the installation deficiencies and over-ambitious requests could be more evident. Learning about real-life cases can help recognize these deficiencies and assist in their elimination. The installations for calibration and verification of gas flow meters are very expensive and any change in the requirements may cause the necessity of their structural modifications.

Keeping in mind the number of points from production to the final consumer, where measurement of gas quantities is performed (see Fig. 1), the prescribed requirements are very important and they should be feasible for on-site measurements, but at the same time additional steps should be taken to make these requirements achievable in order to reduce deficiencies in installations for on-site measurements.

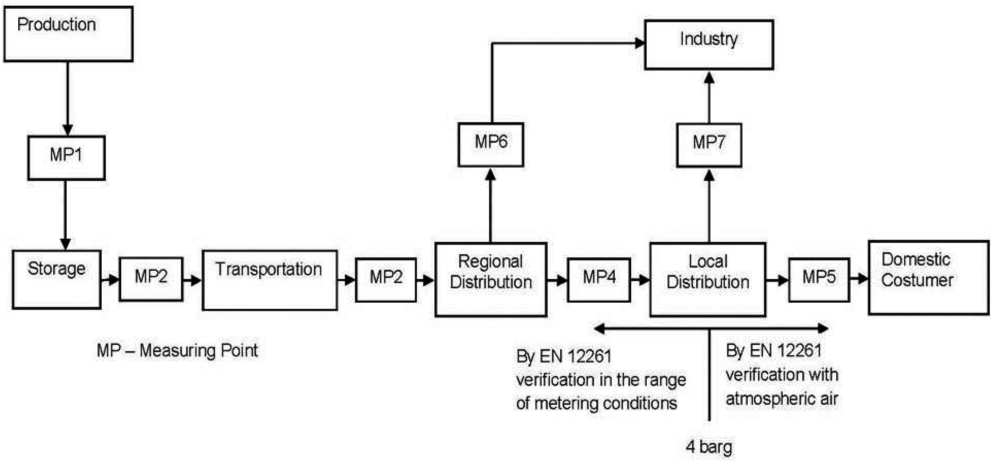

Fig. 1. Main measurement points of gas flow (quantities) from production to the final consumers.

How to make the correct judgment regarding measurement results obtained from identical meters using different procedures, installation approaches, working fluids, and working parameters is still the subject of research. Zero hypotheses in this paper state that more comprehensive and traceable measurement results and calibration certificates of gas flow meters, matching specific installation conditions, can be achieved and created. This statement can be proved by performing carefully controlled experiments that involve aspects of the real measurement parameters in given conditions that accurately reflect the empirical experience.

The concept of measurement uncertainty which is based on a theoretical definition in some cases is insuficient. Therefore, it is necessary to widen understanding of measurement uncertainty onto the measurement results assuming the total unawareness and/or inexperience of the measurement process declared in [12] as "degree of belief". It is imperative that estimation of all contributions that influence measurement results is correctly made. These contributions to flow measurements are, but not limited to, flow disturbances, flow profile, multicomponent flow, the impact of pulsation, stability in pressure and temperature, different coeficients, fluid density, viscosity, electrical conductivity, compressibility, thermodynamic expansion, pressure effects, and non-Newtonian features. These contributions are sometimes misinterpreted or neglected, which can lead to a wrong interpretation of the measurement results, especially in real measurement conditions.

When talking about gas flow meters in use, more problems arise. In practice, additional problems exist related to the usage of some flow meters for the purposes for which they are not intended or in any way planned to be used. It is important to understand the capabilities as well as the limits of gas flow meters in order to make the correct estimation of all contributions to the measurement uncertainty in real calibration conditions. If we consider this as an issue, then an additional problem is related to the classification of all contributions mentioned above into those that are random and those that are somehow accepted as systematic ones. If these concerns are tackled in detail and certain flow measurements are analysed, the number of unsolved problems of traceability of measuring results of flow measurements in a real calibration process will decrease.

The estimation of measurement uncertainty should be considered according to the number of defined influencing parameters (sources of uncertainty) and to the number of factors that can be mathematically formalized. The selection of an appropriate probability function and a numerical model is another challenge for real-life calibrations or a real calibration process. Because of all issues mentioned above, the measurement uncertainty of one meter used in real conditions will hardly meet the measurement uncertainty defined by the written standards for laboratory conditions.

The measurement uncertainty sources for laboratory conditions include: the method, calibration procedure, data acquisition and data processing [13]. The mentioned consideration is related to uncertainty and error in relation to the phenomena occurring during the gas flow measurements. The described uncertainty evaluation is a process which consumes time and resources, but the quality management standards are more and more inclined to the results accompanied with statements of uncertainty [14].

Many accredited laboratories and NMIs/DIs laboratories participate in *inter-laboratory comparison* (ILC) to prove their metrological competence. In ILC a method is evaluated for its repeatability in each of the laboratory conditions and for its reproducibility in inter-laboratory conditions. These ILCs are carried out according to the predetermined rules. These rules are usually predetermined for laboratory conditions [15] that do not correspond to real calibration conditions. This leads to new issues (measurement contributions) that have to be taken in account when estimating the measurement uncertainty for real calibration conditions. Many errors in gas flow measurements can be identified only by experts who are familiar with this measurement technique [16]. In order to remove this obstacle for less experienced people and in industrial applications, it is necessary for the reference documents to be updated regarding the flow measurements that prescribe calibration methods in line with the measurement uncertainty sources.

The GUM approach predicts uncertainty in the form of variance from the variance associated with inputs to the mathematical model. This implies that the input quantities are measured or assigned. The GUM method [6] is based on individual input quantities, and this method is sometimes called a bottom-up approach to uncertainty evaluation or simply "uncertainty approach". The Error method [1] uses the facts that the same influences vary in time, and in this case the observed variance is a direct estimate of the same uncertainty. This method focuses on the performance of the applied methods, and it is sometimes called a top-down approach or "error approach". The estimates of uncertainty obtained with these two methods are different because of many reasons. If it is known that a system being evaluated is behaving within reasonable limits with no significant outliers, making the variance of measurement a representative form for the uncertainty expression, then the Error approach [1] is more suitable. The instrument is considered as a "black box". In this paper the Error approach is recognized as more suitable for real calibration conditions of gas flow meters, particularly because of the presence of unknown effects which can influence the measurement uncertainty (random error in reproducibility conditions), and the reproducibility conditions. This means that the measurement uncertainty will depend on the reproducibility conditions or, in other words, the Error approach gives a better assessment of the behaviour of gas flow measurement system and the measurement uncertainty for real calibration conditions.

In addition, these findings will launch changes in other aspects regarding flow measurement, such as legal metrological requirements related to fair trade and consumer protection.

3. Applied research methods and results

This paper presents and gives insight to one practical example that deals with the agreement of the results of measurements performed with the standardized procedures given by the standards [12, 13]. In this case, the uncertainty (GUM) approach is used to calculate the measurement uncertainty for each particular gas meter [6]. The constructed setup was designed and used to simulate the complex part of real-life distributed system. The Error approach is used for the calculation of the measurement uncertainty of the constructed setup [1]. The measurements were performed in an internationally recognized laboratory that is equipped with the calibrated equipment with proved traceability and competences through ILC [15], [17], [18]. The first phase of research case (RC1) on-site gas meters (see Fig. 2) were calibrated according to the following program: a) Nine rotary meters G 25 [8] each were calibrated separately in 13 flows (0.6; 2.0; 6.0; 8.0; 10.0; 13.0; 16.0; 20.0; 24.0; 28.0; 32.0; 36.0; and 40.0 m^3/h). b) Three rotary meters G65 [8] each were calibrated separately in 13 flows (0.6; 5.0; 15.0; 20.0; 25.0; 32.5; 40.0: 50.0; 60.0; 70.0; 80.0; 90.0; and 100.0 m^3/h). c) One turbine meter G250 [7] was calibrated in 10 flows (20; 40; 80; 160; 240; 280; 320; 360; 400 m^3/h).

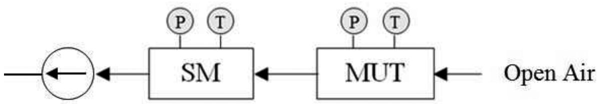

Fig. 2. First Phase of Research Case (RC1). SM – standard meter (Rotary gas meter G25, G40, G100, G160 and Turbine gas meter G250); MUT – meter under test (Rotary gas meters 9× G25 and 3× G65, One Turbine gas meter G250); P – Pressure meter; T – Thermometer.

RC1 was performed with air as the working fluid at ambient temperature and pressure atmospheric conditions. The absolute pressure and temperature of the meters were precisely measured. After reaching the stable flow, every single test lasted minimum 180 seconds. The tests for each of the calibration flows were repeated three times. The error of the meter under test was calculated after correction of volume indicated by the master meter to the pressure and temperature conditions of the meter under test. Standard meters used in RC1 were: Rotary gas meter G25, G40, G100, G160 and Turbine gas meter G250 and the range of flows was from 0.6 m^3/h to 400 m^3/h. The relevant ranges of applied flow, velocity and Reynolds numbers are given in Table 1.

Table 1. Flow data in RC1.

G (size)	DN (m)	Q_{min} (m^3/h)	Q_{max} (m^3/h)	KV (m^2/s)	V_{min} (m/s)	V_{max} (m/s)	Re_{min}	Re_{max}
25	0.04	0.6	40	0.0000149	0.13	8.85	356.2	23748.8
65	0.05	0.6	100	0.0000149	0.08	14.15	285.0	47497.6
250	0.10	40.0	400	0.0000149	1.42	14.15	9499.5	94995.2

Respective calibration curves for rotary and turbine gas flow meters are given in Figs. 3–5.

A non-standardized model of measurement system for real conditions has priority when developing a fit-for-purpose approach that, with certain approximations, can be transformed into the standard approach. The aim of this paper was to analyse accuracy of the non-standardized

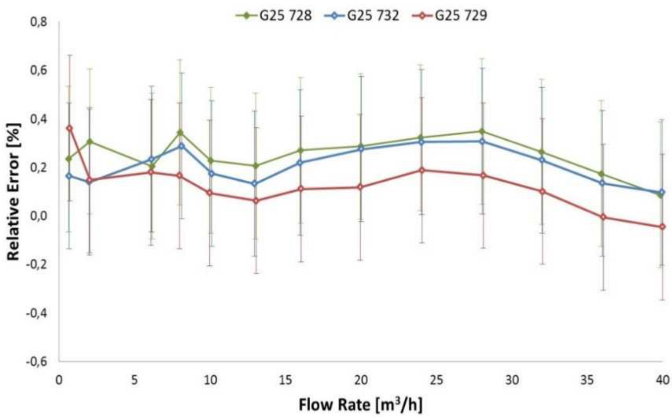

Fig. 3. Calibration of G25 728/ 732/ 729 (Standard conditions: 15°C and 1013.25 hPa).

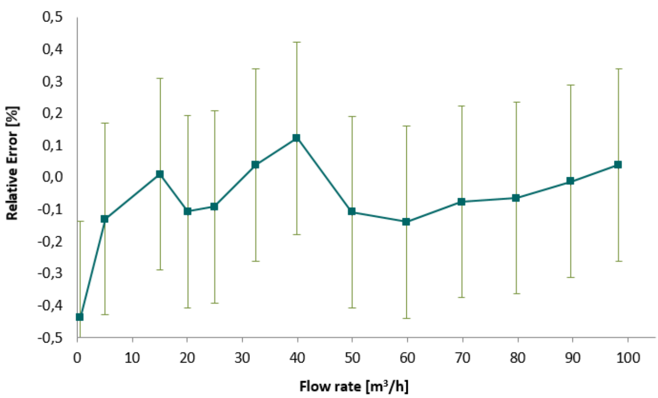

Fig. 4. Calibration of G65 390 (Standard conditions: 15°C and 1013.25 hPa).

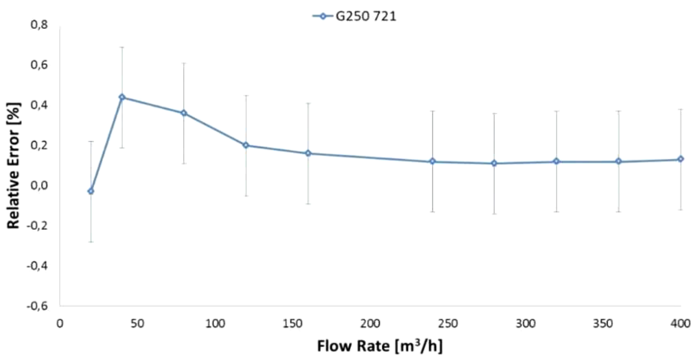

Fig. 5. Calibration of G250 721 (Standard conditions: 15°C and 1013.25 hPa).

model in gas flow measurement. The observed system was given as one real pipeline system which consists of a flow meter on one side and a set of flow meters on the other side (supply points) (see Fig. 6).

Table 2. Technical data of calibrated flow meters.

Producer	Model	Serial number	Type	Size [NO]	Q_{min} (m^3/h)	Q_{max} (m^3/h)	K-factor (pls/m^3)[3)]
Elster	G25	20520 728-09	IRM-3	40	0.6	40	10
Elster	G25	20520 732-09	IRM-3	40	0.6	40	10
Elster	G25	20520 729-09	IRM-3	40	0.6	40	10
Elster	G65	20520 390-10	IRM-3	50	0.6	100	10
Elster	G250	105 15 721	SM-RI-X	50	40	400	10

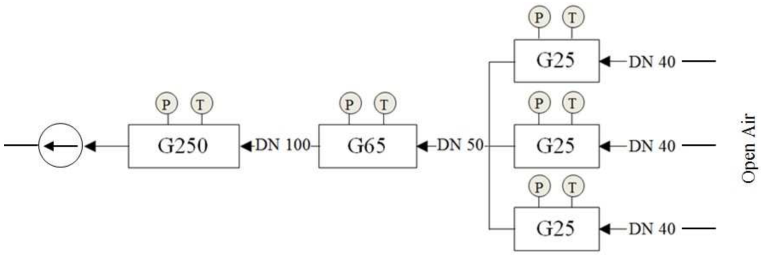

Fig. 6. Second Phase of Research Case (RC2). SM – standard meter (Rotary gas meter G25, G40, G100, G160 and Turbine gas meter G250); MUT – meter under test (Rotary gas meters 9× G25 and 3× G65, One Turbine gas meter G250); P – Pressure meter; T – Thermometer.

The second phase of research case (RC2) comprises analyses of accuracy of the non-standardized setup of meters. This system consists of one turbine meter G250 (High Frequency readout), one rotary meter G65 (Low Frequency readout), and a set of three rotary meters G25 (Low Frequency readout). The turbine meter G250 and the rotary meter G65 are connected in series, and they serve as the reference meters. Three rotary meters G25 are connected in parallel and they serve as the meters under test. They are also connected in series with the reference meters.

Three rotary meters G25 connected in parallel simultaneously measure 3 flows each (app: 8.33; 13.33; and 23.33 m^3/h) while in the same time one turbine meter G250 and one rotary meter G65 measure the quantity of total flow that passed through these three G25 meters, *i.e.* the sum of 3 flows (app: 25.0; 40.0; and 70.0 m^3/h). The relevant ranges of applied flows, velocities and Reynolds numbers are given in Table 3.

Table 3. Flow data in RC2.

G (size)	DN (m)	Q_{min} (m^3/h)	Q_{max} (m^3/h)	KV (m^2/s)	V_{min} (m/s)	V_{max} (m/s)	Re_{min}	Re_{max}
25	0.04	8.33	23.33	0.0000149	1.84	5.16	4,945.7	13,851.5
65	0.05	25.00	70.00	0.0000149	3.54	9.91	11,874.4	33,248.3
250	0.10	25.00	70.00	0.0000149	0.88	2.48	5,937.2	16,624.2

The measurements were done with three different sets. There were used nine G25 meters divided into three groups in combination with three G65 meters. The research results that came out from one set group are given in this paper. Air as the working fluid in this research case study was used in the laboratory operating conditions. The temperature and pressure of the employed meters were measured. Every single test lasted minimum 180 seconds. The measurements were repeated three times for each of steady calibration flows. Based on the performed measurements, the error was calculated after making all necessary corrections.

The volume was corrected based on the conditions (pressure and temperature), which correspond to the working conditions of network meters.

The laboratory calibrations of one set of three G25 gas flow meters with a *low frequency* (LF) readout signal that are connected in parallel and a serially connected reference G250 turbine gas meter with a *high frequency* (HF) readout signal provided the results with an uncertainty at the level of acceptance and with the error curve drifted in plus in favour of G250 for at least 0.2% of a given flow (see Fig. 7).

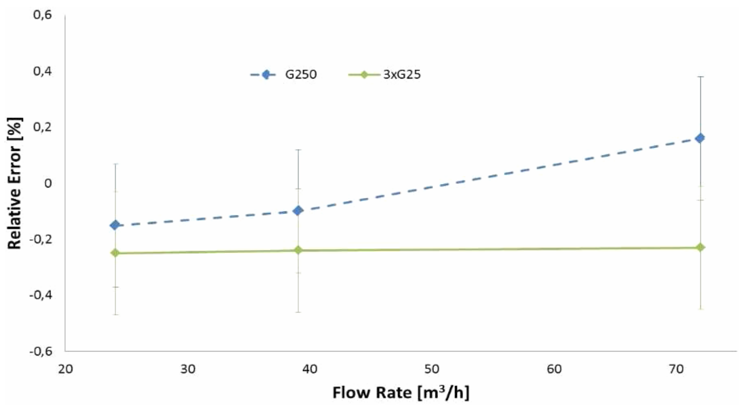

Fig. 7. Calibration of set of meters 3× G25 (LF) by G250 (HF): Dashed line – flow through G250 Turbine gas flow meter (HF); Full line – cumulative flow as the sum of flows through three G25 Rotary gas meters (LF).

The laboratory calibrations of one set of three G25 gas meters, the same ones as in the previous case, that are connected in parallel and a serially connected G65 rotary gas meter with a low frequency (LF) readout signal provided the results with an acceptable value of uncertainty and with the error curve drifted in plus in favour of G65 for at least 0.2% of a given flow (see Fig. 8).

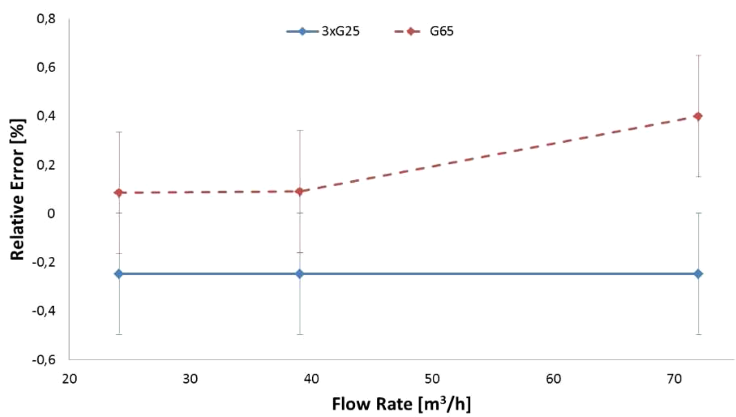

Fig. 8. Calibration of set of meters 3× G25 (LF) by G65 (390) (LF): Dashed line – flow through G65 Rotary gas flow meter (LF); Full line – cumulative flow as the sum of flows through three G25 Rotary gas meters (LF).

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As previously, all gas meters used in the research in both cases were calibrated in a laboratory with internationally recognized capabilities (Figs. 4–6).

4. Practical implications of research

The analyses presented in this paper are focused on the flow measurements of gaseous fluids for reasons of greater generality because of the fact that the meters used for gaseous fluids are more complex and sensitive to external conditions than the meters used for liquid fluid flow. Because of their sensitivity, the measurements of gaseous fluid flows are less reliable and are accompanied with higher uncertainties compared with the liquid flow meters. Based on the presented, the results can be interpreted as follows:

- Two techniques were used when the setup of a non-standardized model of real gas measurement system was analysed: one with HF with a turbine meter as a reference and one with LF with a rotary meter as a reference. The evaluation of the results generated by application of these two techniques proved the previously stated: the curve of reference drift is about 0.2% above the curve that represents the sum of flows of three meters connected in parallel. This implies that the total quantity delivered through three meters shows a smaller value than the one measured by either the turbine HF gas meter or the rotary LF gas meter. Regardless of these facts, the approach with a turbine meter with HF and a rotary meter with LH implies very different measurement conditions. The curves presented in Figures 7 and 8 show the same trend indicating that the correlations between the meters dominate the overall behaviour, and as such, they have to be taken into account in a precise analysis of the characteristic measurement setup. If three meters connected in parallel produce a significant drift of about 0.2% from the sum of flows it would be interesting to see the trend when a larger number of meters are connected in parallel.
- The equations for calculation of the combined standard uncertainty are valid only if the input quantities are independent or uncorrelated (the random variables, not the physical quantities that are assumed to be invariants). If some of the input quantities are significantly correlated, the correlations must be taken into account [6]. Considering the fact that there are correlations between the used meters, these correlations need to be fully investigated if the meters are to be used in any standardized approach. This issue leads to an unrealistic estimated uncertainty budget, most often in the direction of lowering the real value of measurement uncertainties that has implications on the measurement quality and which subsequently leads to the inability to meet the requirements of the directives [2, 3]. The results of the study imply that the standardized uncertainty approach to modelling measurement uncertainty is less appropriate than the error approach, for real-life gas flow measurements.
- In order to keep under control as many uncertainty sources as possible, the described experiments were set in a high-class laboratory assuring very high-quality and complex – and thus quite expensive installations. It is important to keep in mind that other sources of uncertainty coming from a poor installation and from using different meter types have to be taken into account for each individual case. The question is how the results of a similar setting would look like in poor laboratory conditions and performed by a less experienced staff, which is quite common in practice.
- During the research, it was noticed that the same meters connected in parallel with the same piping do not measure the same quantity. The meter placed in the middle of each set had the smallest delivered quantity in all cases, while the other two meters delivered approximately the same quantity. This finding will be the subject of further research.

5. Conclusions

The applied here uncertainty and error approaches to modelling and estimation of measurement uncertainty provide the opportunity that is obviously useful in selecting the most argumentative process to generate real and significant values. As it was mentioned before, only the experts familiar with the behaviour of measuring systems in real conditions can provide the input for specific purpose that, with certain approximations, can be transformed into a standard procedure.

The paper results and outcomes can improve the present status of processes in providing a traceability chain of flow measurement results to the *International System of Units* (SI) and consequently the reliable measurements of gas flow.

Also, the paper results can assist and contribute to the pre-normative research with the aim to optimize existing methods with the proposed inputs. That means that the inputs can technically improve the existing methods or develop new test methods to support the application of written standards including appropriate estimation of measurement uncertainty expectations. Considering the written standards referred to in the findings and results of measurements performed in an internationally recognized laboratory, this research provides an added value that is a more precise and objective measurement result reflecting a specific gas flow installation. In reality, these facts are demonstrated by comparing the entire quantity of gas at one side of a complex distributed system with the cumulative sum of gas flown through the individual gas meters at a specific installation – on the other.

The achievement of less unreliable and less uncertain measurement results of delivered (supplied) gas and energy is a task that is prescribed by the directives [2, 3] and is interesting for both suppliers and consumers in the transport of natural gas. Reliable measurement results with a lower uncertainty help to avoid distrust between suppliers and consumers and can help in loss control. Energy is an important part of a company's business and can be one of the most important controlled costs [19]. The paper findings can improve the present status of processes related to the activities in legal metrology.

A so-called custody transfer measurement (measurement of quantity for billing purposes) involves the use of equipment that is verified [10, 20] or calibrated according to the standards that comply with the international recommendations for a measurement unit with the assumption that all calibrations imply standardized procedures. The results of this research will help to satisfy the requirements given in [2] that Member States shall ensure that the "billing information is accurate and based on actual consumption", as well as the requirements given in [3] which state that "the final customers for natural gas are provided with individual meters that accurately reflect the final customer's actual energy consumption".

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