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Gas Flow Meters with Thermal Time-of-Flight Technology

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Abstract

The thermal mass flow meters based on the calorimetry for utility gas metering have been recently deployed in a few countries and in a fast growth, but several technical issues including the compliance with the existing tariff standards have also been under scrutiny which prevents the desired massive installation. In this paper, we present a new utility gas meter with the thermal time-of-flight sensing technology that can simultaneously measure the mass flow rate, flow velocity, gas pressure, temperature and gas composition variations with the state-of-the-art electronics. These values can be further relayed to the thermal values of the measured gases providing the possibility for the future metrology and tariffs as well as the energy management of the distribution of the city gas. The multi-parameter data acquired from the integrated sensing elements on the other hand challenge the conventional verification process specially when the cost-effectiveness is also critical for the applications. The current meter design with integrated data output, which employs the multi-parameter acquisition and signal modulation, is substantially different from the traditional flow meter for which the metrology standard is normally having a single parameter standard being referenced. The meter also has an integrated harvester that can convert the flow energy induced temperature gradient into electrical energy that can be used for powering the flow measurement.

1. Introduction

Demands for better gas distribution management have continuously driven the development of the smart utility gas meters. On the other hand, the utility industry is however very conservative and traditional in accepting new technologies as the sensitivity in tariffs. As of today, the key technology advancement is largely limited in data transmission and management. Even this development was mostly due to a wave of governmental funding for economy stimulus in a decade ago. In a report by the market research firm IHS earlier in 2019 [1], the current annual worldwide utility gas meter shipment is about 50 million units, of which however only 20% have data communication capability and the original metrology technologies invented over two centuries ago are nearly intact. This is vastly in contrast to the pace of the contemporary electronic technologies.

The phenomenon could also reflect the complexity of a flow meter for utility applications where accuracy, long-term reliability, cost as well as regulatory requirements including the difficulties in change of the tariff system have less tolerance for the technology imperfection, which in turn prevents the investment for the innovation in a wide scale and for a long run [2]. The utility gas meters based on ultrasonic technology have been a success for distribution tariff as the precision can be guaranteed with multiple channel detection and precise compensation of the environmental variants but the deployment to the residential gas metering has been limited by the cost and some technical difficulties for long-term performance. Further, the velocity only gas meters with ultrasonic technology are losing their attractiveness to the gas distributors, and even with a European standard in place in 2007, the shipment and installation of ultrasonic meters have not been substantiated for the deployment [3]. The concept of a calorimetric utility gas meter proposed by a few companies in earlier this century using micromachined calorimetric mass flow sensors that have a low power consumption as well as a better metrology performance has also a brilliant point of the mass metering metrology which could provide the much fairer tariffs and the better gas distribution management. It is also an all-electronic meter that enjoys a seamlessly data transmission without any mechanical or optical to electronic data conversion. The deployment of this new utility gas meter has been started in China since 2007 for commercial users and in Italy since 2012 for both commercial and residential users. Italy has published its standard for the utility gas meters based on the calorimetric sensing technology [4], and an estimation of more than 2 million units have been installed as of today with a failure rate of about 0.26% in the field [5]. Europe community is now in discussion to convert the Italian standard into a European one.

There are several technical issues being intensively discussed for the calorimetric sensing technology for its wider acceptance by the utility gas industry, as the traditional thermal mass flow sensing is not applicable for tariff due to its measurement uncertainties often are much larger than those required by the tariff meters. The micromachining technology together with the advanced electronics has shown its significantly improvement in metrology performance as well as the measurement dynamic range. Another key issue is the gas compatibility or the additional metrology errors due to the variation of the natural gas compositions as it is well known that the gas composition may vary even in the same distribution line due to the supply sources. The calorimetric sensing is dependent on the thermal properties of the gases, the uncertainties based on the traditional thermal mass flow concept are then unpredictable. Although it has been shown that using addition thermal property sensor such as a thermal conductivity sensor can help to compensate the deviation of the metrology due to gas composition variations but some uncertainties need to be acknowledged. Moreover, the calorimetric sensing flow measurement is utilizing thermistors which are also dependent on the temperature of the medium that they measure. Hence compensation of the thermistor properties due to the variation of the medium temperature must also be done properly. In the Italian national standard, the above two factors both yield metrology uncertainties. As the micromachined sensing element has a small dimension, contamination shall be always a concern as the long-term reliability requirement for the tariff meters. Finally, compared to the mechanical metrology technology, the electronic meters shall add labour cost for after sales even though the remote data may catch up such abnormal precisely.

In this paper, we report a new thermal time-of-flight sensing technology that is designed and made to address the above concerns in the current calorimetric utility gas meters, while to provide additional data sensing capability that shall ultimately beneficial for the industry.

2. Design of the thermal time-of-flight gas flow meter

2.1 Thermal time-of-flight sensing principle

Thermal time-of-flight sensing has been proposed for over 70 years but no major branded products have been made available with this technology. For an ideal thermal time-of-flight sensing with one-dimensional proximity, the change of the temperature *T* with time *t* in the flow direction *x* can be expressed as below,

$$\frac{\partial T}{\partial t} = D\left(\frac{\partial^2 T}{\partial x^2}\right) - V_x\left(\frac{\partial T}{\partial x}\right) \qquad (1)$$

where *D* represents the fluid properties and V_x is the fluid velocity. Therefore, in order to obtain a fluid property independent measurement, at least two sensing elements (receivers) with different distances to the thermal transmitter (microheater) shall be required:

$$V_x = \sqrt{(d_1^2/t_1 - d_2^2/t_2)/(t_1 - t_2)} \qquad (2)$$

where d_i is the distance between the thermal transmitter and the receiver, the two distances must not be the same in order to obtain the above proximity. In addition, the thermal transmitter and receiver shall be thermally isolated, and the distances between the transmitter and receiver shall be reasonable such that other thermal effects can be minimized. In an earlier report [6], a hot-wire thermal time-of-flight technology was used to build a prototype for the natural gas metering which was shown to be gas composition independent and the pure volumetric flow rate could be established. However, the hot wire construction was very fragile in a real gas flow medium. The prototype could only be a laboratory demonstration of the concept for the technology and the conversion into a product was not feasible.

The main purpose for a fluid property independent velocity or volumetric measurement is to establish the compliance with the existing metrology and tariff standard that is based on the mechanical measurement technologies, as the differences in the measurement principles would lead to a significant debating on the tariff standard and the consumer sensitivity. However, the desired tariff system shall have the temperature and pressure compensation for the pure velocity measurements, which then requires additional metrological budget for the incorporated temperature and pressure sensors, which on the other hand inevitably shall cost tariffs. Therefore, it is not the desired one to develop a meter only being capable of pure volumetric data acquisition. This could also be one of the reasons that a pure thermal time-of-flight flow meter would not justify the efforts of development.

2.2 Micromachined thermal time-of-flight sensor
Compared to the traditional how wire approach, the micromachined sensors have much more spaces as more sensors can be integrated onto the same sensing chip that shall be able to acquire the desired data. The design of a micromachined thermal time-of-flight sensor can be therefore not only to have the capability of measuring volume and mass flow rate that is fluid property independent in order to be in compliance with the existing metrology standards, but it is to further explore the addition capabilities that can address the other technical issues with the current calorimetric meters.

The basic structure of a micromachined thermal time-of-flight sensor can be found in the earlier disclosure [7] that also detailed the basic process for making of the actual sensor. Such a structure nevertheless did not address the current technical issues associated with the calorimetric meters. In the present work, we added an additional sensor to ensure the data acquisition is gas property independent. The thermal isolation shall be kept via the openings around the thermistors (sensors). The major changes in the current sensor design from the disclosed ones are the addition of a pair of the thermal energy harvesters located at the edge of the membrane on the same sensor chip.

2.3 Gas flow meter design
Even with the current advanced electronics, it is still desired to have the electronics for the smart gas meters being split into two major functional modules: one of the modules will be only designated to the metrology and another one for data communication. Such a design is based on the consideration that the communication module shall be the one that consumes most of the power while the metrology module shall be the one for tariffs. The communication protocol may change or vary depending on the local customers' requirements, but the metrology shall be universal once installed. In the practical case, the end users can be granted the access to the communication module such as to change the battery, but the metrology module shall be kept from access by untrained personnel.

For the metrology module, the electronics shall drive the microheater with a pulsar, and modulate the pulsar such that frequency can be tuned accordingly. The signals received by the two sensors at the downstream shall be processed to extract the time lag as well as the amplitude changes. The time lags shall be used for the volumetric flow while the amplitude changes shall be a direct register of the mass flow as it is measured with the same principle as that for the calorimetric sensing. With the on-chip temperature sensor, the pressure could also be calculated by

$$V_{mass} = C \times V_{volume} \times (P/T) \qquad (3)$$

where *C* is the constant related to the pressure and temperature at the reference conditions.

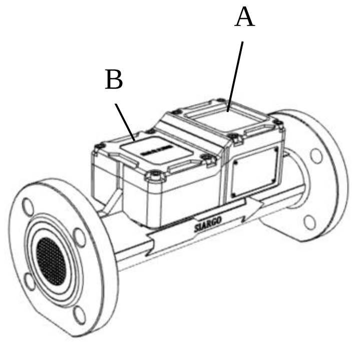

Figure 1: Design of a utility gas flow meter with micromachined time-of-flight sensing element. A – the metrology module; and B – the battery power chamber with data transmission module options.

Figure 1 shows the design of the utility meters for the commercial applications. Flow conditioner is installed at the inlet where flange connection is opted. The meter head has two chambers where chamber A is the metrology chamber that shall be sealed after calibration and/or verification. Chamber B contains the power pack with lithium ion batteries and the interface/module for data transmission. The modules are readily available and can be customized with communication protocols such as NB-IoT, LPWA or GPRS. In this paper, we shall not discuss the detailed design and options of the data transmission protocols.

3. Meter performance

3.1 Metrology performance in air
The meter was first calibrated with air at a sonic nozzle test bench that is described in a previous work [8]. Both the time lag and the amplitude data are registered during calibration. At the reference conditions (20°C, 101.325kPa), either the time lag or the amplitude data could be calibrated to the 150:1 dynamic range with the ±1.5% uncertainties based on the design target. In general, the meter had a better accuracy in the dynamic range using the time lag data, while the amplitude (calorimetric) data were required to be applied with the offset stability algorithm.

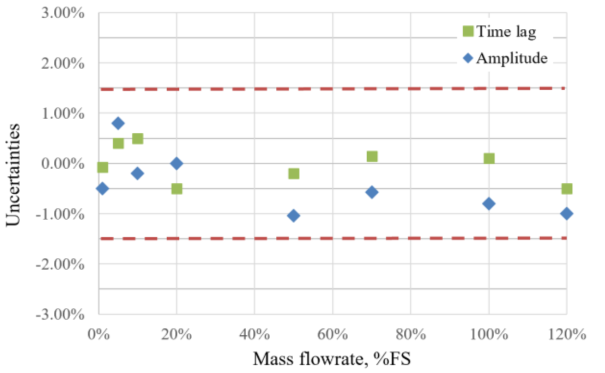

Figure 2: The uncertainties measured from time lag and amplitude data at the reference conditions.

The meter was then subject to the verification of the metrology performance at conditions deviated from the reference to confirm the design goals of both volumetric and mass flow rate measurement. In the experiment, air was applied as the flow medium, and the reference meter is a laminar block mass flow meter with the volumetric value available simultaneously from Alicat Scientific with an uncertainty of ±0.4%. The time lag data were compared for the reference condition (101.325kPa) and a positive pressurized flow at 170.182kPa while the mass flow rates were kept the same for both measurements. The temperature during the measurements were kept at the same ambient, which was 19.5°C in an air-conditioned environment. The amplitude (calorimetry) data verification for mass flow rate was also performed but it shall not be shown here since the calorimetric measurement principle was well known.

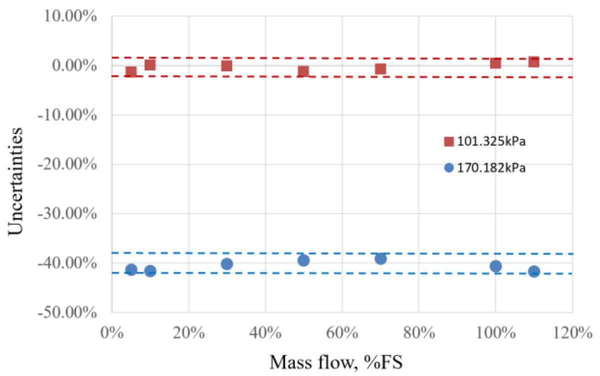

Figure 3: Time lag data verification against different pressure at the reference temperature.

The data shown in Figure 3 verified the volumetric flow measurement character as the pressure increases, the gas volume is compressed at the same mass flow rate. The volumetric flow will yield a smaller value vs mass flow rate with the increase of the line pressure if the temperature of the medium is kept the same. In the above measurement shown in Figure 3, as the temperature was the same for both measurements, the relationship between the mass flow the volumetric flow then shall be determined by the pressure only,

$$(V_1 - V_0)/V_0 = (P_0/P_1) \text{ -1= 101.325/170.182-1=-0.404}$$

which matches well to the measured data. The data also indicated that if a temperature sensor is installed, for a specific gas with calibration, the pressure could be calculated via the simultaneously acquired time lag and amplitude data. In the micromachined sensing chip, since all sensors are made of thermistors, the temperature information is readily available. This would however be more complicated if the measured flow medium does not have a constant gas composition. The measured deviations between the amplitude and time lag data would not be registered correctly during the calibration. In such a case, direct calculate the pressure value would be difficult, it will then require an additional pressure sensor for the data.

3.2 Metrology performance in the natural gases of different gas compositions

For the current calorimetric metering technology with the micromachined sensing elements, to compensate the metrology uncertainties due to the gas composition change in flow medium, a thermistor that is not in the flow stream or perpendicular to the flow stream was used as a thermal conductivity sensor to metering the composition changes and calculate back for the corrected “volume”. This is simply to have the measurement in compliance with the current tariff scheme which is based on the volume measurement. However, because of the thermistor is also temperature sensitive, there could be dependence on the flow rate as well, and the complete volumetric conversion scheme by the thermal conductivity values in a real product would be very challenging, making the conversion a proximity in most of the cases. This would be part of the reasons that the published Italian national standard allows additional metrology errors due to the gas composition variations [4].

Since the present thermal time-of-flight sensing could eliminate the gas property effects and lands on a volumetric measurement without additional compensation, the gas composition effects were tested for its metrology performance. The meter calibrated in air was then connected to a gas line that can supply pre-mixed gases. The reference meter was the same laminar block flow meter by Alicat Scientific. Two pre-mixed CH4 based gases with different gas compositions were selected to verify the metrology data of the air calibrated meter. The composition of these two gases are shown in Table 1. Both of the measurements with the time-of-flight time lag data (-TL) and the amplitude data (-A) were acquired for comparison.

Table 1: Compositions of the natural gases tested.

Gas \ Con.	CH4	C2H6	C3H8	Others
CH4	100%	0	0	0
CxHy	86.9%	8.5%	2.3%	2.3%

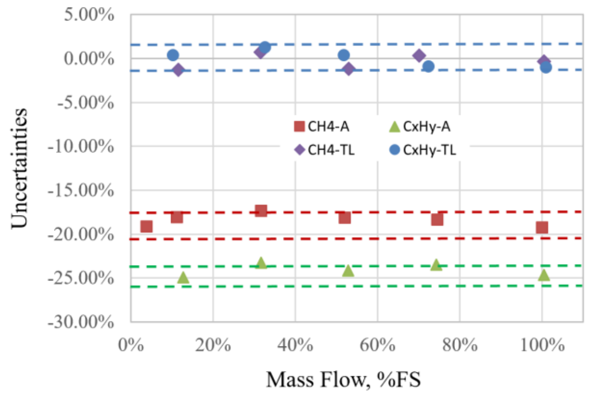

Figure 4: Verification measurements for gases with different compositions.

Figure 4 shows both of the acquired time lag data and amplitude data from two CH4 based pre-mixed gases with the meter calibrated in air. The data indicated that the time lag data are not sensitive to the gas composition which is in consistence with the previous conclusions of the volumetric sensing character. Whereas the amplitude data are gas composition dependent, which was also in consistent with the calorimetric sensing characteristics. It is also showing that the time lag measurement would be more accurate if the volumetric tariff must be observed, although the conversion of the amplitude data to the volumetric data was feasible since the deviations were in parallel and the correction would then be readily achievable by applying a constant correction factor. However, it would be a directly observation that the conversion for an unknown gas composition could not be done without additional measurement, or additional sensing elements would be required to determine the gas properties which in turn would introduce additional uncertainties that were also registered in the Italian national standard [4].

3.2 Metrology performance due to temperature variations

Thermal mass (calorimetric) flow sensing was often mistaken by a claim that the measurement is intrinsically compensated with both temperature and pressure per the *mass flow* concept. However, as the measurement actually utilizes the thermistors as the sensing elements, and the thermistors have a temperature dependence. Therefore, it is necessary to eliminate or compensate the thermistor temperature effects in order to have an accurate measurement which is a must for tariff. This compensation then inevitably shall introduce additional measurement uncertainties, which is also acknowledged in the Italian national standards. For thermal time-of-flight sensing, the time lag measurement shall have less effects by nature as the time domain data acquisition shall be dependent only on the delay of the thermal energy transferred with the flow medium. However, in the practical case, the thermal response and diffusivity might still play a role, and then the compensation would be required for the high precision data acquisition.

To test the temperature effects, the meter was connected to a copper pipeline with a temperature sensor inserted and the complete unit was placed into an environmental chamber that can have temperature varied. The same reference meter used in the experiment discussed in the previous sections was placed outside the environmental chamber at ambient. The data acquisition was started at a serial of set flow and temperature combinations after the temperature reading from the sensor was stabilized (<1% changes in 5 minutes).

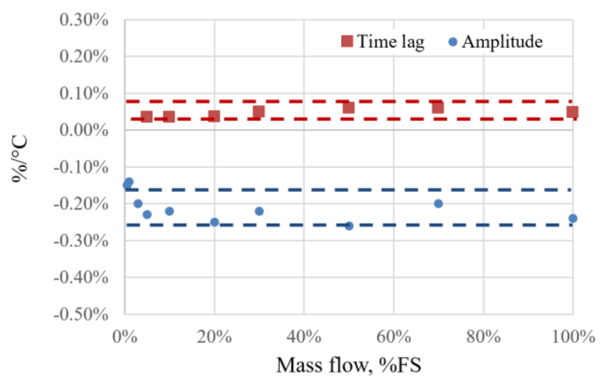

Figure 5: Verification measurements for gases with different compositions.

Figure 5 shows the averaged deviations of the measurement uncertainties per degree Celsius. The time lag sensing data were acquired from a circuitry without a feedback loop based on the environment temperature whereas the amplitude sensing data did operate at the constant temperature mode. The temperature effects were clearly much smaller for the time lag measurement and the temperature effects were opposite to the calorimetry revealing the characteristics of the mass flow and volumetric flow, respectively. A slightly flow rate dependence for both sets of data could be observed. Therefore, to achieve a high precision measurement, temperature compensation would be required for the thermal time-of-flight measurement scheme as well, which could be due to the complete elimination of the thermal response and other related effects would not be feasible even with calibrations.

4. Integration of an energy harvester

Another concern for the all-electronic utility meters is the power failure, as no battery manufacturer is willing to guarantee a zero-failure rate and the discharge pattern for each battery would not be 100% the same. Failure of the power shall directly lead to the cease of tariff records.

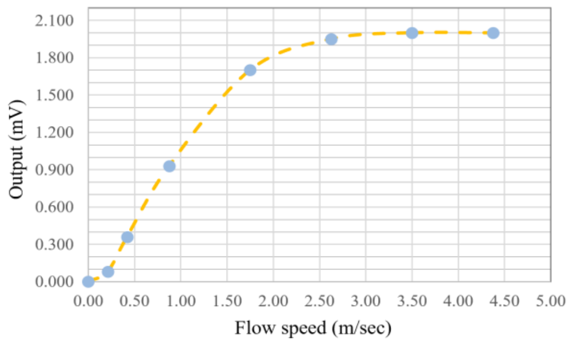

Figure 6: Direct output from a thermal (temperature) energy harvester.

Therefore, it has been a challenge whether the flow energy can be utilized to generate the power for metrology such that the tariff would not be lost due to power failure. For the utility gases, there would be three possibilities for energy harvesting: 1) the gas energy; 2) the flow (wind) energy; and 3) the thermal (temperature) energy. Among these three, the first two shall require some complicated physical process, and the reliability and safety would be also a challenge with the current status quo. The thermal energy would then be a possible and viable option. Figure 6 showed the direct output of voltage from such a device on the same sensor chip. The output started from a flow speed at about 0.05 m/sec and to about 2.5m/sec the output became unchanged. The large voltage output enables the circuitry to be waken up from a sleep mode which is another approach for power conservation. For a typical utility meter for residential applications, this would also make it possible for metering the flow from about 0.1 to 3 m^3/hr without the microheater that is the main power consumption source. Hence, another than multiple onboard memories for data safety, the harvester could assist the basic functions of the meter even at the situation that the battery fails to power.

5. Other considerations

The dual data acquisition scheme with the thermal time-of-flight sensing makes it possible to have the meter alarms for any possible presence of contaminants, as for the same reason that the time lag signal shall be less sensitive to the surface conditions of the sensing elements whereas the amplitude data have a close correlation.

6. Concluding remarks

The current work presents a new flow measurement approach with the micromachined thermal time-of-flight sensing elements to obtain not only the volumetric but also the mass flow rate at the same time. This approach addresses the current concerns in existing tariff compliance for utility gases, and provide the mass flow capability for value added tariff. With further studies, the additional thermal values of thermal capacitance and thermal conductivity could also be measured from the modulated signals leading to the possibility of the ultimately desired thermal value metrology for the fairness of utility gas distributions.

The energy harvester shall be a direction for future work to a perfection of an electronic meter that shall be operated without a large battery source, or even without any external sources.

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