Journal of Natural Gas Science and Engineering 22 (2015) 540–550

Contents lists available at ScienceDirect

Journal of Natural Gas Science and Engineering

journal homepage: www.elsevier.com/locate/jngse

Potential use of capillary tube thermal mass flow meters to measure residential natural gas consumption

M. Farzaneh-Gord [a], S. Parvizi [a], A. Arabkoohsar [b, *], L. Machado [c], R.N.N. Koury [c]

[a] *Faculty of Mechanical Engineering, Shahrood University of Technology, Shahrood, Iran*
[b] *Department of Mechanical Engineering, Minoodasht Branch, Islamic Azad University, Minoodasht, Iran*
[c] *Department of Mechanical Engineering, Universidade Federal de Minas Gerais (UFMG), BH, Brazil*

ARTICLE INFO

Article history:
Received 14 October 2014
Received in revised form
3 December 2014
Accepted 5 January 2015
Available online 8 January 2015

Keywords:
Flow metering
Methane
Thermal flow meter
Two-dimensional heat transfer
Capillary tube flow meter

ABSTRACT

Accurate natural gas measurement is an important issue especially in domestic usage level in which the lack of accurate measurement is well sensed. On the other hand, thermal mass flow meters are widely used in industries such as semiconductor manufacturing and chemical processes. Capillary tube thermal mass flow meter is one of the most common types of thermal mass flow meters which are mostly used for low mass flow rates. In this work, the use of capillary tube mass flow meters for measuring residential natural gas consumption, where the flow rate is extremely low, was proposed. A capillary tube flow meter was simulated, two-dimensional steady state heat transfer in its sensor tube was numerically analyzed and the sensitivity of this type of flow meter to Methane, as natural gas is mainly constituted by Methane, was investigated. In order to validate the simulation approach and conditions taken in this study, the simulation was also accomplished for Nitrogen, for which experimental data was available in the literature, leading to satisfactory results. Considering all the possible effective parameters, the uncertainty of the flow meter was also calculated to be 1.56%. Finally, the simulation was accomplished for a sample natural gas composition with 94.38% methane, resulting to an uncertainty equal to 1.83%.

1. Introduction

In addition to many places in natural gas industry in which mass flow metering is required, in many countries such as some European countries, the natural gas is sold on a basis of mass flow rate. Thus, density metering along with volume flow metering is required in such places. Over the last years, many devices such as multiple ultrasonic transient-time meters, conventional orifice plates and turbine meters are employed in order for fiscal metering of natural gas (Froysa and Lunde, 2005). Basically, these devices meter the volume flow rate of natural gas stream. Natural gas mass flow rate can also be directly measured, independent of pressure and temperature effects, by various instruments such as Coriolis density meters, mass flow controllers, gas chromatographs. Another device which is widely used in mass flow metering is thermal mass flow meter (Hiismaeki, 1993). However, none of these devices have been employed in natural gas metering sites yet.

In residential use level, where the natural gas mass flow rate is extremely low, diaphragm flow meters are normally used. The range of flow rate in residential use is normally between 0 and 4 m^3/hr and this value rarely may come up to 6 m^3/hr. Diaphragm volume flow meters as positive displacement meters are the most common type of metering devices in natural gas industry, especially in domestic usage level. In fact, a diaphragm flow meter is a volumetric flow meter that measures the gas flow rate by counting the number of times that a cyclic nominal volume is emptied and filled (Ficco, 2014). In spite of some main advantages of these flow meters such as low price and long life expectancy, these flow meters have some limitations such as having moving parts which caused them to require periodic maintenance and the gas cleanliness. However, the main disadvantages related to this kind of flow meter is that in very low flow rates, which are very common in residential use of natural gas, the inaccuracy is relatively high. In addition, diaphragm flow meters measure volumetric flow rate, thus, pressure and temperature compensation are required for achieving mass flow rate. Due to these drawbacks, there are always huge amount of lost natural gas in the natural gas distribution network (Chapman and Etheridge, 1994; Vasconcelos et al., 2013). The amount of lost gas in Iran's natural gas network, for example,

---

* Corresponding author.
E-mail address: mani.koohsar@yahoo.com (A. Arabkoohsar).

http://dx.doi.org/10.1016/j.jngse.2015.01.009
1875-5100/

has been about 10 billion cube meters (around 5% of total residential natural gas consumption in the country) in 2013 (http://www.iraniangas.ir/).

Thermal mass flow meters, on the other hand, which are mainly used in gas flow metering, employ heat to measure the flow rate. These devices, in fact, impose heat to the fluid flow and measure how much thermal energy is dissipated by employing temperature sensors. As the amount of dissipated heat is a functional of thermal properties of fluid and can change by variation of pressure and temperature, thermal mass flow meters are mainly appropriate for those applications in which the thermal properties of fluid are constant during actual operation. Moreover, due to the problem of heat absorption in liquids, this type of measurement device is much more appropriate to be used for gas flow measurement goals (Cubukcu et al., 2014). The amount of dissipated heat can be measured by two different approaches namely constant temperature differential and constant current both of which take advantage of two temperature sensors. In the first type, which uses constant temperature differential method, the mass flow rate is a functional of the amount of required electrical power to keep the temperature difference between the two sensors constant (Viswanath et al., 1976). In the second type, which uses constant current method, the mass flow rate is a functional of temperature difference between the sensors (Cappa et al., 1996).

In this work, the use of capillary tube thermal mass flow meters instead of diaphragm flow meters for metering residential natural gas consumption is proposed. For this objective, a capillary tube thermal flow meter is simulated. Two-dimensional heat transfer in its sensor tube in steady state is analyzed in FLUENT software and the sensitivity of this type of mass flow meter for Methane is investigated. Note that in this work, for the sake of simplification, Methane was used to represent natural gas in the simulation process because it presents a much similar thermal behavior to natural gas as it forms more than 90% of total volume fraction of natural gas in most cases (Beronich et al., 2009).

2. Capillary tube thermal mass flow meters

There are two types of thermal mass flow meters namely immersible and capillary tube mass flow meters. Although, in the both types thermal energy is employed, the operation principles are totally different. In immersible thermal mass flow meters the heated element is an immersible cylinder that transfers heat to the fluid around itself while in capillary tube type the heated element is a capillary tube that heats the fluid flowing through itself (ASME MFC-21.2-2010, 2010). Immersible thermal flow meters are much more appropriate to be used for measuring higher mass flow rates and capillary tube thermal flow meters are mainly employed for low mass flow rates (Olin, 1999).

A few studies have already been done specifically on capillary tube flow meters. Komiya et al. (Komiya et al., 1988) presented a one dimensional steady state solution for heat transfer in the sensor tube of capillary tube flow meters. In this study, they neglected the temperature variation in radial direction and axial thermal conductivity of the fluid as well as assuming the thermal situation of the fluid to be constant. Hinkle and Mariano (Hinkle and Mariano, 1991) used a two dimensional model to simulate the heat transfer phenomena in the sensor tube. They assumed that the flow in the sensor tube was fully developed both thermally and hydrodynamically. They also assumed that The Nusselt number is 4.36 at the interface between the tube wall and the gas stream in the entire sensor tube. Kim et al. (Kim and Jang, 2001) studied the heat transfer interaction between the sensor tube and the fluid in steady state numerically and experimentally. They also investigated both the transient and steady state heat transfer in sensor tubes by presenting a numerical model and then studied the sensitivity of thermal flow meters (Han et al., 2005; Kim et al., 2007, 2009). In the last work in this regard, John G. Olin (Olin, 2013) explained the operation principles of capillary tube flow meters for industrial and experimental purposes.

Fig. 1 shows the schematic diagram of a typical capillary tube mass flow meter. According to the figure, the total inlet flow is divided into two parts. The first part ($\dot{m}_1$) flows through the sensor tube and the remaining portion ($\dot{m}_2$) flows through the laminar flow element (LFE). If the flow is laminar, the ratio of mass flow rate entered the laminar flow element to the mass flow rate entering the sensor tube remains constant. Therefore, the LFE has been considered to keep the flow laminar and uniform. In addition, the pressure drop made by the LFE causes only a small portion of the fluid to pass through the sensor tube.

Regarding the explanation given above, the total mass flow rate flowing through the capillary tube thermal mass flow meter can be given by the following equation.

$$\dot{m}_t = \dot{m}_1 + \dot{m}_2 = \dot{m}_1\left(1 + \frac{\dot{m}_2}{\dot{m}_1}\right) = k\dot{m}_1 \tag{1}$$

To obtain the value of k, hydraulic relations can be employed. For this aim, the correlation related to the amount of pressure drop in a tube with a fully developed regime could be as (Graebel, 2007):

$$\Delta P_s = \frac{128\cdot\mu\cdot l}{\rho\cdot\pi\cdot D_{in}^4}\dot{m}_1 \tag{2}$$

Where, ΔP_s, D_{in}, l, ρ and μ represent the pressure drop in the sensor tube, the diameter and length of the sensor tube, the density and dynamic viscosity of the fluid, respectively. In the case of the same length and diameter for the sensor tube and the LFE and assuming N tubes in the laminar flow element, the amount of pressure drop in LFE can be obtained by (Graebel, 2007):

$$\Delta P_{LFE} = \frac{128\cdot\mu\cdot l}{\rho\cdot N\cdot\pi\cdot D_{in}^4}\dot{m}_2 \tag{3}$$

In which, ΔP_{LFE} is the pressure drop of the fluid while flowing through the laminar flow element. As the pressure drops at the end and beginning of the sensor tube and laminar flow element are equal, therefore:

$$\Delta P_{LFE} = \Delta P_s \rightarrow \frac{\dot{m}_2}{\dot{m}_1} = N \rightarrow \dot{m}_t = (N+1)\dot{m}_1 \rightarrow k = N+1 \tag{4}$$

The operation principle of capillary tube flow meters are based on the first law of thermodynamic and heat transfer principles. The mass flow rate flowing through the sensor tube is measured by three coils, two sensors and a heater in the middle. The heater heats the sensor tube and this heat is then transferred to the fluid. The fluid carries this heat from upstream to downstream i.e. unlike the upstream in which the heat is transferred from the fluid to the sensor tube, in the downstream the heat is transferred from the fluid to the sensor tube, causing temperature difference between the sensors. Rising in the mass flow rate (in a specific range) leads to linear increase in this temperature difference and if the mass flow rate is zero the temperature difference between the sensors is also zero and temperature distribution along the sensor tube is symmetrical. This issue is clearly illustrated in Fig. 2 (Kim et al., 2009). In this figure, L_s and $-L_s$ are the distance of sensors from the middle of the sensor tube on which the heater is installed. The green curve shows the temperature distribution along the length of the sensor tube when the flow rate is zero (totally symmetrical) and the blue curve shows the temperature distribution in the presence