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Experimental and simulation studies of the effect of restrictor and distributor on the performance of thermal mass flow meter

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ABSTRACT

In this paper, a thermal mass flow meter has been fabricated in the operating range of 0–500 sccm and the main affecting parameters on its performance have been investigated. In addition, a computer simulation is performed to obtain the proper operation conditions and to compare the experimental data with simulation results. The performance of the device was evaluated by using a commercial flow controller and N_2 and CO_2 gases. Results showed that the output signal for the device was linear in the range of 0–100 sccm (R^2 = 0.96). The effect of flow restrictor and number of its orifices was studied to determine the appropriate working range of the flow meter. Using of restrictor for measuring the mass flow in the range of 0–500 sccm has shown a good accordance with signal output (R^2 = 0.99). Overall accuracy of the device was found to be ± 4% of full scale. The effect of distributor in the input of the device and the input pressure was also investigated and discussed. In addition, CO_2 was used as alternative gas to compare its results with N_2 as the base gas. Finally the simulation studies demonstrated a good accordance with the experimental data.

1. Introduction

In addition to the temperature and pressure, flow rate is also one of the most important measurable parameters in many different domains such as industry, domestic purpose, medical applications, and research laboratories [1,2]. Selection of an appropriate flow meter depends on different factors such as accuracy, measuring range, cost, size, response time, longevity, and repeatability [1,3]. Flow meters can be divided into four distinctive groups based on the measurement mechanism: differential pressure, electrical, mechanical and mass flow meters [1]. Thermal mass flow meter is one of the best type mass flow meters which can measure the mass flow rate of gases and liquids directly. Thus, they are often used in monitoring or controlling of mass-related process such as chemical reactions, aerospace and nuclear industries [4]. Regardless of many flow meter types, thermal mass flow meter can be usually used in a wide range of flow rates [5,6]. Thermal mass flow meter depending on measurement range and its technology, can be broadly classified into two categories: capillary mass flow meters and insertion thermal mass flow meters [7,8].

Insertion thermal mass flow meters consist of two finger type sensors which are exposed into the fluid main stream and are used for either laminar or turbulent flow. However, capillary thermal mass flow meters are placed in the main stream but the flow measurement does not occur in the main flow. A narrow proportional laminar flow stream is separated from the main stream to measure the flow rate [8]. One of the oldest research in the field of thermal mass flow meter is back to 1911 reported by Thomas who indicated that gas mass flow rate is proportional to heat input and inversely proportional to specific heat and temperature difference [9]. In 1947, Laub proposed a theory that only the boundary layer of gas is in contact with hot wall. He was able to relate temperature rise to the mass flow rate under ideal conditions. In Laub's findings, boundary layer depends on Reynolds number, velocity profile and the viscosity of the gas crossing in pipeline [10]. Renken et al. (1985) developed a silicon sensor that was based on thermal mass flow meter principles. The response time of his invented flow meter was about milliseconds [11]. Heat flow measurement for the fuel consumption in vehicles, spacecraft and for liquid fuels in industrial processes studied by Huijsing et al. in 1988 [12]. He was able to measure the maximum flow rate with no need for side stream or a long tube. In 1995, Bartos reported that the accurate flow measurement highly depends on the velocity profile of the flow i.e., the laminar flow must be attained in the capillary tube. [13]. Viswanathan et al. (2001) achieved the following results using experimental data from thermal mass flow meters: it is possible to measure the flow rate with ± 0.3% of errors in full scale; the numerical simulation of thermal mass flow meters is qualitatively in accordance with the experimental results; the effect of changes in ambient temperature is negligible on the performance of thermal mass flow meters [14]. Dong et al. presented a simple

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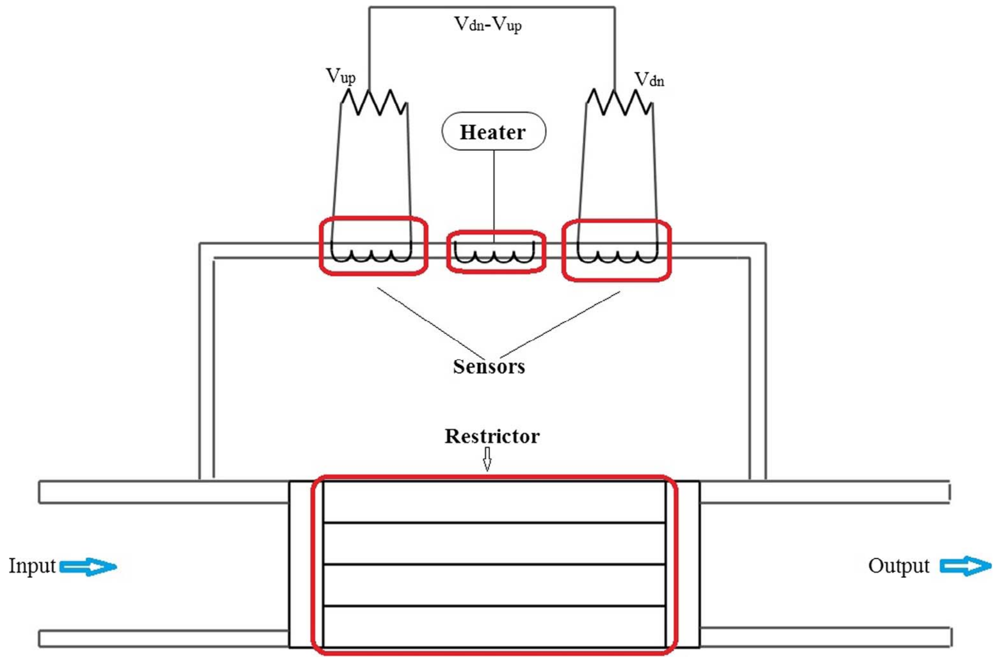

Fig. 1. A view of two thermal mass flow meter, (a) Capillary tube thermal mass flow meter, (b) Insertion thermal mass flow meter [8].

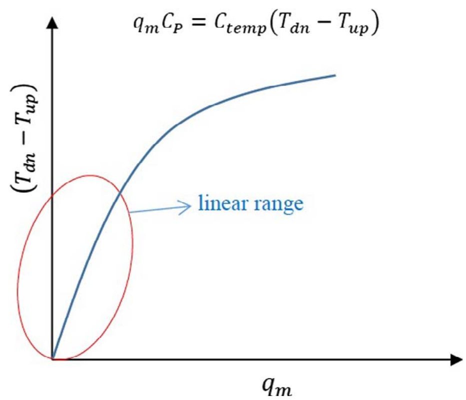

Fig. 2. Schematic of the flow measurement technique by thermal mass flow meters.

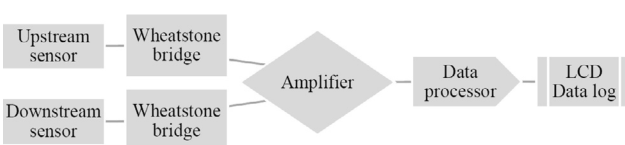

Fig. 3. Schematic representation of the electronic readout system and signal flow.

numerical model for sensor tubes of a thermal mass flow meter in 2006, where they provided a relationship to predict linear range of thermal mass flow meter. This relation predicts numerical results with a 15% error [15]. In 2009, Agrawal used a very thin stainless steel pipe for capillary tube with tungsten thermocouples as the sensor. His flow meter was composed of a cylindrical restrictor and was created with more than 180 orifices [7].

Despite the good works that have been performed in designing thermal mass flow meter, further researches still seem necessary to improve their performance. Full-scale simulation of a flow meter as well as existence of a distributor at the flow input can be helpful to establish a laminar flow and prevent turbulence that have not been investigated very well. In this paper, first a flow meter is fabricated, then its performance will be investigated and compared with the result obtained by simulation. In the end, the effect of distributors and restrictor that lead to laminar flow at flow input will be discussed.

2. Theory

For a thermal mass flow meter, the basic principle of capillary thermal of the operation is in accordance with the first law of thermodynamics and heat transfer phenomena. Process fluid is split into two paths after entering the flow body of the instrument. The main fraction of fluid flow passes through the restrictor at laminar flow. Whereas the small fraction of total flow is transferred to a small capillary bypass sensor tube [16]. A schematic of the flow meter is shown in Fig. 1.

By flowing the gas through the heated capillary tube a temperature difference (T_{dn}−T_{up}) is achieved between downstream and upstream of heater. Thus, the basic output of the sensor is a temperature difference and for low flow rates it is caused entirely by the heat capacity of the gas [17]. This temperature difference is directly proportional to $q_m C_P$:

$$q_m C_P = C_{temp}(T_{dn} - T_{up}) \quad (1)$$

where q_m and C_P are mass flow rate and heat capacity of the gas, respectively. C_{temp} stands for a constant related to geometry and design of the sensor tube. The point is that in no flow condition the temperature difference is equal to zero and the temperature profile becomes symmetric alongside the sensor tube [17].

Fig. 2 demonstrates the typical response of a capillary type flow sensor in terms of the temperature difference versus gas flow rate. As it can be seen, the response is nearly linear at low flow rates which makes it possible to fabricate an accurate flow meter on the mentioned principle [7].

The thermal mass flow meter sensor generates an output signal related to the mass flow rate and converts the mechanical variable (mass flow rate) into an electrical signal (voltage) via a thermal variable (heat transfer) which can be processed by a microcontroller [7].

In order to satisfy the laminar flow condition inside the sensor tube, the maximum Reynolds number must be less than 100 [18]. Furthermore, to achieve the fully developed velocity distribution and constant convective heat transfer coefficient over the entire length, the ratio of the inner diameter to the total length of the sensor tube is less than 0.01 [18]. In addition to the conditions mentioned above, the radial

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