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Modelling of a thermal dispersion mass flow meter

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ABSTRACT

This paper deals with the modelling of a thermal dispersion mass flow meter. A steady-state, two-dimensional numerical model of a thermal flow sensor is built, and the heat transfer conditions in the thermal flow sensor and the effects of influential parameters on its measurement characteristic are analysed. The modelled sensor is considered to have an axisymmetric internal structure with defined dimensional and material properties. It is inserted into the flow pipe with a gas flow that has a defined pressure, temperature, mass flow rate and a fully developed velocity profile. The free parameters of the model are set to obtain the best fit between the sensor's modelled and measured characteristics. A heat transfer analysis shows that the heat convection is, as expected, the most dominant heat transfer mechanism, but both the heat radiation and the heat conduction along the sensor's stem are significant as well. The thermal conductivity of the sensor's filler material significantly affects the measurement characteristic, the radial temperature gradient in the sensor and its surface temperature. The length of the part of the sensor outside the flow pipe influences the heat loss along the sensor's stem, while the length of the part of the sensor in the flow pipe affects the convective and radiative heat transfer. The effects of these dimensional parameters are relatively larger at lower mass flow rates.

1. Introduction

Thermal mass flow meters are mostly used to measure the mass flow rate of gases. They can be divided into two types: capillary thermal mass flow meters and thermal dispersion mass flow meters [1,2]. The thermal dispersion mass flow meter typically consists of a thermal flow sensor, a gas-temperature sensor, measurement and control electronics, an enclosure and, optionally, a flow pipe. The measurement principle of the thermal dispersion mass flow meter is based on the effect of the gas flow on the convective heat transfer from the thermal flow sensor. The resistance-type temperature sensing element is typically heated in order to maintain a constant temperature difference above the gas temperature and the heating electrical power changes with the mass flow rate. The other possibility is to maintain a constant heating electrical power (or, in some cases, a constant electrical current) and the resulting temperature difference changes with the mass flow rate. The performance of the thermal dispersion mass flow meter is affected by the constructional and operational parameters of the thermal flow sensor, and both the installation and the process conditions.

Thermal dispersion mass flow meters have been studied theoretically by various analytical and numerical models. Baker and Gimson [3] investigated the effects of the eccentricity of the sensor's construction, the immersion length of the sensor and the construction of the clearance hole in the pipe wall using one-dimensional analytical models for the heat transfer. Jiang et al. [4] developed a two-dimensional analytical model for a thermal flow sensor and compared the predicted effects of the gas temperature on the measurement characteristic with the experimental results. Rupnik et al. [5] presented a method for identifying the type of measured gas, where the physical background was explained on the basis of the radial analytical model of the thermal flow sensor. Rupnik et al. [6] developed a method for correcting the axial heat transfer along a sensor's stem, where the axial analytical model and the two-dimensional numerical model of the thermal flow sensor were employed in the study. Pape and Hencken [7] modelled a thermal flow sensor using the finite element method and analysed the effect of the coatings deposited on the sensor's surface. Badarlis et al. [8] modelled the fluid flow and the heat transfer using a CFD model with the conjugate heat transfer method in order to optimize the heater design and its position in the thermal flow sensor. Gibson [9] also used a CFD model to study the effect of a single bend and misaligned pipes upstream of the thermal flow sensor that was modelled as a cylinder with defined temperatures on its surface.

The aim of the presented research work was to build a steady-state, two-dimensional numerical model of a thermal flow sensor that would make it possible to analyse the heat transfer conditions in the sensor and the effects of influential parameters on its measurement characteristic. The model is based on a practical realisation of the thermal flow sensor with a circular cross-section, which is one of two thermal

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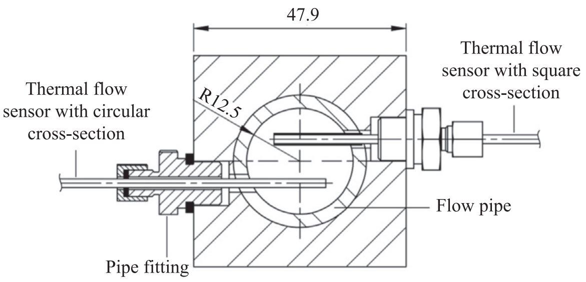

Fig. 1. Scheme of the thermal flow sensors installed in the flow pipe of the developed thermal dispersion mass flow meter.

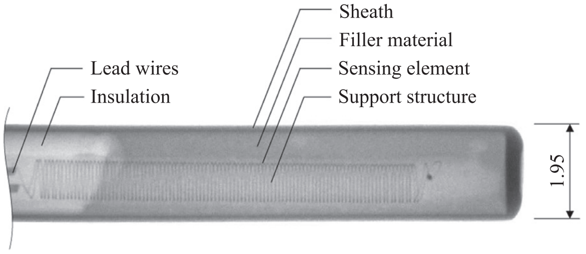

Fig. 2. X-ray image of the thermal flow sensor.

flow sensors – another is with a square cross-section – in the developed flow meter with the gas-identification capability (Fig. 1) [5,10]. The X-ray image of the internal structure of the discussed thermal flow sensor is shown in Fig. 2. The two-dimensional numerical model considers only the temperature gradients in the radial and axial directions. The energy balance method is used for the formulation of the heat transfer problem in the difference form [11].

This paper is structured as follows. Section 2 describes basic assumptions, governing equations and discretization of the numerical model. Section 3 presents the modelling results and discussions of the predicted performance of the thermal flow sensor. The conclusions and possibilities for further research work are given in Section 4.

2. Numerical model

2.1. Physical model

A physical model of the thermal flow sensor is shown in Fig. 3. The sensor's components are considered as axisymmetric layers with defined dimensions and thermal conductivities. The sensing element in the form of the winding on the support structure (see Fig. 2) is modelled as a cylindrical layer with the same volume, considering the actual length L_{SE} and the effective thickness Δr_{SE}. The lead wires are also modelled as a cylindrical layer with an effective thickness $\Delta r_w = \Delta r_{SE}$. In order to preserve the intensity of the axial conductive heat transfer along them, the effective thermal conductivity of the lead wires is considered.

The sensor with the outer diameter d is inserted into the flow pipe with the diameter D, for the distance l from the pipe's centreline. The immersed part of the sensor that has the length L_{im} is exposed to the gas flow with the defined temperature T_g, pressure p, mass flow rate q_m and velocity profile at the sensor's axis $v(x)$. The part of the sensor outside the flow pipe has a defined effective length L_{eff} and is exposed to stationary ambient air with the temperature T_a.

The heat generation rate $\dot{Q}_G$, which is equal to the heating electrical power $P = R_{el}I^2$, results from the electrical current I passing through the sensing element with the electrical resistance R_{el} and causes an increase of the sensing element's average temperature $\overline{T}_{SE}$ by the temperature difference ΔT above the gas temperature. The generated heat is conducted to the surface of the sensor and along the stem. The convection and radiation heat transfer rates from the sensor's surface are modelled separately for the immersed part, $\dot{Q}_\alpha^S$ and $\dot{Q}_\sigma^S$, the part outside the flow pipe, $\dot{Q}_\alpha^{S'}$ and $\dot{Q}_\sigma^{S'}$, and the tip, $\dot{Q}_\alpha^T$ and $\dot{Q}_\sigma^T$. The conductive heat transfer rate at the location where the sensor is inserted into the flow pipe ($x = 0$) represents the heat loss $\dot{Q}_{loss}$. The sensor is considered to be mounted to the base with the constant temperature T_B. The conductive heat transfer rate to the base is denoted by $\dot{Q}_B$.

2.2. Governing equations

For an arbitrary part of the computational domain of the sensor, the balance of the input and output conductive heat transfer rates and the heat generation rate holds true for steady-state conditions:

$$\dot{Q}_{in} - \dot{Q}_{out} + \dot{Q}_G = 0. \tag{1}$$

The conductive heat transfer rate in the direction of the normal n to

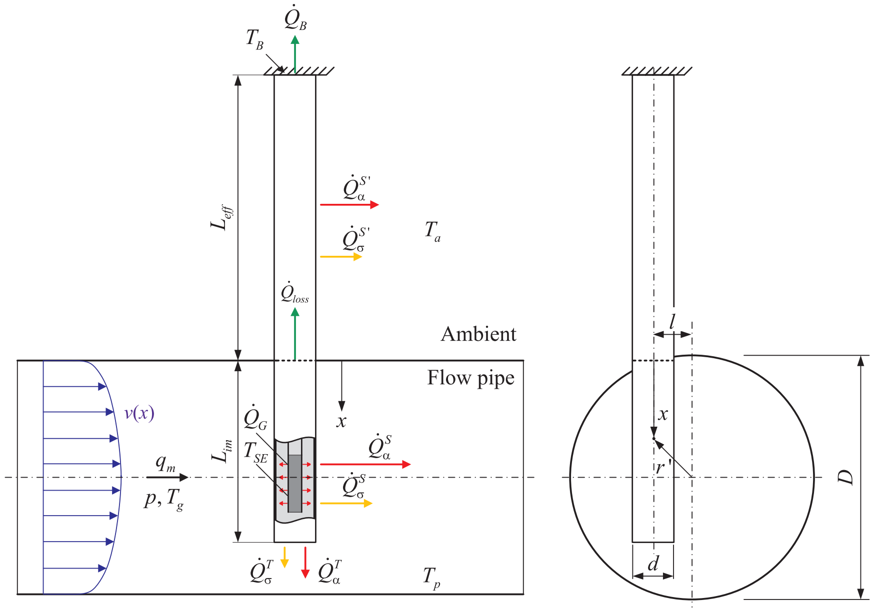

Fig. 3. Physical model of the thermal flow sensor.