Sborník vědeckých prací Vysoké školy báňské - Technické univerzity Ostrava
číslo 2, rok 2006, ročník LII, řada strojní
článek č. 1524

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MICROFLOW SENSOR

SENZOR MIKROPRŮTOKU

Abstract

In the presented investigation, the problem of accurate determination of low mass flow was studied. In this paper a flowmeter design applicable for measurement of low gas flow amounts is presented. To this end, the numeric model of designed flowmeter was made and the flowmeter was numerically simulated using compressible Navier – Stokes equations in two and three dimensions. The computations were carried out for several types of constructive materials of flowmeter and for several types of agitated gases. The results were compared with experimental data.

Abstrakt

V předloženém příspěvku je řešena problematika měření malých průtoků tekutin. Je prezentován návrh průtokoměru vhodného pro měření malých průtoků plynů. Za tím účelem byl navržen dvourozměrný a třírozměrný numerický model s využitím Navier – Stokes rovnic. Ve vytvořeném modelu byly studovány vlastnosti průtokoměru zhotoveného z různých konstrukčních materiálů, byly vytvořeny modely pro různé druhy proudícího plynu. Výsledky matematického modelu byly porovnávány s experimentálními daty.

1 INTRODUCTION

The measurement of flow and flow direction is very important in laboratory tests, medical and industrial applications. As compared to other methods, the thermal method for mass flow determination of flowing media is independent on their pressure and temperature. For media where the relevant substance parameters are not dependent on pressure, the output signal is dependent only on the product of density and velocity. In laminar flow the signal is almost proportional to the mass flow [1].

Many biochemical laboratories interested in biodegradation reactions use the flowmeters for determination of reaction kinetics. In many cases the actual gas flow range is very small, e.g. (50-100) *ml/hr* [2]. In these cases the utilization of common measuring principles of flow is impossible, they have great operating range. Number of promising new methods for small flow rate measurement has been recently developed. One relatively simple flow measurement device is so – called the time – of – flight sensor, in which the mass flow is determined by observing the relationship between the time and the flow velocity. At the relatively low flow rates, the time difference depends mainly on the diffusivity of the fluid medium. At relatively high flow rates, the time difference tends to relate to the ratio of the heater – sensor distance and the average flow velocity [3].

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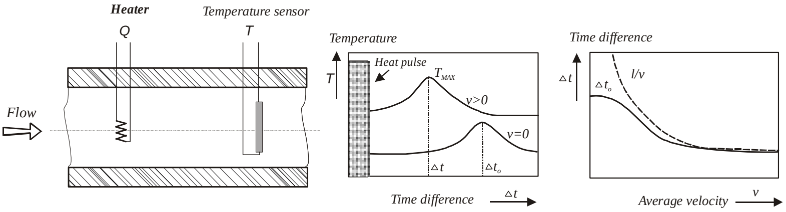
This paper is organised as follows: Section 2 contains description of the principle of the time – of – flight sensor; Section 3 presents a numerical model of the sensor (basic configuration, modelling results); Section 4 describes design of the flowmeter (experimental validation of modelling results).

2 PRINCIPLE OF THE TIME – OF – FLIGHT SENSORS

The time – of – flight sensor consists of a heater and one or more temperature sensors downstream, Fig.1. The heater is activated by current pulses. The transport of the generated heat is a combination of diffusion and forced convection. The resulting temperature field can be detected by temperature sensors located downstream. The sensor output is the time difference between the starting point of the generated heat pulse and the point in time at which a maximum temperature at the downstream sensor is reached, Fig.1b. The time – of – flight sensors have the same limitations as the intrusive type of calorimetric sensors: corrosion, erosion and leakage. Since the signal processing needs a short while to measure the time difference, this sensor type is not suitable for dynamic measurement.



a) b) c)

Fig. 1 Time – of – flight sensors

The transport of the heat generated in line source through a fluid is governed by the energy equation:

$$\frac{\partial T}{\partial t} + v\nabla T = \left(\frac{\lambda}{\rho c}\right)\nabla^2 T + \frac{q'}{\rho c}, \tag{1}$$

where:

T - temperature,

c - specific heat at the constant pressure,

ρ - density,

v - kinematic viscosity of the fluid,

λ - thermal conductivity,

q' - amount of heat per unit of volume and time.

The analytical solution of this differential equation for a pulse signal with input strength q'_o is given in [4] as :

$$T(x,y,t) = \left(\frac{q_o'}{4\pi\lambda t}\right)\exp\left\{-\frac{\left[(x-vt)^2\right]}{4at}\right\}, \tag{2}$$

where:

a - thermal diffusivity.

3 NUMERICAL MODEL

In the present work, the properties of the time – of – flight sensor were investigated using commercially available program FEMLAB. Femlab is an interactive environment for modelling and solving problems based on partial differential equations. This program applies the finite element method (FEM) for solving of the PDEs system.

The simulated time – of – flight sensor is a multiphysics model, meaning that it involves more than one kind of physics. In this case, there are Navier-Stokes equations from fluid dynamics together with a heat transfer equation that is essentially a convection-diffusion equation. There are four unknown field variables: the velocity field components u and v, the pressure p and the temperature T. They all are interrelated through bidirectional multiphysics couplings.

The pure Navier-Stokes equations consist of a momentum balance (a vector equation) and a mass conservation. The equations are:

$$\rho \frac{\partial u}{\partial t} + \rho(u.\nabla)u = -\nabla p + \eta \nabla^2 u + F \tag{3}$$

$$\nabla . u = 0 \quad , \tag{4}$$

where:

F - volume force,

ρ - fluid density,

η - dynamic viscosity.

The heat equation is an energy conservation equation that only says that the change in energy is equal to the heat source minus the divergence of the diffusive heat flux:

$$\rho c_p \frac{\partial T}{\partial t} + \nabla .(-k\nabla T + \rho c_p T u) = Q \tag{5}$$

3.1 Basic configuration

Since a typical fully three – dimensional simulation of the sensor requires in excess on 10^5 cells and therefore several computational days, it was decided at first to investigate several configurations in two dimensions. The two dimensional configuration assumed in the present work can be seen in Fig. 2.

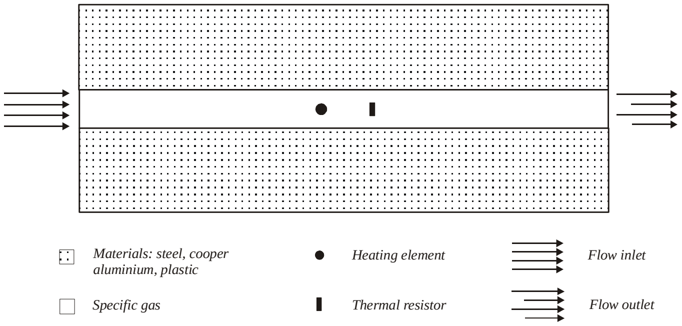


Fig.2 Basic configuration studied

A structured computational grid consisting of more than 23000 cells was generated. Close attention was paid to the grid resolution in critical areas such as boundary layers and surrounding of the heater. A part of the grid is displayed in Figure 3 for the basic configuration. Even in the two dimensional case, the convergence to correct solution required several computational hours on 1,6 *GHz* PC.

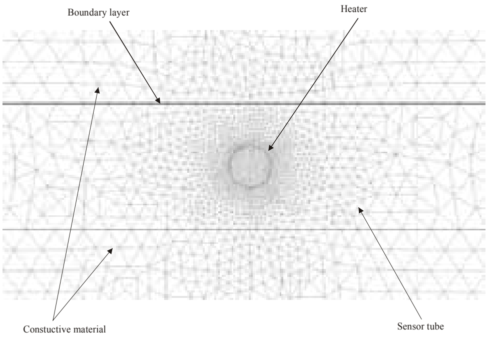


Fig. 3 Partial view of the computational grid for the basic configuration

The dependence of the sensor output on diffusivity of the fluid medium was studied [3]. The properties of the time – of – flight sensor were investigated at the relatively very low flow rates. In Tab.1 are shown inlet speeds *v* of gas used in the sensor model and corresponding flow rate *Q* (diameter of the sensor tube is 3*mm*).

Tab.1 Inlet speeds of fluent gas

$v[m\ s^{-1}]$	0,002	0,004	0,006	0,008	0,01
$Q[ml\ h^{-1}]$	50	100	150	200	250

At the same time the effects of a constructive material of sensor tube on the sensor output were investigated too. The boundary conditions of the sensor model and the heat coefficients can be found in Fig.4. The transport of the heat from sensor tube to ambient is expressed as:

$$h = \frac{1}{\frac{1}{\alpha_1} + \frac{\delta}{k} + \frac{1}{\alpha_2}} \quad , \tag{6}$$

where:

h - heat transfer coefficient,

α_1 - coefficient of heat transfer by convection (from sensor tube to constructive material),

k - thermal conductivity of the constructive material,

α_2 - coefficient of heat transfer by convection (from constructive material to ambient),

δ - is the thickness of the constructive material.

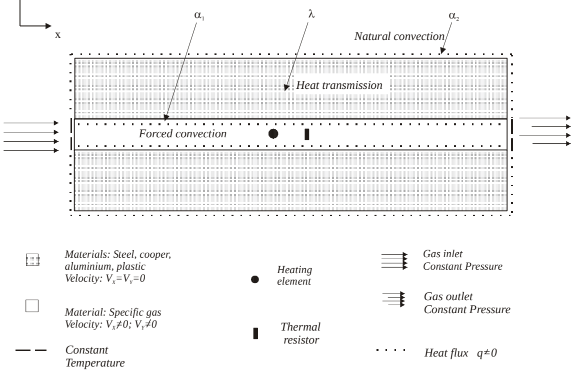


Fig.4 Boundary settings in the model of the time – of – flight sensor

In the sensor model the temperature of the heater has changed periodically, a length of the heat pulse is 0,3*s*; Fig.5.

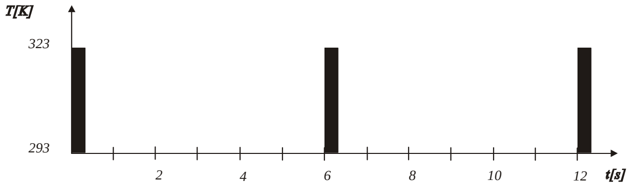


Fig.5 The time path of the temperature of the heater

3.2 Modeling results

The properties of the time – of – flight sensor were simulated and verified for different constructive materials and different flowing gases. The dependence of T_{MAX} (Fig. 1) on flow velocity v can be found in Fig.6; the temperature T_{MAX} was measured in the distance 10*mm* from the heater. Fig.7 shows the dependence of time difference Δt on flow velocity v. As can be seen in Fig.1, Δt is difference between the time of the heat pulse and the time of T_{MAX}.

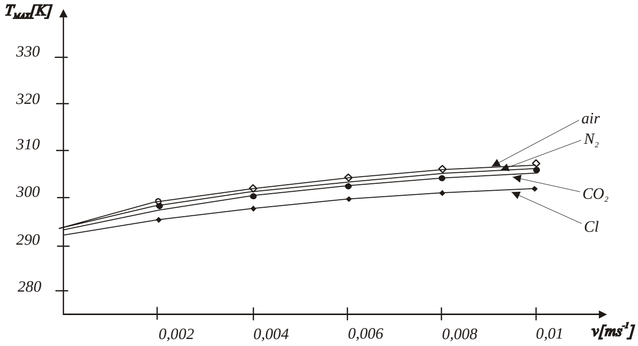


Fig.6 The dependence of T_{MAX} on flow velocity v, constructive material cooper

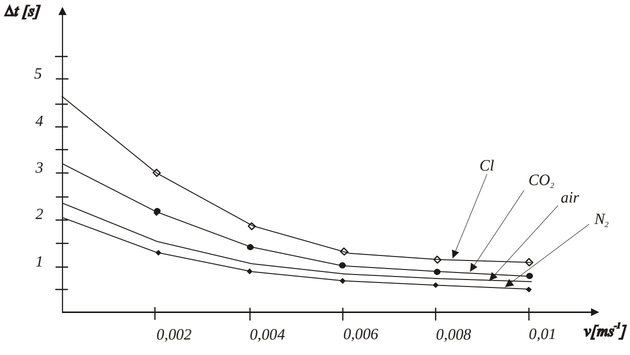


Fig.7 The dependence of time difference on flow velocity v, constructive material steel

4 EXPERIMENTAL VALIDATION OF MODELLING RESULTS

The validation of the finite-element/analytical model of the designed flow meter is to directly compare with experimental data. The peristaltic pump was used for the calibration of the designed time – of – flight sensor. The flow sensor was calibrated for air and CO_2. The measuring data can be seen in Fig.9.

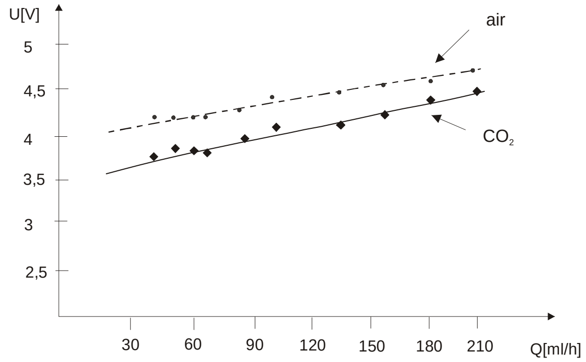


Fig.9 The static characteristic of the designed flow meter

ACKNOWLEDGEMENTS

The work has been supported by the Ministry of Education of the Czech Republic under grant MSM 7088352102. This support is very gratefully acknowledged.

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