Microflow sensor modelling.

Abstract: The tiny liquid flows measurement and control within the range nanolitres to mililitres per minute is becoming more and more important for a lot of applications in the science, e.g. analysis, biotechnologies, synthesis (of e.g. pharmaceuticals) and nanotechnology markets. Accompanying demands to flow sensors suited for this low flow range are an extremely small internal volume, the use of fused silica as wetted material for the flow sensor tube (instead of stainless steel), and a modular set-up of the instruments, so they can be easily exchanged and adapted to a new need.

Key words: Modelling, flow, sensor, Femlab, measurement.

1. INTRODUCTION

The microsystem modelling requires appropriate compact or macro models for microdevices. The compact models allow the microsystem fast system level simulation. Microflow sensor modelling has been examined by several authors (Swart et al. 1992). These approaches have used a solution of the partial differential equations (PDEs) for the coupled fluid/thermal problem. The work of (Swar et al. 1994) employs equivalent circuit descriptions that are solved in SPICE whereas (Mayer et al. 1996) solve the PDEs using the finite-element and the finite-difference methods, respectively. However, none of these methods provide a simple and accurate macromodel for the flow sensor.

2. FLOW SENSOR MODELLING

This work is focused on the thermal method modelling for the flowing media mass flow determination. A basic principle of a design flowmeter is shown in Figure 1. This flowmeter type is called a Time-of-flight sensor. The time-of-flight sensor consists of a heater and one or more temperature sensors downstream. 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.

[FIGURE 1 OMITTED]

2.1 Basic configuration

The temperature in a classical design of the Time-of-Flight sensor is measured by temperature sensors located downstream. There are two sensors usually; they measure a temperature in two points. In the modified version of designed flowmeter a temperature field is measured by semiconductor film--figure 2. The temperature profile depends on the gas velocity. The heater is activated periodically; the period of the heat pulses generation can differ for different velocity size or can be constant.

2.2 Basic equations for T(x,y)

The simulated time-of-flight sensor is a multiphysics model. 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 mo-mentum balance (a vector equation) and a mass conservation. The equations are:

$$\rho \frac{\partial u}{\partial t} + \rho (u \cdot \nabla) u = -\nabla p + \eta \nabla^2 u + F \quad (1)$$

$$\nabla \cdot u = 0 \quad (2)$$

where F is a volume force, ρ is the fluid density and v is the 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:

$$\rho c_p \frac{\partial T}{\partial t} + \nabla \cdot (-k \nabla T + \rho c_p T u) = Q \quad (3)$$

where c_p is the heat capacity of the fluid and ρ is fluid density as before. The expression within the brackets is the heat flux vector and Q represents a source term. The heat flux vector contains a diffusive and a convective term, where the latter is proportional to the velocity field u.

2.3 Boundary settings in the model

The boundary conditions of the sensor model and the heat coefficients are shown in Figure 2. The transport of the heat from sensor tube to ambient is expressed as:

$$h = \frac{1}{\frac{1}{\alpha} + \frac{\delta}{k}} \quad (4)$$

where h is the heat transfer coefficient, α is the coefficient of heat transfer by convection (from sensor tube to semiconductor film), k is the thermal conductivity of the semiconductor film and δ is the thickness of the semiconductor film.

[FIGURE 2 OMITTED]

The coefficient of heat transfer by convection from sensor tube to constructive material α was derived (forced convection) by the help of Nusselt number Nu expressed as (Hardy et al. 1999):

$$NU = 1,86\left(Pe \frac{d}{l}\right)^{1/3} \left(\frac{\eta}{\eta_W}\right)^{0,14} \quad (5)$$

where Pe is Peclet number, v is dynamic viscosity, η_W is dynamic viscosity at wall temperature, l is length of heat transfer surface and d is inside diameter of the heat exchanger shell.

3. THE MODELLING APPROACH

The modelling approach uses a numerical solution of the PDEs for constructing the model. The sequence of steps is outlined below:

1. A numerical solution is obtained for T(x, y) from equations (1), (2) and (3) for different values of the velocity u, the height of the fluid channel d and the sensor width l

2. This solution yields discrete data points for T_1, T_2, and T_3 as a function of u, d and l

3. The discrete data points can be used for study of dynamic behaviour of study sensor.

The PDEs can be solved by using a numerical solver, such as CFD-ACE+ (Rasmussen et al. 1999). However, for circuit-level simulations a macromodel is required. The macromodel must be computationally efficient and provide an accurate description of the temperature in semiconductor film.

In the present work, the properties of the time-of-flight sensor were investigated using commercially available program FEMLAB. This program applies the finite element method (FEM) for solving of the PDEs system.

[FIGURE 4 OMITTED]

Because of model symmetry a two dimensional model was made. A structured computational grid consisting of more than 12 000 cells was generated. Close attention was paid to the grid resolution in critical areas such as semiconductor film and surrounding of the heater.

Even in the two dimensional case, the convergence to correct solution required several computational hours on 2,5 GHz PC.

The temperature profiles in different time intervals in semiconductor film are shown in Figure 4.

Figure 5 shows the time response of studied flow sensor. In the model the speed was changed from 30ml/hr to 100ml/hr. A disadvantage of the designed model is in the relatively great time response; [tau]=5,2s. This designed flowmeter can be used in a slow process measuremet.

[FIGURE 5 OMITTED]

4. ACKNOWLEDGMENTS

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