MODELLING AND DESIGN OF MICROFLOW SENSORS BASED ON MEASURING OF TEMPERATURE FIELD

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Abstract: This article describes modelling and measurement of tiny liquid flows of the order of microlitres through mililitres per minute. The measurement of mentioned flow range is becoming more and more important for a lot of applications in the life science, 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 for instance PEEK and 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: Flow, sensor, modelling, temperature profile.

1. INTRODUCTION

The modelling of microsystems requires appropriate compact or macro models for microdevices. In general, it is difficult or almost impossible to obtain closed form analytical models for microdevices. Thus, models are obtained by a simplification of the full physical model. The compact models allow for fast system level simulation of the microsystem. However, the accuracy of such a model can be questionable because of the simplifications made during the model development phase. Model accuracy and simplicity are important for the design of complex systems. Microflow sensor modelling has been examined by several authors [1]. These approaches have used a solution of the partial differential equations (PDEs) for the coupled fluid/thermal problem. The work of [2] employs equivalent circuit descriptions that are solved in SPICE whereas [3] 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.

In this paper is presented modelling approach for microflow sensor and design of microflow sensor.

2. DESCRIPTION OF PRINCIPLES OF FLOW SENSOR

This work is focused on the modelling of a thermal method for mass flow determination of flowing media. A basic principle of a design flowmeter is shown in Fig.1. This flowmeter type is called as 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.

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.

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

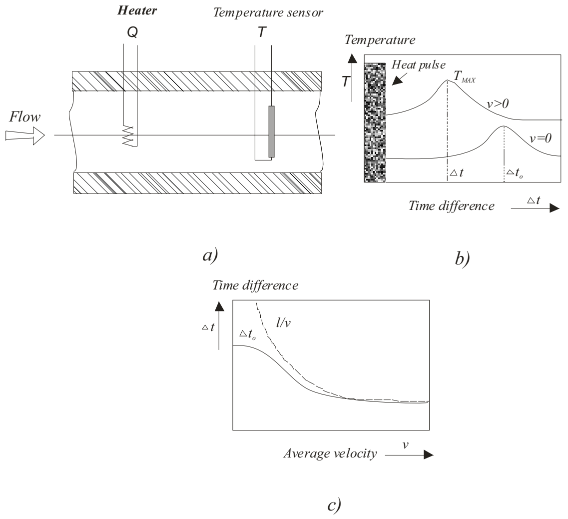

Fig. 1. Principles of the Time – of – flight sensor

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

where T is the temperature, c is the specific heat at the constant pressure, ρ is the density, v is the kinematic viscosity of the fluid, λ is the thermal conductivity and q' (in $W\,m^{-3}$) is the 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 ($W\,m^{-1}$) is given in [6] as :

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

where a denotes the thermal diffusivity.

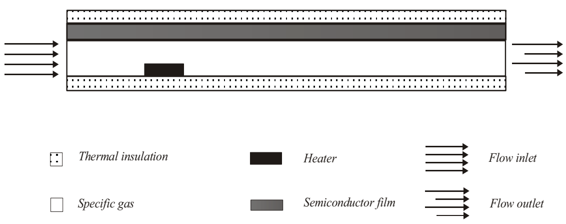

Fig. 2. Modified version of the Time – of – flight sensor

The designed flowmeter is modified version of the time – of – flight sensor. In this case a temperature field is measured by semiconductor film located in top part of sensor tube. The temperature profile in semiconductor film depends on gas velocity. The heater is activated periodically; the period of the heat pulses generation can be different for different velocity size.

3. NUMERICAL MODEL

3.1 Basic Equations for T(x,y)

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

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

$$\nabla.u = 0 \qquad (4)$$

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

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

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.

3.2 Modelling Approach

The modelling approach uses a numerical solution of the PDEs for constructing the model. First a steady-state model is developed and this is then extended to include the dynamic behaviour. The sequence of steps is outlined below

- a numerical solution is obtained for $T(x, y)$ from equations (3), (4) and (5) for different values of the velocity u, the height of the fluid channel d and the sensor width l
- this solution yields discrete data points for T_1, T_2, and T_3 as a function of u, d and l
- 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+ [1]. 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. Femlab is an interactive environment for modeling and solving problems based on partial differential equations. This program applies the finite element method (FEM) for solving of the PDEs system.

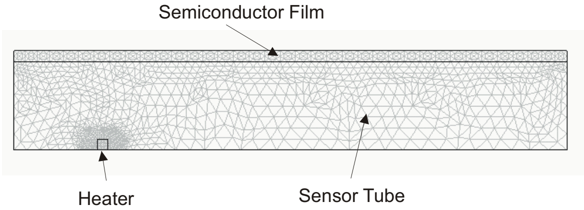

Fig. 3. Partial view of the computational grid for the basic configuration

The two dimensional configuration of the designed flowmeter in the present work can be seen in Fig. 3. The properties of the flow sensor were investigated at the relatively very low flow rates. In Table 1 are shown inlet speeds v of gas used in the sensor model and corresponding flow rate Q.

Table 1 Gas flow volumes and velocities according to the pipe eight 0.3 *mm*

Q[mlh^{-1}]	10	30	50	70	90
v [m.s^{-1}]	0.0309	0.0926	0.1543	0.2160	0.2778

The heater generates heat in the time interval <0,1> seconds. In the models the temperature change of the heater in time is shown in Fig. 4.

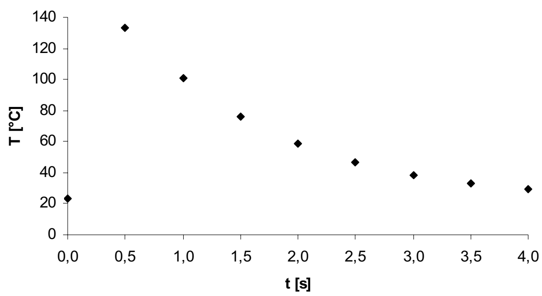

Fig. 4. Temperature change oh the heater in time

In the sensor model the temperature of the heater has changed periodically, Fig. 5.

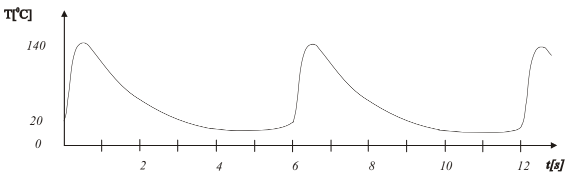

Fig. 5. The time path of the temperature of the heater

3.3 Modelling Results

The properties of the modified time – of – flight sensor were simulated and verified for different flowing gases, Table 2 and Table 3. The dependence of T_{MAX} on flow velocity v can be found in Fig.. 7, 8, 9; the temperature T_{MAX} was measured in semiconductor film.

Table 2 Gas Constants

Gas	Density [kg.m^{-3}]	Thermal conductivity [W.m^{-1}.K^{-1}]	Heat capacity [J.kg^{-1}.K^{-1}]	Dynamic viscosity [Pa.s]
O_2	0.66	0.025	1006	1.60×10^{-5}
CO_2	1.98	0.016	837	1.48×10^{-5}
N_2	1.25	0.026	1034	1.75×10^{-5}

Table 3 Material Constants

Material	Density [kg.m^{-3}]	Thermal conductivity [W.m^{-1}.K^{-1}]	Heat capacity [J.kg^{-1}.K^{-1}]
Silicon (Semi. film)	2330	1.63	703
Iron (Heater)	7870	76.2	440

The temperature profiles in different time intervals in semiconductor film are shown in Fig. 6.

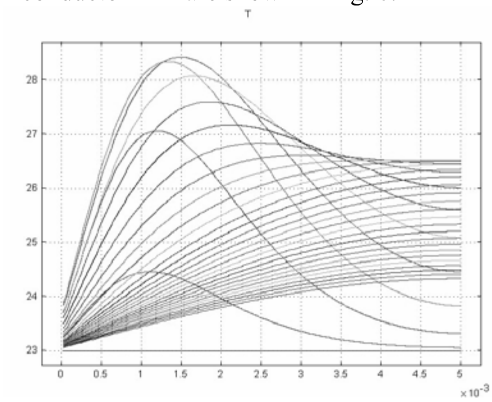

Fig. 6. The profile in semiconductor film

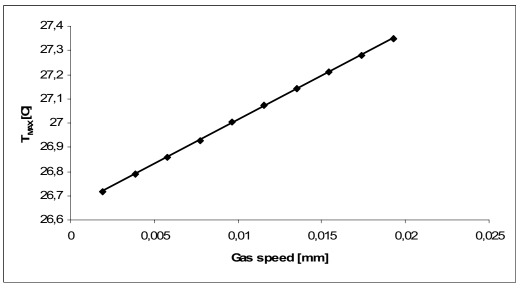

Fig.7. The dependence of T_{MAX} in semiconductor film on flow velocity v, gas–air, the height of the fluid channel d = 1,2 *mm*

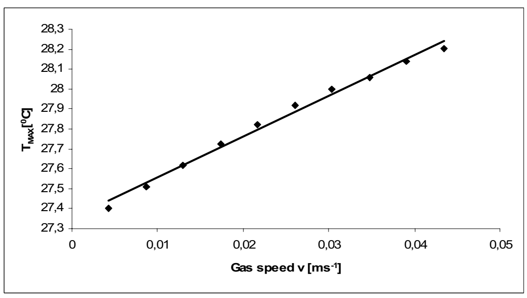

Fig.8. The dependence of T_{MAX} in semiconductor film on flow velocity v, gas – carbon dioxide, the height of the fluid channel d = 0,8*mm*

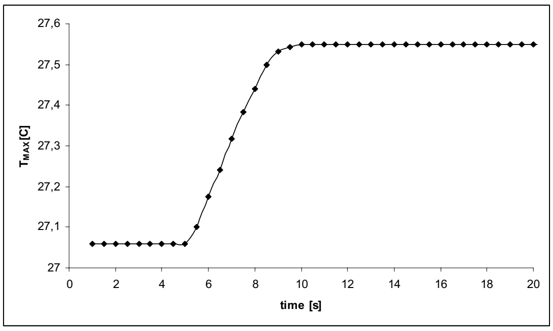

Fig.9. The time response of flow sensor: flow variation from 30*ml/hr* to 100*ml/hr*, the height of the fluid channel $d = 0{,}8mm$

IV. EXPERIMENTAL SET-UP

The modified time-of-flight sensor consists of a heater placed on the pipe's floor and series of downstream sensors (semiconductor diodes) placed in the pipe's upper wall. The heater is activated for 1 second by a current pulse. The heat generated by the heater spreads with the flowing gas and leads into resistance changes on the diodes. The resistance change upon each diode is measured as a voltage change by an A/D converter. From the particular points along the pipe is set the wave's heat profile which is scanned for the temperature maximum position. The flow volume is proportional to the position shift in time. The scheme drawing is shown in Fig. 10.

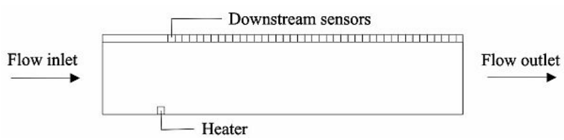

Fig.10. Experimental set-up of modified flow sensor

The heater is made from iron wire leaf, the semiconductor array is made of silicon. The whole pipe is put into a polystyrene casing to become thermally insulated from the ambient temperature conditions. The length of the pipe body has been set as 5*mm*.

4.1 Control Program

A program CONTROLWEB was used for visualization and saving of measuring data. A flow chart is presented in Fig. 12. The resistance change upon each diode is measured as a voltage change by an A/D converter. The voltage drops are measured in very short time periods, the period of measuring is 1ms. The voltage values are measured before bracing of the heating circuit and past disconnection of the heating circuit. By this philosophy is realized independence of the sensor output on the temperature of flow gas.

4.2 Experimental validation of modelling results

The validation of the finite-element/analytical model of the designed flowmeter was directly compared with experimental data. The peristaltic pump was used for the calibration of the modified time – of – flight sensor. The flow sensor was calibrated for air and CO_2. The measuring data can be seen in Fig. 13.

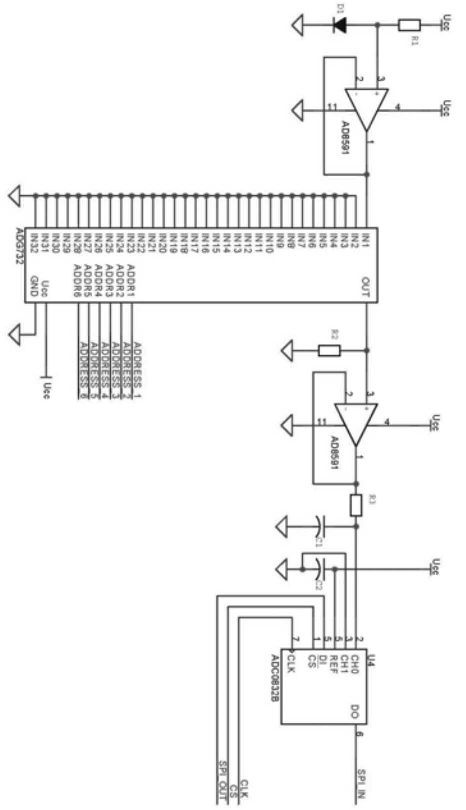

Fig.11. Block diagram of the modified sensor

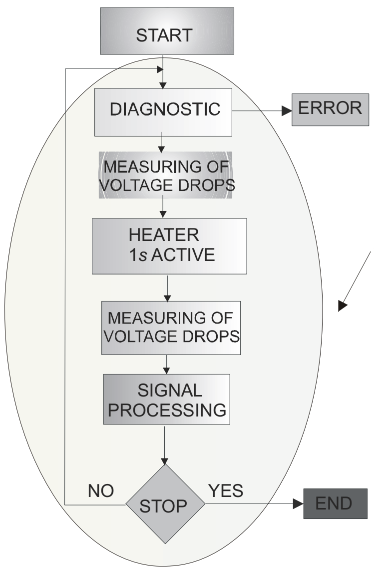

Fig.12. Flow chart

V. CONCLUSION

This article describes properties of the modified time – of – flight sensor. The designed flowmeter has been used in a biochemical laboratory for study of reaction kinetic of a decomposition of sediments in waste water.

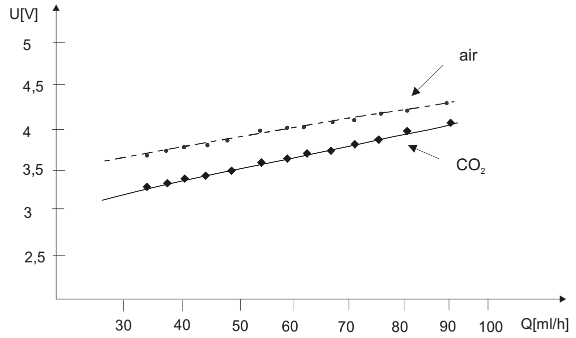

Fig.13. Static characteristic of modified sensor

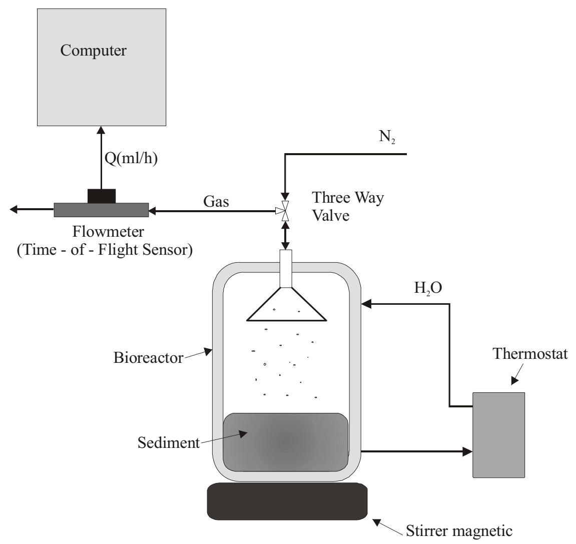

Fig.14. Using of designed flowmeter in biochemical laboratory

The basic configuration is shown in Fig. 14. The decomposition reaction has three parts:

- degradation
- hydrolysis
- acetolysis.

The reaction kinetic of the studied decomposition reaction can be seen in Fig. 15.

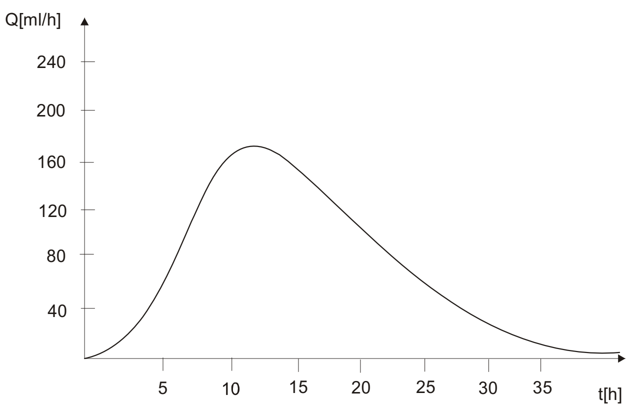

Fig. 15. The reaction kinetic of the decomposition reaction

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