ISSN 1848-0071
UDC 620.9+536.2=111
Recieved: 2011-07-19
Accepted: 2011-11-18
Preliminary communication

DESIGNING LOW GAS FLOW METERS BASED ON THE CALOMETRIC PRINCIPLE OF FLOW RATE MEASURING

MARIÁN LÁZÁR, TOMÁŠ BRESTOVIČ, EVA SCHVARZBACHEROVÁ

Faculty of Mechanical Engineering, Technical University in Košice, Slovakia
e-mail: eva.schvarzbacherova@tuke.sk

The current assortment of sensing devices for measuring rate of fluid flow covers a wide range of requirements related to normal operation conditions. In the area of the low and very low fluid flow devices the offered assortment is being diminished sharply. Availability of the devices is very limited and costly. The aim of the article is to design a methodology for constructing a sensor for measuring the low liquid flows and the experimental verification of design. The gas flow meter is based on the calometric measurement principle so that the flow rate it assessed taking into account the known transferred amount of heat to the fluid flow and the temperature differences of the medium before and after electric coil of Thomas cylinder determined by thermocouples.

Key words: nitrogen, gas flow meter (Thomas cylinder), thermal flow sensor.

Projektiranje mjerača za niske protoke plina temeljeno na kalorimetrijskom načinu mjerenja protoka. Trenutni asortiman osjetnika za mjerenje protoka fluida pokriva širok raspon potreba vezanih za normalne uvjete rada. Na području mjernih uređaja za mjerenje niskih i vrlo niskih protoka fluida asortiman je znatno sužen. Dostupnost uređaja je vrlo ograničena i praćena s visokom cijenom koštanja. Cilj članka je razraditi metodologija za izgradnju osjetnika za mjerenje niskih protoka fluida te provesti eksperimentalni postupak provjere metode. Mjerač protoka plina temelji se na kalorimetrijskom načinu mjerenja tako da se kod određivanja protoka uzima u obzir poznata vrijednost prenesene toplinske energija na struju fluida kao i temperaturna razlika medija prije i poslije električne zavojnice Thomasova cilindra izmjerena termoparovima.

Ključne riječi: dušik, mjerač protoka plina (Thomasov cilindar), osjetnik toplinskog toka.

INTRODUCTION

The technologies using plasma gasification are represented in various fields of industry starting with metallurgical processes, through synthesis of materials, to the destroying of different kinds of waste. High temperature and energy density of plasma arc ensure the destruction of organic materials, disposal and reuse of inert components. The outputs of the process are flammable gas known as syngas, recyclable metals and vitreous slag. To determine the percentage ratio of the gaseous components in the plasma gasification process (in the reducing atmosphere) it is important to correct syngas composition according to the amount of the inert gas (nitrogen) injected into the process. The standard methodology for determining the volume is based on the flow measurement of the gas consumed by the plasma torch.

As described Gardner, Julian W. in his book Microsensors, MEMS, and Smart

Device the most commonly used principle to detect flow in gases and liquids using microsensors is based on the concept of a thermal flow sensor that was first postulated by Thomas in 1911. The basic principle is shown in Fig. 1 in which the heat transferred per unit time from a resistive wire heater to a moving liquid is monitored at two points via thermocouple temperature sensors [1].

THOMAS CYLINDER DESIGN

The developed Thomas cylinder (TC), used for measuring the flow rate of gaseous fluid, is a device using calorimetric principle of flow rate measuring (Fig.1).

The most important element of TC is a kanthal coil with reguladable output providing energy input to the flowing fluid by transforming electrical energy into heat.

Sensing element of the device consists of the concentrically situated thermocouples which are placed in the specified distances from the electric coil.

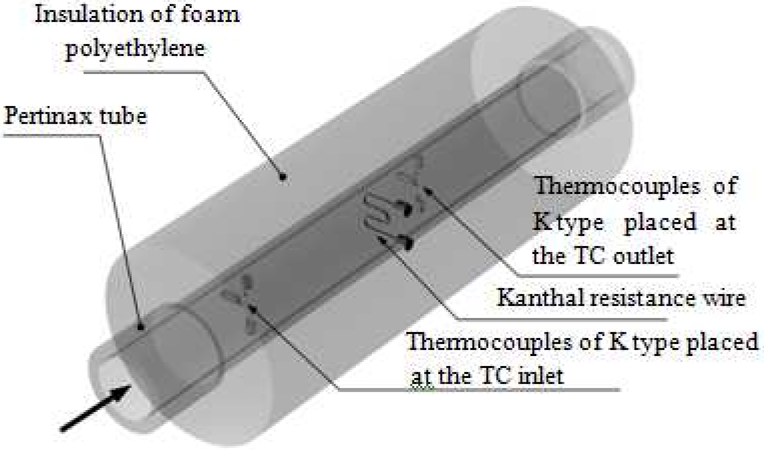

Figure 1. 3D view of final Thomas cylinder design
Slika 1. 3D prikaz konstrukcije Thomasova cilindra

When a steady state has been achieved, the transferred amount of heat to the flowing medium (nitrogen) by the electric coil (Kanthal resistance wire) with a thickness of 0.5 mm may be expressed by the following equation

$$Q = m \cdot c_p \cdot (T_2 - T_1) \quad \text{(J)} \qquad (1)$$

where are:

m - the mass of the gas overflow through TC (kg),
c_p - heat capacity of gas at constant pressure ($J \cdot kg^{-1} \cdot K^{-1}$),
T_1 - inlet temperature of TC (K),
T_2 - outlet temperature of TC (K)
[1,3].

The relationship for calculating the output necessary for heating up the flowing media is obtained if the equation (1) is divided by time

$$P = q_m \cdot c_p \cdot (T_2 - T_1) = \rho \cdot q_V \cdot c_p \cdot (T_2 - T_1) \quad \text{(W)} \qquad (2)$$

where are:

q_m - the mass flow of the gas overflow through TC ($\text{kg}\cdot\text{s}^{-1}$),
q_V - volumetric flow rate of gas ($\text{m}^3\cdot\text{s}^{-1}$),
ρ - density of gas at a mean temperature ($\text{kg}\cdot\text{m}^{-3}$).

By measuring of the known energy output and temperature difference in the defined cross-sections, which are placed at the one end – at the other end of the electric coil, it is possible to determine the amount of gas flow rate by using the following calculation. On assumption that the total output of the electric energy provided to the resistance wire is transformed into the thermal energy, the volumetric flow rate can be calculated from the following relationship

$$q_V = \frac{P}{\rho \cdot c_p \cdot (T_2 - T_1)} = \frac{U \cdot I}{\rho \cdot c_p \cdot (T_2 - T_1)} = \frac{R \cdot I^2}{\rho \cdot c_p \cdot (T_2 - T_1)} \quad (\text{m}^3\cdot\text{s}^{-1}) \qquad (3)$$

where are:

q_V - the volumetric flow rate of gas ($\text{m}^3\cdot\text{s}^{-1}$),
P - output necessary for heating up the flowing fluid (W),
U - is one-way electric voltage (V),
I - one-way electric current (A),
R - is electric resistance of heating coil (Ω).

For designing and optimalization of TC it is necessary to determine correctly the dimensions of resistance wire. By modification of equation (1) and on assumption that $q_{V,10}$ $\dot{V}_{10}$= 10 $\text{ml}\cdot\text{s}^{-1}$, I_{10} = 0,5 A, ρ = 1,165 $\text{kg}\cdot\text{m}^3$ (nitrogen at 20 °C), c_p = 1039 $\text{J.kg}^{-1}.\text{K}^{-1}$ and at temperature increase of $\Delta T \Delta T$ = 5 K, the amount of electric resistance of the wire is R_{10} = 0,2421 Ω. Required length of resistance wire of heating element (Kanthal) can be calculated on the basis of geometric dimensions and material of resistance wire by using the following relationship

$$R = \rho_m \cdot \frac{l}{S} \ (\Omega) \quad \Rightarrow \ l = \frac{\pi \cdot d^2 \cdot R}{4 \cdot \rho_m} = 0{,}0267 \ \text{(m)} \qquad (4)$$

where are:

ρ_m - specific electric resistance of resistance wire (Ω·m),
l - length of resistance wire (m),
S - area of cross-section of resistance wire (m^2),
d - is the diameter of Kanthal wire (m) [2].

Calculated theoretical length of heating element is used only as directive value of design. The real length of kanthal wire, which is in the shape of meander, is l_{sk} = 25,4 mm long, because of the construction reasons. The heating coil of TC is placed in pertinax tube of 10 mm inner diameter and its insulation is made of foam polyethylene.

The purpose of solving the construction arrangement of particular elements of TC, determination of optimal parameters and considering the right arrangement of thermocouples, ANSYS CFX software simulation tool was used.

The results and of the visual representation of requested flow rate (10 ml.s^{-1}) at the heat flux of the heating coil to overflow gas were determined by the temperature field in the plane perpendicular to the direction of the flow.

Regarding the great high heat flux from nitrogen to the insulation and very small total output provided to the kanthal wire in the core of the fluid, the temperature rapidly decreases with the increasing distance from the heating element. Due to this, the thermocouples were situated in the outlet only 10 mm from kanthal coil in order to keep $\Delta T \approx 5$ K between the surfaces of the measured temperatures (Fig. 2).

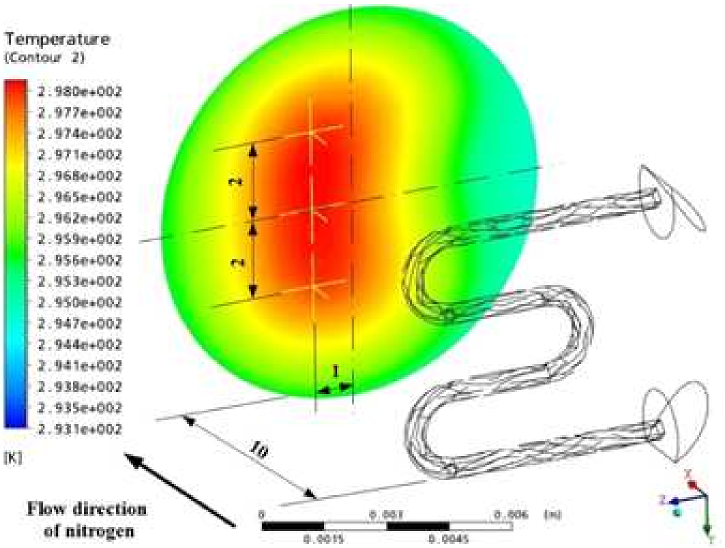

Figure 2. Thermocouple placement in the plane perpendicular to the flow direction
Slika 2. Položaj termopara u ravnini okomitoj na smjer strujanja fluida

In subsequent simulations of flow rate the average temperature was evaluated in the further three points location of the thermocouples. Necessary boundary conditions for calculation were used from Tab. 1

Table 1. The selected parameters of Thomas cylinder at $\Delta t = 5$K
Tablica 1. Odabrani parametri Thomasova cilindra za $\Delta t = 5$K

Volumetric flow q_V	***Velocity*** v	***Electric current*** I	***Heat flux of electric coil*** q
$(m^3.s^{-1})$	$(m.s^{-1})$	(A)	$(W.m^{-2})$
4.10^{-6}	0,051	0,324	606,3
8.10^{-6}	0,102	0,458	1212,2
10.10^{-6}	0,127	0,512	1515,9
20.10^{-6}	0,255	0,725	3031,7
30.10^{-6}	0,382	0,887	4547,6
40.10^{-6}	0,509	1,025	6063,4
50.10^{-6}	0,636	1,146	7579,3

The temperature difference between input and output of TC has under the given conditions calculated value of 5K.

The temperature fields in the plane of thermocouples in the output of TC at the different nitrogen flows are shown in Fig. 3.

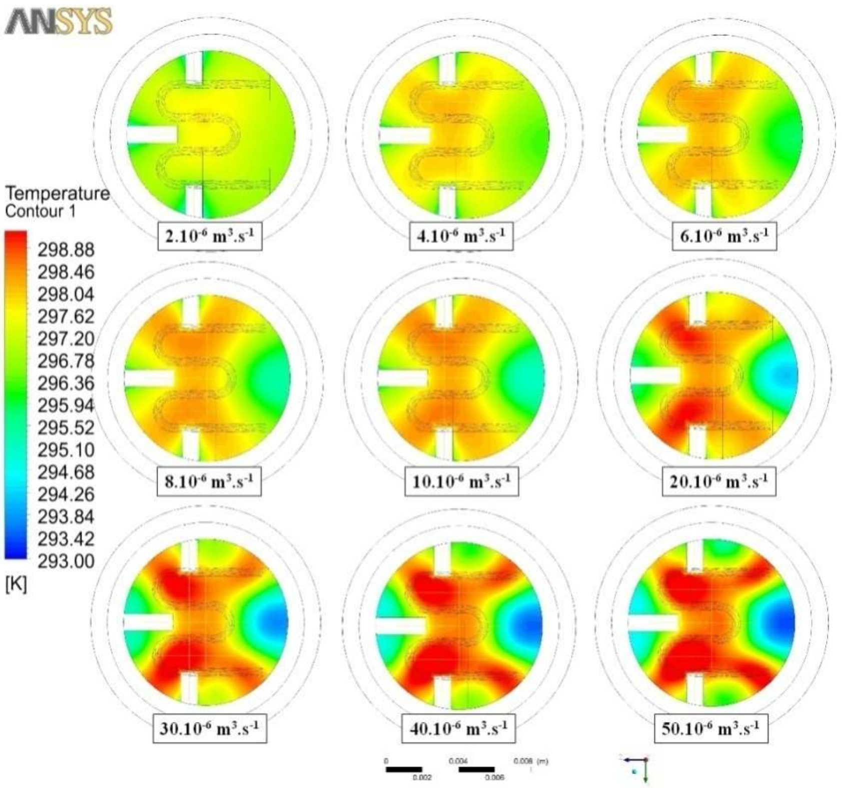

Figure 3. Temperature fields in the plane of thermocouples at different flows
Slika 3. Temperaturna polja u ravnini termoparova za različite protoke

The difference between the expected value and the calculated value in the programme ANSYS CFX can be corrected by using the theoretical correction coefficient k_T, which is dependent on the measured flow that can be expressed by the regression equation of the curve (Fig. 5).

The course of the calculated temperature differences before and after electric coil in the locations where the thermocouples are placed is shown in the Fig. 4. The graph in this figure shows the temperature difference increases with increasing flow rate due to the close location of thermocouples in the vicinity of a large resistive wire, where the temperature field in the cross section of TC is not sufficiently stabilized.

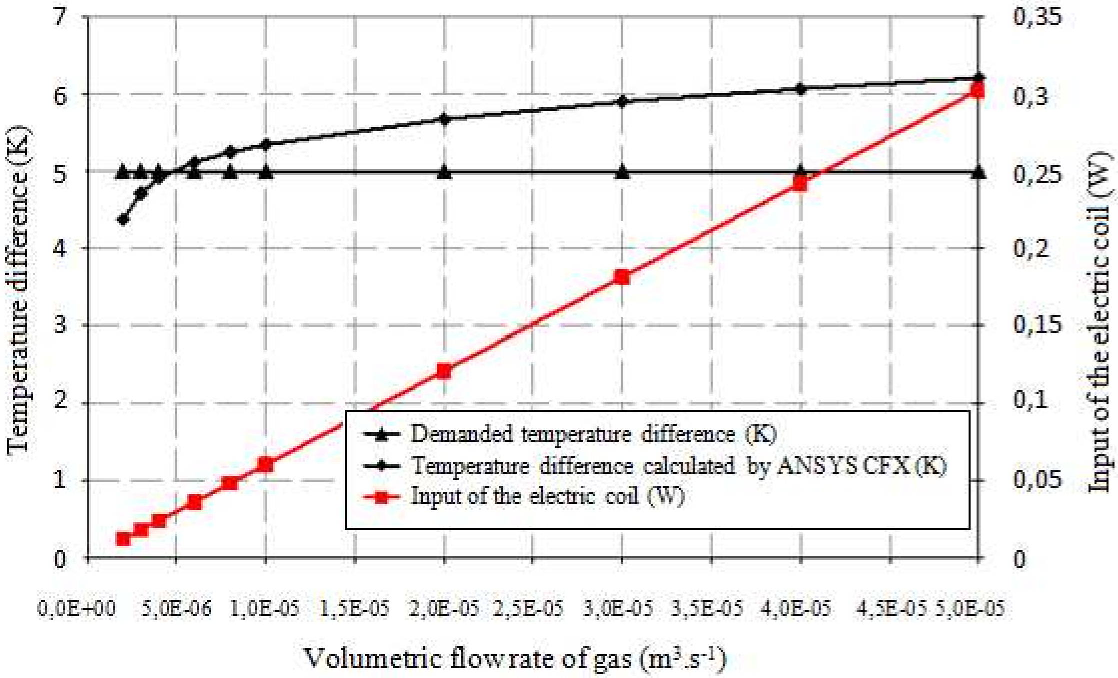

Figure 4. The course of the calculated temperature differences in the programe ANSYS CFX
Slika 4. Promjena vrijednosti izračunatih temperaturnih razlika u programu ANSYS CFX

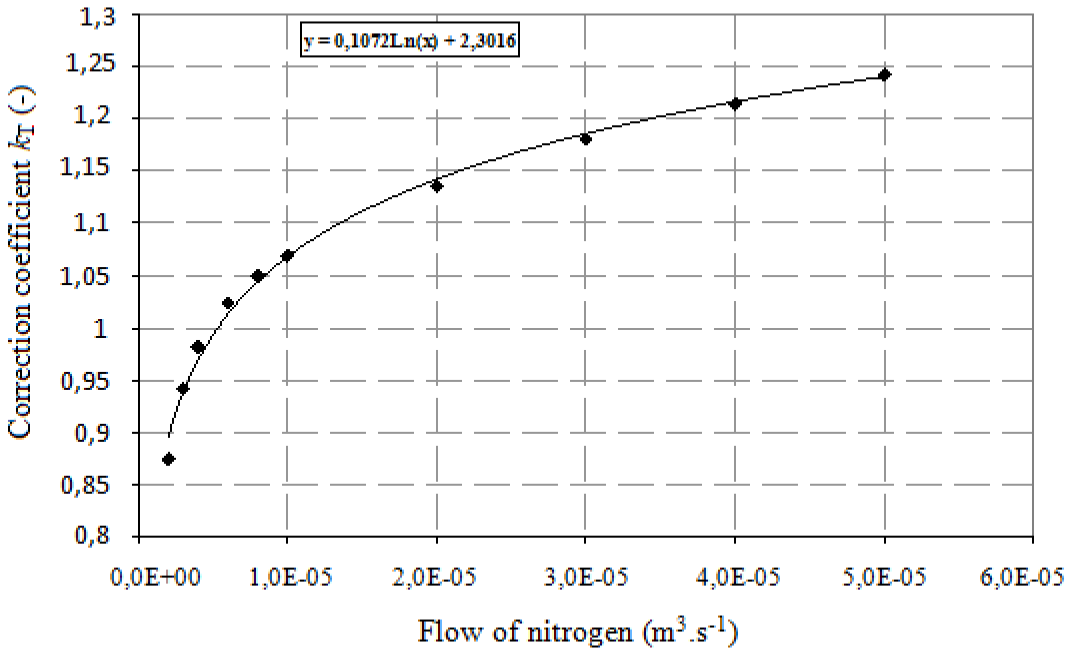

Figure 5. Dependence of the theoretical correction factor k_T on the measured flow rate
Slika 5. Ovisnost teorijskog korektivnog faktora k_T od izmjerene vrijednosti protoka

Theoretical correction factor represents the ratio of the temperature difference calculated by the program ANSYS CFX and the temperature difference expressed by the equation.

By combining the theoretical correction coefficient with equation (3), a final equation for calculating the actual flow of nitrogen q_V is obtained

$$q_V = \left[2{,}3016 + 0{,}1072 \cdot \ln\left(\frac{U \cdot I}{\rho \cdot c \cdot \Delta T}\right)\right] \cdot \frac{U \cdot I}{\rho \cdot c \cdot \Delta T} \quad (\mathrm{m^3 \cdot s^{-1}}) \qquad (5)$$

This equation is based on simulation calculation and its validity must be verified by experimental measurements.

Another important aspect was to place the thermocouples in the considerably steady temperature field. The thermocouples of K type with wire diameter of 0.013 mm were designed. They were reinforced with pertinax pillars with cross-section of 1 mm^2.

Two triples of anti-serially connected thermocouples (Fig.6) to eliminate measuring of the comparative temperature with simultaneous elimination of thermoelectric voltage between metals Chromel® - Alumel at placing these joints in the tight closeness at the same temperature $T_{\mathrm{surrounding}}$.

The resultant measured voltage was three times higher and simultaneously represented by average temperature along the cross-section.

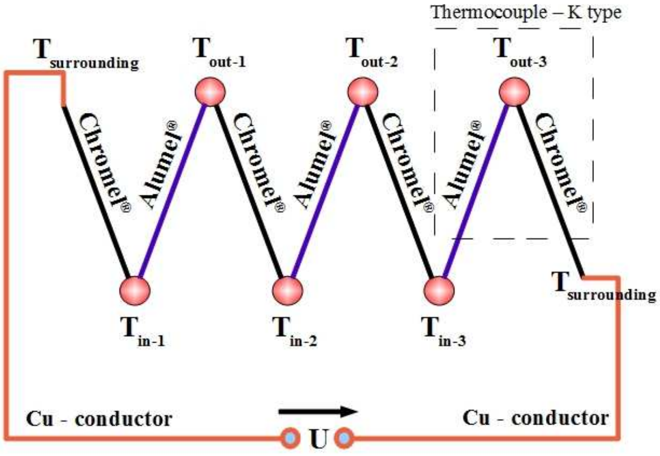

Figure 6. Connection of K type thermocouples
Slika 6. Priključak termoparova tipa K

EXPERIMENT

Unfortunately, the relationship between the flow rate and temperature difference is more complex and the precise relationship should be determined experimentally for different fluids. For more details on boundary layer thermal sensors, readers are referred to Meijer and van Herwaarden (1994) [1]. Preliminary calibration of the gas flow meter was complete in laboratory conditions. At the steady temperature difference of $T = 5$ K, the measurement were made at different flow rates of nitrogen. Calibration was based on measuring the volume of gas passed through TC per unit time.

The constant of proportionality, k_{um}, reflects the dependence between temperature difference ΔT and the measured voltages on the thermocouple. For a specific K type thermocouple and at temperature difference of 5 K on inlet and outlet near surrounding temperature of 20 °C, the difference in thermoelectric voltage is 0,5 mV. This assumption is valid for three pairs of anti-serially connected TC.

$$\Delta T = k_{um} \cdot U_{\mathrm{TC}} \qquad \text{(K)} \qquad (6)$$

where are:

ΔT - the temperature difference at fixed cross sections (K),

k_{um} - the constant of proportionality between the voltage on the thermocouples and the temperature difference ($\mathrm{K{\cdot}mV^{-1}}$),

U_{TC} - the voltage is connected through the anti-serially thermocouples (mV).

The actual flow of gas passed through the anti-serially thermocouples correction takes the form

$$q_V = k_T \cdot \frac{U \cdot I}{\rho \cdot c_p \cdot \Delta T} = \frac{k_T}{k_{\mathrm{um}}} \cdot \frac{U \cdot I}{\rho \cdot c_p \cdot \Delta T} \qquad (\mathrm{m^3{\cdot}s^{-1}}) \qquad (7)$$

Based on the experiment set flow values obtained through the TC, using the secondary device, the curve of ratio k_{T} / k_{um} of gas passed through the TC was constructed. Fig. 7 shows the curve of ratio k_{T} / k_{um} in the range of flow rates from 30 to 40 $\mathrm{ml.s^{-1}}$

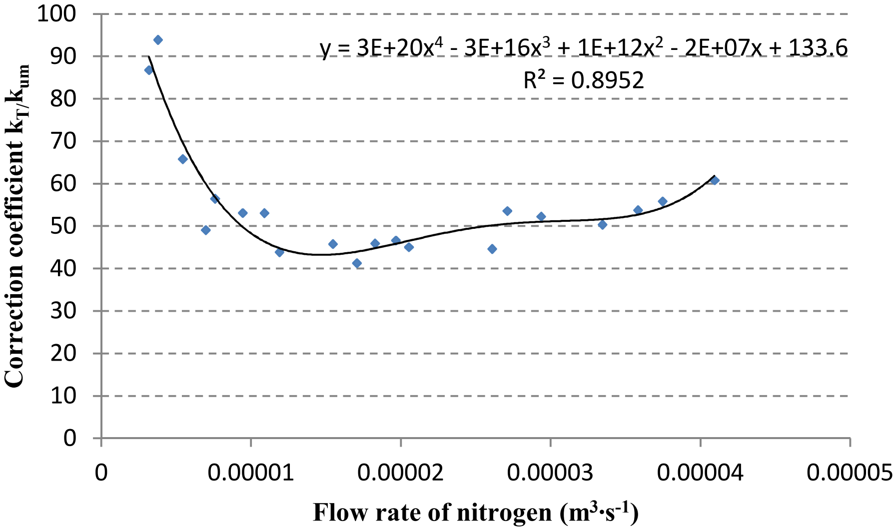

Figure 7. Dependence of the ratio k_T / k_{um}
Slika 7. Ovisnost omjera k_T / k_{um}

With regard to the functional dependence between the ratio k_T / k_{um} and the search of the flow is necessary to use an iterative calculation to achieve the required accuracy with the initial estimate of the ratio k_T / k_{um} on the level 50 $\mathrm{V{\cdot}K^{-1}}$.

DISCUSSION

As follows from experimental findings constructed gas flow meter based on the calorimetric measuring principle has minor deficiencies. When considering the flow range a confidence interval from 3 to 40 ml.s^{-1} flow equation constructed on the basis of measured data shows the value of R^2 = 0.895 of the polynomial function series 4. This function is used to automate the measurement for the subsequent iterative calculation of gas flow.

Deviation of the measured values from the polynomial curve appears on account of the uncertainly range of scanning device due to the material properties of TC parts and structural irregularities in the laboratory prototype. Location of thermocouples at a distance of 10 mm from the heating coil, because of the heat transfer by radiation and free convection flows in less than 10 ml, increases the measurement uncertainly. At a flow rate greater than 50 ml the temperature is not stabilized in the cross-section of location of the thermocouples.

The gas flow meter is suitable for measuring the stationary discharge is not changed when the heat storage and no ongoing transition phenomena in terms of heat transfer outer sensor. In the case of rapid changes of flow rate the heat balance of the flow gas is affected by heat transfer between the inner walls of Pertinax tube and the gas. Therefore it is necessary to obtain relevant values have to consolidate the heat flow across the sensor arrays.

The compensation for heat leakage is possible either by using other liquid – binding material in the production of that show better material properties corresponding to the required criteria and along with applying a reflective coating on the inner surface of Pertinax tubes along the length respectively at least in the heating coil.

Planned changes in the structure and related results will be published after reviewing the current proposal and the results will be continuously published.

CONCLUSION

Seems to be the fluids flow rate by using the designed method in the area of low flow rates is very complicated because of the heat losses of the sensing element and low heat capacity of gaseous fluid. It is evident that indirect way of volumetric fluid flow rate's calculation demands measuring of a great number of physical magnitudes and determining of correction coefficient k_T whose characteristics and dependence on flow rate needs to be determined by experiments. Based on experimental findings by measuring the gas flow meter designed certainly require construction modifications. This fact doesn´t deny the usefulness of the measurement methods and designed gas flow meter in area of small flow rates.

We would like to express sincere appreciation to the agency of MŠ SR for EU Structural Funds: Operational Programme "Research and Development", the projects no. ITMS 26220220044.

REFERENCES

1. Gardner, Julian W.; Varadan, Vijay K.; Awadelkarim, Osama O.: *Microsensors, MEMS, and Smart Devices.* Pub.: John Wiley & Sons, 2001, p. 528, ISBN 978-1-60119-081-9
2. Udrea, F., Julian W. Gardner, *Design of a silicon microsensor array device for gas analysis*. *In Microelectronics Journal,* [online]. 1996, vol. 27, issue 6, p. 449-457 [cit. 2011.04.23] Dostupné na internete: http://www.sciencedirect.com/science/article/pii/0026269295001123
3. B. W. van Oudheusden, *Silicon thermal flow sensors In Sensors and Actuators A: Physical,* [online]. 1992, vol. 30, issue 1-2, p. 5-26 [cit. 2011.04.23] Dostupné na internete: http://www.sciencedirect.com/science/article/pii/0924424792801926
4. Mikolaj, D., Čarnogurská, M.: *Určovanie charakteristiky ventilátora pomocou Thomasovho valca.* In: 26. Setkáni kateder mechaniky tekutín a termomechaniky, Herbertov, 2007, 6 p. ISBN 80-86786-09-9.
5. Brestovič, T., Lázár, M.: *Návrh Thomasovho valca pre meranie malých prietokov dusíka v plazmovom reaktore* In: 29. Setkáni kateder mechaniky tekutin a termomechaniky : mezinárodní konference : 23. - 25. 6. 2010, Rožnov pod Radhoštem. - Ostrava : VŠB-TU, 2010, p. 13-16, ISBN 978-80-248-2244-0.
6. Ražnjevič, K.: *Termodynamické tabuľky*, Bratislava, 1984.
7. Čarnogurská, M., Dobáková, R.: *Hydrodynamika a termodynamika.* Košice: TU v Košiciach, Strojnícka fakulta, 2009, 263 s. ISBN 978-80-553-0223-2.