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INTERNATIONAL CONFERENCE of SCIENTIFIC PAPER
AFASES 2011
Brasov, 26-28 May 2011

GLOBAL FLOW RATE MODELING WITH LOCAL HEATING TRANSITORY REGIME

Jinga Vlad*, **Oros Ramona Georgiana***, **Samoila Cornel***, **Ursutiu Doru***

*Faculty of Material Science and Engineering, Transilvania University, Brasov, Romania

Abstract: *This paper represents a theoretical approach of a measurement problem regarding a gas flow in special conditions.*

The modeling problem that will be presented in this paper was generated by the idea of measuring the flow in a transitory regime and without alterating the flow section.

Theoretically speaking, we have a problem regarding the heat and mass transport, more precisely a laminar convective transport, in which over the diffusional transport is interfering the property carries because of the fluid flow.

So, for this matter, in this paper, some theoretical aspects regarding the above mentioned subject will be shown and also, if possible, the results of the simulations that are currently done – if all the work will be finished in due time; if not, in the worst case scenario, some theoretical suppositions and forecasts regarding the evolution of the fluid temperature will be shown, underlining the direct relation between the heat transport and the length of the sensor (starting from the generation point of the heat pulse and ending after the receiving point) and also the traveling speed of gas.

Also, there was established a set of equations which describes the behavior of the gas temperature in the superficial layer after the thermal impulse, and the thermal balance in the transient stage, all for the determination of the correlation between the temperature and the gas flow.

Keywords: *gas flow measurement, heat impulse, thermal flow meter*

1. INTRODUCTION

Coming with the last years, the industrial domain got a more and more alert development rhythm because of the bigger and bigger demands on the specific market. Because of that, the authors of this paper are proposing a new sensor for measuring flows of different types of gases that are used in numerous industrial processes.

Most of the existing flow meters on the market these days have the tendency to disturb the pipe section through which the fluid flows, thus resulting a measurement of a local flow that is different from the total gas volume traveling along the pipe. Therefore, for determining the global flow of the fluid, a soft correction is necessary to be applied, causing some small errors regarding the wanted measurements.

The solution proposed by the authors of this paper is to develop a new sensor that can measure the gas flow in a transitory regime, without the disturbance of the flow section, by using a very easy and simple working principle: thermal pulses. For that reason, this paper will present a first mathematical approach regarding the functionality of the desired flow measuring sensor.

2. PROBLEM DEFINITION

The thermal impulse sensor can be assimilated with a thermal nozzle like in the next figure, in which the growth of the gas

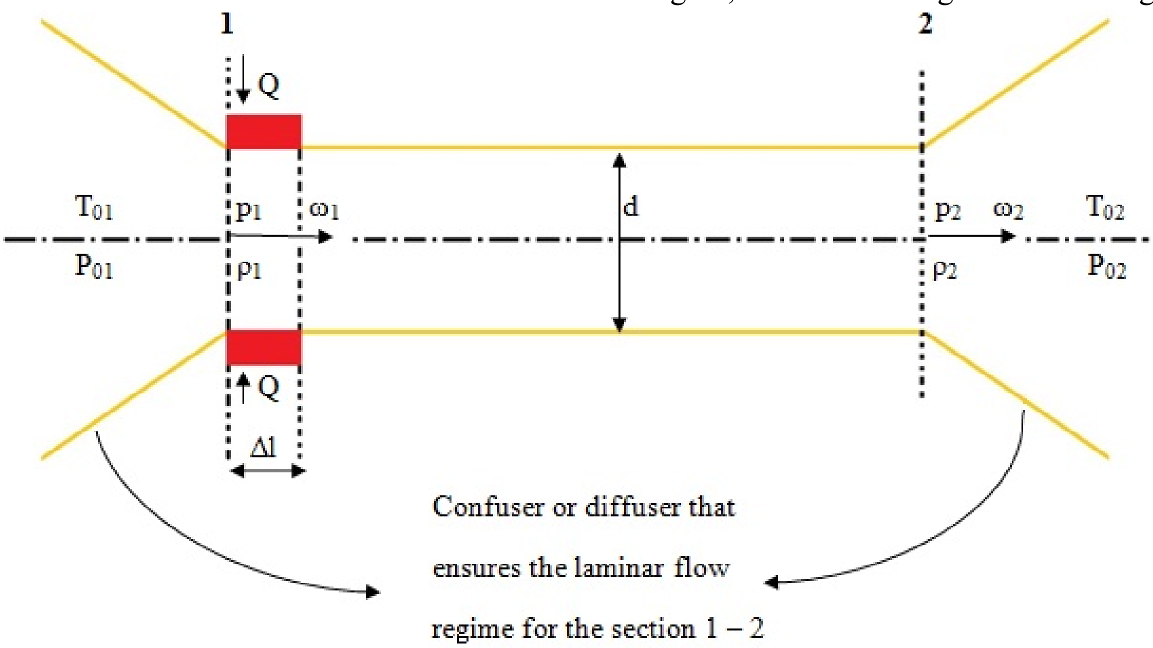

Fig. 1. Schematics of the thermal pulse gas flow measuring sensor

speed regarding the 1 – 2 section is related to a gas heating on a specific length Δl. The presented situation differs from a classical thermal nozzle because the heating does not occur on the whole length of the sensor, but only on a limited length of it, Δl.

As a following of the heating process, the density of the gas will decrease ($\rho_2 > \rho_1$) and the traveling speed of the gas along the pipe will increase. Both of the above mentioned modifications caused by the heating will make the momentary pressure to fall down ($p_2 < p_1$).

On the whole length of the pulse sensor, the flow will be subsonic, meaning that M << 1 so $M_1 < 1$ and also $M_2 < 1$.

Because the flow section of the pipe is constant (A = constant), the continuity equation is written:

$$\rho_1\omega_1 = \rho_2\omega_2 = \text{constant} \quad (1)$$

The equation regarding the applied impulse to the gas mass between section 1 – 2 on the flow direction, disregarding the friction, is:

$$p_1 - p_2 = \rho_1\omega_1 * (\omega_2 - \omega_1) \quad (2)$$

The Bernoulli equation regarding the total loss of pressure for the same section 1 – 2 is:

$$P_{01} - P_{02} = (p_1 - p_2) + \left(\frac{\rho_2\omega_2^2}{2} - \frac{\rho_1\omega_1^2}{2}\right) \quad (3)$$

Where p_1 and p_2 are:

$$p_1 = P_{01} - \frac{\rho_1\omega_1^2}{2}$$
$$p_2 = P_{02} - \frac{\rho_2\omega_2^2}{2} \quad (4)$$

The impulse equation can be written also:

$$p_1 - p_2 = \rho_1\omega_1\omega_2 - \rho_1\omega_1^2 \quad (5)$$

Because $\omega_1 = \rho_2\omega_2/\rho_1$ from the continuity equation, replacing this in the last relation (5), the impulse equation will become:

$$p_1 - p_2 = 2 * \left(\frac{\rho_2\omega_2^2}{2} - \frac{\rho_1\omega_1^2}{2}\right) \quad (6)$$

This transformation was made for rewriting the equation that describes the total loss of pressure (relation 3) under a more convenient form:

$$P_{01} - P_{02} = \frac{\rho_1 w_1^2}{2} * \left(\frac{\rho_1}{\rho_2} - 1\right) \quad (7)$$

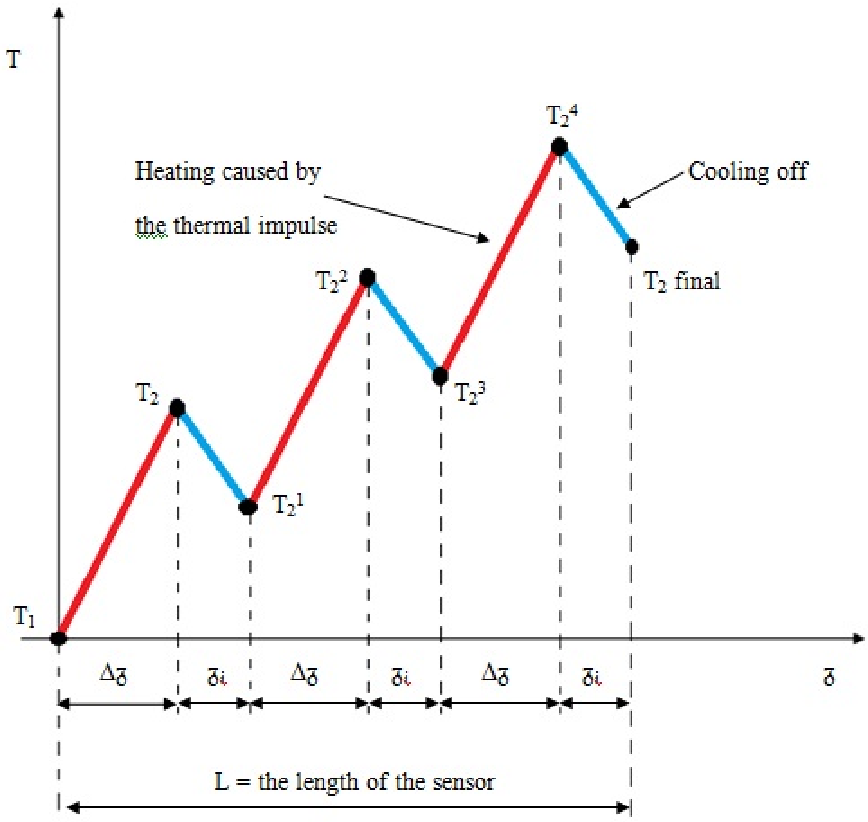

Fig. 2. Evolution of the gas temperature due the sequential impulse

Relation 7 represents the analytical proof that the decreasing of the momentary pressure ($p_2 < p_1$) depends on the growing of the gas temperature, fact which influences the densities ratio ($\rho_2 > \rho_1$). Because for a specific gas, the densities ρ_1 and ρ_2 are depending only on the temperature, the last equation can be written also like:

$$P_{01} - P_{02} = E_c * \left[\rho_1\left(\frac{\rho_1}{\rho_2} - 1\right)\right] = E_c * f(\rho) \quad (8)$$

Where $E_c = \omega_1^2/2$ represent the kinetic energy of the gas. In this case, it is possible to draw a variation of the gas kinetic energy depending on the values regarding the gas densities, on various sections of the flow sensor.

Because on the whole Δl segment of the section 1 – 2 a heat impulse transfer takes place (on the whole pipe periphery) in a specific Δ□ time interval, afterwards continuing with a time break □i, the gas will behave as following: after receiving the pulse and having reached its maximum temperature, the heated gas will cool down without reaching its initial temperature (previous of the thermal impulse); the cycle described before is a repetitive one, thus resulting a step heating of the gas from temperature T_1 until the final temperature T_2, like shown in Figure 2.

Because from the beginning it was accepted the fact that M << 1, from the continuity equation (relation 1) a simplifying hypothesis that doesn`t introduce significant errors to the model can be written as follows:

$$\frac{\omega_1}{\omega_2} = \frac{\rho_2}{\rho_1} \approx \frac{T_1}{T_2} \approx \frac{T_{01}}{T_{02}} \qquad (9)$$

This hypothesis is allowing the assumption that $P_{01} - P_{02} \cong 0$ meaning that the Bernoulli equation (relation 3) becomes:

$$0 = (p_1 - p_2) + \left(\frac{\rho_1\omega_1^2}{2} - \frac{\rho_2\omega_2^2}{2}\right) \qquad (10)$$

The expression for the pressure fall on the pipe is $\Delta p = P_{01} - p_2$. Keeping into account relations no. 4 and 5 and simplifying the new equation as much as possible, the final expression of the pressure fall on the pipe will be:

$$\Delta p = P_{01} - p_2 = $$
$$= \frac{\rho_1\omega_1^2}{2} * \left(2 * \frac{\omega_2}{\omega_1} - 1\right) \qquad (11)$$

The gas volume that flows through the pipe section 1 – 2 is $D = \rho_1 * \omega_1 * A$, where A represents the flow section (A is the interior diameter of the pipe through which the gas flows and is constant all along).

The relation between the gas flow and the temperature of the gas is as follows:

$$D = \frac{2 * \Delta p}{\omega_1} * \frac{1}{2 * \frac{T_2}{T_1} - 1} \qquad (12)$$

For introducing in the calculations also the thermal flux received by the flowing gas through the pipe, for characterizing the flow described by the last relation (12), the equations regarding the braked enthalpies must be written:

$$h_{01} = h_1 + \frac{\omega_1^2}{2}$$
$$h_{02} = h_2 + \frac{\omega_2^2}{2} \qquad (13)$$

The thermal flux received by the gas mass unit in the specific time interval is q = Q / D, where Q is the heat quantity, which implies the assumption of the simplifying hypothesis that $C_p = C_{p1} = C_{p2} = \ldots$, thus resulting:

$$q = C_p * (T_{02} - T_{01}) =$$
$$= C_p(T_2 - T_1) + (\omega_2^2 - \omega_1^2)/2 \qquad (14)$$

As a final result of this part of the mathematical model regarding the thermal pulse gas flow measuring sensor, a four equation system with four unknown variables will be presented:

$$\rho_1\omega_1 = \rho_2\omega_2$$
$$p_1 - p_2 = \rho 1\omega 1(\omega 2 - \omega_1)$$
$$\frac{p_1}{\rho_1 T_1} = \frac{p_2}{\rho_2 T_2} \qquad (15)$$
$$C_p(T_2 - T_1) + \frac{(\omega_2^2 - \omega_1^2)}{2} = \frac{Q}{\frac{2 * \Delta p}{\omega_1 * (2 * \frac{T_2}{T_1} - 1)}}$$

The first equation of the above system is relation 1 – the continuity equation, and the second one is the expression of relation no. 5 where a common factor was applied.

The third relation of the system is an expression of the perfect gases equation and the last equation was obtained by combining the relations no. 12 and 14.

The presented system has four unknown variables, all of them being gas parameters after the thermal pulse has been generated and the heat exchange took place: T_2, p_2, ρ_2 and ω_2. All the other variables are input factors, well known as value and are regarding the initial condition of the gas (before the appearance of the thermal pulse): T_1, p_1, ρ_1, ω_1, Q and C_p.

3. FUTURE WORK

All the variables calculated from the previous four equation system are needed as inputs for the next step of the mathematical model concerning this thermal pulse gas flow sensor.

The next stage is to determine the heat transfer that occurs inside this flow sensor because of the thermal pulse by using the method of the thermal balance in transient regime of the elementary cube.

At the end of that part, the desired results should be two relations. First of them should show the dependence between the travelling speed of the gas in the pipeline and its temperature in the moment of heating and in the second one, the relation between the travelling speed of the gas in the pipeline and the gas temperature in the moment of the cooling should be seen.

Afterwards, by knowing these dependences some graphs and some simulations can be done, thus resulting the theoretical approach for measuring gas flows with the help of thermal impulses.

As expected, every theoretical aspect obtained from the mathematical modeling will be verified and compared with the practical results of the experiments that will be done in the near future.

4. CONCLUSIONS

After finishing all the simulations (work in progress) of the above described system with all the working hypothesis and conditions, the obtained results are to be satisfactory and conclusive, according to the original expectations. The next step will be to start the development of an experimental booth that will help to put to practice all the theoretical aspects presented along this paper, and to start practical work for determining the frequency for the repeatable cycle: generating the thermal impulse, thus heating and then cooling and receiving all the needed data for determining the gas flow in a transitory working regime without alternating the flow section.

5. ACKNOWLEDGMENT

This paper is supported by the Sectoral Operational Programme Human Resources Development (SOP HRD), financed from the European Social Fund and by the Romanian Government under the contract number POSDRU/88/1.5/S/59321 and POSDRU/6/1.5/S/6.

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