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MEASUREMENT OF THE MOLAR CONCENTRATION IN AIR-CARBON DIOXIDE MIXTURE BY MEANS OF HOT-WIRE ANEMOMETRY

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Summary: *The diffusion of the fluid particles is one of the important fundamental problems of the research of transitional and turbulent flows. This phenomena is of great importance in case of pollutants spreading. In experimental study of the diffusion there is commonly used an admixture gas as a tracer, which enter the main airflow. The paper deals with the simultaneous measurement of the velocity and the molar concentration in binary-gas mixture by means of hot-wire anemometry. A special three-sensor probe has been manufactured and the calibration in Air-CO_2 mixture is presented.*

1. Introduction

Hot-wire anemometer (HWA) is capable to follow rapid changes of the velocity and the molar concentration of a flow. A heated element is sensitive not only to the velocity but also to the thermophysical properties of a flow. Sensitivities to the observed quantities depends on the wire orientation and the wire temperature. It makes a simultaneous measurement of the velocity and the molar concentration possible with multiple-sensor probe. Such measurement allows evaluation of the mean values, the standard deviations and the covariance of velocity and concentration of the gas mixture.

2. Cooling of the sensor

Heat transfer is frequently described by the cooling law of Collis and Williams (1959), which was modified by Koch and Gartshore (1972) to the form suitable for hot-sensor of finite length. It may be expressed for all three hot-sensors as follows:

$$Nu_j \left(\frac{T_{mj}}{T_a} \right)^{m_j} = A_j + B_j \, Re_j^{n_j} \quad ; \quad j = 1,2,3 \tag{1}$$

Nusselt and Reynolds numbers are defined by equations:

$$Nu_j = \frac{Q_j}{\pi l_j \lambda_{mj} \left(T_{wj} - T_a \right)} = \frac{R_{wj} E_j^2}{\pi l_j \lambda_{mj} \left(R_{Aj} + R_{wj} \right)^2 \left(T_{wj} - T_a \right)} \quad ; \quad Re_j = \frac{d_j u \rho_{mj}}{\mu_{mj}} \tag{2}$$

Subscript j denotes the number of a hot-sensor of the composite probe, and m means, that properties of fluid are considered at the mean film temperature T_{mj}=0,5(T_{wj}+T_a) , which is a mean of heating temperature T_{wj} of j-sensor and the gas temperature T_a. E_j is an output voltage

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of the anemometer connected to the j-sensor and l_j and d_j are its length and diameter respectively, R_{wj} denotes the heating resistance of j-sensor and R_{Aj} is a sum of leads resistance R_{Lj} from anemometer to j-sensor and certain fixed resistance R_B in an anemometer bridge, which is connected in series with R_{wj} and R_{Li}. The density ρ, thermal conductivity λ and molecular viscosity μ of the mixture are evaluated for the concentration C and the mean film temperature T_{mj} by formulas quoted in Mazur et al. (2003).

3. Three-sensor probe

A hot-wire probe with three wires has been made. The probe (fig. 1) is composed from two parallel heated wires (space between wires is about 0.5 mm) and one inclined wire. The first sensor W1 has a Pt-Rh wire (platinum-rhodium alloy) of the diameter d_1=10e-06 m and the length l_1=1.22e-03 m. The second sensor W2 has a tungsten wire of the diameter d_2=2.5e-06 m and the length l_2=1.54e-03 m. The third sensor W3 has an inclined (angle β=48°) tungsten wire of the diameter d_3=5e-06 m and the length l_3=1.25e-03 m.

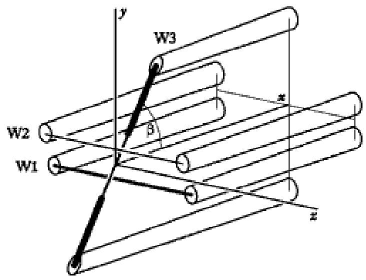

Fig. 1 Arrangement of the sensors of the probe.

Each heated sensor of the probe was calibrated against the velocity u and the mean temperature T_m at a series of the molar concentrations C. Calibration of the probe was performed at the Institute of Thermomechanics AS CR in a special close-circuit rig designed for probe calibrations and measurements in gas mixtures. The test section has circular cross section (diameter 14 mm). The rig can be filled up with a non-explosive gas from a gas bottle (detailed description of the facility is e.g. in Mazur at al. 2001). The admixture concentration was measured using Carbon Dioxide Monitor Guardian Plus (Edinburgh Instruments and Sensors). Temperature of the gas T_a was measured by Pt100 thermometer. The three channel CTA system DANTEC Streamline was used for operating wires. The output signals are then digitalized using the A/D transducer (National Instruments data acquisition system, sampling frequency 25 kHz, 16 bit).

4. Results

Statistical estimates of the parameters A, B, m, n appearing in the cooling law (1) were calculated from the measurement at the given concentration C=0–0.91 and several flow velocities u=3–20 m.s^{-1}. Operating wire temperatures are T_{w1}=773 K, T_{w2}=T_{w3}=473 K. The distributions of m and n varied litle with C in the whole interval of the concetration. Distribution of n is shown on graphs.

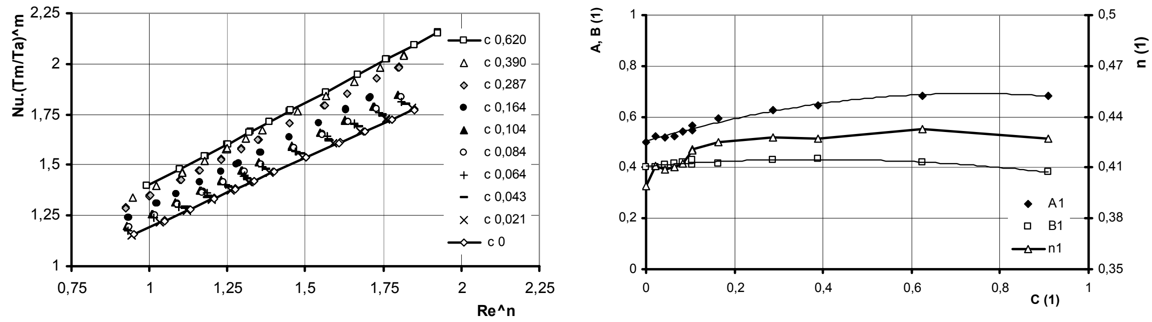

Fig. 2 Wire 1 **-** Heat transfer data in the mixture and calibration coefficients.

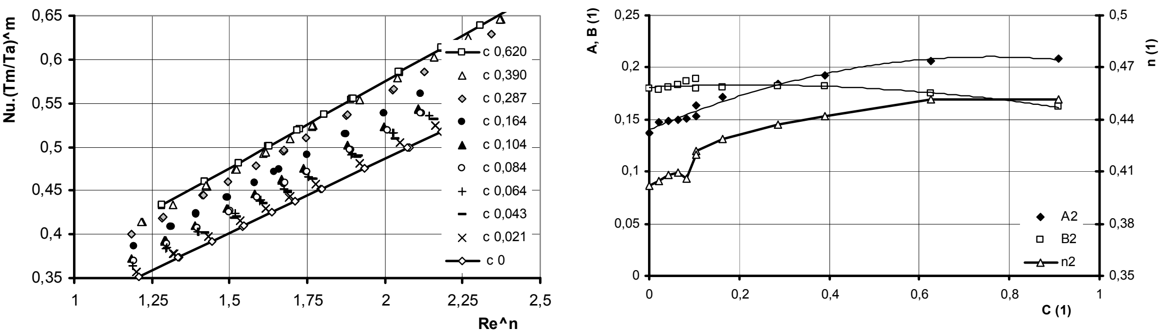

Fig. 3 Wire 2 **-** Heat transfer data in the mixture and calibration coefficients

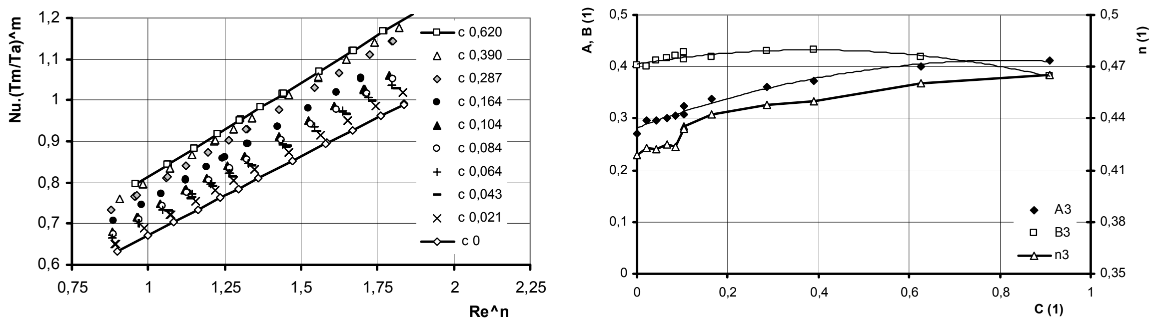

Fig. 4 Wire 3 **-** Heat transfer data in the mixture and calibration coefficients

Exponents *m* and *n* can be considered as constants (taking the mean values), for simplification of evaluation procedure. The analysis of correlations gives regression functions of coefficients *A* and *B* with concentration *C* as following:

$$A_j = \sum_{k=0}^{2} a_{jk} C^k \ ; \ B_j = \sum_{k=0}^{2} b_{jk} C^k \tag{3}$$

The coefficients for all wires are given in Table 1.

j	*A*	*B*	*m*	*n*
1	$0.512+0.337C-0.207C^2$	$0.385+0.251C-0.246C^2$	-0,22	0,41
2	$0.151+0.102C-0.069C^2$	$0.170+0.106C-0.103C^2$	-0,67	0,42
3	$0.302+0.217C-0.139C^2$	$0.385+0.253C-0.248C^2$	-0,71	0,44

Table. 1 Calibration coefficients of hot sensors.

Due to small space between wires W1 and W2, both of them should indicate the same velocity u of the mixture. Calculating of the molar concentration from cooling laws of both parallel wires using equations (1)-(3) leads to the following relation:

$$\frac{\mu_{m1}}{d_1\rho_{m1}}\left[\frac{1}{B_1}\frac{R_{w1}E_1^2}{\pi l_1\lambda_{m1}\left(R_{A1}+R_{w1}\right)^2\left(T_{w1}-T_a\right)}\left(\frac{T_{m1}}{T_a}\right)^{m_1}-\frac{A_1}{B_1}\right]^{\frac{1}{n_1}}= \\ =\frac{\mu_{m2}}{d_2\rho_{m2}}\left[\frac{1}{B_2}\frac{R_{w2}E_2^2}{\pi l_2\lambda_{m2}\left(R_{A2}+R_{w2}\right)^2\left(T_{w2}-T_a\right)}\left(\frac{T_{m2}}{T_a}\right)^{m_2}-\frac{A_2}{B_2}\right]^{\frac{1}{n_2}} \quad (4)$$

Temperature of the gas mixture T_a has to be measured independently. For a given hot-wires operated at a given heating temperatures T_{wj} are quantities ρ_{mj} , λ_{mj} , μ_{mj} and coefficients A_j, B_j known functions of a gas mixture temperature T_a and molar concentration C. Equation (4) represents an implicit equation for C and it can be solved numerically.

5. Conclusion

Sensitivity of the heated sensor to the molar concentration of Air-CO_2 mixture is substantial. This allows us to measure this quantity by means of hot wire. In experiments on diffusion, where the admixture gas is used as a tracer, the molar concentration is usually small. As we can see from calibration data, the sensitivity decreases with increase of the concentration value. The sensitivity is the highest at low concentration values C~0–0.2 (0–20% CO_2).

6. Acknowledgement

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7. References

Collis, D.C., Williams, M.J. (1959): *Two-dimensional convection from heated wires at low Reynolds numbers*. J.Fluid Mech. **6**, pp. 357-384.

Koch, F.A., Gartshore, J.S. (1972): *Temperature effects on hot-wire anemometer calibrations.* J.Phys.E: Sci.Instrum., 5, pp. 58-61.

Mazur O., Řehák V., Šarboch J., Uruba V., (2001): *Formation of an air-helium mixture and determination of their concentration in a hermetically closed calibration device*. (In Czech), In: Proc. Coll. Fluid Dynamics, IT AS CR Prague (ISBN 80-85918-67-6), 59-62.

Mazur, O., Jonáš, P., Šarboch, J ., Uruba, V. (2003): *Calculation of the physical properties of some gases mixtures* (in Czech). In: Proc. Topical Problems of Fluid Mechanics 2003, IT AS CR Prague, pp.67-72.