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HOT-WIRE ANEMOMETRY MEASUREMENT OF DIFFUSION OF AIR-CARBON DIOXIDE ADMIXTURE IN FLOW OVER TWO-DIMENSIONAL HILL

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ABSTRACT

In experimental study of the diffusion there is commonly used an admixture gas as a tracer that enters the main airflow. The paper deals with the simultaneous measurement of the molar concentration in binary-gas mixture by means of hot-wire anemometry. A special three-sensor probe has been manufactured and used for this task. A case of polynomial shaped 2D hill with the line source of tracer gas has been studied in detail. Geometry of the hill was taken from Almeida at al. Experimental study of the binary-mixture concentration field over the hill has been done.

INTRODUCTION

Measurement of the velocity and the molar concentration by means of hot-wire anemometer (HWA) is possible using a multiple-sensor probe. A heated element is sensitive not only to the velocity but also to the thermophysical properties of a flow.

NOMENCLATURE

u	[m/s]	fluid velocity in main free-stream direction (x direction)
v	[m/s]	fluid velocity in y direction
C	[-]	molar concentration of CO_2 in the mixture with air
Q	[m^3/s]	fluid volume rate
x	[m]	Cartesian coordinate, in the undisturbed flow direction
y	[m]	Cartesian coordinate
Tu	[-]	turbulence intensity
E_j	[V]	anemometer output voltage of j-sensor
S_{Cj}	[V]	concentration sensitivity of j-sensor
S_{uj}	[V.s/m]	velocity sensitivity of j-sensor
Nu_j	[-]	Nusselt number of j-sensor
Re_j	[-]	Reynolds number of j-sensor
A,B,n,m	[-]	parameters of heat-transfer law
T_{wj}	[K]	operating temperature of j-sensor
T_a	[K]	temperature of the flow
ρ, λ, μ		thermophysical properties of the mixture
d_j,l_j	[m]	diameter and length of j-sensor
h	[m]	height of the hill
H	[m]	height of the channel

Sensitivities to the observed quantities depend on wire temperature HWA measurement allows evaluation of the mean values and the variance of concentration of the gas mixture.

There was a two-dimensional polynomial shaped hill in the channel. Carbon dioxide was streamed into the main air-flow as a tracer. Experiments have been provided on the open type wind rig, which is powered by ventilator. All measurements were done at one value of mass flow of the main stream and one value of mass flow of the tracer stream.

EXPERIMENTAL SETUP

A scheme of the hill in the channel is in fig. 1. Cross section of the channel is of a width of 0.1 m and a height of 0.25 m. The channel downstream the hill was 0.4 m in length, and the ratio of the hill height h to the channel height H was 6.07.

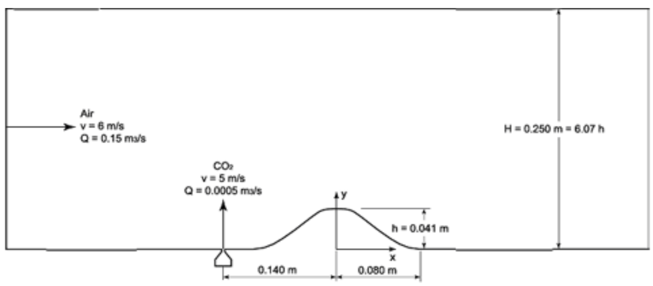


Figure 1 Experimental arrangement.

The tunnel has rectangular cross section with filled corners, honeycomb and a system of damping screens followed by contraction with contraction ratio 16. The time-mean velocity departures from homogeneity in planes perpendicular to the tunnel axis are of order tenth of percent with the exception of corners, where corner vortex starters could be detected. Reynolds number based on the height of the hill and volume velocity was about 1.3e4. The natural turbulence level was about 0.2% in the working section input.

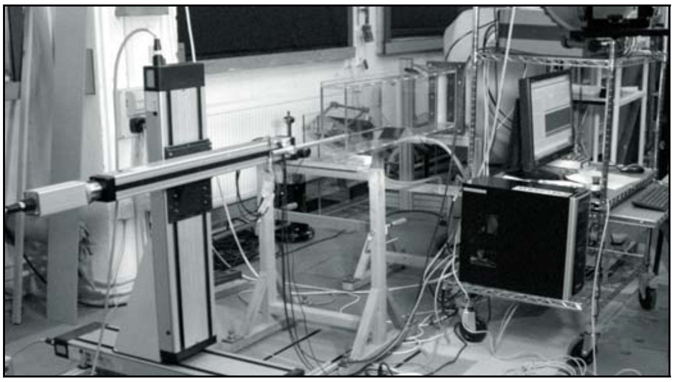


Figure 2 The slot upstream the hill and the total-pressure probe.

The channel has perspex walls (see Fig. 2). Upstream of the hill there is a slot for admixture input. The width of the slot is 1e-3 m. The admixure was supplied from a gas bottle. Pressure of the gas flow is maintained by reduction valve on a constant value. A metering nozzle is placed ahead of the slot.

MEASUREMENTS

The special three-sensor probe was used for the concentration measurement. The probe (Fig. 3) is composed from two parallel heated wires (space between wires is about 5e-4 m) and one inclined wire. The first sensor W1 has a Pt-Rh wire (platinum-rhodium alloy) of the diameter d_1=10e-6 m and the length l_1=1.22e-3 m. The second sensor W2 has a tungsten wire of the diameter d_2=2.5e-6 m and the length l_2=1.54e-3 m. The third sensor W3 has an inclined (angle β=48°) tungsten wire of the diameter d_3=5e-6 m and the length l_3=1.25e-3 m. Operating wire temperatures are T_{w1}=773 K, T_{w2}=T_{w3}=473 K.

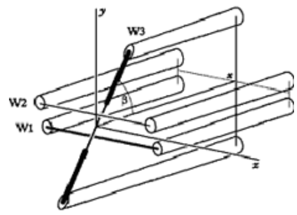


Figure 3 Arrangement of the sensors of the probe.

Heat transfer is 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:

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

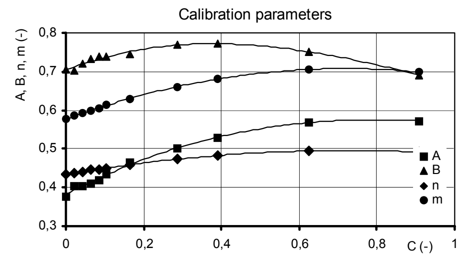
Nusselt and Reynolds numbers are defined by equations:

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

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 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).

Calibration in mixture air-CO_2 at several concentrations C=0–0.91 and several flow velocities u=3–20 m.s^{-1} was performed in a hermetic close-circuit rig. The admixture concentration was measured using Carbon Dioxide Monitor Guardian Plus (Edinburgh Instruments and Sensors). Calibration curves for one sensor demonstrate Graph 1.



Graph 1 Variation of calibration parameters *A, B, n, m* with the concentration *C* (sensor W2).

Then a polynomial regression of calibration parameters for each wire is done. Example of sensor W2:

A = 0,0908C^3 - 0,4487C^2 + 0,5437C + 0,3812
B = 0,2006C^3 - 0,6229C^2 + 0,3859C + 0,7045
n = -0,1174C^2 + 0,1699C + 0,4344
m = -0,2521C^2 + 0,3626C + 0,5776

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).

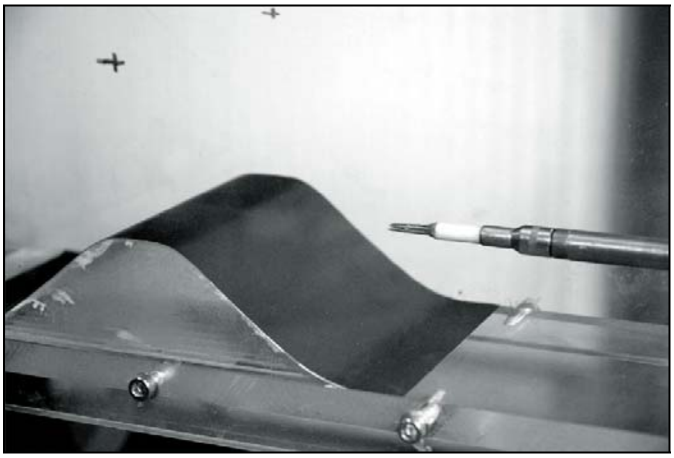


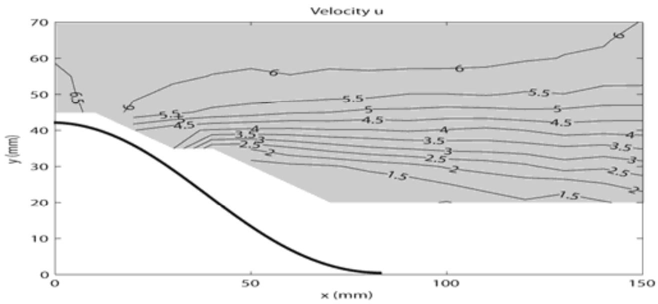
Figure 4 The hot-wire probe behind the hill.

The operating flow parameters in the test rig were measured by means of a Pitot-static tube and a RTD thermometer Pt100 inserted upstream the hill. The mass flow through the slot was calculated from pressure differences measured on the metering nozzle and temperature measured upstream from the inlet of metering nozzle.

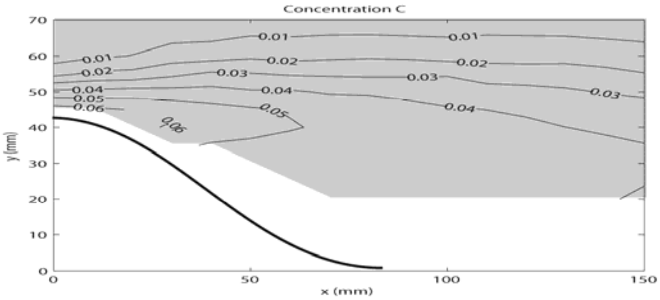
RESULTS

The velocity of the main flow was set at 6 m/s. Volume rate of CO_2-admixture was set at 5e-4 m^3/s. It corresponds with velocity in the slot of 5 m/s. Time-averaged values of the molar concentration over the hill were measured by CO_2-analyzer mentioned above.

Time-averaged distribution of the velocity u and the concentration C over the hill show graphs 2 and 3.



Graph 2 Velocity u (m/s) over the hill.



Graph 3 Molar concentration C (-).

From time series of hot-wire measurements were evaluated: the velocity u, the intensity of turbulence Tu, and the variance of concentration Var(C).

Intensity of turbulence Tu is computed to a reference, free-stream, velocity in the channel (u_∞=6.0 m/s)

$$Tu = \frac{1}{u_\infty}\left[\frac{1}{N}\sum_{k=1}^{N}\left(u_k - \overline{u}\right)^2\right]^{\frac{1}{2}} = \frac{1}{u_\infty}\left[\mathrm{Var}(u)\right]^{\frac{1}{2}} \quad . \tag{3}$$

Variance of concentration Var(C) is defined as follows

$$\mathrm{Var}(C) = \frac{1}{N}\sum_{k=1}^{N}\left(C_k - \overline{C}\right)^2 \quad . \tag{4}$$

From the hot-wire probe we employed two wires parallel to each other, W1 and W2. We recorded time series of output voltages E_1 and E_2. Linearized Taylor expansion leads to the expression

$$E_j(C,u) = \overline{E}_j + \frac{\partial E_j}{\partial C}dC + \frac{\partial E_j}{\partial u}du \quad . \tag{5}$$

Sensitivities to the concentration S_C and the velocity S_u can be computed from calibration of sensors

$$S_{Cj} = \left.\frac{\partial E_j}{\partial C}\right|_{\overline{C},\overline{u}} \quad , \quad S_{uj} = \left.\frac{\partial E_j}{\partial u}\right|_{\overline{C},\overline{u}} \quad . \tag{6}$$

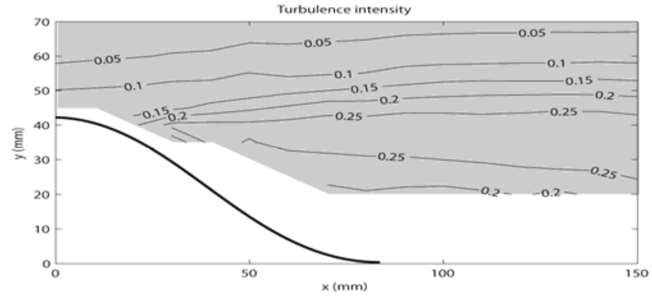
We can computed variances Var(E_1) and Var(E_2) and a covariance Covar(E_{12}) directly from measured output voltages.

$$\begin{aligned} &\mathrm{Var}(E_1) = \frac{1}{N}\sum_{k=1}^{N}\left(E_{1k} - \overline{E_1}\right)^2 \quad , \quad \mathrm{Var}(E_2) = \frac{1}{N}\sum_{k=1}^{N}\left(E_{2k} - \overline{E_2}\right)^2 \\ &\mathrm{Covar}(E_{12}) = \frac{1}{N}\sum_{k=1}^{N}\left(E_{1k} - \overline{E_1}\right)\left(E_{2k} - \overline{E_2}\right) \end{aligned} \tag{7}$$

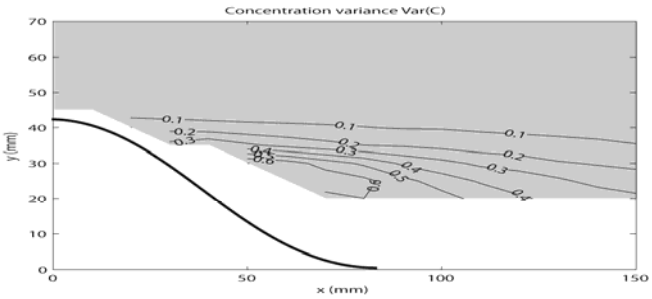
Then we are able to find Var(C) and Covar(Cu) by solving a system of three equation:

$$\begin{aligned} &\mathrm{Var}(E_1) = S_{C1}^2.\mathrm{Var}(C) + 2S_{C1}S_{u1}.\mathrm{Covar}(Cu) + S_{u1}^2.\mathrm{Var}(u) \\ &\mathrm{Var}(E_2) = S_{C2}^2.\mathrm{Var}(C) + 2S_{C2}S_{u2}.\mathrm{Covar}(Cu) + S_{u2}^2.\mathrm{Var}(u) \\ &\mathrm{Covar}(E_{12}) = S_{C1}S_{C2}.\mathrm{Var}(C) + \left(S_{C1}S_{u2} + S_{C2}S_{u1}\right).\mathrm{Covar}(Cu) + \\ &\qquad + S_{u1}S_{u2}.\mathrm{Var}(u) \end{aligned} \tag{8}$$

Distribution of the turbulence intensity Tu and the concentration variance Var(C) show graphs 4 and 5.



Graph 4 Turbulence intensity *Tu* (-).



Graph 5 Concentration variance Var(*C*) (-)

CONCLUSION

Distributions of the velocity, the concentration, the turbulence intensity and the concentration variance over a two dimensional polynomial-shaped hill are presented in the paper. Statistical moments of the concentration and the velocity fluctuations were obtained from CTA hot-wire measurements with multiple-sensor probe. This special probe was manufactured for measurement in gas mixture. A developed procedure of simultaneous measurement of the concentration and the velocity employing two parallel wires works satisfactory. However, a calibration in the mixture is time consuming and must be done very carefully.

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