Experimental Study of a Boundary Layer on a Heated Flat Plate

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Abstract. Boundary layer on a uniformly heated flat plate was studied experimentally. Both, the velocity boundary layer and the temperature boundary layer, was investigated by means of hot-wire anemometry. A probe with parallel wires was used for velocity-temperature measurement. Experiment was performed in the closed-circuit wind tunnel with several levels of heat flux at the wall. The wall temperature was set up in the interval from 20 ºC to 200 ºC.

1 Introduction

The subject of the paper is an experimental investigation of boundary layer over a flat plate with heat transfer. The flat plate with aerodynamically smooth heated surface was tested. Boundary layer was traversed by thermoanemometry probes. A parallel-wire probe was applied for the velocity and the temperature measurement. The sensors operated in CTA mode with different overheat ratios. In case of unheated plate also an X-wire was used. Calibration of the probes was carried out in a calibrator that allows setting of the flow temperature by heating element inside.

2 Experimental setup

The heated flat plate was inserted into a free stream in the test section of wind tunnel. Measurements were performed in the closed-circuit wind tunnel of the CET Telč with a cross-section of dimensions of 1.9 m × 1.8 m. The plate was installed parallel to test section walls. It was placed on pillars in height of 0.3 m above a lower tunnel wall to be out from boundary layer developed on the wall. The plate of a length of 1000 mm has a sharp leading edge of a length of 50 mm. A sketch of the leading edge one can see in fig. 1.

Fig. 1 Leading edge of a plate

The plate is made modularly of four electrical heating elements with separated control. Temperature of the plate was measured by a number of thermocouples placed inside. Lower surface of plate is covered with heat insulation. The free stream velocity during the experiments was kept at nominal value of U_∞=3 m/s or 5 m/s and the temperature of plate was ranged in the interval from T_s=20 ºC up to 200 ºC. Depending on velocity, usually achieved value of natural intensity of turbulence of free stream in the test section is 0.8−1.2 per cent.

Hot wire anemometry is an appropriate tool for measurement in turbulent flow (i.e. [3]). A platinum thermometer was placed next to hot-wire probe (fig. 2) to check the mean temperature of the flow.
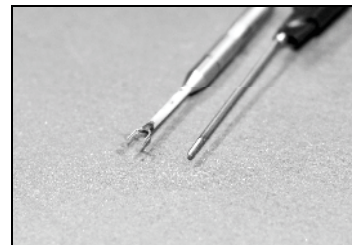

Fig. 2 Hot-wire parallel-wire probe and thermometer

Two types of hot-wire probes were used. The first one was a probe manufactured in the Institute of Thermomechanics of the Czech Academy of Science. The probe is composed from two parallel wires (space between wires is about 0.5 mm). The first sensor has a tungsten wire of the diameter 5 μm and the active length 1.25 mm; the second sensor has a platinum-rhodium wire of the diameter 3 μm and the length 5 mm. Tungsten wire was operated in the range of (120−220) ºC and the PtRh wire at 400 ºC. The second probe was an X-wire Dantec 55P61. Both wires of diameter of 5 μm and length of 1.2 mm were operated in CTA mode at 220 ºC.

A cooling law of Collis and Williams, later modified by Koch and Gartshore, in form:

$$\mathrm{Nu}\left(\frac{T_m}{T}\right)^{m_w} = A_w + B_w\,\mathrm{Re}^{n_w}$$

was used for each sensor of hot-wire probe w=1,2. Theory of measurement of scalar quantity by parallel-

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wire probe using above cooling law is described in [1]. From time records of output anemometer voltages it is possible to evaluate both the velocity and temperature, when a proper calibration is done. Details of procedure of velocity-temperature measurement can be found in [2].

Sensors of the X-wire probe were calibrated in the range of velocities U=(0.5−20) m/s, wire temperatures $T_{w1,2}$=(180−240) ℃, at ambient flow temperature T_∞≈20 ℃.

Sensors of the parallel-wire probe were calibrated in the rig with variable flow temperature in the range of velocities U=(0.5—10) m/s, wire temperatures T_{w1}=(120−220) ℃, T_{w2}=(320−420) ℃ and flow temperatures T_∞=(20−60) ℃.

The CTA system Dantec Streamline was employed for operating wires. The output signals are then digitalized using the A/D transducer (National Instruments data acquisition system, sampling frequency 75 kHz, 16 bit). For setting the probe a Dantec traversing system was used.

3 Results

Presented data result from hot-wire measurements. A coordinate system is sketched in fig. 3. U and V are the horizontal and the vertical velocities in direction x and y coordinates, respectively. A heated wall with surface temperature T_s is located in y=0. U_∞ denotes a free stream velocity.
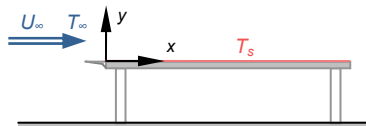

Fig. 3 Scheme of the flat plate

Intensity of turbulence is defined

$$Tu = \sqrt{\frac{\mathrm{Var}(U) + \mathrm{Var}(V)}{U^2 + V^2}} \quad . \tag{1}$$

Intensity of temperature fluctuation is defined as follows:

$$I_t = \sqrt{\frac{\mathrm{Var}(T)}{(T_s - T_\infty)^2}} \quad . \tag{2}$$

Dimensionless temperature Θ is introduced

$$\Theta(x,y) = \frac{T(x,y) - T_s}{T_\infty - T_s} \quad . \tag{3}$$

From the X-wire measurement were evaluated both velocity components U and V, their standard deviations Std(U), Std(V) and intensity of turbulence Tu.

From the parallel-wire probe measurement were evaluated temperature T and velocity U_e, intensity of temperature fluctuations I_t, and intensity of turbulence Tu. The probe with paralell wires indicates an effective velocity U_e, which is a sort of composition of U and V. As we see later, vertical component is much less then horizontal $V \ll U$ in our case. It means that measured velocity is very close to $U_e \simeq U$.

Then, the intensity of turbulence can be computed

$$Tu \cong \sqrt{\frac{\mathrm{Var}(U_e)}{U_e^2}} \tag{4}$$

from a parallel-wire probe data.

A natural intensity of turbulence of free stream was measured by X-wire probe upstream of leading edge at x=-300 mm. In the range of velocities U_∞=(3−5) m/s, the intensity of free stream turbulence evaluated from eq. (1) was of magnitude of Tu_∞=0.012.

3.1 Unheated plate

The first series of test on installed plate was carried out without heating. In that case, the free stream velocity in the experiment was kept at nominal value of U_∞=3 m/s. Results are obtained mainly from X-wire measurements. The horizontal and the vertical dimensionless velocity profiles are shown in fig. 4 and fig. 5. They are plotted over y/δ, where δ is a conventional boundary layer thickness at level U/U_∞=0.99. Similarly, for temperature profiles is used a temperature boundary layer thickness δ_T.
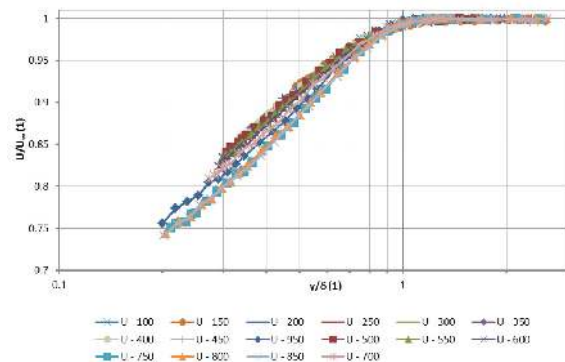

Fig. 4 Dimensionless velocity profiles U/U_∞=f(y/δ), x=(100−950) mm. Unheated plate.
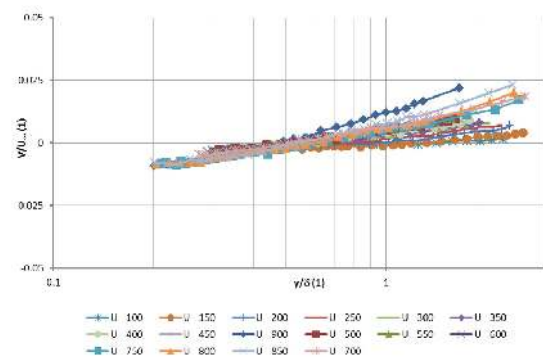

Fig. 5 Dimensionless velocity profiles V/U_∞=f(y/δ), x=(100−900) mm. Unheated plate.

Measured values of vertical dimensionless velocity V/U_∞ were under 0.01, as one can see from graph in fig. 5. It proves assumption given above, that vertical and horizontal component differ by two orders of magnitude.

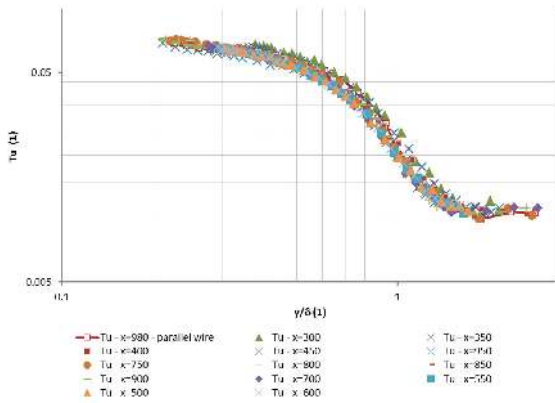Profiles of intensity of turbulence are shown in fig. 6.

Fig. 6 Turbulence profiles Tu=f(y/δ), x=(300−950) mm. Unheated plate.

For comparison, there is plotted a profile of turbulence, which was measured by the parallel-wire probe (solid line) and evaluated via eq. (4). It mathes the other ones, evaluated from the X-wire probe via eq. (1).

3.2 Heated plate

At the series of measurement with heat transfer, the free stream velocity was set to U_∞=5 m/s. During experiment, the temperature of plate surface was kept at the value of T_s=(35, 50, 75,100, 125, 150, 175, 200) °C. The first set of measurements with parallel probe was done at the end of the plate (x=980 mm).
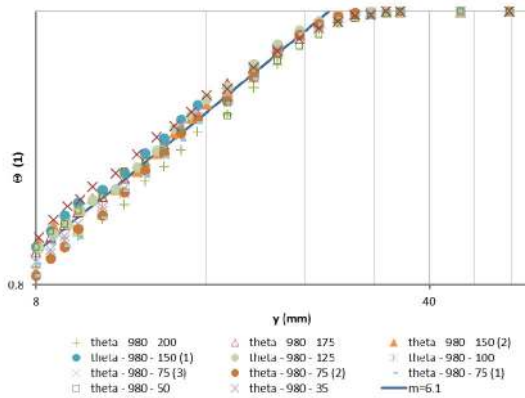

Fig. 7 Dimensionless temperature profiles Θ=f(y), x=980 mm. Heated plate T_s=(35−200) °C.

Dimensionless temperature profiles Θ=f(y) measured for various wall temperatures are plotted in logarithmic graph in fig. 7. A good fit of data represents a power law of the form:

$$\Theta = \left(\frac{y}{\delta_T}\right)^{\frac{1}{m}} \qquad (5)$$

with m=6.1.

Next set of measurement was performed along the length of the plate for the wall temperature of 200 °C.

Results are the dimensionless temperature profiles (fig. 8) and in the dimensionless velocity profiles (fig. 9).
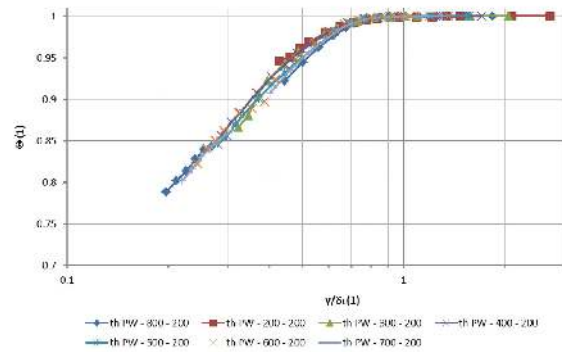

Fig. 8 Dimensionless temperature profiles Θ=f(y/δ_T), x=(200−980) mm. Heated plate T_s=200 °C.
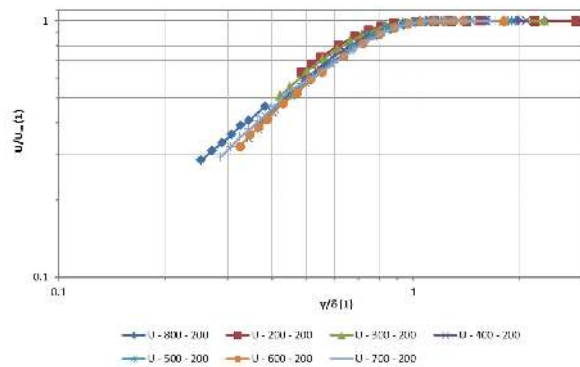

Fig. 9 Dimensionless velocity profiles U/U_∞=f(y/δ), x=(200−980) mm. Heated plate T_s=200 °C.

From measurements at the end of the plate, also the fluctuations were computed for heated plate on wall temperature T_s=200 °C. In fig. 10, intensity of turbulence Tu and intensity of temperature fluctuations I_t are plotted for x=900 mm and x=980 mm. At x=900 mm, two sensor temperature settings were used.
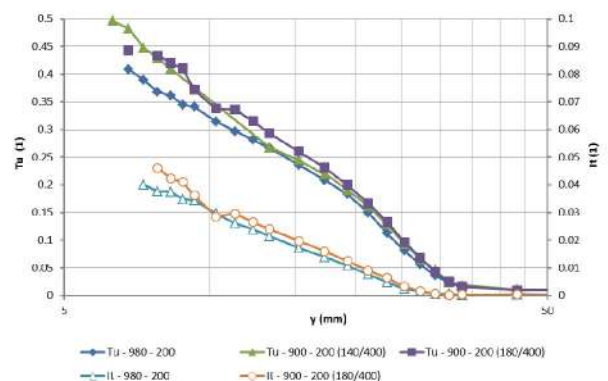

Fig. 10 Intensity of turbulence Tu and intensity of temperature fluctuations I_t, x=(900, 980) mm. Heated plate T_s=200 °C.

At the and of the plate x=980 mm at height y=10 mm, the turbulence intensity has a magnitude of Tu=0.35 and

the intensity of temperature fluctuations reaches approximatelly value of I_t=0.03.

5 Conclusions

Several isothermal heat-transfer runs were made at free-stream velocity of 3 m/s or 5 m/s and free-stream turbulence intensity of 1.2 percent. Wall temperature was maintained constant along the plate, in the range (20−200) °C. The temperature and the velocity boundary layer development was studied by means of hot-wire anemometry. The velocity-temperature measurement was done by parallel-wire probe. Intensity of temperature fluctuations and intensity of turbulence are presented. Satisfactory power representation of dimensionless temperature profile gives an exponent m=6.1.

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