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Towards a theoretical model of heat transfer for hot-wire anemometry close to solid walls

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ABSTRACT

Hot-wire anemometry readings where the sensor is close to a solid wall become erroneous due to additional heat losses to the wall. Here we examine this effect by means of experiments and numerical simulations. Measurements in both quiescent air as well as laminar and turbulent boundary layers confirmed the influences of parameters such as wall conductivity, overheat ratio and probe dimensions on the hot-wire output voltage. Compared to previous studies, the focus lies not only on the streamwise mean velocity, but also on its fluctuations. The accompanying two-dimensional steady numerical simulation allowed a qualitative discussion of the problem and furthermore mapped the temperature field around the wire for different wall materials. Based on these experimental and numerical results, a theoretical model of the heat transfer from a heated wire close to a solid wall is proposed that accounts for the contributions from both convection and conduction.

1. Introduction

Hot-wire anemometry (HWA) has been the most widely used laboratory method to measure local fluid velocities in experimental fluid mechanics, which enabled the study of instability waves and turbulent fluctuations quantitatively. Furthermore, it was the only method capable of measuring high frequency and amplitude velocity fluctuations with a high spatial resolution and has been dominant in the experimental field until the development of laser-based techniques such as laser Doppler velocimetry (LDV) and particle image velocimetry (PIV). Nowadays, HWA remains the preferred measurement technique for acquiring data in both laminar and turbulent wall-bounded flows.

However, a well-known major drawback in HWA is that a hot-wire probe calibrated in the wall-remote region registers a seemingly higher mean velocity in the near-wall region, known as the wall-proximity effect. Additional heat losses from the heated sensor to the cooler wall are erroneously read as an increase in velocity as the wire approaches the wall surface. The wall-proximity effect causes a problem especially for measurements of the velocity derivative close to the wall, or when the absolute wall position needs to be obtained/corrected, through a fit of the data in the linear velocity region existing close to the wall (Örlü et al., 2010).

The wall-proximity effect has been investigated in many studies, and several of them have been concerned with possible correction schemes for the mean velocity and its dependence on operational and geometrical parameters. Generally, it is widely accepted that the wall conductivity, overheat ratio, and sensor dimensions have an influence on the erroneous velocity reading. In particular, it is known that highly conductive materials register larger apparent velocity readings than poorly conductive materials (Polyakov and Shindin, 1978; Bhatia et al., 1982; Durst and Zanoun, 2002). Similarly, larger length-to-diameter ratios l/d of the wire result in a larger apparent velocity reading (Krishnamoorthy et al., 1985; Chew et al., 1995). Also, the larger the overheat ratio is, the larger the apparent velocity reading becomes (Krishnamoorthy et al., 1985; Zanoun et al., 2009).

However, despite the aforementioned results the detailed principle of the heat transfer for the hot-wire in the near-wall region including its interaction with the wall material is still not fully understood. Furthermore, most of the previous studies are concerned with errors in the mean velocity and there is little knowledge of the measured turbulence quantities, i.e. turbulence intensity, higher-order moments and in turn probability density distribution. In light of the recent demands for increased accuracies in determining the friction velocity and/or absolute wall-position (Örlü et al., 2010), the interest in higher-order moments in the near-wall region (Örlü et al., 2016) as well as its wall-limiting quantities, e.g. the fluctuating wall-shear stress (Alfredsson et al., 1988; Örlü and Schlatter, 2011; Lenaers et al., 2012; Vinuesa et al. 2017), there is a

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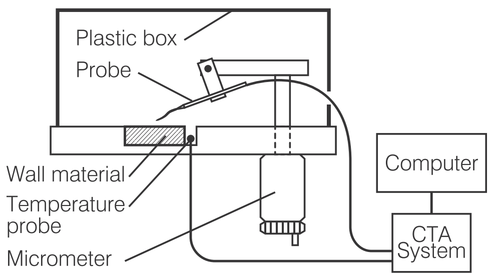

Fig. 1. Schematic of the setup for the no flow, i.e. free/natural convection, measurements.

need to revisit the effect of hot-wire measurements close to solid walls.

In the present investigation a systematic parameter study on the misreading of hot-wire anemometry in the near-wall region is carried out so that further insight can be provided in order to eventually help researchers to correct for or correctly acknowledge these effects. In particular, measurements under no-flow (i.e. free convection) and flow conditions (i.e. forced convection), in a laminar and a turbulent boundary layer, have been performed by varying the wall material, overheat ratio, and probe dimensions and the details and results are reported in Section 2. The numerical counterpart including a study on the heat conduction inside the wall material is given in Section 3. Based on the results from Sections 2 and 3, a theoretical model to simulate the wall effect is proposed in Section 4 and its capability of estimating the heat transfer from a heated wire close to a solid wall is discussed, upon which the work is summarised and concluded in Section 5.

2. Experimental part

2.1. Natural convection measurements

To study the effect of various parameters on the heat transfer from the hot wire in the absence of a forced flow, i.e. under free convection conditions, measurements in an enclosed Plexiglas box were performed. The schematic of the setup is illustrated in Fig. 1. The hot-wire probe can manually be traversed normal to the wall by means of a linear micrometer and to study the influence of the wall distance the output voltage E of the anemometer was acquired at thirty-five heights up to a distance of $y = 2$ mm from the wall. Additionally, the voltage output at $y = 5$ mm was recorded as E_0, where the effect of the wall is considered to be negligible.

The effect of thermal conductivity of the wall was investigated by changing the wall material between aluminum, brass, steel, Plexiglas, and styrofoam. Besides the wall material, the wire length and resistance overheat ratio

$$a_R = \frac{R_{\mathrm{w}} - R_0}{R_0}, \tag{1}$$

were also taken as parameters to see their influence on the voltage reading. Here, R_0 denotes the sensor electrical resistance at ambient temperature, i.e. the reference state, and R_{w} denotes the resistance under operation.

2.2. Forced convection wind-tunnel experiment

Hot-wire measurements were also carried out inside the *Minimum Turbulence Level* (MTL) closed-loop wind tunnel located at KTH Royal Institute of Technology in Stockholm, which has a 7 m long test section and a cross-sectional area of 0.8×1.2 m^2. Details about the specific wind-tunnel setup can be found in Sanmiguel Vila et al. (2017).

A probe was mounted on a computer controlled traversing system above a flat plate as shown in Fig. 2. The flat plate has both

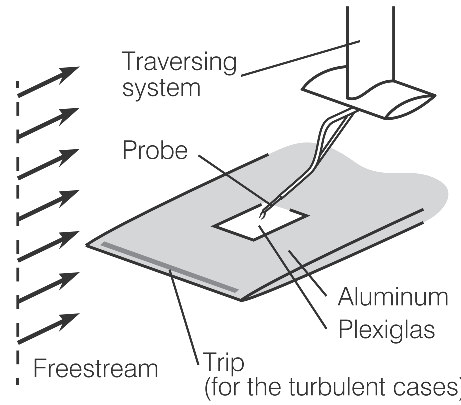

Fig. 2. Schematic of the setup for the wind-tunnel, i.e. forced convection, experiments.

aluminum and Plexiglas surfaces at different spanwise positions at the same streamwise location, which were used to investigate the effect of wall conductivity. Furthermore, both laminar and turbulent boundary layers developing on the plate with zero-pressure gradient were considered with momentum-loss thickness Reynolds numbers (Re_θ) of around 400 and 950, respectively. The established boundary layers adhere to canonical zero-pressure gradient laminar, i.e. Blasius, and turbulent boundary layers as will be shown later on in Fig. 5a) and Figs. 6 and 7, respectively. The sampling frequency in this measurement was 20 kHz and the sampling time was 10 s.

The calibration of the probes was carried out in the free-stream and upstream of the flat plate, against a Prandtl tube which was also used to monitor the free-stream velocity in the tunnel. The free-stream velocity is controlled by a computer and the corresponding voltage output from the probe was recorded. The voltage without flow E_0 was also recorded and used for the calibration. In the present study, a 4th-order polynomial was used to relate the top-of-the-bridge voltage to the velocity reading (see e.g. George et al., 1989).

2.3. Experimental results

Results from the measurements on different wall materials in quiescent air are shown in Figs. 3a) and 4a) and show the expected dependency of the wall conductivity on the hot-wire reading (platinum core wire with 2.5 μm diameter and 0.7 mm nominal length operated at an resistance overheat ratio $a_R = 0.8$). In accordance with Durst et al. (2002), large differences can be observed between poorly conducting walls (Plexiglas and styrofoam with heat conductivities of the order of 10^{-1} and 10^{-2} Wm^{-1}K^{-1}, respectively), while the results from highly conducting materials (such as aluminum, brass and steel, with heat conductivities of the order of 10^1–10^2 Wm^{-1}K^{-1}) do not vary between each other. Due to the lack of wall materials that show a dependence on the conductivity on the hot-wire reading (in the present study), we are not in a situation to propose a scaling. However, as apparent from Fig. 4a), where the values on the ordinate are scaled with its wall-closest value (where $E^* = (E - E_0)/E_0$), the curves behave self-similar. The dependency on the overheat ratio for the same probe on the aluminum wall, shown in Fig. 3b), is also in accordance with the main body of previous studies (Krishnamoorthy et al., 1985; Durst and Zanoun, 2002). However, it was found that the three curves for these different overheat ratios can be collapsed into a single curve by utilizing the wall-remote hot-wire output voltage E_0 as shown in Fig. 4b), albeit with a noticeable discrepancy for the $a_R = 0.30$ case at the wall proximity. Likewise, the voltage output from probes with different sensor length is plotted in Figs. 3c) and