Experimental study of the aerodynamic perturbations induced by the single normal hot-wire probe positioned normally in the vicinity of a wall

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Experimental study of the aerodynamic perturbations induced by the single normal hot-wire probe positioned normally in the vicinity of a wall

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Abstract. The conducted research, though still at the preliminary stage, is a step toward a better understanding of the flow phenomena accompanying hot-wire probes. For the flow in the vicinity of a wall, a potentially non-optimal case was analyzed – a single normal hot-wire probe oriented normally to the surface. According to the results, undisturbed flow, as measured in the absence of a hot-wire probe, was significantly altered in its presence. Differences in the vertical profiles of the velocity magnitude in the upstream direction of up to 40% were observed 0.43 mm from the probe’s longitudinal axis of symmetry, and up to 8% at a distance of 3.73 mm. The lower Reynolds numbers were considered the more complex velocity profile perturbations were present. The highest differences in undisturbed vs. disturbed flow were observed at the level of the wire and below, regardless of the distance from the hot-wire probe.

1. Introduction
Hot wire anemometry (HWA) is a well-known technique used on a daily basis in many laboratories around the world. Even though the laser Doppler anemometry (LDA) optical technique seems to be more appropriate nowadays – it is more precise and has a higher temporal resolution – HWA has obvious advantages – it is much cheaper and does not require seeding particles nor sophisticated optical access.

The foundations of HWA were probably laid at the very beginning of the 19th century or possibly even earlier with the papers of Ser [1] and King [2], among others. Aerodynamic perturbations introduced by HWA probes in high-speed flows were recognized as important quite early. However, at low speeds, this problem was, for the first time, raised in 1967 by Hoole & Calvert [3]. They observed the systematic error occurring in mean-velocity measurements, depending on whether the stem of the probe was aligned with or normal to the flow (up to 20%, according to the probe used).

Because of its small size and high temporal resolution, the HWA was acknowledged as a useful tool to investigate not only turbulence in general, but particularly turbulence in the vicinity of walls. However, even bending prongs into a Z-shape (to create the so-called boundary layer probe) did not solve the problem of prong interaction with the wall, while approaching them to the wall at distances comparable to their diameters. An increase of the distance between prongs reduces the influence of the velocity perturbation on the wire and therefore on the measurement results. On the other hand, the decrease of wire length is highly advisable in order to increase the spatial resolution – a possibility to analyze smaller flow structures [4]. What is more, it turned out that the effect of additional cooling from
the wall affects the mean-velocity profile [5-6]. According to Bogar & Willmart [7], a strong reduction of the wire diameter down to c.a. 0.5 μm serves as a palliative in this case.

There are numerous other phenomena needed to be taken into account while conducting measurements by means of only a single normal hot-wire probe (SN-probe). They originate from the probe’s construction and the materials used [8-9], properties of the media such as fluid composition, pressure and temperature and their stability during the measurement [10-11], extreme velocities [12-13], or effects such as the influence of the wall-normal velocity component on the probe readings [14]. All these issues were solved fully or partially over the years on the basis of theoretical considerations as well as mathematical modelling and experimental research.

An experimental verification of the solutions of the above-mentioned issues, especially regarding complex measurement conditions, until now, typically presupposed the use of another hot-wire probe or LDA at most. In the broadly available literature, the author did not find any attempts of using other optical measurement methods, such as particle image velocimetry (PIV), which allows for a direct and comprehensive study of many flow phenomena. The present paper may serve as an introduction to this task.

2. Measurements

2.1. Measurement stand and conditions

The measurements were carried out in a closed-circuit, low speed wind tunnel at the Strata Mechanics Research Institute of the Polish Academy of Sciences (SMRI PAS) equipped with a 2D PIV measurement set-up based on sCMOS, 5.5 Mpx camera and Nd:YaG, double impulse, 200 mJ per impulse green laser. As seeding, Di-Ethyl-Hexyl-Sebacate (DEHS) was used. In order to obtain the highest possible magnification ratio, a 180 mm micro 1:1 lens was attached to the camera through 2 sets of distance rings. As a result, an area of 6.2 mm x 7.3 mm was projected onto a 2160 px x 2560 px sensor [15]. In the field of view, the edge and the first ~7 mm of the (inclined 1.4°) razor blade surface, with or without the SN-probe oriented normally to the surface, was visible (Figure 1). The wire to wall distance was constant and equal to \( h = 0.55 \) mm. Details on the used SN-probe: tungsten wire, 5 microns in diameter, 1.3 mm long, welded to two straight, conical, 20 mm long prongs.

The measurements were carried out for five free stream velocities \( U_\infty = 0.15, 0.53, 1.57, 3.9 \) and 7.59 m/s corresponding to the following Reynolds numbers \( Re_d = 1.98, 7.0, 20.7, 51.4 \) and 100.1, respectively, to observe possible differences (\( d = 0.2 \) mm regards to diameter of the prongs’ tips).

![Figure 1](image.png)

**Figure 1.** Snapshot from the PIV measurement with the SN-probe present – (a), and sketch presenting the measurement configuration (not in scale) – (b).
Due to demanding conditions related to the small experimental area, simplified lightning conditions were used, i.e. the laser light sheet was positioned above and in front of the SN-probe, outside the wind tunnel measurement chamber. This resulted in a shadow and thus in no measurement results in the downstream part of the measurement area. The flow behavior in this location results mostly from the SN-probe geometry and the first step into its analysis with the use of PIV technique was done in paper [15].

2.2. Observations
Images with such a high magnification ratio tend to expose features and phenomena that are invisible with the naked eyes, which are unexpected or even unwanted. In this case, it was likewise. Image sequences recorded during the measurements revealed, aside from slightly bent tips of prongs, that in higher velocities, the SN-probe and the razor blade were vibrating. These oscillations started being clearly visible for the SN-probe at a velocity of 1.57 m/s, and for the razor blade – at velocity 3.9 m/s, with amplitudes of c.a. 0.01 mm in the case of both. At a velocity of 7.59 m/s, these amplitudes reached a level of c.a. 0.03 and 0.02 mm for the SN-probe and the razor blade, respectively. They result from the natural instability of the measurement set up.

2.3. Measurement results
The tabulation of the resulting ensemble averaged velocity fields is shown in Figure 2. It expresses both qualitatively and quantitatively the main features of the flow over the razor blade without and with the SN-probe present.

A visual comparison of the results leads to an obvious conclusion that, regardless of the $Re_d$ value, the introduction of an SN-probe into the flow, especially in an obstructing way presented here, does disturb the flow significantly. Serious modifications of velocity fields are visible for both components, longitudinal and transverse. The boundary layer formation over the razor blade within the measurement plane is partly disrupted.

Although there were no HWA measurements made for the direct comparison with the PIV results, the presented graphs (Figure 2) clearly indicate that the influence of the SN-probe is visible nearby as well as far in the upstream direction, further than the inflow border of the measurement area. This may explain the high deviation in the velocity estimation observed by Hoole & Calvert [3]. This also suggests that the diameter of the prong was chosen incorrectly as a characteristic dimension for this case. More adequate seems to be the distance between the prongs’ outer edges, which is c.a. 1.5 mm at the level of wire and then slightly increases.

From each measurement at the distance $l_1 = 3.00$ mm past the razor blade edge and $l_2 = 0.43$ mm (see Figure 1) in front of the wire (if present), a vertical, mean velocity magnitude profile was extracted. For each $Re_d$, these profiles were compared in pairs and presented in Figure 3b in terms of relative differences. Additionally, this very procedure was applied to profiles extracted from the position $l_1 = -0.30$ mm and $l_2 = 3.73$ mm (Figure 3a). These graphs enable a more precise comparison of the velocity distribution in the transverse direction.

Two main observations based on the analysis of Figure 3 hold the center stage. Firstly, on average, the lower the Reynolds number, the higher the differences. Secondly, even though conical prongs are an increasing obstacle while moving away from the wire, the highest velocity alternations are observed at the level of the wire and below. This results mainly from the fact that a tiny wire surrounded with a cloud of heated gas is a serious obstacle, which forces the inflowing air stream to move around. What is more, a part of the air stream trying to avoid a couple of prongs and, simultaneously the razor blade surface, increases the mass stream below wire.
It is interesting that this trend of highest velocity alternation at the level of the wire and below holds true even far in the upstream direction in front of the razor blade edge. Even more puzzling is the almost mirror reflection of the curve related to $Re_d = 7.0$ versus the one related to $Re_d = 1.98$ in Figure 3a and
all others in general. This particular behavior may express certain flow phenomena or a mistake during the measurements. On the other hand, a perfectly regular shape of the curve related to $Re_d = 7.0$ in Figure 3b may suggest the former explanation.

![Figure 3. Relative differences of the vectors’ magnitudes.](image)

3. Conclusions
To conclude, the investigation presented above illustrates the complexity of the flow disturbances caused by placing the SN-probe in the vicinity of a wall. However, the phenomena, described by many authors, was never measured directly by means of optical methods, such as PIV.

Major developments in electronics, the miniaturization of probes and the development of mathematical models made HWA a friendly and relatively cheap measurement technique. A variety of probe shapes allows for more accurate measurements in demanding conditions. However, the SN-probe is the most common and versatile. As the above results indicate, one has to remember that, in measurements where such a probe has to be placed in the close vicinity of one [16] or more objects [17], the flow conditions may vary significantly from those in which the probe was calibrated. As a result, a systematic deviation of the measurement results is expected. What is more, as the probe disturbs the flow, if the latter one is prone to such disturbance, it may exhibit different properties.

The latter statement is not as obvious as it seems. Many users regard the HWA as almost a pointwise technique. They not always have the consciousness of how many factors have an impact on the measurement results and how users modify flow structures by adding the hot-wire probe, in particular. The present paper, being also a continuation of previous ones [15, 18], may serve as a handy illustration for this issue.

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