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DEVELOPMENT OF MINIATURE FLOW SENSOR FOR AERODYNAMIC APPLICATIONS

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Abstract

The main aim of the present paper is to introduce a concept for a new measuring sensor to determine wall shear stress in wall-bounded shear flows. The basic principal is to combine two well-known measuring techniques into one sensor module. The techniques chosen for implementation in the new measuring system are a miniaturized version of the laser-Doppler anemometry (LDA) and the hot-film anemometry (HFA). The parallel application of both techniques, i.e. LDA & HFA, was proposed to permit reliable hot-film measurements in the wall vicinity and to achieve good boundary layer investigations. The grade of components miniaturization allows measurements at positions which are hardly accessible in complex flow geometries. The preliminary results of the presented sensor module seems likely to make it a prospective measuring technique in a wide range of aerodynamic applications.

1 Introduction and Aim of the Work

In the last few decades, a dramatic increase in the use of the computational fluid dynamics (CFD) was observed to predict both internal and external flows. This growing use of the CFD with sophisticated algorithms and theoretical models provides significant insight into turbulence physics. However, the lack of the availability of affordable high performance computing hardwares particularly at high Reynolds numbers hampers their support for solving problems in the wall regions of wall-bounded shear flows with high enough spatial resolution and acceptable accuracy. The recent developments of the experimental techniques with high spatial resolution, therefore, provide a vital tool to complement the numerical investigations. For instance, predicting quantitative results for drag of bodies with complex geometries can be achieved utilizing the LDA and/or the HFA. In the present paper, a concept for a new sensor combining the two measuring techniques, i.e. LDA & HFA, to determine wall shear stress in boundary layer flows is presented. This combined technique will provide experimental data which could play a vital role towards refining turbulence models as a basis for improved numerical predictions of particularly relevant flows with heat and mass transfer.

However, both techniques have shortcomings when applied in the wall vicinity. For instance, when hot wires or hot films are utilized for wall shear investigations, the additional heat losses to the wall have the potential for introducing significant errors in the skin friction data, see e.g. Durst et al. [2001] and Durst and Zanoun [2002]. Laser Doppler anemometry as an optical measuring technique has also some drawbacks in the wall region because of the size of the measuring control volume. Due to the finite measuring volume of the LDA systems there was a general believe that applications of the laser-Doppler anemometry close to walls suffer from effects caused by the mean velocity gradients. However, because of the linear velocity distribution in the proximity of the wall, the influence of the control volume size on the mean velocity measurements is negligible, since velocity corrections of the mean flow depend on the second derivative of the mean velocity distribution, e.g. see Durst et al. [1995, 1998]. On the other hand, it has been shown by Durst et al., [1995, 1998] that the LDA turbulence intensity measurements require higher gradient correction in the wall vicinity. It is worth noting also that for the implementation of the two measuring techniques into one sensor module, e.g. for boundary layer investigations, one has to keep in mind that the physical dimensions of the conventional LDA systems are oversized for use in such a prospective module. Notable, there have been various trials in order to miniaturize LDA systems, especially for application in boundary layers (see, e.g., Damp [1991], Fourguette et al. [2001], Czarske [2001]). In the present paper, using laser diodes as light emitting source and photo diodes as detector is proposed.

What will this sensor be good for ?
Since wall shear stress is an essential quantity for reliable investigations of wall-bounded flows it has to be obtained accurately. Therefore, it is the main aim of the current work to determine the wall skin friction data with a reasonable accuracy. The grade of miniaturization of the components of the proposed sensor will allow using it to obtain wall shear stress by carrying out measurements at positions which are hardly accessible in complex flow geometries like rotating turbofan blades. In the past, different techniques, direct and/or indirect, were developed to measure the wall shear stress. An early direct measurements of skin friction, for instance, by force balance was carried out by Schoenherr [1932] and more recently utilizing the oil film interferometry by Tanner and Blows [1976] in laminar and turbulent boundary layers. However, difficulties in situations like flows under pressure gradients, transient conditions and need for instantaneous local measurements have stimulated considerable effort to develop measuring techniques such as thermal probes to obtain the wall skin friction. A good review covering the diversity of situations practically encountered for the variety of wall shear stress measuring techniques is given by Winter [1977], and Fernholz et al. [1996].

As previously mentioned, accurate and preferably independent measurement of the wall shear stress with high spatial resolution is of primary importance in a wide variety of aerodynamic applications. Carrying out mean velocity measurements close to the wall was and even still a common base for different techniques to obtain the wall shear stress by relating the shear stress to the strain rate in the following well-known equation:

$$\tau_w = -\mu \left[\frac{\mathrm{d}U}{\mathrm{d}y} \right]_{wall} \tag{1}$$

However, this requires reliable velocity data within the viscous sublayer, i.e. $y^+ \leq 5$, which are free from wall effects (see Durst et al. [2001], and Durst and Zanoun [2002]). There are some other alternative measuring techniques to obtain the wall shear stress directly such as oil film interferometry (see, e.g., Tanner and Blows [1976], Winter [1976], and Fernholz et al. [1996]) which will be utilized for calibrating the present hot-film sensor in parallel with the mini LDA.

Thereafter, the wall shear stress is utilized to obtain the following characteristic velocity and length scales:

$$u_c = u_\tau = \sqrt{\tau_w/\rho}, \qquad l_c = \nu/u_\tau, \tag{2}$$

to normalize the wall measured data and to estimate the wall skin friction coefficient.

It appears from this short introduction that the current proposal intend to provide a vital data to build up systems for a wide variety of flow dynamic applications. For instance, the presented sensor module can be used for measuring boundary layer transition and therefore may play a key role for flow control technology, e.g., the actuators which have to be controlled by sensing the turbulent fluctuations in wall layer. The new sensor concept will be also a good calibration tool for validating numerical results, particularly the wall skin friction data.

It is worth noting here that the present research is motivated by recent publications by Durst et al. [2001] and Durst and Zanoun [2002] containing suggestions for insitu calibration of hot wire to find a generally applicable correction for hot-wire readings in the wall vicinity. It is worth mentioning also that the present hot-film sensor array is developed by ASI GmbH and Astro and Feinwerktechnik GmbH are developing the miniaturized LDA. The first version of designed sensor model of the combined probe is also presented.

2 Background of Proposed Measuring Techniques

Hot Film Array

The fundamental concept of the thermal hot-film anemometry is based on the convective heat transfer from a heated film placed over the wall surface in a fluid flow to measure the wall skin friction. It consists mainly of a thin metallic film which is fixed to an electrically nonconductive substrate, Fig. 1. The film is electrically heated (Joule effect) and simultaneously cooled by the convective heat transfer induced by the lower temperature incident flow. The rate of heat transfer from the film correlates to the mean velocity gradient at the wall surface and hence with the wall skin friction. The main feature that allows the hot film to be used as a measurement device is that its electrical resistance is temperature-dependent. Therefore, by direct or indirect measurements of the film resistance variations, one can infer the heat transfer taking place and then getting the wall friction information.

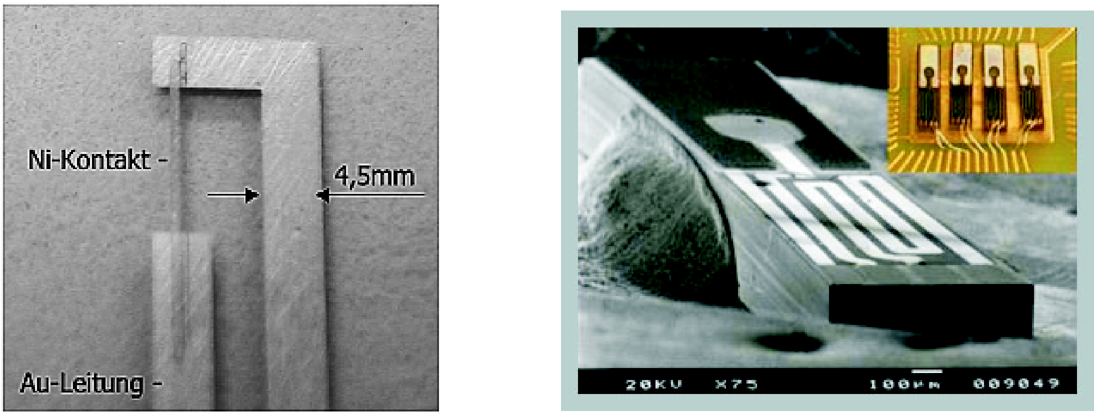

Figure 1: Hot film sensor array, ASI GmbH, with countersunk wiring (left)

For a constant temperature operating mode, the output of the hot-film sensor as a function of wall shear stress is well represented by the well-known power law (King's Law):

$$E^2 = A + B\tau_w^{1/3} \tag{3}$$

where A and B are constants which may be determined by calibrating the hot film against the oil film interferometry in a flat plate boundary layer. The term, A in equation (3) stands for the heat loss to the substrate, which might be larger than the heat loss to the working fluid particularly if the substrate is highly heat conducting. The large heat loss to the substrate suggests a utilize of heat-insulating materials and carrying out an insitu calibration of the hot-film sensor utilizing the mini LDA as proposed in the present paper. However, because of heat loss from the heating element to the substrate and feedback of heat from the substrate to the fluid, it is often quite difficult to assess requirements for the right dimensions of the probe in particular the effective length of the heated element ($L_{eff}^+ < 64\mathrm{Pr}$) where Pr is the Prandtl number, for more details see, e.g., Goldstein [1983] and Löfdahl and Gad-el-Hak [1999]. Therefore, the above relation, equation (3), might be no longer applicable to expect that the heat loss from the hot film varies with the cube root of the wall shear stress. As a result the above equation can be rewritten as follows:

$$E^2 = A + B\tau_w^n \tag{4}$$

where A, B and n are simultaneously and experimentally determined by a least-squares fit, and τ_w and E are the time-averaged wall shear stress and hot film output.

Miniaturized Laser-Doppler Anemometry

The new mini-LDA is constructed as a dual-beam anemometer with fixed focus utilizing a laser diode having a wavelength of $\lambda = 635$ nm and power of 10 mW. The laser beam is split into two identical beams by means of a beam splitter. The two laser beams intersect each other at the point of flow measurement generating interference fringes. Particles crossing the control volume scatter light producing typical burst signals which are detected by an avalanche photo diode APD S9075 (HAMAMATSU).

To be able to measure accurately in the vicinity of walls, the measuring volume has to be small especially in the direction perpendicular to the wall because of its longest axis, and therefore, the fringes be will aligned perpendicular to the wall as well (see Fig. 2).

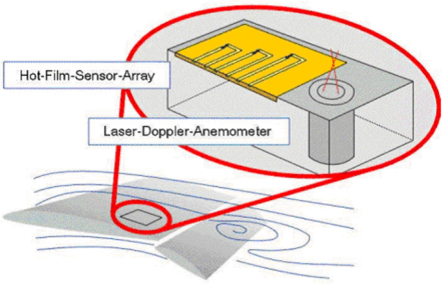

Figure 2: Laser module and HFA, principal sketch

The first setup of the mini-LDA is given in Fig. 3–left. The dimensions of the experimental setup are 140 × 120 × 110 mm without laser and 300 × 270 × 120 mm with laser. The focal length is 150 mm and the control volume approximately has dimensions of 0.094 × 0.093 × 0.828 mm comprising 33 fringes with a separation distance of 2.82 μm. However, the current length of the control volume, i.e. 0.828 mm, which is perpendicular to the wall still too large to carry out boundary layer investigations with high enough spatial resolution particularly for at high Reynolds numbers. The necessity of the control volume reduction will be achieved, e.g., by further reducing the focal length of the transmitting optics or by increasing the angle between the emitted beams, though the latter can not easily be achieved.

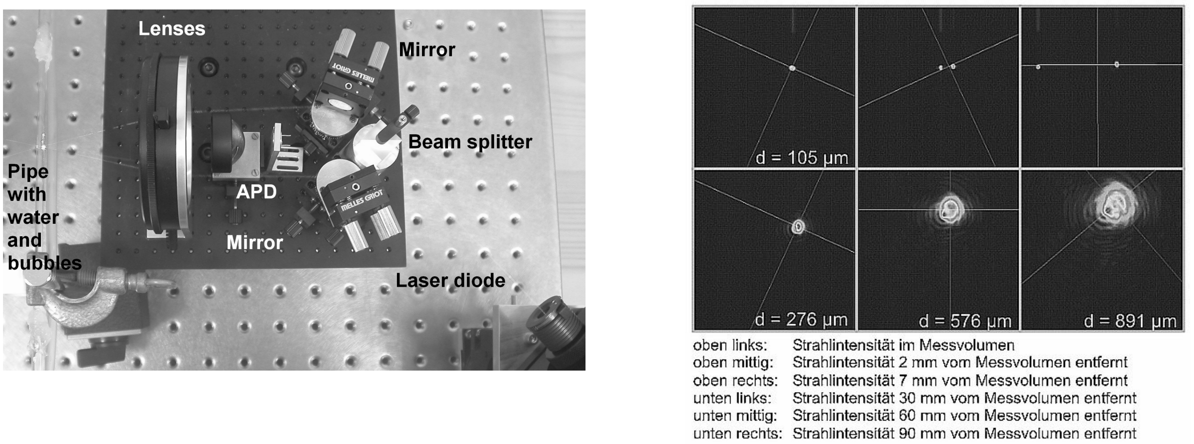

Figure 3: Laser module, first experimental setup (left) and beam intensity as a function of the distance from the measuring volume (right)

First results are shown in Fig. 3–right for forward scattering. To be able to use signals from backward scattering a laser diode with higher power (50 mW) will be used in the next phase of the work.

3 Wind Tunnel Test Facility and Measuring Techniques

The primary purpose of the present work is to carry out boundary layer experimental studies with particular attention being given to the wall shear stress. Of particular interest are measurements within the viscous sublayer to explore the issue of the wall frictional law and to provide further information at different flow conditions with and without pressure gradient. Experiments are carried out in a medium wind tunnel test facility, Göttinger type, at the department of Fluid Mechanics and Aerodynamics (LAS), Brandenburgian Technical University (BTU), Cottbus. Measurements are carried out within the range $3 \times 10^3 < \mathrm{Re}_\theta < 10^4$ where Re_θ is the Reynolds number based on the momentum thickness. Experimental investigations have been also carried out to study wall effects onto heat losses from hot film in wall proximity.

The wind tunnel of LAS Cottbus, is working in a closed loop with test section of $600 \times 500 \times 1500$ mm. The tunnel was designed with smooth bends and diffusers to assure the absence of sudden changes in air flow and the turbulence level is made as low as possible using fine damping turbulence screens. The air passes first through settling chamber for stabilizing and streaming and then through a nozzle of 1:6.53 contraction ratio to get flow velocity within the range 0.5 to 50 m/s with a background turbulence intensity of incident flow less than 0.5 %. Both sides of the test section were made of glass walls to provide an optical access for the laser beams of a conventional laser Doppler system. The wind tunnel test facility is sketched in Fig. 4.

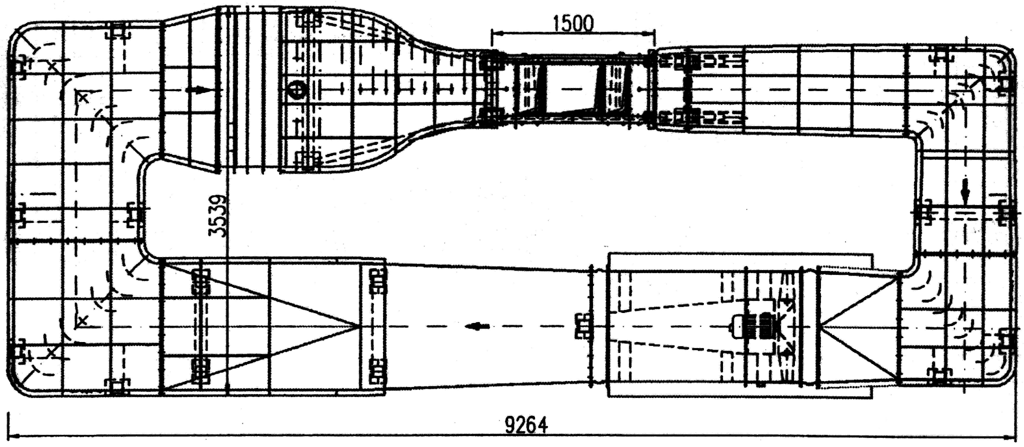

Figure 4: Wind tunnel test setup

Inside of the test section a flat plate of 1050 mm length was mounted permitting good access to the boundary layer flow at different stations from the leading edge of the plate. The mounted plate was made from an eloxide aluminum of dimensions 1050 × 18 × 595 mm. Another glass plate was also prepared as heat-insulating wall to study the effect of wall thermal conductivity on heat loss from the hot film. All plates were aligned to the flow to assure a zero pressure gradient boundary layer flow for the first preliminary experiments.

Hot-Film Calibration

To carry out the hot-film measurements simultaneously with the LDA, a DANTEC Mini constant-temperature anemometer (CTA) was used. Fig. 1 depicts the hot-film sensor utilized in the present measurements. It is composed of a sensing element having dimensions of 0.4 μm × 400 μm × 2 mm (thickness × width × length) positioned over Kapton substrate which has 0.12 W/m K thermal conductivity and a thickness of 500 μm. The hot film resistance at the ambient air temperature, $T_a = 20^\circ$, is 10 Ω. The influences of the wall thermal conductivity and overheat ratio, $a = (R_w - R_a)/R_a$, where R_w is the operational hot-film resistance and R_a is the cold resistance, on the HFA measurements are investigated.

Before carrying out measurements, the hot film was calibrated in undisturbed flow field utilizing the logarithmic skin friction law for the first phase of the work. The temperature of the air stream inside the wind tunnel was kept constant during the calibration and the measurements so as to yield accurate hot film results. However, in case of an unavoidable temperature change a correction for temperature drift was carried out during both the calibration and the measurements procedures. Once the constants of the calibration equation have been obtained the flow field measurements were carried out.

4 Discussion of Preliminary Results

The local measurements of skin friction represent an essential quantity in many flow investigations. Hence, it is the main aim of the present study to obtain instantaneous and local measurements of the wall skin friction utilizing an array of hot film anemometry. In addition, the laser-Doppler anemometry was utilized in connection with the Blasius velocity distribution in order to make sure that the LDA gives the right velocity distribution and then to carry out insitu calibration for the hot-film against the LDA data.

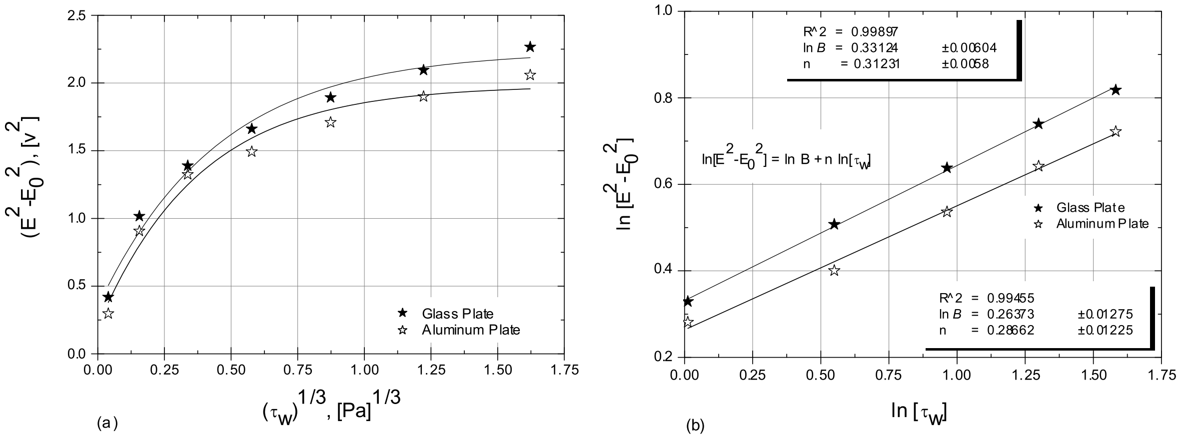

Figure 5: Hot film output over (a) highly heat-conducting (aluminum) and (b) heat-insulating (glass) walls.

To physically understand the behavior of the hot film in the wall vicinity, experiments were carried out using hot film over heat-conducting and heat-insulating walls. The results are shown in Fig. 5 for measurements above an aluminum and glass plates and for a common overheat ratio. For the same wall shear stress, the data clearly indicate the dominance of heat conductivity close to metal walls.

For zero flow velocity (i.e. under zero-flow condition), the output of the hot film denoted by A in equation (3) and/or equation (4) is approximately equal to $E^2_{U=0}$ and therefore equivalent to the net rate of heat transfer, $E^2 - E^2_{U=0}$, which according to equation (3) is proportional to the cube root of the wall shear stress, Fig. 5(a). On the other hand and as might be expected, in the absence of flow the output of the hot film ($E_{U=0}$) above the aluminum plate was found to be higher than the case of the glass plate. This explains why the experimental measurements above the heat-conducting wall material, i.e. aluminum, are lying under the results above the heat-insulating walls, i.e. glass. This is readily understood by looking at the normalized energy equation for steady flow conditions carried out by Durst and Zanoun [2002] taking the following form:

$$\underbrace{U_i{}^* \frac{\partial T^*}{\partial x_i{}^*}}_{I} = \underbrace{\left[\frac{1}{\mathrm{RePr}}\right] \lambda^* \frac{\partial^2 T^*}{\partial x_i{}^{*2}}}_{II} + \underbrace{\left[\frac{\mathrm{Ec}}{\mathrm{Re}}\right] \phi^*}_{III}, \tag{5}$$

The most of the heat loss went into the metal wall was because of heat diffusion, term (II) in equation (5) for constant Pr. Hence, diffusivity is dominant in the wall region and consequently the main role is played by heat diffusion, for more details see, e.g., Durst and Zanoun [2002]. It was also noticed that directly above the highly heat-conducting wall the heat loss from the hot film to the wall and the feedback of heat from the substrate to air reduced the dynamic sensitivity of the hot film array. Therefore, an alternative representation of the hot film calibration equation is given in a general form, equation (4), because of the heat loss from the heating element and the feedback of heat as well, connecting the heat loss from the hot film with the wall shear stress. Hence, solving the calibration equation, equation (4), using the least-squares fit enables getting the three unknowns and hence the outcome is represented in Fig. 5(b). As can be seen from the figure is that the exponent n is less than 1/3 and even smaller in the case of heat-conducting wall.

5 Conclusions and Final Remarks

The conclusions drawn from the results and discussions in the different sections may be summarized as follows:
1-Thermal conductivity of substrate significantly influences the heat loss from the hot film and therefore the exponent of the calibration equation.
2-The measuring volume of the present mini LDA is still big for resolving the boundary layer properly with high enough spatial resolution
In the next phase of the work a vacuum cavity will be produced underneath the substrate to reduce heat transfer to the wall, and therefore, to increase the film sensitivity and the size of the LDA control volume will be minimized further.

Acknowledgment

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