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Analyzing guard-heating to enable accurate hot-film wall shear stress measurements for turbulent flows

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ABSTRACT

In this paper we examine guard-heated hot-film sensors for the measurement of wall shear stress fluctuations in turbulent flows, using analytical and numerical techniques. The new thermal sensor designs proposed here, seek to eliminate the most severe source of error in conventional single-element hot-film sensors – which is indirect heat transfer to the fluid flow through the solid substrate. Published studies of the single-element hot-film show that a significant portion of the heat generated in the hot-film travels through the substrate before reaching the fluid, which causes spectral and phase errors in the wall shear stress signal and can drastically reduce the spatial resolution of the sensor. In addition, heat conduction parallel to the surface, within the fluid near the sensor edges, can produce significant errors when sensors are made smaller to improve spatial resolution. Here we examine the effectiveness of forcing zero temperature gradient at the edges of the hot-film in eliminating these errors. Air and water flow over such guard-heated sensors are studied numerically to investigate performance and signal strength of the guard-heated sensors. Our results show, particularly for low-conductivity fluids such as air, that edge guard-heating needs to be supplemented by a sub-surface guard-heater. With this two-plane guard-heating, a strong non-linearity in the standard single-element designs can be corrected, and substrate conduction errors contributing to spectral distortion and phase errors can be eliminated.

1. Introduction

Wall shear stress, also termed skin friction, is the local tangential force, per unit area, exerted on a solid surface (or "wall") due to the flow of a viscous fluid. In continuum flow of a Newtonian fluid, fluctuations in the wall shear stress (WSS) provide a measure of the fluctuations of a kinematic quantity, the local velocity gradient (or shear strain rate) as well. In turbulent flows, WSS data shows fluctuations over a range of time scales, with positive fluctuation strengths several times the mean occurring more frequently than in the velocity field beyond the viscous sublayer.

Accurate data on the fluctuations of wall shear stress (WSS) is a crucial missing piece in our understanding of wall-bounded turbulent flow. An understanding of the relationship between fluctuating WSS, pressure and velocity fields close to the wall, would help provide a basis for better quantitative models relating instantaneous WSS values at a wall location to the velocity field and possibly to its short-time history, in the neighbourhood. Such models would enable economy in calculations for practically encountered complex turbulent flows. Turbulent flows are prevalent in most engineering applications, industrial processes and in nature. Flow around land, sea and air vehicles, wind turbines, buildings, in pipe flows, large blood vessels and heat exchangers as well as sediment transport by rivers are a few examples of turbulent flows. Direct measurement of WSS in these flows, or numerical simulation with improved near-wall turbulence models from measurements, would greatly help us to enhance our designs for better performance and efficiency.

Manipulating the turbulent flow near the wall can have beneficial results, from reducing fuel consumption for vehicles to achieving more economically and environmentally competitive industrial processes [1,2]. Spatially distributed values of the instantaneous WSS can be used in a feedback control loop to provide active flow control systems for energy saving through drag reduction, lift enhancement, separation delay, vibration suppression, flow-induced noise reduction [3,4]. For instance, wind turbine active control ("smart rotor") systems [5,6], using measurement of wind-induced blade surface forces, could help combat stall, reduce

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fatigue and extreme load failures [7], as well as power fluctuations. WSS data may be used to compute and store parameters representing each blade's wind-load history as a function of turbine location within a wind farm. This would provide a rational basis for preventive maintenance or blade replacement to mitigate the cost of catastrophic failure.

Numerical simulations of turbulent flows in nature and technology rely on models based on experimental data. Measurement of turbulent WSS fluctuations, particularly at high Reynolds numbers, has proved challenging. These fluctuations represent a change in velocity gradient in a region that can be limited to a few microns in thickness. Several new measurement principles for WSS sensors have appeared over the past two decades, often following new microfabrication technologies that become available. At the time of writing, no single experimental technique appears to have clearly outpaced others in performance and range of applicability, and an understanding of the artifacts of each method may be obtained by comparisons between them.

It appears that WSS data obtained from direct numerical simulation (DNS) may also require numerical experiments to resolve discrepancies. A recent assessment [8] comparing seven sets of calculations for skin friction using DNS in turbulent boundary layers, concludes that there are significant differences in the results, mainly due to spatial development of the flow. The Reynolds number for DNS continues to increase, with Re_θ up to 4300 having been reported. DNS data, after resolution of discrepancies should prove to be a valuable basis in the development of WSS sensors.

Several methods have been developed and new principles are being tried for WSS measurements, such as floating-element probes [9–11], micro-pillars [12], optical methods [13] and electrochemical [14] and thermal sensors [15–17]. There are several review papers on shear stress sensors [2,9]. All of these methods have their advantages and disadvantages. Floating-element sensors directly measure the force on the wall and hence are free of errors associated with the indirect methods, which will be discussed. However, they suffer from drawbacks such as dust contamination, pressure sensitivity, sensitivity to acceleration, vibration and thermal expansion [9]. Micro-pillar deflection sensors offer the advantage of readily measuring both components of WSS by processing images of pillar tip deflection – however they are laboratory instruments not easily extended to field measurements. Their intrusion into the sublayer may limit accuracy of their use to relatively low Reynolds number flows, in which their static and dynamic behaviour should be useful to compare with other sensors. Thermal sensors present the advantage that they can be operated with standard constant temperature anemometry (CTA) circuits and can be used in the field in water or air (after overcoming the errors, which is the subject of this work). The main disadvantage of both thermal and electrochemical sensors is that they are indirect methods, which need calibration to relate heat or mass transfer rate to WSS. This relation is obtained by simplifying the energy or concentration transport equations, and the simplifying assumptions make it accurate only in a certain range of WSS magnitudes. Thermal sensors also have limitations such as frequency-dependent heat transfer to the solid substrate [2]. Electrochemical sensors are free of this source of error. However, the special solution chemistry requirements restrict them to laboratory use with liquids and we cannot extend this sensing principle to measurements in air.

2. Thermal sensing

Thermal sensing using constant temperature anemometry has provided a significant portion of the experimental data for turbulent flow velocity fields, on which quantitative models in turbulence are based. This was due to an early achievement of high spatial and temporal resolution and insensitivity to pressure fluctuations. Conventional single-element hot-film sensors for WSS measurement, consist of a single film flush-mounted on a solid wall and electrically heated by a CTA system. A fast servo-amplifier equipped bridge circuit is used to maintain the heated film, with temperature-sensitive resistance R, at a constant temperature above the fluid ambient temperature. The power needed to maintain the constant temperature is equal to the rate of heat transfer from the film to the fluid flow. Based on classical hot-film theory, the rate of heat transfer to the flow Q_F is related to the WSS as $Q_F \propto \tau_w^{1/3}$.

Flush-mounted thermal WSS sensors can be made with a hard, smooth, thin (low thermal time constant) protective dielectric layer to present a smooth surface to the flow. They are thus non-intrusive, and present fewer opportunities for loss of function by particulate fouling and contamination than floating-element, near-wall hot-wire or micropillar sensors. In spite of all the advantages of these sensors, they suffer from unwanted heat transfer to the substrate. This heat, which eventually goes to the fluid, introduces a coupled set of unacceptably large flow dependent errors in the measurement of WSS. Heat diffusion into the substrate results in heat transfer to fluid over a variable area, larger than the sensor film area. This can make spatial resolution and signal sensitivity vary significantly with the magnitude and frequency of the WSS fluctuations, a non-linearity in measurement we seek to remove. Alfredsson et al. [18] compares the rms values of WSS fluctuation from different measurement techniques. The reported values obtained from hot-film measurements in air are much lower compared to other methods (0.06 compared to 0.37), which are related to spatial averaging and substrate conduction of such sensors.

Reducing the effective thermal conductivity of the substrate in the immediate vicinity is one idea that has been explored [15] in a bid to reduce the errors. The idea of using a guard-heater to block this unwanted heat transfer has led to a new hot-film design. In this paper, we investigate to what extent the new sensor design will help us eliminate the effects of substrate heat conduction. Could it enable accurate WSS measurements even for the particularly challenging case of thermal measurement of WSS in low conductivity fluids such as air?

We first discuss the results of non-dimensionalization of the equations governing heat transfer to flow with a spatially uniform, temporally harmonic, imposed shear rate, to highlight performance requirement conflicts that cannot be avoided in single-element sensors. We use these results as well as computational solutions of the conjugate fluid-substrate heat transfer problem to guide the process of new sensor design to *disable* these conflicts. The idea of guard-heating is introduced in Section 3. In Section 4 we first analyze the governing equations and important dimensionless parameters. We then use them to quantify the limits of conventional hot-film sensors and describe how guard-heating helps remove these conflicting limits to overcome the deficiencies of single-element sensors. In Section 6 numerical results are presented and the performance of guard-heated sensors is compared to that of single-element sensors.

3. Guard-heating

The deficiencies of conventional single-element sensors (SE) associated with substrate conduction can be removed or greatly reduced by using guard-heaters. The idea of guard-heating involves forcing zero temperature gradient around the hot-film probe to reduce errors from unwanted heat transfer through the substrate and from axial heat conduction in the fluid. Both can be achieved by