International Journal of Heat and Fluid Flow 46 (2014) 61–69

Contents lists available at ScienceDirect

International Journal of Heat and Fluid Flow

journal homepage: www.elsevier.com/locate/ijhff

Frequency response analysis of guard-heated hot-film wall shear stress sensors for turbulent flows

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ARTICLE INFO

Article history:
Received 21 August 2013
Received in revised form 25 November 2013
Accepted 10 December 2013
Available online 23 January 2014

Keywords:
Wall shear stress fluctuations
Guard-heated thermal sensors
Turbulent flow
Substrate heat conduction errors
Frequency response
Phase lag

ABSTRACT

Guard-heated thermal sensors were recently proposed for the measurement of wall shear stress (or "skin friction") fluctuations in turbulent flow, to overcome the severe errors due to substrate heat conduction encountered in conventional single-element (SE) hot-film sensors. An earlier computational study of steady-state performance showed that a sensor with guard-heating in two-planes (GH2P) can eliminate errors due to spatial averaging and axial heat conduction in the fluid, both of which limit the spatial resolution of conventional SE sensors. Here we present analytical and numerical results comparing the dynamic behavior – frequency response and phase lag – of the guard-heated and conventional designs.

For the water–glass fluid-substrate combination, sensor amplitude and phase errors begin only at a frequency (f_c) near the onset of attenuation due to boundary layer thermal inertia. In this case, although the SE sensor suffers spatial averaging errors, it shows low amplitude attenuation and phase lag, close to that of the GH2P sensors, up to f_c.

For air-glass, analysis suggests and numerical results confirm, that the response of the conventional SE sensor is dominated by unwanted substrate heat transfer, with rapid signal attenuation beginning at frequencies that are five orders of magnitude smaller than f_c. In this case, guard-heating enables strong improvement in the dynamic response, with a small drop in the amplitude response ratio from 0.95 to 0.85 (compared to 0.95 to 0.06 for the SE sensor) and negligible phase lag errors over an additional five decades of frequency. For the guard-heated design, upstream pre-heating occurs, but does not use heat drawn from the sensing element. Numerical results show that signal phase lag is zero and amplitude deviations are small, with modest variation over four decades of frequency. Guard-heated (GH2P) sensors appear to be an attractive option for wall shear stress fluctuation measurement in turbulent flows.

1. Introduction

In this paper, we examine the dynamic behavior of a new hot-film configuration for wall shear-stress measurement in turbulent flows. The work presented here is one segment of a research effort to remove existing barriers to accurate wall shear stress measurement (WSS) by thermal anemometry. This technique is in its hundredth year of use for turbulent flow velocity measurements.

The introduction of several sensing principles for the measurement of turbulent wall shear stress (WSS) described in reviews (Kasagi et al., 2009; Yamagami et al., 2005; Lofdahl and Gad-el-Hak, 1999; Haritonidis et al., 1989; Naughton and Sheplak, 2002) underscores the continuing challenge presented, as well as the importance of the measurement of WSS (alternately known as skin friction). Fully-resolved direct numerical simulations (DNS) of turbulence, though resource-intensive, have become more accessible and are no longer limited to very low Reynolds number flows. These simulations can serve as a resource by yielding valuable WSS data for zero pressure gradient flows in simple geometries, though recent work (Örlü and Schlatter, 2011) has identified the need for numerical experiments to address discrepancies between several reported DNS studies of skin friction. The understanding and prediction of turbulence in more complex wall bounded flows requires accurate measurement techniques. At a practical level, environmental and energy saving concerns have resulted in a strong focus on developing efficient active flow control systems to manipulate and control turbulence to reduce drag, enhance lift, suppress vibration, reduce flow-induced noise and avoid fatigue loads. Several comprehensive reviews of the broad subject of flow control are available (Kasagi et al., 2009; Yamagami et al., 2005; Lofdahl and Gad-el-Hak, 1999; Gad-el-Hak, 2007). For the high flow Reynolds numbers of most industrial processes and engineering applications, turbulent flow control requires actuators, a controller and input from sensors small enough to provide adequate spatial and temporal resolution for WSS measurements.

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http://dx.doi.org/10.1016/j.ijheatfluidflow.2013.12.004

1.1. Hot-film sensors: strong potential and current challenges

Hot-film sensors, flush-mounted with the wall, are non-intrusive, less prone to loss of function by dust contamination or fouling compared to near-wall hot-wires or floating element sensors, insensitive to pressure variations and are easy to use. Thin-film thermal sensors with lateral dimensions in micrometers and sub-micrometer thickness can be mass-produced at low cost, and would appear to have the potential of measuring WSS fluctuations with adequate spatial and temporal resolution in turbulence at high Reynolds number. This potential has not been realized. Reported values of rms turbulent wall shear stress measured using single hot-film sensors vary greatly based on their size and the fluid in which the measurements were made, with large differences between air and water (Alfredsson et al., 1988). Experiments with electrochemical probes (Mao and Hanratty, 1991) and data from DNS (Örlü and Schlatter, 2011) indicate that $\tau_{w,rms}/\overline{\tau}_w$ should be in the range $0.37-0.40$ in turbulent flows. The discrepancy in experimental data, reporting values of $\tau_{w,rms}/\overline{\tau}_w$ between 0.06 and 0.4, is mainly attributed to spatial resolution effects (Alfredsson et al., 1988). Reducing the physical size of single hot-film sensors does not solve this problem. Heat transfer through the solid substrate, eventually goes to the fluid, causing heat transfer from the sensor to the fluid over an area much larger than the physical area of the sensor (Alfredsson et al., 1988; Etrati et al., 2014). Thus the *effective size* of the sensor is larger than the actual size of the sensor and the spatial resolution is reduced. This unwanted, indirect heat transfer, depends on both the shear rate and the frequency of wall shear stress fluctuations. This introduces several uncertainties in turbulent wall shear stress measurements, including variable spatial averaging, deviations from calibration equation, poor frequency response and phase distortion. The assumptions made to get the calibration relation impose several limits on the length of the sensor, and on the range of shear rates and frequencies in which they can operate without significant errors. These limits leave a narrow or a zero window for measurements without errors (Etrati et al., 2014).

The frequency response of conventional single-element hot-film sensors is greatly affected by the frequency and shear dependent heat transfer through the substrate (Haritonidis et al., 1989; Naughton and Sheplak, 2002). The time-constant of the substrate is typically much larger than that of the thin-film sensor element. Its frequency limit for operation without attenuation is much lower than the limit imposed by the heat transfer in the fluid (Meunier et al., 2003). Tardu and Pham (2005) investigated the effects of axial diffusion and substrate conduction on the frequency response of hot-film sensors. They found that when conductivity of the substrate is much higher than that of the fluid, heat transfer through the substrate becomes dominant. As a result, in the case of air as the fluid and glass as the solid substrate for the sensor, the frequency response of the sensor drops at very low frequencies because of substrate heat conduction. Because the dynamic behavior of the substrate and the fluid are different, and depend on various flow field parameters, a laminar calibration cannot be used for turbulent flows (Ajagu et al., 1982). Using a calibration relation based on a laminar flow, results in under-prediction of the r.m.s turbulent shear-stress levels when the substrate heat conduction is significant (Alfredsson et al., 1988).

1.2. Microfabrication to reduce effective substrate conductivity

Many efforts to eliminate the problems introduced by the substrate conduction have been made, and appear to have met with partial success. One of the methods used, aimed at reducing the effective conductivity for substrate heat transfer path, is separating the sensor from the substrate by a vacuum pocket, and placing the sensor on a diaphragm (Yamagami et al., 2005; Lin et al., 2004; Liu et al., 1999). However, heat conduction from the hot-film to the diaphragm on which they are deposited can reduce the sensitivity of the sensor, cause spatial averaging and affect its frequency response. Although Liu et al. (1999) show that the new design has higher sensitivity and better frequency response from a square wave test, the effects of heat transfer through the diaphragm are not characterized and studied. Ruedi et al. (2004) used hot-films placed on a 1.2 μm thick silicon–nitride diaphragm with a 2 μm deep vacuum cavity to reduce substrate conduction. They compared the results of their measurements in air to wall-wire measurements and found that frequency response of the suspended hot-films dropped faster than hot-wires (Ruedi et al., 2004). They argued that this may be a result of unsteady heat transfer effects in the membrane/substrate. Huang et al. (1995) deposited a poly-silicon strip on the top of a thin silicon nitride film. By using a sacrificial-layer technique, a cavity (vacuum chamber) was placed between the silicon nitride film and silicon substrate. They found that the vacuum cavity improved the sensor sensitivity but reduced the frequency response (Huang et al., 1995).

1.3. Near-wall hot-wire for wall shear stress

Another method utilized to avoid substrate conduction difficulties of hot-films, is the use of hot-wires located very close to the wall, to find the value of wall shear stress by measuring velocity and assuming a linear velocity profile (Lofdahl et al., 2003; Khoo et al., 1998). Near-wall hot-wires could be suitable for low Reynolds numbers, since they are required to be located within the viscous sublayer. At high Reynolds numbers, however, the viscous sublayer becomes very thin, requiring the hot-wires to be placed very close to the wall, and subsequently aerodynamic interference from the wall and heat transfer to the wall introduce errors (Khoo et al., 1998). Therefore, corrections are required for prongs and wall interference and heat losses. An alternate approach to reduce substrate heat conduction effects is making a cavity underneath a flush-mounted hot-wire (Meunier et al., 2003; Sturzebecher et al., 2001). Meunier et al. (2003) showed that in the conventional configuration, the frequency response of such sensors is dominated by the filtering effect of the heat transfer via the substrate, when the conductivity of the substrate is more than the fluid. They considered a hot-wire in a micro-cavity flush mounted with the wall, and studied the effects of the geometry of the device on its efficiency. The ratio of the wire-air to wire-cavity heat transfer rates is shown to be significantly reduced. However, dynamic behavior of the sensor was not reported.

We cannot obtain accurate, time-resolved measurements with hot-film or hot-wire sensors, unless we eliminate the effects of the substrate heat conduction from the sensor signal. While most attempts have been focused on reducing the substrate heat conduction by decreasing the effective conductivity of the substrate, the distinctive aim of this work is to use guard-heating to block any unwanted heat transfer from the sensor to the substrate by spatially selective imposition of zero temperature gradients.

1.4. Controlling gradients to reduce unwanted heat transfer: early experiments

Some encouraging results on reducing unwanted heat transfer by selective control of thermal gradients were obtained from early explorations, before the control afforded by microfabrication techniques was widely accessible. Aoyagi et al. (1985) used a sensor made of two commercial probes glued back-to-back, one serving as the sensing device and the other as the guard-heater, located beneath the first probe. They found that using this configuration, errors of using laminar calibration to measure mean wall