Wall shear stress hot film sensor for use in gases

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Abstract. The purpose of this work is to present the construction and characterization of a wall shear stress hot film sensor for use in gases made with MEMS technology. For this purpose, several associated devices were used, including a constant temperature feedback bridge and a shear stress calibration device that allows the sensor performance evaluation. The sensor design adopted here is simple, economical and is manufactured on a flexible substrate allowing its application to curved surfaces. Stationary and transient wall shear stress tests were carried on by means of the calibration device, determining its performance for different conditions.

1. Introduction

The study of shear stress on the walls that make the boundary of a flow is an area of great interest in Fluid Mechanics and Heat Transfer. However its measurement is complex and is generally limited to experimental models. The measurement of wall shear stresses is relevant when studying the drag of blunt or aerodynamic objects, the pressure drop through conduits, the convective heat transfer of surfaces exposed to flows, etc., but it can also be used to detect the passage of fluid-dynamic structures such as hairpin vortices, vortex shearing behind obstacles or large scale coherent structures [1] [2] [3] [4] [5]. Having a good temporal resolution in this kind of devices is of great interest, one reason for this is that the fluctuations of wall shear are relevant in the understanding of the flow and its effect on walls. In turbulent flows, the fluctuations of shear stress reach values as high as 0.46 of the mean wall shear stress [6]. The second reason is that a slow sensor exposed to a turbulent flow yields average measurement values that do not agree with the mean shear stress. That is, the average introduced by a slow sensor is not satisfactory, requiring therefore a turbulent calibration, i.e. a calibration under the same turbulence intensity that will be found in the case to be measured. To avoid such difficulties, it is necessary to obtain measurements with good temporal resolution and eventually to estimate the average value a posteriori.

A technique for wall shear stress measurement that stands out for its simplicity of implementation and accuracy is the use of thermal sensors. Thermal sensors are heaters whose electrical resistance is a function of temperature, which in turn depends on the convection heat transfer between the sensor and the flow. A trend evident in all the measurement techniques of wall shear stress is that the sensors have their sensing areas ever smaller in order to improve the temporal and spatial resolution. In this process of miniaturization micro-electro-mechanical systems (MEMS) manufacturing technology has played a central role in shear stress sensor technology [7]. MEMS technology is based on the same technology developed for semiconductor device fabrication and is well suited for very small thermal sensors, providing superior performance and lower costs, but also the possibility of manufacturing them on flexible substrates that can be applied on curved surfaces. The sensor that is analyzed in this work was fabricated using such technology.

Despite its advantages, in order to make this technology of practical applicability, the sensor should be insensitive to the thermal characteristics of substrate on which it is installed, and should provide a
rapid response to fluctuations of shear stress [8]. In this sense several proposals emerged. Jiang et al [9] achieved a better frequency response of their sensors by manufacturing a vacuum cavity beneath the sensor, thus isolating it from the substrate. On the other hand, Ajagu et al [6] proposed an experimental device consisting of a hot wire sensor located above of a hot film sensor. The hot film acts as thermal shield between the upper sensor and the substrate. Results obtained with this configuration show that this setup can detect very small fluctuations in the measured shear stress. This result served as motivation for pursuing a shear stress hot film sensor of similar performance but of simpler making and constructed on a flexible substrate.

The fabricated sensor was tested for steady state and transient shear stress response by means of a calibration device determining its performance for different conditions.

2. Sensor design and fabrication
The hot-film sensor consists of two flat conductive films: one that will perform as a sensing element, and the other that will serve as a thermal shield between the sensor and the wall. These conductive films were built using a micro fabrication technique. Figure 1 shows a simplified diagram of the sensor exposed to a flow. The flow of air passes over the sensor and parallel to the wall, extracting heat from the sensing element. The strategy used in this work is to keep the sensing element at constant temperature. We do this via a feedback circuit and measure the power dissipated to achieve this, allowing us to measure the shear stress. The shield also operates in constant temperature mode and prevents any variation of wall temperature to affect the sensing element.

An important aspect was that the sensing and shield elements were made separately. As substrate we used a 50 µm thick Mylar layer. The sensor and shield patterns were printed on the corresponding substrate using a photolithographic technique called etching. We first applied a thin film of nickel on the substrates, then applied a layer of photoresist and transferred the etching pattern by exposing the photoresist through a pattern mask. As a result an etching mask of photoresist with the desired pattern was created on the Nickel film. Then the exposed areas of the Nickel film were subject to a chemical attack, and finally the photoresist was removed with Acetone. The Nickel layer deposited on the substrate was 100 nm thick. Once the sensor and shield on their respective substrates were obtained they were joined in a single sensor by means of a cyanoacrylate adhesive. A photograph of the final product is shown in figure 2 and a schematic in figure 3. The finished shear stress sensor has a thickness of 140 µm, and is 30 mm in diameter, the sensing element is 1.88 mm long and 50 µm wide. This slender aspect ratio makes the sensor directional, being sensitive for shear stresses in the direction perpendicular to the sensing element length.
Finally in order to stick the sensor to the calibrator wall an 80 µm thick, double sided adhesive tape was placed on the back of the sensor, summing up a total thickness of 220 µm.

3. Experimental arrangement
To evaluate the dynamic performance or the shear stress sensor we need a method to introduce a known perturbation and to measure the sensor output in response. An effective method used for constant temperature hot wire anemometers is to introduce an electrical perturbation to the feedback bridge and observe its settling time. This procedure is commonly called “electronic test” and is a widely accepted evaluation method for hot wire anemometers. Winter [10], Haritonidis [2], Naughton and Sheplak [11], and Löfdahl and Gad-el Hak [12] have presented studies that show that actual time responses of thermal shear stress sensors cannot be predicted by electronic tests alone, and therefore tests based on the variation of flow conditions must be applied. For this purpose we used a relatively simple rotating disk shear stress calibrator. The shear stress calibrator was based on the design presented by Khoo et al [13] [14] [15]. This type of calibrator has also been used previously by Brown and Davey [16] and Chew et al [17] and it consists of two parallel discs, an upper rotating disk and a lower stationary disk, separated by a small distance. One important advantage of this design is that, with a simple modification, it can also be used to test the dynamic performance of the shear stress sensor [13]. The idea behind this device is to generate a known laminar flow for which the wall shear stress can be calculated from the properties of the fluid and simple kinematic measurements.

The device that was developed for the present work is shown in figure 4. Special care was taken to avoid vibrations through careful design and balancing of the rotating components. The rotating disk has a diameter of 160 mm and its axe is supported by two ball bearings, the lower one being conical. A pulley in the upper end of the axe allows coupling the rotating disk through a belt to a DC motor. The lower disk is supported by three regulation screws that allow the adjustment of the gap between the discs. The pulleys where chosen so that the rotation speed of the motor was higher than that of the disk, increasing the system inertia and therefore the steadiness of the rotating speed. The pitch diameter of the motor pulley and the disk pulley were 48 mm and 90 mm respectively. The rotating and the stationary discs were made of transparent acrylic. This makes it possible to observe the sensor once installed. Acrylic is also relatively easy to machine, therefore a high grade finish can be achieved.
The analytical solution for the flow between a stationary and a rotating disk was provided by Stewartson [18] and Mellor et al [19] and it is a power series solution. Following we show the first terms of the series:

\[
\frac{v_\theta}{\omega r} = \left[ \varepsilon - \left( \frac{\text{Re}_\delta^2}{6300} \right) \left( 8\varepsilon + 35\varepsilon^2 + 63\varepsilon^3 + 20\varepsilon^4 \right) + O(\text{Re}_\delta^4) \right] 
\]

\[
\frac{v_r}{\omega r} = -\left[ \left( \frac{\text{Re}_\delta^2}{60} \right) \left( 4\varepsilon - 9\varepsilon^2 + 5\varepsilon^4 \right) + O(\text{Re}_\delta^3) \right] 
\]

\[
\frac{v_z}{\omega r} = \frac{2\delta}{r} \left[ \left( \frac{\text{Re}_\delta}{60} \right) \left( 2\varepsilon^2 - 3\varepsilon^3 + \varepsilon^4 \right) + O(\text{Re}_\delta^2) \right] 
\]

where \( \text{Re}_\delta \equiv \frac{\omega \delta^2}{\nu} \) is the Reynolds number based on the gap between the discs \( \delta \), \( \omega \) is the angular rotating speed, \( \nu \) is the cinematic viscosity of the fluid, \( \varepsilon \) (= \( z/\delta \)) is the non dimensional vertical coordinate taken from the stationary disc (lower disc), \( r \) is the radial coordinate, and \( v_\theta, v_r \) and \( v_z \) are the azimuthal velocity, radial velocity and normal velocity to the wall, respectively.

For \( \text{Re}_\delta \leq O(1) \) equations (1), (2), and (3) can be approximated as a Couette flow in the azimuthal direction \( \hat{\theta} \). During the experimental work care was taken to keep low values of \( \text{Re}_\delta \), being smaller than 3.5 for all cases. Under these conditions the radial component of the velocity is negligible and the angle between maximum shear stress and the tangential direction is small (< 10°). Therefore the tangential velocity gradient at the lower wall can be approximated by:

\[
\frac{\partial v_\theta}{\partial z} = -\frac{\omega r}{\delta} 
\]

and the tangential shear stress at the lower disc wall \( \tau_{\theta\theta} \) can be calculated as:

\[
\tau_{\theta\theta} = \mu \frac{\omega r}{\delta} 
\]
where \( \mu \) is the dynamic viscosity of the fluid.

The shear stress sensor was mounted on the lower disk and oriented with the sensing element in the radial direction. It should be noted that the sensor analyzed here is relatively insensitive to shear stresses parallel to the sensing element, therefore for the sensor mounted as described, the radial component of the shear stress has a negligible effect.

Once the sensor was in place both the sensing element and the shielding element were connected to two constant temperature feedback bridges. This was done by means of thin (50 \( \mu \)m) wires to avoid flow obstruction. The contacts were done with silver conductive paint. Details of the constant temperature feedback bridges construction are presented by Osorio et al. [20], these electronic circuits are based on a design by Itsweire [21].

4. Results

As we mentioned before the test using electronic perturbations is a good indicator of the sensor response time in the case of the hot wire anemometers, but that is not the case of wall shear stress sensors [6] [22]. As an alternative to evaluate the dynamic response Khoo et al. [13] proposed a test based on the use of a stepped rotating disk, which produces a rapid variation of the wall shear stress. This is the method that will be applied in the present work.

![Figure 5. Calibration curve for the wall shear stress sensor for a flat upper disk and for a disk with steps.](image)

First a calibration was performed with a flat rotating disk and for a 380 \( \mu \)m gap between the disk and the sensor. An analysis of the stationary thermal boundary layer brings the following relation between the wall shear stress \( \tau_w \), and the bridge output signal \( E \) [4] [8]:

\[
E^2 = A + B \tau_w^n
\]  

(6)

where \( A \), \( B \) and \( n \) are calibration constants. This correlating equation is commonly used for hot wire anemometers and is called King’s law.
To perform the calibration the rotating speed was varied so that the imposed shear stress covered the range between 0 and 0.7 Pa. For the present measurements, the overheat ratio was set at 0.06 to avoid any possible alteration of the sensor substrate material. The calibration results using the flat upper disk are shown figure 5. These measurements were fitted by equation (6), obtaining $E^2 = 6.93 + 3.33 \tau_w^{0.5}$, where $E$ is expressed in Volts and $\tau_w$ in Pascal.

The use of the shield reduces the heat losses to the surface and in some degree it also reduces the heat transfer to the flow, which we have observed as a reduction in the output of the sensor. It has also been observed that the use of the shield sacrifices some sensibility. The shield is intended to isolate the sensing element from the surface temperature, this function was verified by heating the lower disk and recording the sensor output with and without activating the shield. An important change in the sensor output was observed when the shield is not active but the variation is undetectable when the shield is working.

To evaluate the dynamic response the upper disk was modified, incorporating a step of height $\delta_s$, as shown in figure 6.

![Figure 6. Schematic of an angular section of the modified upper disk.](image)

In this study it was decided to introduce a single step of $\delta_s = 40 \mu m$ so that half of the upper disk offered a gap with the sensor of 340 $\mu m$ and the other half a gap of 380 $\mu m$. The sensor was located at a radius $r_m = 48$ mm so that the circulation length of the step $(l_s)$ is approximately 150 mm. On the other hand the sensor has a thickness $\delta_s$ of 220 $\mu m$ and the sensing element is located at $l_s \approx 21$ mm from the discs periphery. From these dimensions the following geometrical ratios can be obtained:

$$
\frac{l_s}{\delta_s} = 3750 \quad \frac{l_s}{\delta_s} = 95
$$

These ratios show that the azimuthal and radial dimensions are orders of magnitude larger than axial dimensions. This rotating disk with steps was used previously by Isomoto et.al. [23] and Shu et.al. [24]. It was shown that each step involves a sub-region that can be approximated as a fully developed flow [13], though this approximation is only valid relatively far from the step changes. In other words, for the regions far from the discontinuities the flow may be considered as the flow between two walls separated by distances $\delta$ or $\delta - \delta_s$. According to this the sensor output is expected to resemble a square wave with low and high values corresponding to the shear stresses of the two gap distances. The test proposed by Khoo et al. [13] is based on the observation of the sensor response to different disk rotation speeds. If the sensor response shows some kind of attenuation in the square wave amplitude or it is unable to follow the fluctuations it is assumed that the frequency response limit $f_D$ has been reached. This test for our sensor with the shield is shown in Figure 7.
Figure 7. Wall shear stress sensor response to step variations of the shear stress under different fluctuation frequencies: (a) 56 Hz (b) 40 Hz (c) 29 Hz (d) 20 Hz (e) 14 Hz (f) 10 Hz (g) 7 Hz (h) 4 Hz.

In figure 5 we show two calibration curves. One with a flat rotating disc and the second with the modified disc, provided with steps. In the second case we have considered a gap size equal to the average of the two gaps involved. It can be seen that for low rotation speeds the measurements with the modified disc are slightly higher than with the flat disc. For higher velocities both measurements show equal values.

Figure 8. Sensor response due to perturbations imposed by the modified upper disc for a rotation speed of 4 rev/s.
The dynamic response of the system is not simple as it involves various physical phenomena, some associated to the sensor thermal behavior, for example the variation of the temperature field in the neighborhood of the sensing element, and others to the fluid dynamics, for example the flow recirculation in the steps. Figure 8 shows the sensor output in response to the presence of a step in the modified rotating disc.

Three characteristic times can be observed: an initial startup time (region A) possibly associated to fluid dynamic effects, a fast rising time (region B), and a slower response (region C) which ends when the output reaches the steady state D. From figure 8 we can see the behavior cannot be approximated by a first order response.

![Figure 8. Sensor output in response to a step in the modified rotating disc.](image)

**Figure 8.** Sensor output in response to a step in the modified rotating disc.

Figure 9 shows the relation between the shear stress variation as calculated from the rotating speed and the two gap sizes, and the shear stress variation measured by the sensor. For this last value the previous calibration with the flat rotating disk was used. A fast sensor should show a behavior following a straight line of unitary slope till the frequency limit at which the sensor is incapable of following the changes. This last frequency being the sensor dynamic frequency limit, \( f_D \). As can be observed in figure 9 the film sensor developed in this work and incorporating a thermal shield is still not capable of following the shear stress variations, showing some degree of attenuation in the whole range of measurement frequencies.

**Figure 9.** Comparison between the shear stress variation as calculated from the rotating speed and the two gap sizes, and the shear stress variation measured by the sensor.

5. **Conclusions**

A hot film wall shear stress sensor was built and tested by means of stationary and transient imposed wall shear stress. It was observed that the use of a shield element built in the sensor reduced the sensor element power consumption and eliminated the influence of wall temperature variations by effectively providing active thermal isolation. On the down side it was also noticed that the use of the shield produces some reduction in sensibility. This opens the possibility of performing the shear stress calibration with the sensor placed on a surface different from the surface whose shear stress is to be measured.

The sensor dynamic response was evaluated by means of a modification in the calibrating device which consisted in adding a step of 40 µm height. The test showed a poor dynamic performance of the sensor, equivalent to results reported in previous works using thermal shear stress film sensors. It could be concluded that the losses to the substrate are not the main limitation to the sensor dynamic
response and therefore the limitation most probably lies in the characteristics of the convective heat transfer from the surface during a shear stress transient [25]. Based on these results and on the success of shear stress measurements with hot wire anemometers separated from the wall [6], it is expected that better time resolutions may be achieved by detaching the sensing element from the wall by some suitable distance.

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