Recent Innovations in Wall Shear Stress Sensor Technologies

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Abstract: Over the past decade significant improvements have been made in wall shear stress (WSS) sensor technologies. Due to the need to resolve flow structures on the order of 100 μm at frequencies up to 10 kHz, classes of microelectromechanical (MEMS) sensors have been developed to overcome these limitations. Three main classes exist, including floating element, thermal, and optical MEMS flow sensors. A handful of new patents have been issued in all three of these classes. For floating element MEMS flow sensors recent US patents. For thermal MEMS flow sensor. Floating element sensors have the advantage that they provide a direct measurement, while thermal sensors use an empirical formulation based upon the heat transfer from the sensor to the flow. Floating element sensors suffer from error associated with pressure gradients, cross-axis sensitivity to acceleration and vibration inputs, and fabrication issues including misalignment between the floating element and gap, debris becoming trapped in the gap between the floating element and the sensor mount and a compromise between durability and sensitivity. Thermal sensors are more mature as they are based on well established methods; however, the major flaw with this technique is the difficulty associated with minimizing heat transfer between the sensing element and the substrate. The third class of sensors, optical MEMS flow sensors, are quickly emerging as perhaps the most accurate and reliable of the three techniques.

Keywords: Wall shear stress, MEMS, flow sensors.

BACKGROUND AND INTRODUCTION

Accurate measurements of wall shear stress (WSS) in wall bounded flows are of particular interest to the Navy and Air Force due to the need to reduce energy consumption and acoustic signatures, and increase operational speeds and maneuveribility. This is particularly true for turbulent boundary layer flows. It is desirable to perform high-fidelity mean (time-averaged) WSS measurements in order to evaluate and reduce energy consumption or increase operational speeds due to the fact that the two go hand-in-hand; as operational Reynolds numbers have increased over the years the percent contribution of viscous stress now reaches values on the order of 50% for air vehicles and 90% or more for water submersed vehicles. At the same time, the transfer of energy in turbulent boundary layers occurs at very small scales and over a broad range of frequencies. The need to perform these measurements in harsh or complex environments, such as in salt water or multi-phase bubbly flows, applies further restrictions to sensing technologies.

Accordingly, current state-of-the-art in WSS sensing technologies is driven by a need to resolve near wall flow structures in high Reynolds number flows. Namely, it is desirable that sensors are capable of resolving structures of size on the order of 100 μm with frequencies up to 10 kHz [1]. Conventional technologies, such as hot-wire and hot-film anemometers have been unable to provide sufficiently accurate measurements over this range of scales, and are generally unsuited to harsh conditions.

Most recently, microelectromechanical (MEMS) devices have emerged as a new class of sensors that has the potential to overcome these limitations. MEMS fabrication techniques have allowed size reduction, increasing the spatial and temporal resolution of the sensors down to dimensions on the order of hundreds or even tens of microns. Three main types of MEMS sensors exist, each with distinctly different characteristics in their sensing modes, accuracies, and frequency responses. Namely, these are floating element, thermal-based, and sonic/optical MEMS. Floating element MEMS sensors, as the name suggests, utilize one or more transduction mechanisms coupled to a support arm of a floating element wafer, providing a direct measurement of skin friction over a small area [2-5]. Thermal-based MEMS sensors operate based upon the transduction of temperature fluctuations to a voltage signal [6]. The third type of MEMS sensor utilizes ultrasound or laser Doppler effects to determine the frequency shift of light scattered by particles near the wall. Ultrasound Doppler velocimetry (UDV) sensors measure the Doppler frequency shift between emitted and reflected signals. Their optical counterpart, known as optical MEMS (MOEMS), calculates wall shear as the product of the dynamic viscosity, the Doppler (scattered) frequency of particles passing through a diverging fringe pattern, and the fringe divergence rate. Other novel WSS sensors include sensors based on active ionic polymers and fiber optic transducers. This paper presents a comprehensive review of these current state-of-the-art technologies for WSS measurements.

FLOATING ELEMENT MEMS

Floating element MEMS sensors measure the integrated force on a flexible membrane supported by thin flexures, typically on the order of 100 to 500 μm in size. The advantage of this technique is that it is a direct measurement of skin friction and therefore requires no advanced knowledge of the flow or fluid properties. However, the sensors suffer from error associated with misalignment between the floating element and gap, pressure gradients, cross-axis sensitivity to acceleration and vibration inputs, and debris that may become trapped in the gap between the floating element and the sensor mount. Moreover, the floating element must be sufficiently flexible to resolve forces on the order of 10 pN, compromising its durability [6]. Another limitation of the design is sensitivity to pressure. MacLean and Schetz [7] present a numerical study on the operation of such a sensor and find that the theoretical overall error in the presence of pressure gradients is 17%.

Quite possibly the most thorough calibration effort presented thus far in the literature, Sheplak *et al.* [8] investigated the response of a floating element MEMS sensor to static and dynamic wall shear stress. The sensor is composed of a 500 x 500 μm square silicon floating element of 7 μm thickness suspended 1 μm above the surface of a silicon wafer by four 500 μm long x 7 μm wide x 7 μm thick silicon tethers. Static calibration was achieved over a range of 0.0014 to 10 Pa, and a noise floor of 0.0004 Pa was measured. One major contribution of this work was the use of a plane wave tube setup to generate a Stokes-layer oscillation for dynamic calibration. The apparatus allowed for a fluctuating shear envelope of 0.1 Pa at 100 Hz up to 1 Pa at 10 kHz; however, frequencies above 4 kHz were not obtained due to the structural resonance of the tube at this frequency. The response of the sensor was shown to be linear over most of the range of shear stresses and

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frequencies. A limitation of the study is that the dynamic calibration was presented in the form of a bode plot of the magnitude of the frequency response function; an error analysis of the actual signal in the time-domain was not performed. A form of the invention was patented as US. patent number 20056966231 in November 2005 [2]. A similar invention using capacitive elements capable of yielding shear magnitude and direction was patented as US patent number 20026341532 by Xu *et al*. [2].

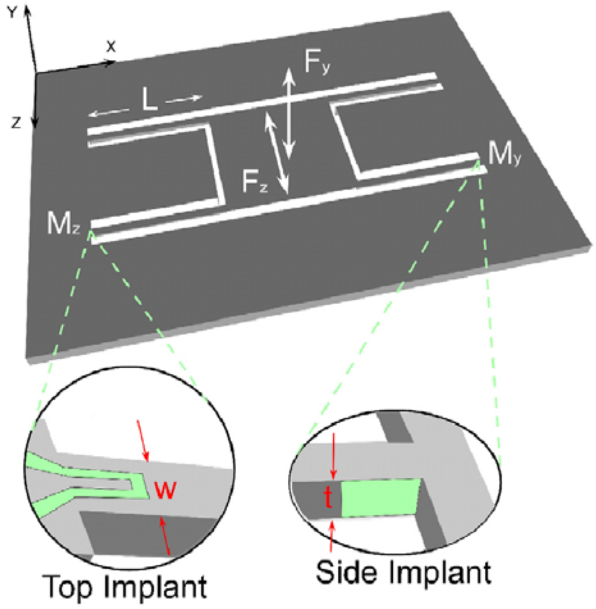

Fig. (1). Floating element MEMS sensor design with sidewall and top-mounted piezoresistive elements [10].

Schober *et al*. [9] have performed an investigation of the performance of a MEMS surface fence sensor, which is essentially a variation of a floating element sensor. The sensor operates on the principle of a pressure difference measured across a flexible membrane that extends from the silicon chip into the viscous sublayer. This pressure difference generates a measurable deflection that is transduced via two piezoresistors located on either end of the fence. Static calibration was preformed in a Preston tube for wall shear values ranging from -0.7 to 0.7 Pa with a resolution of 0.02 Pa; a dynamic calibration was not attempted. Also, time-averaged results for wall shear in a region of separated flow downstream of an obstacle were presented and showed good agreement with time-averaged pulsed hot wire data. However, the fluctuating component of the wall shear measurements showed discrepancies when compared with the time resolved pulsed hot wire data.

Most recently, Barlian *et al.* [10] have fabricated a floating element MEMS sensor combining both sidewall to measure lateral forces and stresses and more conventional top-implanted piezoresistors to measure normal forces and stresses Fig. (**1**). The sensors are designed for use in hydrodynamic applications. A hydrogen annealing process was utilized to smooth scalloped surfaces resulting from the deep reactive ion etch (DRIE) process. This process was found to decrease the noise floor by an order of magnitude. A temperature sensitivity analysis was conducted, and the sensitivity of the piezoresistive elements was found to be 0.0081 kOhms/C^{-1}. The group proposes to use temperature compensating signal conditioning in future sensor fabrication.

Pulliam *et al.* [3] developed a floating-element WSS sensor using optical interferometry. Light is delivered through an optical fiber to create an interferometric region between the fiber and a supported floating head. As fluid shear deflects the floating head, the interferometric region is changed, and this change is measured for correlation with the applied shear. The sensor is patented as US patent number 20026426796 [3]. Horowitz *et al.* [11] presented a novel approach to floating-element WSS sensing by using an optical Moire technique Fig. (**2**). The Moire technique is achieved by patterning aluminum lines on two separate gratings with differing pitches. The combination of the two gratings creates a translation-dependent Moire fringe pattern, which is illuminated from the wafer side to minimize flow disturbance from the illumination. A charge-coupled device (CCD) camera is used to record the fringe pattern The sensor is immune to EMI effects and its output is not affected by transverse element movement due to pressure fluctuations and vibrations. Initial results appear very promising for both mean and dynamic WSS measurements, with calibrations performed up to 1.3 Pa with a sensitivity of 6.2 mPa, although some non-linearity in the sensor seems apparent from the data. The sensor has been patented as US. patent number 20060137457 [4].

THERMAL MEMS

The second category of MEMS shear sensors is the thermal-based sensor which operates based upon the transduction of temperature fluctuations to a voltage signal in the same manner as hot-wire anemometers. The major drawback of this technology is that the frequency response of thermal-based sensors is difficult to characterize due to the frequency-dependent heat conduction to the substrate, further complicating the calibration process. One of the earliest forms of this class of MEMS sensor was developed by Huang *et al.* [12], patented as US patent number 19995883310 [5]. The sensor consists of a 1 μm thick heating element separated from the substrate by a 2 μm vacuum, and has built-in self-frequency and temperature calibration. Sheplak *et al.* [13] characterized a thermal-based MEMS sensor under both static and dynamic shear environments. Static calibration up to 1.7 Pa was achieved via a laminar flow channel. Dynamic calibration was performed using the plane-wave tube with Stokes-layer oscillation as described above, with a

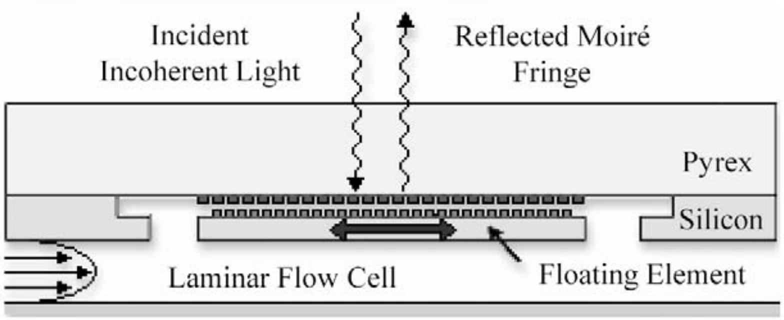

Fig. (2). A MOEMS based WSS sensor using a geometrical Moire optical transduction technique [11].

theoretical fluctuating wall shear stress envelope of 0.9 mPa at 0.2 Hz to 6.1 mPa at 7 kHz. A noise floor of 100 nV/Hz$^{1/2}$ was observed, with a resolution of 9 μPa/Hz. Lofdahl *et al.* [14] investigated the response of a hot-wire MEMS sensor for micro-wires placed at varying heights above the wall between 50 and 250 μm. The sensor was calibrated for time-averaged steady shear stress values between 0 and 0.5 mPa; dynamic calibration was not performed. Time-resolved measurements were presented for a flow field employing periodic sucking and blowing at 260 Hz of a laminar boundary layer 80 mm upstream of the sensor providing a disturbance to the flow in order to demonstrate the frequency response of the sensor.

Liu *et al.* [15] have developed a similar thin film sensor array for detecting separation in aerodynamic applications using the principle of thermal anemometry Fig. (**3**). The sensor consists of a platinum thin film resistor situated on a silicon nitride substrate. The thin film resistor is passed an electrical current to heat its surface, allowing the WSS to be determined from the heat transfer to the environment. The sensor was shown to be useful for detecting the point of separation on flow over a circular cylinder.

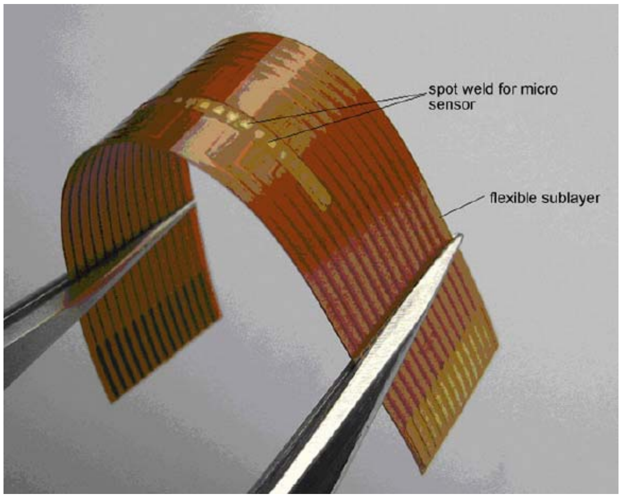

Fig. (3). Thin film sensor array for detecting separation points [15].

Recently, Kim and Lee [16] developed a thermal WSS sensor Fig. (**4**) using a backside cavity connection to prevent heat transfer to the substrate. Small cavities were also made at interconnection passage holes for connecting to the substrate. Thermal oxidation was applied at moderately low temperature to insulate the exposed substrate after it had been etched. Steady shear calibration was achieved using a rotating disk (Couette flow), delivering WSS magnitudes from 0 to 0.9 Pa, for a range of overheat ratios from 0.05 to 0.20. The sensor sensitivity increases with overheat ratio and decreases with WSS magnitude. Overall, the sensor displayed a higher sensitivity range than similar thermal sensors, on the order of 200 to 800 mV/Pa. Dynamic characterization was performed up to 400 Hz by using a stepped rotating disk, and it was hypothesized that the signal would be discernable over 1 kHz.

In application to microfluidics, Xu *et al.* [17] fabricated a MEMS multi-sensor for simultaneous shear stress, pressure, and temperature sensing for microchannel flows Fig. (**5**). The sensor exhibits a sensitivity of 82.9 μV/(kPa V). The WSS sensor portion of the device was tested in a microchannel at Mach numbers of 0.2 and 0.6 and showed very similar responses between sensors. However, the WSS sensor was not calibrated. Soundararajan *et al.* [18] developed a similar MEMS thermal WSS sensor for application to microcirculation. For this sensor, a polysilicon element was doped with phosphorous in order to increase the sensitivity of the resistivity of the sensing element to 2.5 kOhms. However, the use of phosphorous in doping the polysilicon element caused the temperature coefficient of resistance (TCR) to be negative. Interestingly, the voltage shows a linear relationship with shear stress, but has a negative slope due to the negative TCR. More recently, Tung *et al.* [19] successfully implemented laterally aligned carbon nanotubes in a 360 by 90 μm wide conductive trace. The trace was aligned between two triangular shaped micro electrodes Fig. (**6**) by applying a high frequency AC electric field. A room-temperature resistance of 580 Ohms, corresponding to a conductivity of 2.7 x 10^4 S/m was reported. The absolute temperature coefficient of resistivity was found to be an order of magnitude less than for highly doped polysilicon sensing material, ranging from 0.01 to 0.04% C^{-1}. This reduction in resisitivity is not favorable, as it does not yield any improvements in energy consumption for moving to nanoscale flow measurements. However, the ability to create sensors with smaller size and thermal mass than doped poly-silicon sensors is a distinct advantage for nanofluidic applications.

OPTICAL AND ACOUSTIC MEMS

The third type of MEMS sensor utilizes ultrasound or laser Doppler effects to determine the frequency shift of light scattered by particles near the wall. Ultrasound Doppler velocimetry (UDV) sensors measure the Doppler frequency shift between emitted and reflected signals. Their optical counterpart, known as optical MEMS (MOEMS), calculates wall shear as the product of the dynamic viscosity, the Doppler (scattered) frequency of particles passing through a diverging fringe pattern, and the fringe divergence rate. Both sensor types provide direct measurements of the local wall shear, are non-invasive, highly accurate under optimal conditions, and can respond to high-frequency fluctuations. However, the measurements are significantly limited by the particle seeding, which limits the data rate [20,13]. Moreover, the methods are currently limited by the difficulty to fabricate a sensor with a probe volume that is contained entirely within the viscous sublayer [6]. In flows where natural seeding is employed, the accuracy of the measurement may be affected by the size and properties of the particles. [20] estimated the total error of UDV to be +/- 8.4 %. Optical sensors have the potential to provide the highest accuracy in WSS measurements, as the method of scattered Doppler shifts is extremely robust. In this method, a diverging fringe pattern is projected above the surface using a laser diode and conventional optics Fig. (**7**). The local fringe separation is designed to be linear and given by $\delta = ky$, where k is the rate of divergence of the fringes. Assuming that the measurement location is within the linear viscous sublayer region, which is not necessarily the case, the velocity gradient is the product of the frequency shift and the fringe divergence rate. Fourgette *et al.* [21,22] present static calibration results for a MOEMS shear stress sensor with a probe volume located 66 μm above the wall surface. The group theoretically estimated accuracies on the order of 99% for low Reynolds number (laminar) boundary layer flows. However, the accuracy of the method decreases rapidly as the Reynolds number increases due to the large probe volume height with respect to the height of the viscous sublayer. They estimate accuracy as low as 70% depending upon the ratio of these two quantities.

IONIC POLYMER TRANSDUCER BASED WSS SENSOR

Etebari *et al.* [23] introduced a class of wall shear stress sensors based on ionic polymer transducers (IPTs). IPTs are materials consisting of an ion-exchange membrane plated with conductive metal layers that exhibit electromechanical coupling under the application of electric fields and imposed mechanical deformation

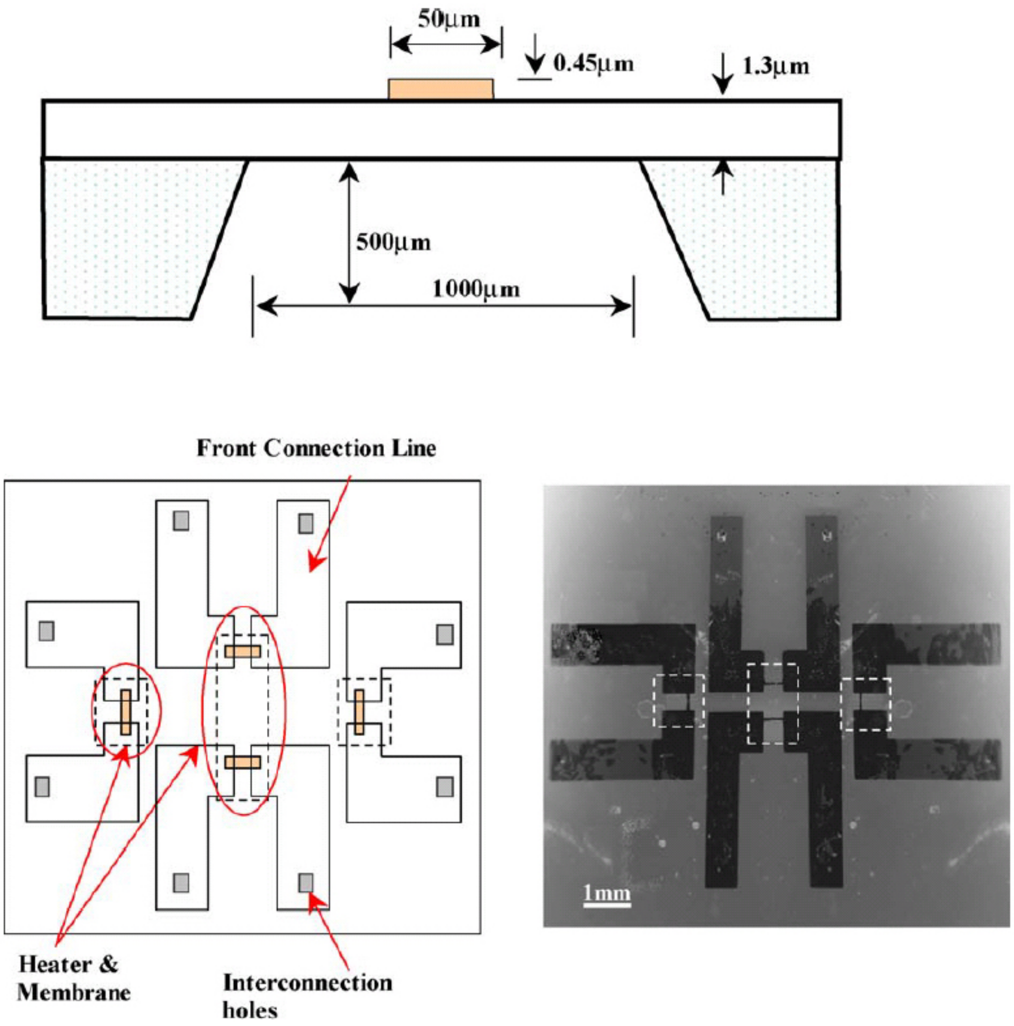

Fig. (4). Thermal WSS sensor with backside insulating cavities [16].

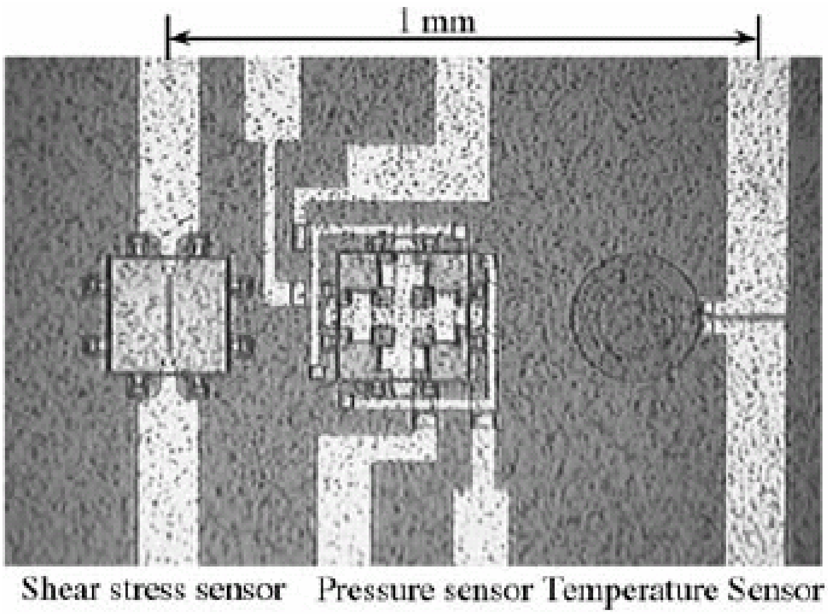

Fig. (5). A MEMS multi-sensor for simultaneous shear stress, pressure, and temperature measurements in microfluidic applications [17].

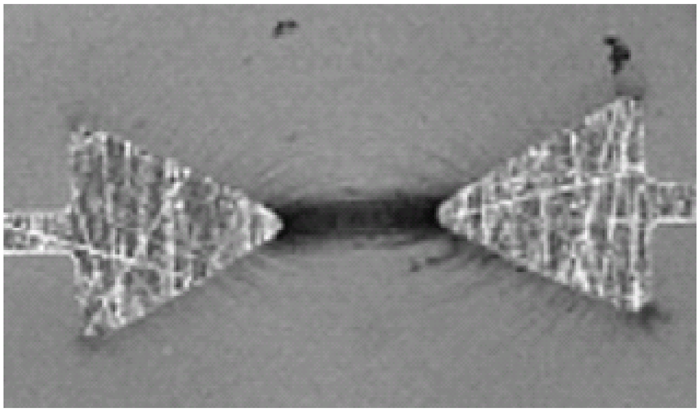

Fig. (6). Carbon nanotubes arranged in trace between triangular shaped micro electrodes [19].

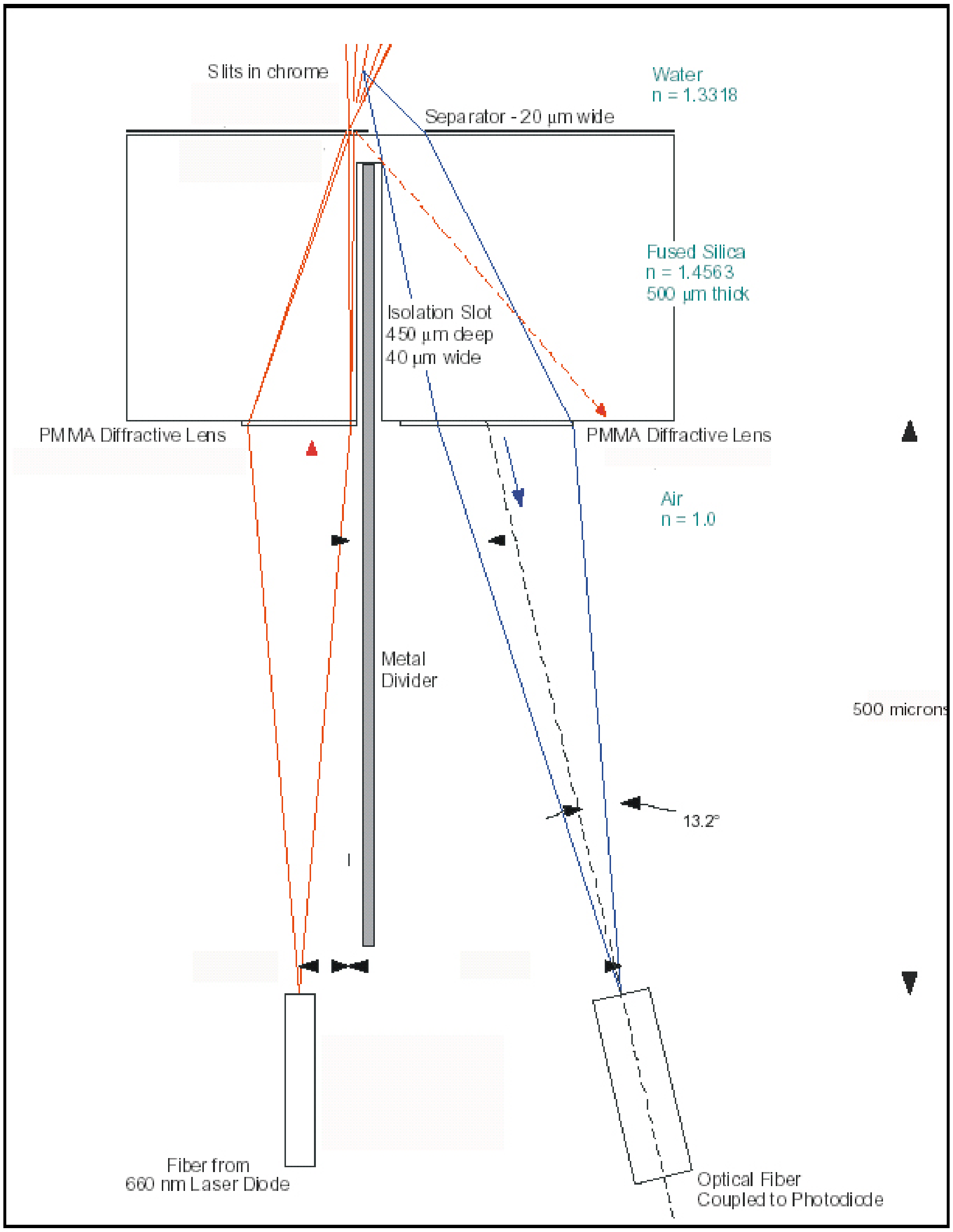

Fig. (7). A MOEMS based WSS sensor From Fourgette *et al.* [21]; reprinted by permission of the American Institute of Aeronautics and Astronautics, Inc.

[24-26]. These materials display charge-sensing properties similar to those of piezoelectric materials [27,28]. Charge aggregation due to mechanical deformation gives the transducer charge sensing capabilities. Furthermore, they can be manufactured as thin as 25 microns in height. The IPT based WSS sensor (Fig. **8**) consists of a Nafion™-117 membrane that is plated on both surfaces [29]. The polymer is swollen with an ionic liquid [30] to provide ion transport through the polymer. A copper-clad polyimide substrate is used to mount the sensor using conductive epoxy. Two electrical traces are etched onto this substrate in order to make contact with the surface electrodes on the sensor. Thin wires are soldered to the traces to acquire the signal from the sensor. Finally, the sensor is laminated with a thin (2.5 μm) Mylar film to protect and seal the sensor. Steady WSS calibration was performed on a flat plate in a 24" square water tunnel, while unsteady calibrations were achieved by using a cam-shaft mechanism connected to a flat plate to generate an oscillating Stokes layer. Due to the high capacitance of the IPT, the sensor displays excellent frequency response, responding well to high frequency fluctuating WSS. However, it does not yield reliable steady measurements, making it more suitable for separation measurement applications.

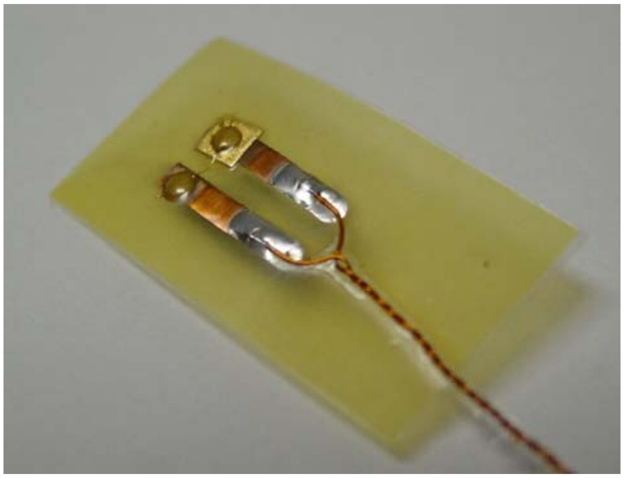

Fig. (8). WSS sensor based on an active ionic polymer transducer.

CURRENT & FUTURE DEVELOPMENTS

Wall shear stress sensing technologies have progressed significantly in the past decade. All relevant technologies have aimed to increase spatial resolution without compromising sensitivity. Naturally, microelectromechanical systems have become a common factor in the development of WSS sensing technologies. Of the available technologies, thermal based sensors are the most mature, having been inspired by previous technologies, i.e. hot-films and hot-wires. However, their main limitation is due to heat transfer between the sensing element and the sensor substrate. The incorporation of cavities for insulation [16] may allow future technologies to overcome this obstacle. Floating element sensors can provide direct, dynamic WSS measurements, but require careful fabrication to ensure gap alignment, and are more subject to mechanical degradation/fouling. Optical sensors provide the most reliable and accurate of all measurements, provided that the measurement region is contained within the viscous sublayer. Thus, for low Reynolds number flows they are the sensors of choice. However, in order to reach widespread acceptance they will require future modifications to their optical systems in order to bring the measurement probe within the viscous sublayer for high Reynolds number flows. This necessity will require the probe volume to reside within a region not more than 10 to 20 microns away from the wall.

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