TURBULENCE MEASUREMENTS USING SILICON BASED SENSORS

by

L. Löfdahl*, G. Stemme** and B. Johansson*

*Department of Applied Thermodynamics and Fluid Mechanics

** Department of Solid State Electronics

Chalmers University of Technology

ABSTRACT.

Small and highly sensitive velocity sensors have been designed and fabricated using silicon microelectronic technology. To determine the performance of these silicon sensors, comparisons with conventional hot-wire sensors were done in a well-defined two dimensional turbulent flat plate boundary layer at a constant Reynolds number of $4.2 * 10^6$. The silicon sensors were found to have a spatial and frequency resolution that makes them suitable for turbulence measurements. In the studied flow field the silicon based sensors determined profiles of mean velocity, turbulent normal as well as shear stresses with the same accuracy as the hot-wires.

1. INTRODUCTION.

The turbulence models used for the solution of the Reynolds equations have so far most commonly been based on some eddy-viscosity approach and assume isotropy of the flow field. However, the rapid development of todays computers towards faster and larger units has made it feasible to employ more complex turbulence models. These models are usually based on the transport equations for the Reynolds stresses, and give possibility to compute complex anisotropic flow cases. This modern approach to the modelling of turbulence calls not only for measurements of profiles of double and triple velocity correlations, but also for the determination of velocity/pressure correlations.

Double and triple correlations have for many years been measured using hot-wire techniques, see for example Perry (1982). Very few measurements of velocity/pressure correlations have, however, been reported so far. (To the author's knowledge only one work back in the fifties of Kobashi (1957). To support developing and testing turbulence models, requirements have been raised of new measuring techniques and sensors, which can be used both as a complement to hot-wires and also enable the determination of the velocity/pressure correlations. Sensors based on silicon technology have the potential to fulfil these requirements, and in the present paper the first part, determination of mean velocities and turbulent stresses, in the development of such sensors is described.

In the fabrication of the sensors, well known materials silicon, silicondioxide and other materials all of extremly high purity have been used. These materials and the batch fabrication technique have made it possible to make small and indentical components. Futhermore, new techniques have been developed and added to standard semiconductor processes. Micromachining of silicon has been used where, by using wet chemical etches, it is possible to form the silicon into different three dimensional shapes.

In the present paper, two versions of flow sensors, both capable for turbulence measurements (velocity correlations), are presented. All sensors have been fabricated by using the above mentioned techniques. The first version was used for mean velocity measurements and for the determination of the turbulence intensity in the main flow direction, see Löfdahl et al (1989). The second version of sensors was considerably smaller, and had a length/width ratio, which made them sensible to changes in the flow direction, and thus permitting the determination of the turbulent shear stresses as well as normal stresses perpendicular to the main flow direction.

Comparisons between the performance of the silicon sensors and conventional hot-wires are carried out. All measurements were made in the well known and well defined two dimensional turbulent boundary layer of a flat plate.

2. SENSOR DESIGN

Originally, the sensor consisted of a base plate with electric bonding pads and a beam extending from the base plate. At the far end of the beam a small sensor chip (0.3 mm * 0.4 mm * 30 µm) was mechanically attached and electrically connected to the beam, see Figure 1. A resistor and a diode are integrated on the sensor chip.

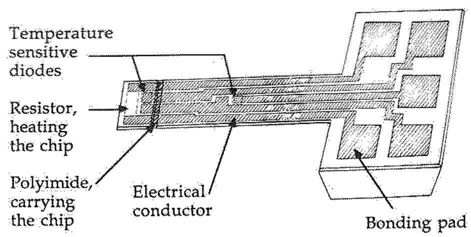

Figure 1. Principle drawing of the original silicon sensor with its three parts:

The base plate (1.5 mm * 1.0 mm * 0.3 mm)

The silicon beam (1.6 mm * 0.4 mm * 30 µm)

The chip (0.4 mm * 0.3 mm * 30 µm)

The principle of operation relies on a diode monitoring the temperature of the chip, which is electrically heated by the integrated resistor and cooled by the flow. Using a temperature feedback regulator control, the sensor chip is maintained at a constant elevated temperature, for example 50°C, above the ambient temperature, which is measured with a separate diode integrated on the beam. The power dissipated in the heated resistor is thus a measure of the flow velocity.

In the fabrication of the sensors a new method has been developed, using a polyimide bridge between the beam and the chip. The purpose of this is twofold; Firstly, the polyimide, which is a form of plastic, is strong enough to carry the chip and secondly the polyimide has a very low thermal conductivity, thus reducing the thermal losses by conduction, see Stemme (1986). The good thermal insulation and the extremely small size of the sensor chip increase the sensitivity, give a fast response and minimize the flow perturbation as well.

The small mass of the chip yields a temperature time constant of 50 ms (milliseconds), ie of the same order as the response of a standard hot-wire. These responses are, however, far too low to allow the sensor to be used for turbulence measurements without frequency compensation. The frequency response may, however, be increased considerably, by using the method of constant sensor temperature together with electronic feed back of the amplified temperature variations. For full account of the calculations of the frequency response see Perry, (1982) or Hinze, (1975).

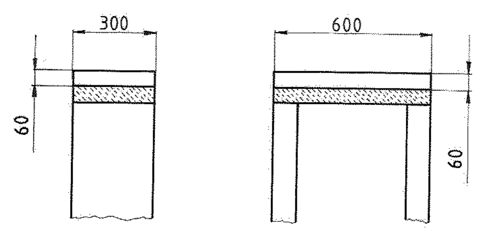

Figure 2. Silicon sensors with length to width ratio of 10/1 and 5/1 respectively. The total length is 300 μm and the thickness of the chip is 30 μm.

New sensor configurations have been developed mostly for improving the directional sensitivity and the frequency resolution. The length to width ratio is an important parameter in this context, and therefore two configurations with the ratios of 10/1 and 5/1, respectively have been designed and manufactured. In figure 2 a layout drawing of these two sensors is shown.

To enable measurements of turbulent stresses, velocity correlations, a double chip sensor was designed. Figure 3 shows a layout drawing of this sensor, which consists of two 5/1 sensors integrated to form an "L" on one sensor. In the shear stress determination this sensor is positioned as to form an angle with the main flow direction.

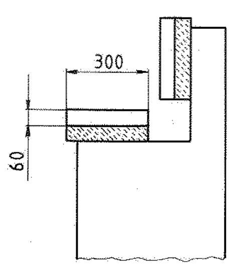

Figure 3. Double chip sensor for the determination of velocity correlations.

For futher details of the silicon based sensor and the fabrication process, see Stemme (1986 and 1988) and Löfdahl et al. (1989).

3. FLUID DYNAMIC EXPERIMENTAL SET UP.

All measurements were carried out in a low-speed wind tunnel at a constant Reynolds number of $4.2 * 10^6$. In the horisontal symmetry plane of the test section (1.25 m * 1.80 m * 3.00 m) of the wind tunnel, a flat plate of 2.5 m length was positioned. The material of the flat plate was wood, and its upper and lower surfaces had a thin plastic laminate coating for obtaining a smooth surface. The measuring point was located 0.5 m from the trailing edge. Variation in the streamwise pressure distribution was determined to be less than one percent

$(\nabla c_p / c_p > \pm 0.005)$, and no variation was found in the

spanwise pressure distribution. This flat plate has earlier been used for the evaluation of hot-wire methods, see Löfdahl and Larsson, (1984), and the plate is a simplified copy of the "classical" flat plate used by Klebanoff in his experiments back in the fifties, se Klebanoff (1954).

In the present measurements the boundary layer thickness at the measuring station was 37 mm, and the friction velocity was determined to be u* = 1.18 m/s. The probes were traversed through the boundary layer using a traverse mechanism described by Löfdahl, (1988).

All sensors were directed in the main flow direction to minimize the disturbances, and were calibrated against a Prandtl tube. In the calibration model, the silicon sensor was considered as a flat plate with a laminar boundary layer. The Reynolds number varies in the interval 20 through 1200. According to Schlichting (1978) the heat transfer from the plate is proportional to the square root of the Reynolds number. Thus, the same equations, which are used in hot-wire technique, are also applicable for the silicon sensors. In the present investigation, a computerized version of the calibration law of Siddal and Davies, (1972) was used for the conversion of voltage into velocity.

In the hot-wire measurements the simplest possible equipment was used, i.e. standard boundary layer and cross-wire probes, Dantec No. 55P05 and No. 55P51, respectively, together with a standard Dantec anemometer system, No. 5600.

4. MEASUREMENTS AND DISCUSSION.

The comparison between the hot-wire and the silicon sensor was emphasized throughout the measurements, and this means that as many parts as possible of the measuring chain were kept similar in the experiments. A calibration was performed before and after each measurement, and in no case any deviation in the calibration curves was accepted. All output data from the electronic unit of the different sensors were digitized, and the same data aquisition and time of integration were used for all sensors. Details of the used evaluation methods are available in Löfdahl, (1986).

Figure 4 shows the results of the mean velocity measurements. All measurements were carried out just outside the viscous sublayer, in the buffer layer, in the logarithmic region and in the outer layer of the boundary layer. A comparison between the profiles obtained with the silicon sensor and the conventional hot-wire reveals a good agreement in all these regions. In the innermost region of the profile, $y^+ = 8$ through $y^+ = 35$, the cha-

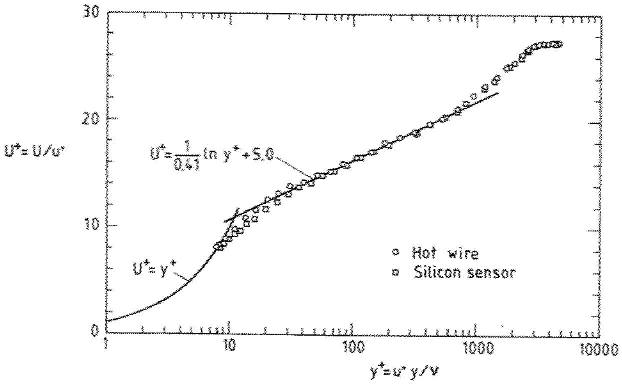

Figure 4. The mean velocity profile at the measuring point.

(U / u^* = f (u^* y /ν) ; u^* - friction velocity)

racteristic deviation from the theoretical lines, which has been noted by many other investigators, for example by Ligrani and Bradshaw, (1987), also appears in the present measurements. Due to the very thin plastic laminate of the surface of the flat plate this plate may be classified as a non-conducting wall, and since the innermost points of the present measurements are located as far from the wall as at $y^+ = 8$, no wall corrections are needed according to Bhatia et al, (1982).

Figure 5 shows the directional sensitivity of the second version of sensors. As a comparison hot-wire measurements are also shown in the figure together with the simplest cooling law, "the cosine law", used in hot-wire measurements. The silicon sensor with a length/width ratio of 5/1 seems to agree fairly well with the hot-wire measurements and the simple cooling law. At the larger angles, a deviation occurs from this cooling law, and if a more sofisticated cooling law is employed, for exemple the law of Champange et al (1967) a calculation of the k value in this cooling law reveals an approximate k value of 0.4, which is in good agreement with what usually is obtained for hot-film probes according to Johansson and Alfredsson (1987).

The silicon sensor with a length/width ratio of 10/1 deviates considerably from the hot-wire data and the simple cooling law at larger angles. This can, however, be explained by the formation of eddies at the supporting beams (prongs) and the squared section of the beams as well as the chip.

Figure 6 shows profiles of the determined turbulence intensity in the main flow direction. Closest to the wall, in the region $y^+ = 8$ through $y^+ = 20$, a clear difference in the turbulent intensities, determined with the different sensors, can be noted. This deviation can be explained by the fact that the used reference hot-wire is a standard wire with a comparatively long active length, $\ell^+ = 90$, and this means that this hot-wire is not able to capture the maximum of the turbulence intensity in this region since the fluctuating motions are strongly attenuated if their length scales are smaller than the active wire length. The measured turbulence intensities do not contain all available energy in the turbulence spectra. Using hot-wires with a shorter active length, as has been done in many investigations, for exemple by Ligrani and Bradshaw (1987), reveals a clear maximum in the turbulence intensity in this region.

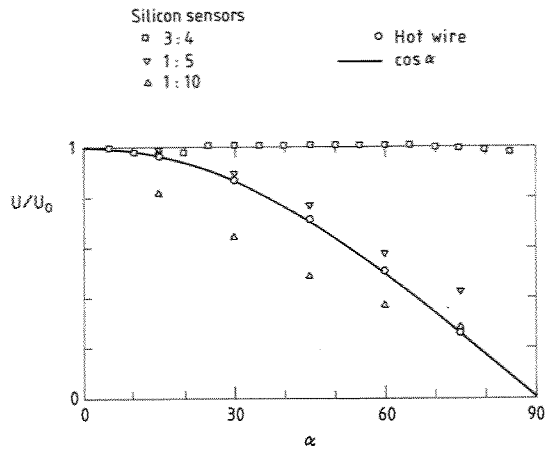

Figure 5. Directional sensitivity of the silicon sensor with a length/width ratio of 4/3, 5/1 and 10/1 respectively.

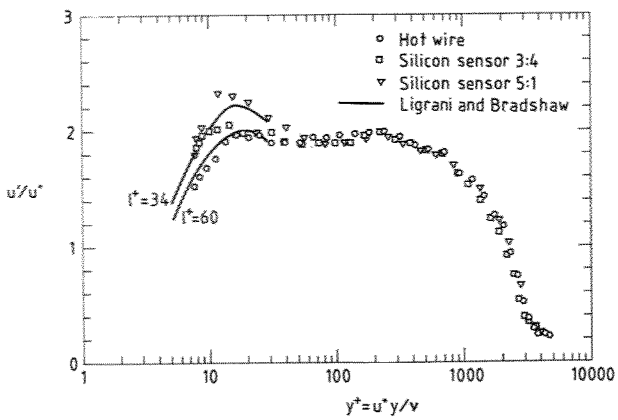

Figure 6. The turbulence profile at the measuring point.

(u' / u^* = f (u^* y /ν))

As a comparison two typical measurements with a short active wire length, $\ell^+ = 34$ and $\ell^+ = 60$, of Ligrani and Bradshaw (1987) have been included as references in figure 6. Considering the silicon sensors the value of the active length, ℓ^+, is 31 and 23, respectively, and,as is visible in the figure both are capable of capturing the maximum in the turbulence intensity, i. e. the attenuation of the fluctuating motions are reduced, so that a larger portion of the turbulent energy is included in these points. A shorter active length gives, as can be expected, a higher maximum. In the region $y^+ = 10$ through $y^+ = 25$ a fairly large deviation between the hot-wire measurements, $\ell^+ = 34$, and the original sensor with a $\ell^+ = 31$ can be noted. This deviation can, however, be explained by the fact that this silicon sensor has an extension in the flow direction of 0.3 mm ($\ell^+ = 26$), and since the turbulence is three dimensional the fluctuating moting is attenuated also in this direction. A comparison with the second version of the silicon sensor, $\ell^+ = 23$, reveals that the maximum in turbulence intensity is captured in the same way as with the hot-wire.

In the outer portion of the log-layer, the measurements agree quite well with each other as well as with measurements in other works, for example Ligrani and Bradshaw, (1987).

Considering the outer region of the boundary layer, where the boundary layer thickness determines the level of the turbulence intensities, the agreement between the hot-wire and the silicon sensor also seems to be very good.

Figure 7 shows the turbulent shear stress, which has been determined with the double chip sensor. Also in this figure, hot-wire measurements with a cross-wire have been included for reference purpose. The shear stress is expressed as a correlation, $\overline{uv}/u'v'$, and seems to be approximately constant through most of the boundary layer. The constant value of, -0.40, is fairly low as compared to the measurements of Klebanoff (1954), but as compared to the ones of Perry and Abell (1975) almost the same value of the correlation (-0.37) is obtained. Comparing our hot-wire measurements to the silicon sensor measurements the agreement is quite good. It should, however, here be pointed out that the silicon based sensor can be employed for measurements much closer to the surface than a standard cross-wire.

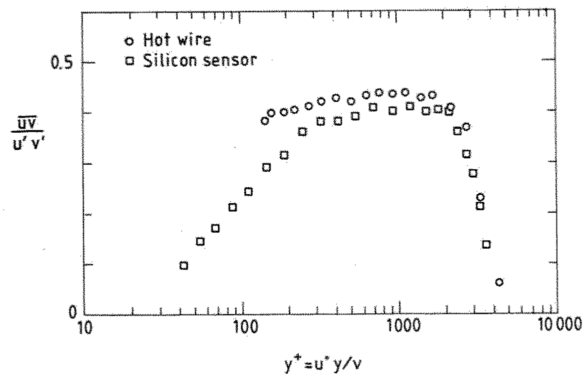

Figure 7. Turbulent shear stresses determined with the double chip sensor.

5. CONCLUSIONS.

An investigation in which the profiles of the mean velocity and turbulence intensity were measured in a two demensional turbulent boundary layer, using silicon based sensors, has been carried out. Comparisons are made with corresponding conventional hot-wire sensors, and these comparisons the following conclusions may be drawn.

* The silicon based sensor seems to satisfy the demands on spatial and frequency resolution for measurements in a turbulent flow field.

* Comparisons of the mean velocity and turbulence intensity profiles reveal that the silicon sensors determine these quantities with the same accuracy as the hot-wire

* The double chip sensor has been used for the determination of turbulent shear stresses with the same accuracy as can be obtained with a cross-wire.

Compared to a hot-wire the silicon based sensor has the advantage that important functions, such as temperature diodes, pressure transducers, pre-amplifiers and other control electronics, can be integrated on the sensor chip.

6. ACKNOWLEDGEMENTS.

This work was supported by a grant from the Swedish Board for Technical Development.

7. REFERENCES.

Bhatia, J.C., Durst, F. and Jovanovic, J. 1982, Corrections of Hot-Wire Anemometer Measurements near Walls, J. Fluid Mechanics Vol. 122, pp. 411-431.

Champange, F.H., Sleicher, C.A., and Wehrmann, O.H., 1967, Turbulence Measurements with Inclined Hot-Wires. Part 1. Heat Transfer Experiment with Inclined Hot-Wires, J. Fluid Mech., vol. 28, 153.

Comte-Bellot, G. 1976, Hot-Wire Anemometry, Annual Review of Fluid Mechanics, Vol. 8, pp. 209-231.

Hinze, J.O. 1975, Turbulence, McGraw-Hill Bool Company.

Johansson, A.V., and Alfredsson, P.H. 1983, Effects of imperfect spatial resolution on measurements of wall bounded turbulent shear flows, J Fluid Mech., 137, 409.

Klebanoff, P.S., 1954, Characteristics of Turbulence in a Boundary Layer with Zero Pressure Gradient, NACA Report No. 1247.

Ligrani, P.M. and Bradshaw, P. 1987, Spatial Resolution and Measurements of Turbulence in the Viscous Sublayer Using Subminiature Hot-Wire Probes, Experiments in Fluids, Vol. 5 pp. 407-417.

Löfdahl, L. 1986, Hot Wire Techniques for the Determination of the Reynolds Stress Tensor in Three-Dimensional Flows, Dantec Information Vol. 3.

Löfdahl, L. 1988, Traverse Mechanisms for the Determination of Reynolds Stresses Using Hot-Wire Techniques, Experiments in Fluids, Vol. 6. No. 5.

Löfdahl, L. and Larsson, L. 1984, Turbulence Measurements Near the Stern of a Ship Model, J. of Ship Research, Vol. 28, No. 3, pp. 186-201.

Siddal, R.G. and Davies, T.W. 1972 An Improved Response Equation for Hot-Wire Anemometry, Int. J. Heat and Mass Transfer, Vol. 15, pp. 367-368.

Stemme, G. 1986, A Monolithic Gas Flow Sensor with Polyimide as Thermal Insulator, IEEE Transactions on Electron Devices, Vol. Ed. 33, No. 10.

Stemme, G. 1988 A CMOS Silicon Gas Flow Sensor with Puls-Modulated Output, Sensors and Actuators, Vol. 14, No. 3, pp. 293-303.

Perry, A.E. 1982, Hot-Wire Anemometry, Claredon Press Oxford.

Perry, A.E., and Abell, C.J. 1975, Scaling laws for pipe flow turbulence, J. Fluid Mech., 67, 257.