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Pulsed hot wire anemometry; an accurate method to measure highly turbulent flows at low speeds

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PULSED HOT WIRE ANEMOMETRY;

an accurate method to measure highly turbulent flows at low speeds

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Summary

The operating principle of the Pulsed-Hot-Wire-Anemometry has been described. This type of anemometers has proven a reliable and accurate measuring device for highly turbulent and recirculating flows. Since the measurement principle consists of measuring a time of flight of a temperature tracer, the accuracy of the device increases as the velocity decreases, in contrast to most other measurement systems. Its ability to measure velocities in flows where the general flow direction is not known a priory and the insensitivity of the device to changes in flow temperature and gas composition makes it a very versatile device. It has been demonstrated that for measurement devices that cannot detect changes in flow direction severe measurement errors may occur. Being sensitive only to the part of the velocity vector in a predefined direction makes it possible to map the total flow velocity vector at a point with a limited number of measurements.

Introduction

Most measurement systems for flow velocities are operated and has a response function that require some prior knowledge about the mean flow direction. For Pitot-static tubes and turbine meters the measured velocity can only be regarded as reliable if the device is directed in the mean flow direction to within about ±10 degrees. A single hot wire can measure the norm of the velocity vector if the plane in which the velocity vector lies is known, but can not give any directional information. In order to add directional sensitivity two slanted wires known as an X-probe may be used, but this technique is again limited to a velocity vector that does not vary by more than about ±15 degrees from the probe axis. In order to avoid this problem one may seek devices that are only sensitive to one component of the velocity vector and then by doing measurements at three different directions the velocity vector may be constructed. Two such methods are the Laser-Doppler-Anemometer (LDA) and the Pulsed-Hot-Wire-Anemometer (PHWA). Both methods have the unique property that the output only depends on the velocity component in one predefined direction and unlike the other methods mentioned these methods are capable of detecting when this component reverses flow direction.

Whereas the cost of a PHWA is of the same order of magnitude as for a conventional Hot-wire anemometer the expense of having a LDA-system is almost two orders of magnitude higher. Also the application of a PHWA is fairly straight forward whereas considerable experience is required to operate the LDA.

In this paper the operating principles of the PHWA will be described and the application to a backward facing step is demonstrated. The flow characteristics of the step are similar to the flow found near a ventilation slot exhausting air horizontally close to the ceiling. The errors in the measured mean and standard deviation obtained in the horizontal velocity component if the reversed flow can not be detected is demonstrated.

The Pulsed-Hot-Wire-Anemometer

The PHWA principle was first proposed by Bauer (1). It was later developed into a useful measurement system by the group of Bradbury and Castro (2,4) primarily as a means of measuring velocity in highly turbulent and recirculating flows. The accuracy of the measurements obtained by the PHWA has been investigated by Dengel and Vagt (5) who compared PHWA measurements with conventional hot-wire measurements in a free jet and a boundary layer. Similar experiments were performed by Jaroh (6). Krogstad and Sinangil (7) made comparative measurements between LDA, PHWA and HWA in the near wake of a circular cylinder. They concluded that the measurements using the PHWA are in good agreement with LDA data even at high turbulence levels where HWA data may be in considerable error.

The measurement principle of the PHWA consists of generating a thermal tracer in the flow field and then detect the time used by the tracer to travel a predefined distance. Because one wishes this to be as close to a point measurement as possible it is essential that the measurement distance is small. To obtain this a probe geometry as shown in figure 1 is used. The probe consists of 3 fine wires made of 5 μm diameter platinum coated tungsten welded on to a set of prongs. The forward and rear wires are parallel and the middle wire is perpendicular to the two. The length and spacing between the wires must be optimized for the velocity range of interest but typical lengths are 10 mm and spacing is 1 mm. The middle wire is heated to high temperatures for a short period of time (of the order of 1 ms) thus locally heating the air. The two detection wires are operated as very sensitive resistance thermometers and if the distance between the wires are known the velocity is calculated directly from the time of flight.

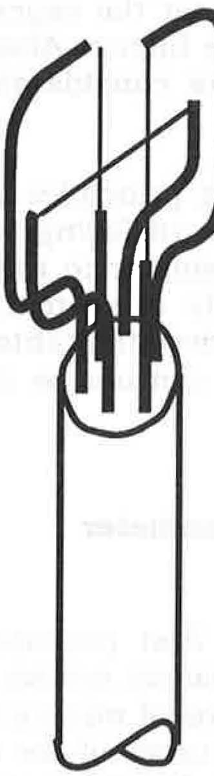

Figure 1 Typical Pulsed-Hot-Wire probe geometry

In principle the temperature signals from the heated and one of the detecting wires will look like the traces indicated in figure 2. The heated wire is heated periodically to a predefined temperature and kept constant at this temperature. After some time defined by the wire spacing and flow velocity the tracer is detected at the downstream wire. Due to thermal diffusion the temperature is considerably reduced, but still well detectable. Also, the width of the tracer is broadened so the tracer received is in fact bell shaped. The accuracy of the device is therefore somewhat linked to the algorithm used to compute the time of flight from the signal received.

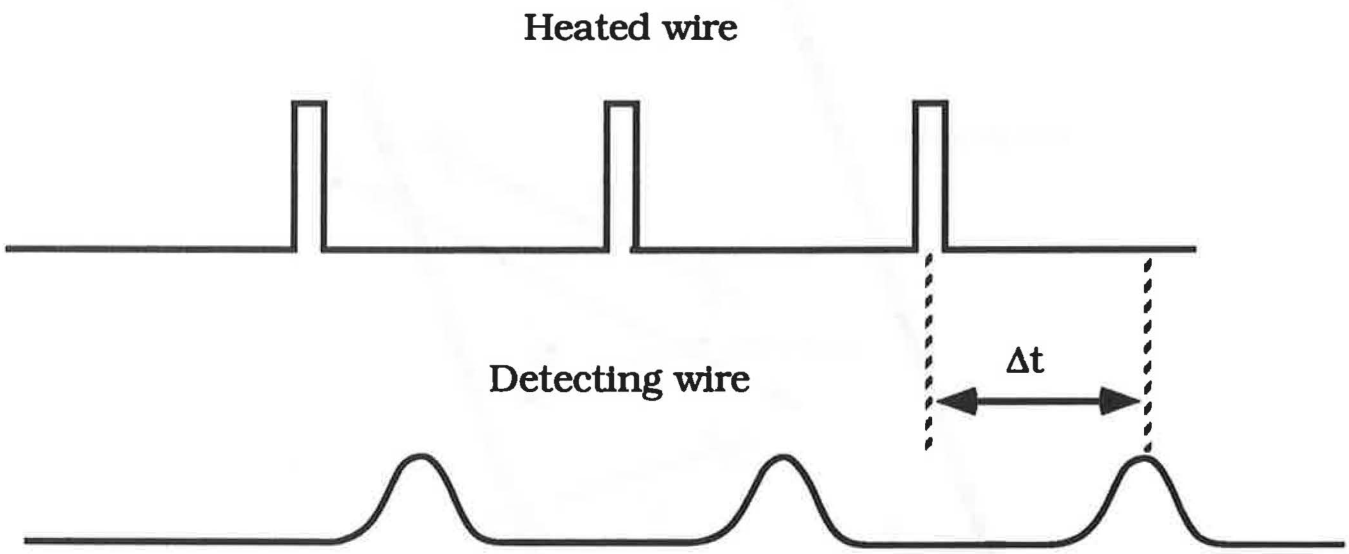

Figure 2 Surface temperature - time traces for heated and detecting wires (principle).

Figure 3 shows a cut through the plane formed by the two detecting wires. The heated wire is then located between the two wires perpendicular to the paper plane. This is indicated by the solid circle.

Let **U** denote the velocity vector with components u_1 and u_2 in some laboratory oriented coordinate system x and y with unit vectors **i** and **j**. The thermal tracer emitted from the heated wire will hit one of the detectors after having travelled a distance ΔL. If ΔS is the shortest distance between the heated and detection wire and the unit direction vector along this line is **n** with components n_1 and n_2 it follows that the ratio between the two distances may be written

$$\frac{\Delta S}{\Delta L} = \mathbf{n} \bullet \frac{\mathbf{U}}{|\mathbf{U}|} \qquad (1)$$

where

$$\mathbf{U} = u_1\mathbf{i} + u_2\mathbf{j}$$
$$\mathbf{n} = n_1\mathbf{i} + n_2\mathbf{j} \qquad (2)$$

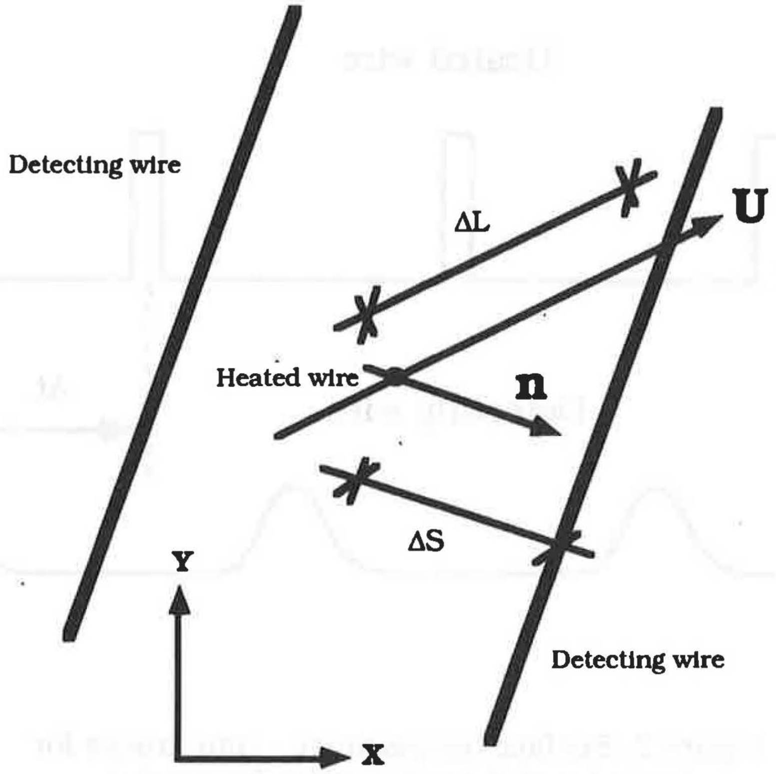

Figure 3 Probe and coordinate definitions

Obviously the norm of the velocity vector is also the distance travelled divided by the time used, i.e.

$$|\mathbf{U}| = \frac{\Delta L}{\Delta t} \qquad (3)$$

Combining equations 1 to 3 the following expression is obtained

$$u_1 n_1 + u_2 n_2 = \frac{\Delta S}{\Delta t} \qquad (4)$$

This shows that the velocity calculated by dividing the geometric distance between the heated and detecting wire by the measured time of flight is in fact only depending on the component of the velocity vector that is aligned with the unit vector **n**. (If the probe is oriented so that the unit vector **n** is along the x-axis, n_1 will be 1 and n_2 will be 0 so the output is seen to depend on u_1 only). Another important consequence is that since the output only depends on geometry and time the measurement is neither sensitive to changes in temperature or gas composition in the flow. Thus a probe calibrated in air at a certain temperature may well be used to measure for example velocities in a Helium flow mixing with air at a different temperature.

From this it is seen that the response function of the device is very simple and depends linearly on the measured time of flight. Thus it may be seen that the accuracy of the device in fact increases as the velocity decreases since the relative uncertainty in measuring the time then goes down. This is in contrast to most other measurement systems where the measurements usually become more unreliable for very low velocities.

The response function may be written

$$\frac{1}{u} = A\Delta t \qquad (5)$$

where the constant A is the inverse of ΔS and u is the probe oriented velocity component of **U**. This would be exact if Δt was measured exactly. In practice there will be some thermal diffusion of the thermal tracer which slightly modifies A. Also, due to filtering and electronic processing of the signal there will be a time delay in the electronics so the response function must be written

$$\frac{1}{u} = A(\Delta t + \tau) = A\Delta t + B \qquad (6)$$

where τ accounts for the electronic delays.

Because the distance between the wires is difficult to measure exactly the response function is obtained by calibration. Figure 4 shows a typical calibration curve. The electronic circuitry outputs a voltage that is directly proportional to the measured time.

The calibration curve is deviating slightly from the theoretical straight line so the curve fitted to the data is

$$\frac{1}{u} = A\Delta t + B\Delta t^2 + C \qquad (7)$$

rather than equation 6.

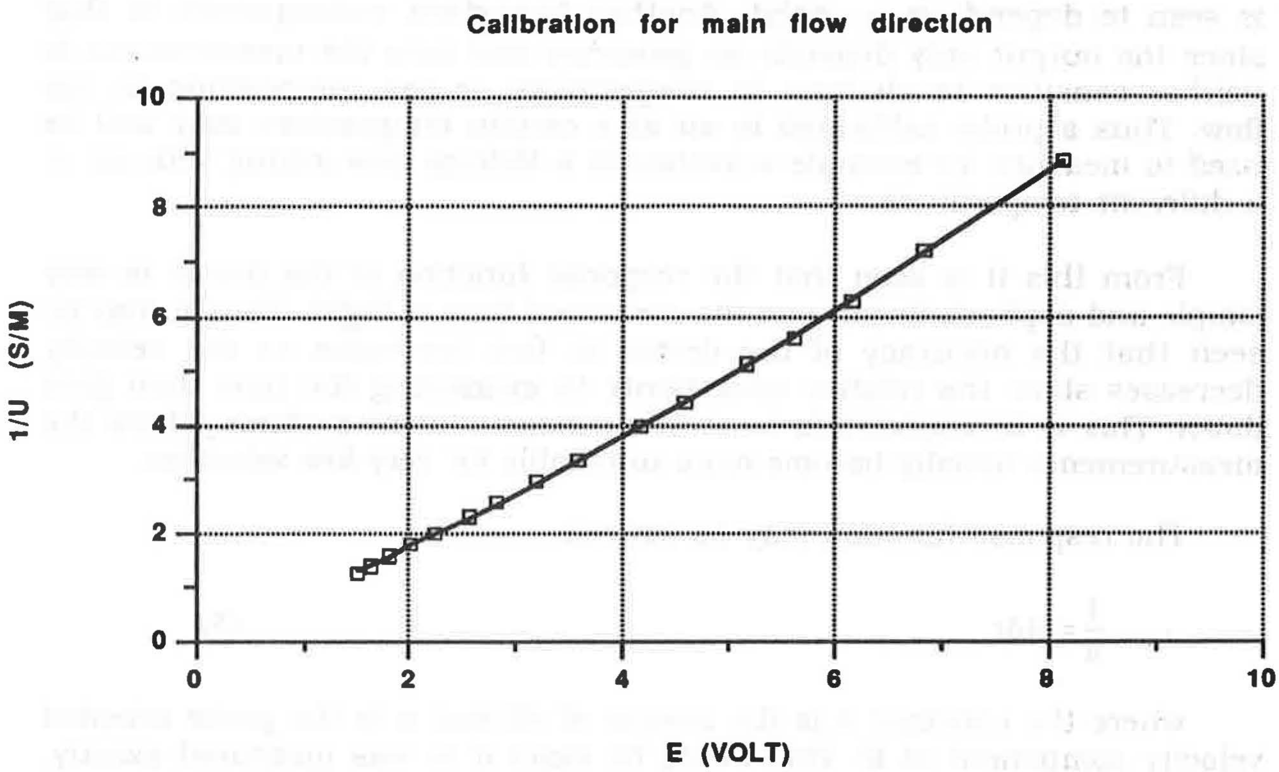

Figure 4. Typical calibration curve taken in the range U={0.11,0.80}

Reversed flow measurements

Due to the symmetric construction of the probe reversed flows can be measured with the same degree of accuracy as for the main flow direction. This makes the PHWA particularly suited to do measurements in flows with very high turbulence intensity. The turbulence intensity is here defined as

$$T = 100\% \frac{\sigma_u}{\bar{u}} \qquad (8)$$

where $\bar{u}$ is the time averaged velocity and σ_u its standard deviation

$$\bar{u} = \frac{1}{2T}\int_{-T}^{T} u(t)dt$$

$$\sigma_u^{\,2} = \frac{1}{2T}\int_{-T}^{T}\left[u(t) - \bar{u}\right]^2 dt \qquad (9)$$

If the turbulence is assumed to be statistically random having a normal distribution, it may be shown that if the turbulence intensity is higher than 39% the flow will be reversed 5 % of the time irrespective of the value of the mean velocity. In many heating and ventilation applications the time averaged velocity is very low while the instantaneous velocity may be high. Then the turbulence level may be considerably higher than this. (In the limit when the mean velocity becomes 0 the turbulence level goes to infinity). If the measurement equipment is unable to detect changes in the flow direction, considerable measurement errors will then dominate both the mean velocity and estimated turbulence quantities due to unreal rectification of the signal. Hence Pitot-static tubes, conventional hot wire anemometers and even turbine meters should only be used at very low turbulence intensities. (Normally the turbine meters must be discarded as a means of measuring turbulence quantities due to unacceptable frequency response).

Experimental results

The PHWA has been used in many applications at NTH where conventional measurement devices have proven unsuitable. Some of these are velocity measurements in simulated releases of LPG from storage tanks using liquid Nitrogen as test gas, measurements in stratified flows using Helium as the light gas and air as the heavy, recirculating flows around bluff bodies and simulated blow outs from a LNG production rig again using Helium to simulate the released gas.

To demonstrate the applicability of the PHWA and the errors to be expected by measurement devices unable to detect flow direction the PHWA was used to measure the velocity behind a backward facing step.

Figure 5 shows the experimental setup. In a wind tunnel with a 7 m long, 1.4 m wide and 1.1 m high test section a 0.2 m high step was produced at the tunnel floor. The experiment was carried out at a nominal speed of 1.1 m/s. Only the horizontal component of the velocity vector, u, was measured at different stations downstream of the step. The probe used was designed to measure velocities from 0.1 to 7.5 m/s. The probe volume may be considered to consist of two cones each 1.5 mm high with a diameter of 10 mm.

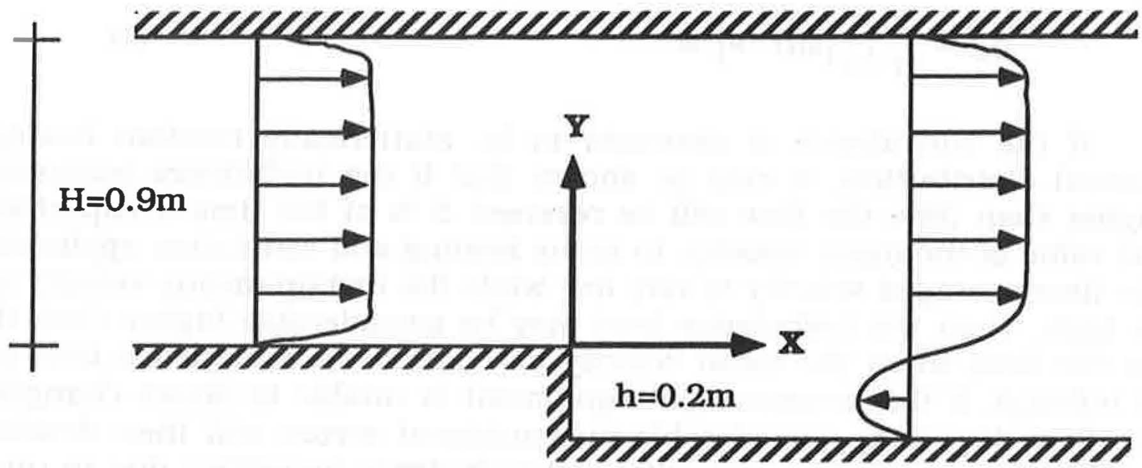

Figure 5 Wind tunnel experiment geometry

Figure 6 shows the measured velocity signal at 2.5 step heights downstream and 0.4 heights below the step. The flow is seen to change direction frequently and the PHWA is seen to be able to detect this as well as showing the detailed structure of the flow.

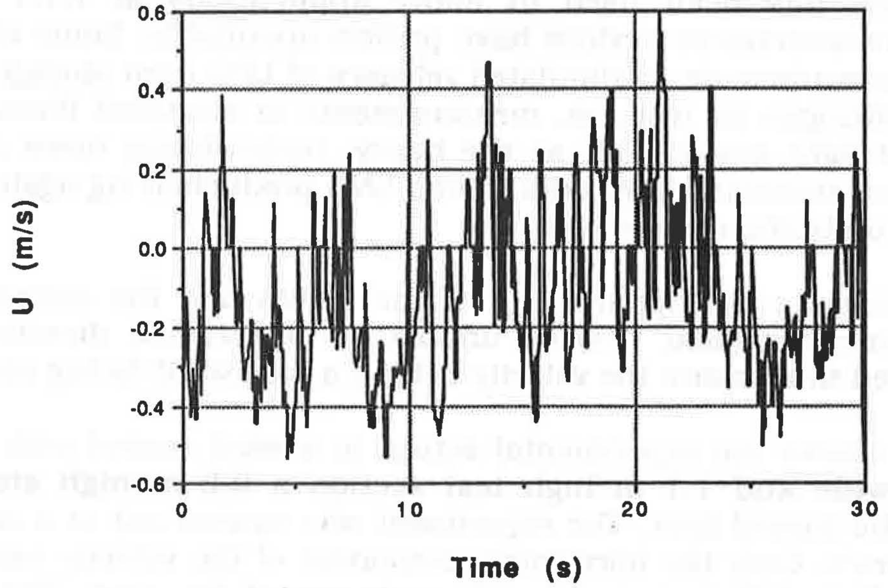

Figure 6 Velocity signal obtained at X/H=2.5 and Y/H=-0.4

Figure 7 shows the probability density function of the signal. The probe cannot detect zero velocity since in this case there will be no pulse to pick up at the receiver. Also, from figure 3 it is seen that there is a maximum flow angle with respect to the probe axis that can be detected. Typically if the angle between **n** and **U** is more than ±80 degrees the tracer will slip out vertically between the detecting wires. In this case the u component which the probe is made to detect must be very small. Therefore all lost traces have been assumed to be u=0. Since part of this information probably belong to the two neighboring intervals this explains the high probability density at 0 and the low values in the neighboring intervals.

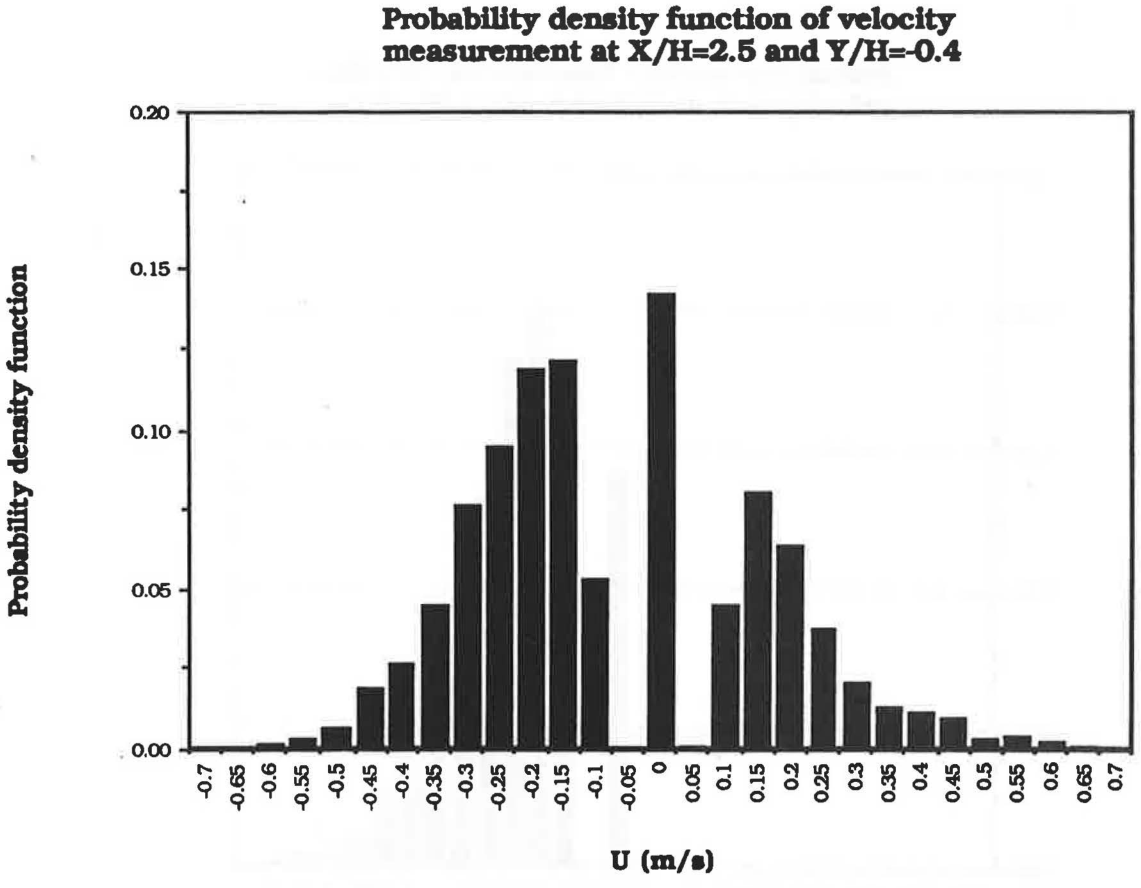

Figure 7 Probability density function of the measured velocity at X/H=2.5 and Y/H=-0.4

From the density function it may be seen that at this particular position the flow is in the main direction (to the right in figure 5) about 29 % of the time while for the rest of the time the flow is reversed. If it is assumed that the measurement system was unable to detect the change in sign the lower part of the signal would be mapped to the same numeric value at u>0. To a first approximation this is what would happen to a Laser-doppler anemometer without Bragg cell, a hot-wire anemometer or Pitot-static tube. Then the probability density function of figure 8 would be obtained.

In the case of a rectified signal the mean velocity would be estimated to be u=0.200 m/s whereas the PHWA value is u=-0.071 m/s. Similar errors are found for the standard deviation. For the rectified data σ_u=0.138 m/s whereas the PHWA value is 0.232 m/s showing that the correct value is about twice as high as the value obtained if changes in flow direction can not be detected.

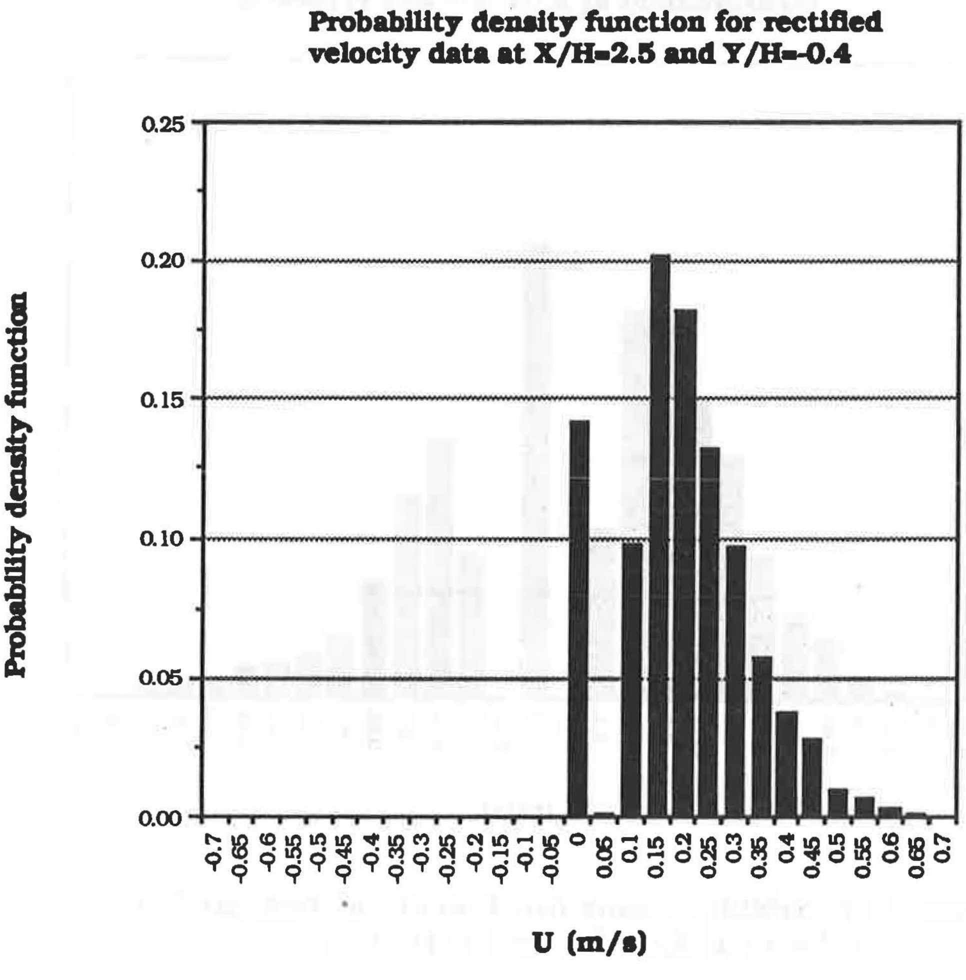

Figure 8 Probability density function of the rectified measured velocity at X/H=2.5 and Y/H=-0.4

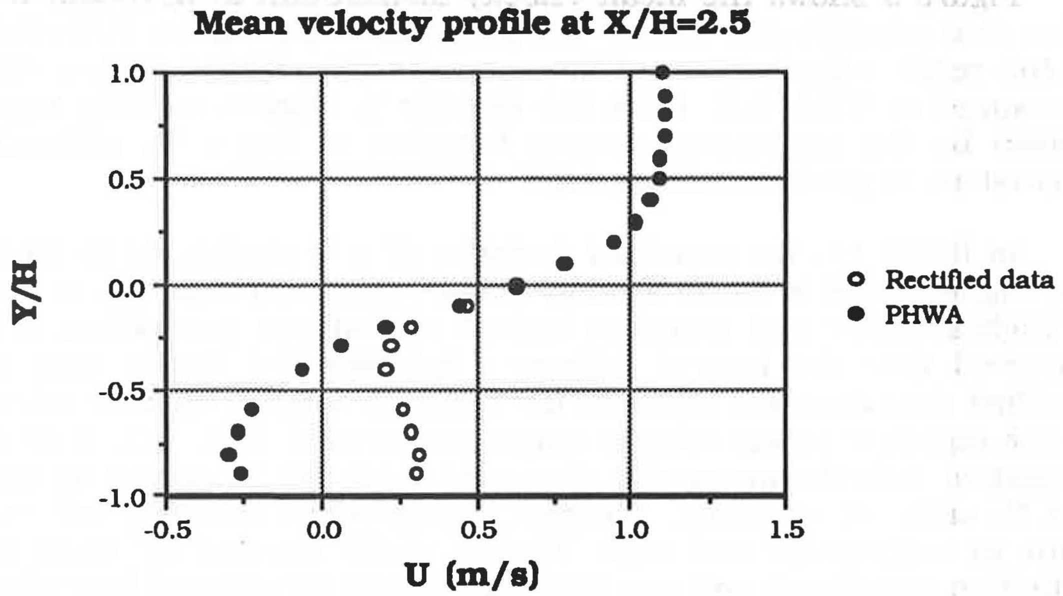

Figure 9 Mean velocity profile of the horizontal component measured X/H=2.5

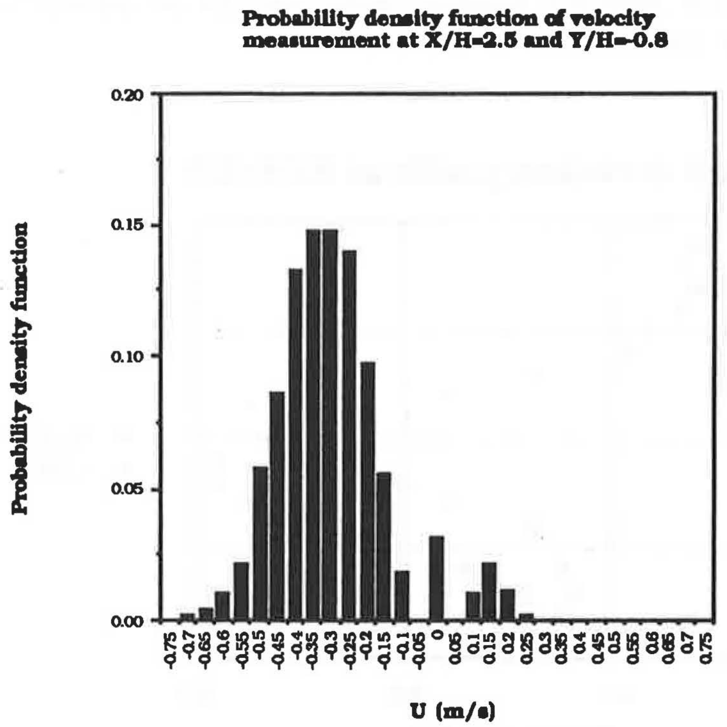

Figure 10 Probability density function of the measured velocity at X/H=2.5 and Y/H=-0.8

Figure 9 shows the mean velocity distribution at X/H=2.5. It may be seen that considerable effects of rectification exist below Y/H≈-0.2 which is the region where reversed flow prevails. The most negative velocity is measured at Y/H≈-0.8. Here the velocity is almost entirely negative as shown by the probability density function in figure 10 although some excursions to positive velocity exist.

In figure 11 the standard deviation of u is shown. As to be expected the highest level is found around Y/H=0 which corresponds to the region of highest shear and therefore highest turbulence production. It may be observed that the largest difference between the PHWA data and the rectified data does not occur in the region of largest negative velocity, but in the region of lowest velocity magnitude around Y/H≈-0.3. If all data are measured with the wrong sign the mean value will be correct in magnitude but its sign will be wrong. However, the standard deviation will be correct both in magnitude and sign. This is easily verified by inspecting the definition equation 9 and was demonstrated by the data at Y/H=-0.8 (figure 10). Here the velocity was measured to be -0.296 with a standard deviation of 0.158 whereas the rectified data gave 0.311 as the mean value with a deviation of 0.126. In the region where the velocity vector continuously changes sign as it does around Y/H≈-0.3 the effect of rectification will be large both on the mean and fluctuating components as demonstrated by the probability density functions.

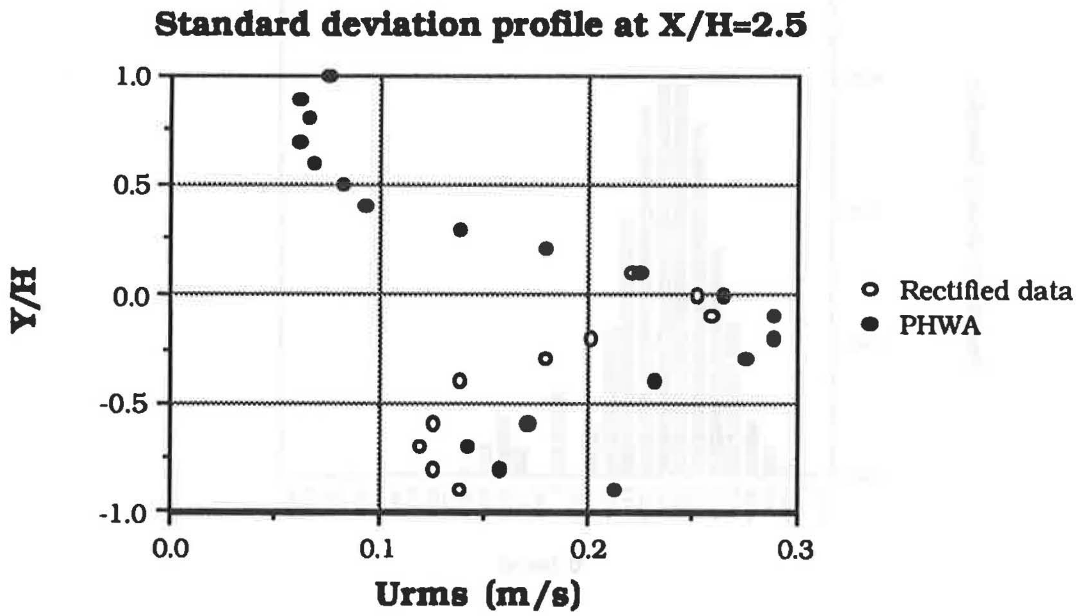

Figure 11 Standard deviation of the horizontal velocity component measured X/H=2.5

Conclusions

The operating principle of the Pulsed-Hot-Wire-Anemometry has been described. This type of anemometers has proven a reliable and accurate measuring device for highly turbulent and recirculating flows. Since the measurement principle consists of measuring a time of flight of a temperature tracer, the accuracy of the device increases as the velocity decreases, in contrast to most other measurement systems. It is demonstrated that the device may provide detailed information about the flow structure not readily available with conventional measurement techniques. Its ability to measure velocities in flows where the general flow direction is not known a priory and the insensitivity of the device to changes in flow temperature and gas composition makes it a very versatile device. It has been demonstrated that for measurement devices that cannot detect changes in flow direction severe measurement errors may occur. Being sensitive only to the part of the velocity vector in a predefined direction makes it possible to map the total flow velocity vector at a point with a limited number of measurements.

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