Hot Wire / Hot Film
Paper 22

THE DUAL HOT WIRE ASPIRATING PROBE

Tony Arts, Rémy Dénos, Jean-François Brouckaert, Oliver Popp

Von Karman Institute for Fluid Dynamics
B-1640 Rhode Saint Genèse

THE DUAL HOT WIRE ASPIRATING PROBE

Tony Arts, Rémy Dénos, Jean-François Brouckaert, Oliver Popp
von Karman Institute for Fluid Dynamics
72, chaussée de Waterloo - 1640 Rhode Saint Genèse - Belgium
Tel: +32/(0)2/359.9611 - Fax: +32/(0)2-359.9600 - Email: arts@vki.ac.be

ABSTRACT

This contribution presents the experience gained at VKI in using the dual hot wire aspirating probe. This instrument is able to resolve high frequency pressure and temperature fluctuations. Its principles of operation are described in detail as well as the associated calibration procedures. The effect of several operating parameters such as overheat ratio, wire material, free stream velocity and incidence are put in evidence. The response of the probe to a steep gradient is investigated as well as the spurious conduction effects occuring during short duration events.

1. INTRODUCTION

Modern aero-engines operate nowadays at high pressure ratios and at gas temperatures far above the blade, endwall and disk material melting temperatures. The need for this environment results from a constant demand for a higher thermal efficiency of the gas turbine cycle and for a lower specific fuel consumption, size and weight of the engine. A correct, and even more, an accurate prediction of the aerodynamic and thermal performances of the various components therefore remains of crucial importance in order to guarantee an acceptable life time.

The definition of aero-thermal characteristics of high pressure turbine linear and annular cascades and turbine stages has been for a long time and still remains one of the important research activities within the Turbomachinery Department at the von Karman Institute. These research programs were conducted in the two VKI Isentropic Light Piston Compression Tube facilities, namely the linear cascade tunnel CT-2 (Richards, 1980) and the annular one CT-3 (Sieverding and Arts, 1993). Both facilities correctly simulate the main engine operating conditions (Mach and Reynolds number as well as gas to wall temperature ratio) and are characterized by a rather short operation time, of the order of 0.5 s. The latter implies, as a consequence, the use of transient measurement techniques, mainly applied for the determination of convective heat transfer and of high frequency response transducers, especially for the quantitative evaluation of total pressure and temperature profiles downstream of the blade row under investigation.

The time-resolved measurement of total temperature in a gas stream has always been and remains a challenging task. Conventional thermocouples are usually limited to a frequency response of at most 1 kHz. The electronically or numerically compensated cold wire (Dénos and Arts, 1996) allows to reach higher frequencies, but remains nevertheless limited to a frequency response below 10 kHz. Non intrusive spectroscopic techniques show considerable promise but need high power lasers and high pulse rates to resolve the flow field fluctuations.

Among several instruments, the use of a dual-wire aspirating probe has been considered in order to obtain time resolved values of gas total pressure and total temperature. The operating principles of this type of probe were developed by Ng and Epstein (1983) about a decade ago. They were based on constant temperature anemometry, which is known to usually provide a frequency response of several tens of kHz.

Besides the original work of Ng and Epstein (1983), and to the best knowledge of the authors, the only open literature on the use of this type of probe for pressure and temperature measurements was provided by Ng (1986), Kotidis (1989) and Van Zante (1994). A research program on this subject was also started a few years ago at the VKI. A number of these aspirating probes were constructed, statically and dynamically calibrated and finally tested in a short duration testing time environment. The main goal of the present contribution is to report on the experience gained in this field, especially on the probe response time characteristics and on its transient behavior.

2. THE DUAL-WIRE ASPIRATING PROBE OPERATING PRINCIPLE

Conventional hot wires measure the thermal energy lost by convection to the fluid in which they are immersed. The classical theory of constant temperature hot wire anemometry shows that the voltage V necessary to maintain a wire of resistance R_w at a constant temperature T_w in an air flow of velocity U, density ρ, and total temperature T_0 is expressed as follows:

$$V^2 = f_1(\rho U)(T_w - r.T_0) \tag{1}$$

$$R_w(T_w) = R_w(T_{amb})\left[1 + \alpha_w\left(T_w - T_{amb}\right)\right] \tag{2}$$

The bridge output of a simple constant temperature hot wire anemometer is amplified and controls the excitation voltage in order to maintain the wire temperature at a constant value T_w. The latter is fixed by adjusting the adjustable resistance R of the bridge and expressed as the overheat ratio $[R_w(T_w) / R_w(T_{amb})]$.

Eq. (1) can be written in a more classical form, usually adopted for a constant temperature hot wire :

$$V^2 = \frac{(R_s + R_w)^2}{R_w} . \pi . l . k . Nu . (T_w - r . T_0) \tag{3}$$

where l and k are respectively the hot wire length and the thermal conductivity of the fluid and Nu is the Nusselt number quantifying the convection process. A correlation between Nusselt and Reynolds numbers (based on the wire diameter) has been the subject of many investigations. A widely adopted expression was proposed by Collis and Williams (1959) :

$$Nu_d = 0.56\, Re_d^{\,0.45} + 0.24 \qquad [0.02 \le Re_d \le 44] \tag{4}$$

In order to reduce the number of unknowns (ρ, U, T_0, P_0) from 4 to 2, Ng and Epstein proposed to install the sensor, i.e. a hot wire, normally to the flow direction, into a small tube of constant cross-section A, ended by a choked ($M^* = 1$) section A^* (Fig. 1).

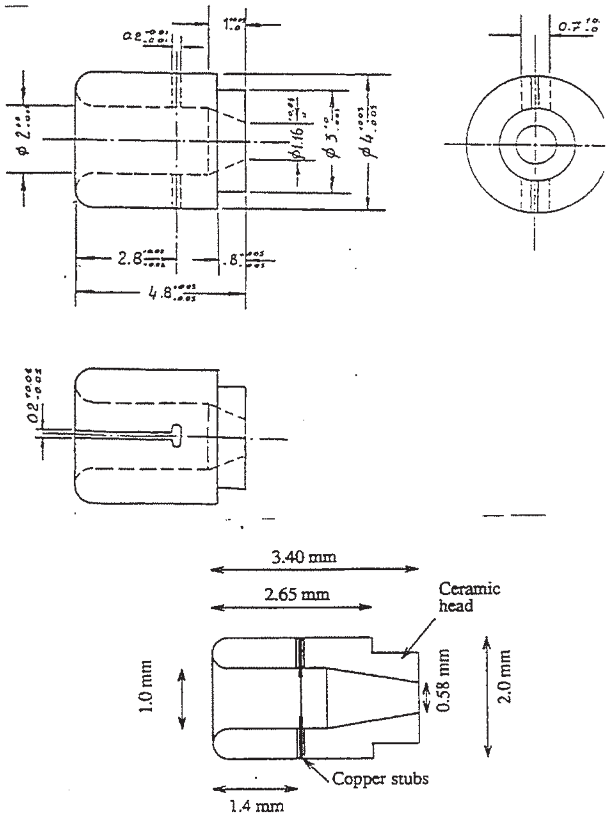


Fig. 1 - VKI designs of the dual wire aspirating probe

The choked conditions are maintained in A^* by means of an ejector or a vacuum pump. As a result, the Mach number M in the plane of the wire is constant and only function of the area ratio (A^*/A) and of the nature of the fluid (γ and $\Re$). It is, theoretically, completely independent from the Mach number field around the probe.

Applying the one-dimensional continuity equation between sections A and A^* for a perfect gas of uniform composition (γ and $\Re$ are constant) leads to the following expressions :

section A :
$$\rho U = \left(\frac{P_0}{\sqrt{T_0}} \right) \sqrt{\frac{\gamma}{\Re}}\, M \left(1 + \frac{\gamma - 1}{2} M^2 \right)^{-\frac{\gamma+1}{2(\gamma-1)}} \tag{5}$$

section A^* :
$$(\rho U)^* = \left(\frac{P_0}{\sqrt{T_0}} \right) \sqrt{\frac{\gamma}{\Re}} \left(\frac{2}{\gamma + 1} \right)^{\frac{\gamma+1}{2(\gamma-1)}} \tag{6}$$

continuity :
$$\rho U A = (\rho U)^* A^* \tag{7}$$

$$\rho U=\left(\frac{P_0}{\sqrt{T_0}}\right)\frac{A^*}{A}\sqrt{\frac{\gamma}{\Re}}\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{2(\gamma-1)}} \tag{8}$$

Eq. (1) can therefore be written as follows, with the assumption that the conductive loss at the wire ends is small compared to the convective heat loss :

$$V^2=f_2\left(\frac{P_0}{\sqrt{T_0}}\right)\left(T_w-r.T_0\right) \tag{9}$$

The combination of Eqs. (8), (4) and (3) finally leads to the following expression :

$$V^2=\frac{\left(R_s+R_w\right)2}{R_w}.\pi.l.k.\left\{0.56\left[\frac{d}{\mu}\frac{P_0}{\sqrt{T_0}}\frac{A^*}{A}\sqrt{\frac{\gamma}{\Re}}\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{2(\gamma-1)}}\right]^{0.45}+0.24\right\}\left(T_w-r.T_0\right) \tag{10}$$

This expression indicates that the voltage applied to the wire is now only function of the total pressure and temperature of the known fluid, and hence does not depend upon velocity fluctuations. In order to solve Eq. (10) for the two remaining unknowns, two co-planar hot wires are independently operated at two different temperatures (or overheat ratios) in section A. Eq. (10) can be more simply written as :

$$V_i^2=\left[C_i\left(\frac{P_0}{\sqrt{T_0}}\right)^{n_i}+D_i\right]\left(T_{w_i}-r.T_0\right) \qquad (i=1,2) \tag{11}$$

The constants C_i, D_i and n_i (i =1,2) have to be determined from a calibration process. Van Zante (1994) quoted, from experience of Ng, that the constant D_i could eventually be dropped. The difference between the wire temperatures is a strong measure of the independence of the two equations (11). As a matter of fact, the sensitivity in pressure and temperature increases with $|T_{w1}-T_{w2}|$.

It is worth recalling that these operating principles are based on two important assumptions :

- the flow field is spatially uniform in the wire plane
- the conduction heat losses at the wire ends are negligible

As will be discussed in following sections, those assumptions could eventually be violated in strong gradient flows or because of important transient conduction effects in the nozzle supporting the wires. These effects have therefore to be taken into account to obtain reliable information from the probe.

3. DESIGN AND CONSTRUCTION

The first dual-wire aspirating probes were constructed by Ng and Epstein at MIT (Epstein, 1985). The probe was made of different parts in order to allow easy assembly and replacement of the wires. The same design was maintained by Van Zante (1994).

The VKI probes were rather different. It is made of only two parts : (1) the head (or nozzle), carrying the two co-planar hot wires and ended by the throat (choked) section and (2) a hollow stem, connected to the aspirating device. The probe head is made of ceramic; Macor as well as Zircone oxide were used. This type of material exhibits high dielectric strength to avoid any electrical interference between both wires and a relatively low thermal conductivity in order to maintain the conduction losses at the wire ends as low as possible. The little nozzles are machined by milling or ultra-sonic drilling. Different designs were considered over the years (Fig. 1). The first probe built at the VKI (Neris, 1986) had an external diameter of 4 mm and an internal diameter, in the wire plane, of 2 mm. As a matter of fact, the smallest probe dimensions are limited by the spurious effects (conduction mainly) at the wire ends. The wire length to diameter ratio (*l/d*) should be of the order of 200 to maintain these conduction losses as low as possible with respect to the convection process. As the diameter of the wires used at VKI ranges between 5 and 9 µm, the minimum internal diameter of the wire plane will not be below 1 mm. A few probes were built at these dimensions (Lamonte, 1992; Brouckaert, 1995). The size of the throat section was determined in order to maintain a Mach number of the order of 0.2 in the wire plane.

The wire material is one of the parameters investigated over the last years. A special paragraph will be devoted to this discussion. The wire plane is located at about 1.5 inner diameter downstream of the probe inlet. The extremities of the wires are copper plated in order to maintain their active length outside of the thermal boundary layer developing within the probe head. The distance between the wires ranges between 0.7 and 0.35 mm respectively for the largest and smallest probes.

The ceramic nozzle is glued on the probe stem, made of a stainless steel tube. The wiring between the sensors and the servo-loop is also glued on the stem. Finally, the aspiration mass flow is obtained from a small supersonic ejector, ensuring sonic conditions at the probe throat section. A photography of one of the last VKI probes is shown in fig. 2.

4. HISTORICAL RECORD OF THE VKI ASPIRATING PROBES

The first dual-wire aspirating probes were constructed by Ng and Epstein at MIT in 1983. This 3 mm outer diameter / 1.5 mm inner diameter probe was equipped with 6.2 µm platinum coated tungsten wires.

The VKI contribution in this field was realized by a number of undergraduate and graduate students. They all contributed in an important way to the development of the dual wire aspirating probe knowledge at the institute. The major steps of this investigation are now briefly summarized. Neris (1986) built the first VKI version of this measuring device. The outer and inner diameters were respectively equal to 4 and 2 mm. The probe head was made of Macor machinable ceramic; 5 µm diameter Wollaston wires (silver plated platinum) were used. These Wollaston wires were selected in order to ease the construction process. The active length was obtained by etching the wires with acid. The Mach number at the wire plane was equal to 0.2. The mechanical resistance of the wires was the weakest point of this design. The decision was therefore taken to use 5 and 9 µm diameter platinum plated tungsten wires.

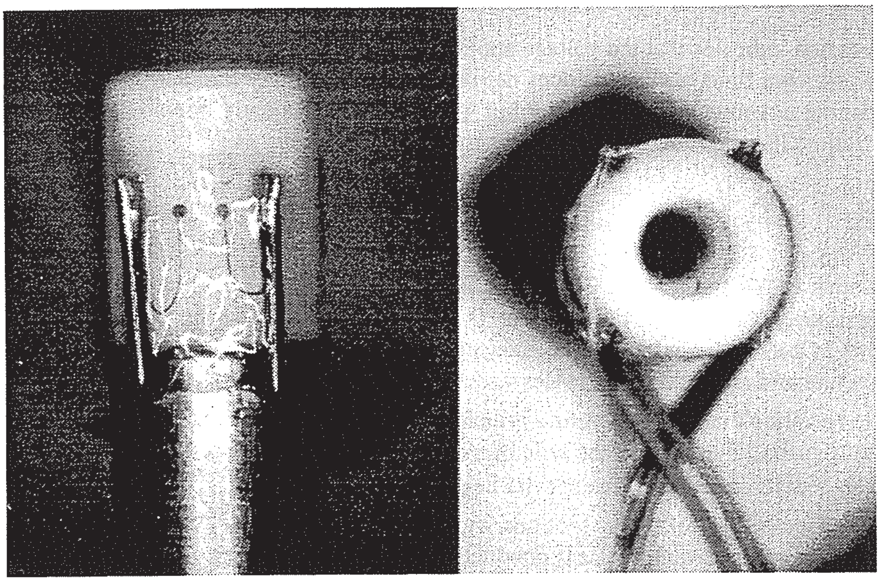


Fig. 2 - Photography of one of the latest VKI probes

Doerr (1988) used the probe in the VKI isentropic compression tube facility CT-2. This facility is mainly used for the determination of the aero-thermal performance of two-dimensional linear cascades. It generates air flows at variable pressures and temperatures for a short time (typically 0.5 s); it therefore requests decent frequency response for the instrumentation to be used in its environment. At this occasion, to the best knowledge of the authors, the spurious conduction effects in the probe head were put in evidence for the first time. Both (1991) focused his attention to the behavior of the probe response in strong pressure and temperature gradients; the spatial resolution of the probe was carefully investigated. The miniaturization of the probe head was performed by Lamonte (1992); the external diameter of the ceramic nozzle was reduced to 2 mm. Alansatan (1992) and Martin (1992) compared the behavior of various versions of these probes.

Rheims (1992) investigated the behavior of the wires, operated at very low overheat ratios, as well as the spurious conduction effects observed in these conditions. Patoureaux (1993) proposed a modeling of the conduction effects by a semi-empirical approach. He also performed tests in the short duration facility to validate the uncertainties attributed to the pressure and temperature measurements. Denos (1994) investigated the conduction problem by means of step tests and proposed a correction method based on a first order system modeling the thermal transient behavior of the ceramic nozzle. Brouckaert (1995) investigated, among other points, the use of different materials for the wires. He also initiated the first applications of this probe in the rotating frame of reference. This problem was investigated by Popp (1996) but will nevertheless not be covered in the present paper.

5. CALIBRATION PROCEDURES

The calibration of the dual-wire aspirating probe requires independent variations of total pressure and total temperature. As the relationship (11) linking the wire voltages V_1 and V_2 to P_0 and T_0 is not linear, a detailed calibration map needs to be constructed. This data set can then be further processed by e.g. Eq. (11) or used as a look-up table for subsequent data reduction.

5.1 Static calibration (1)

A first series of calibrations were made in air at rest. The probe was introduced in a sealed and insulated reservoir, equipped with an adjustable heat source (a 220 Volt lamp), a small fan (for homogenization purposes), 7 control thermocouples and connected to a pressure supply. P_0 and T_0 were independently varied and V_1 and V_2 were simultaneously recorded after thermal stabilization. A typical result (large probe, 9 µm diameter Platinum plated tungsten wires) is presented in Fig.3. The overheat ratios of wire 1 and 2 were respectively equal to 1.6 (T_w = 190 °C) and 1.4 (T_w = 140 °C). This map is represented under the form of isobars and isotherms. A bilinear interpolation can eventually be used in between measured calibration points.

The sensitivities of both wires are pressure and temperature dependent. In this particular case, they are observed to be about -7 to -10 mV/°C and 370 to 300 mV/bar respectively for wires 1 and 2. This low sensitivity to pressure eventually justifies its frequent combined utilization with a fast response pressure transducer (Ng, 1983; Van Zante, 1994). The uncertainties on V_1 and V_2 were estimated to be of ± 3 mV, corresponding to ± 1.5 °C and ± 10 mbar for temperature and pressure. Repeatability of the calibration was demonstrated to be below 0.5 % as long as the hot wire servo-loops remained switched on. Significant drifts (typically 50 to 70 mV) were observed between successive voltage application to the associated electronics.

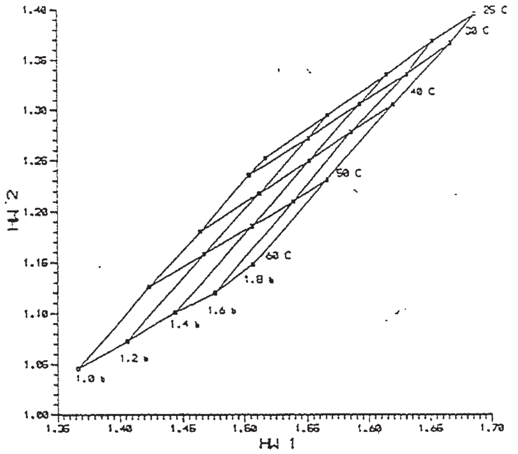


Fig. 3 - Static calibration results

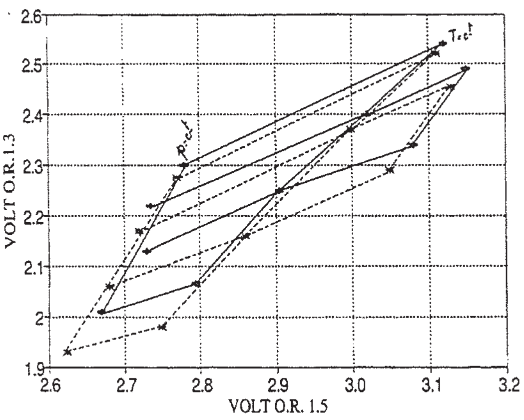


Fig.4 - Static calibration results with probe head cooling

The main drawback of this procedure is the long time needed before thermal stabilization in this "stagnation" reservoir. The probe temperature therefore significantly varies and influences the results of the calibration. This spurious conduction effect was clearly put in evidence by repeating the experiment while the head of the probe was closely surrounded by several turns of a small plastic tube. A circulation of ambient temperature air was forced through the latter to maintain the ceramic head at a temperature as constant as possible in time. Fig. 4 presents the results obtained with the cooling air stream off (dotted line) and on (full line). The differences between both results clearly increase with temperature. It is also clear that it is mainly the iso-temperature lines which are translated (their slope does however not change). The iso-pressure lines remain almost aligned from the first calibration to the second one.

5.2 Static calibration (2)

In order to reduce the calibration time, a second setup was designed and constructed. The objective of this approach was to obtain a faster thermal equilibrium between the head of the probe and the flow by performing the calibration in a continuous heated jet.

This new calibration chamber is presented in Fig. 5.

The first settling chamber is ended by a nozzle (ϕ = 12 mm) from which the jet exits; its dynamic pressure is controlled (valve v1). A heater, between the air supply and the setup, allows temperature variations. The air discharges in a second chamber in which static pressure can be adjusted (valve v2). A minimum forced convection level is maintained around the probe head (M = 0.2 or v = 70 m/s at atmospheric pressure) during a temperature change in order to minimize the temperature difference between the probe head and the flow.

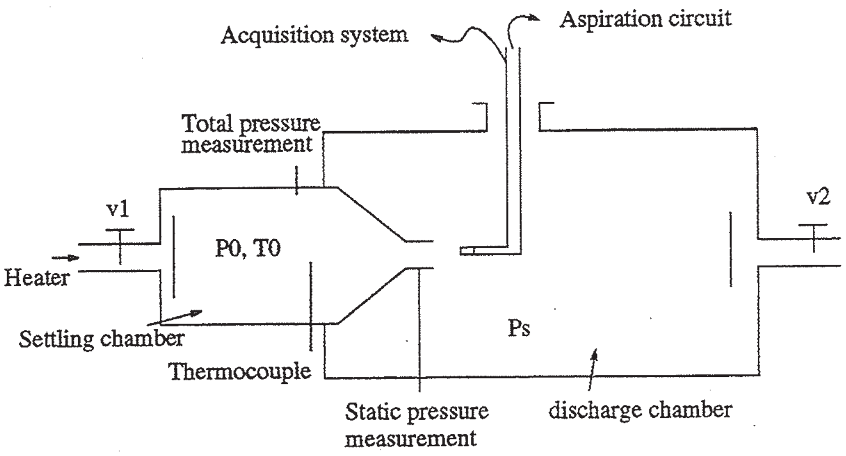


Fig. 5 - Static calibration setup (2)

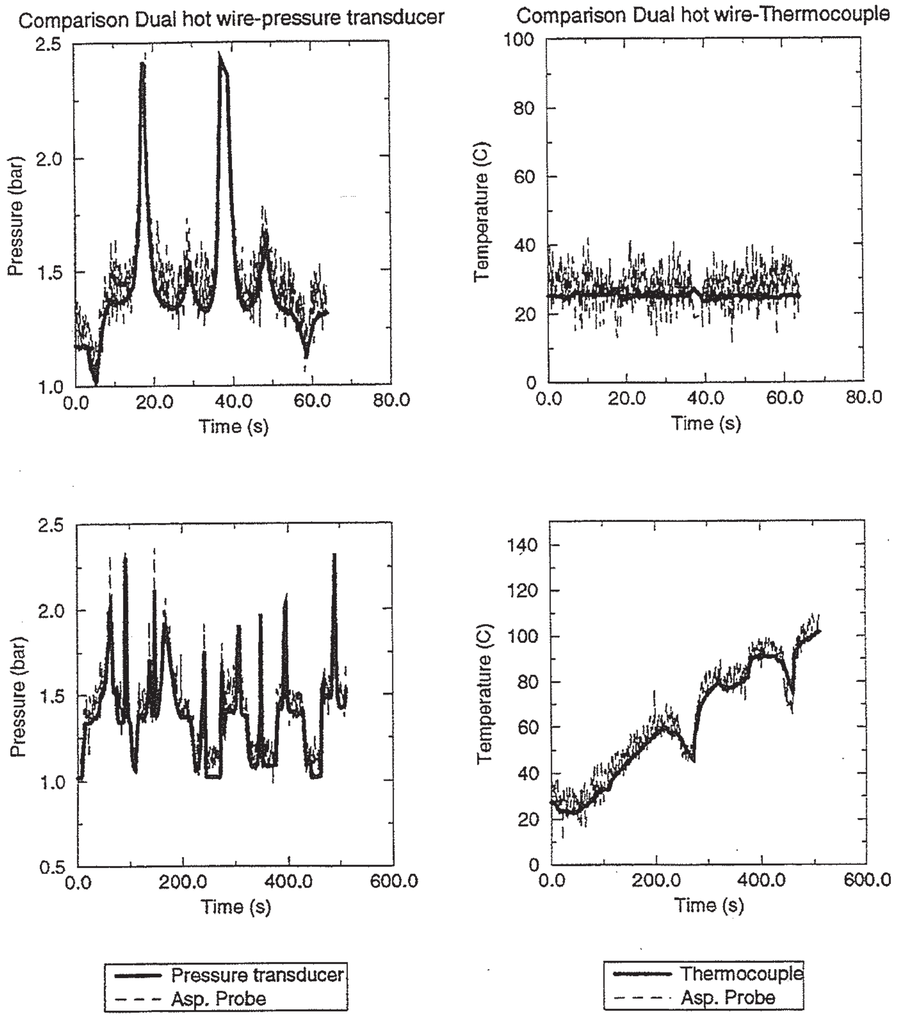


Fig. 6 - Converted signal

An example of a variable pressure and temperature signal measured by a thermocouple and a pneumatic probe as well as by the aspirating probe is presented in Fig. 6. These conditions were generated by modifying abruptly the settings of the control valves and of the heater in the second static calibration setup. The signal to noise ratio is obviously smaller for the aspirating probe.

5.3 Effect of overheat ratio

The influence of overheat ratio is demonstrated in Fig. 7. A theoretical (V_1, V_2) calibration map was calculated for three different pairs of overheat ratios (1.4-1.6, 1.4-1.8 and 1.4-2.0) by means of equation (10) and the pressure/temperature map presented in the upper part of Fig. 7. These "theoretical" wires (ϕ = 5 μm) were made of platinum plated tungsten. The wire temperatures corresponding to the different overheat ratios are computed from Eq. (2) :

overheat ratio :	wire temperature :
1.4	140 °C
1.6	201 °C
1.8	262 °C
2.0	323 °C

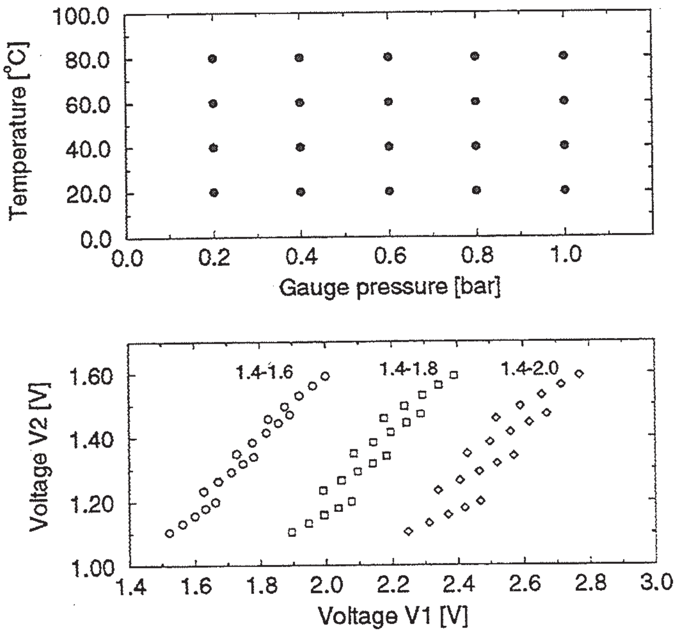


Fig. 7 - Effect of overheat ratio

In the case both wires would have the same temperature, they obviously would measure the same thing; pressure and temperature could therefore not be separated. As observed from Fig. 7, the area covered by the (V_1, V_2) chart increases as the temperature difference between the two wires increases. As a consequence, the signal to noise ratio increases and larger sensitivities to pressure and temperature are obtained. The selection of overheat ratio is however limited. For tungsten wires, the upper temperature of both wires is limited to 300 °C to avoid weakening problems whereas their lowest temperature has to remain above the maximum flow temperature to measure. It would therefore be interesting to find other materials that could be used at higher temperatures.

5.4 Effect of wire material

Because of the relatively low maximum operating temperature of tungsten wires (≅ 300 °C), a wide spreading of the (V_1, V_2) calibration map is out of reach. Van Zante (1994) therefore proposed to use platinum iridium alloy wires; the upper limit in temperature is as high as 800 °C. A significant difference in wire temperatures can in this way be achieved. Two other parameters should nevertheless also be considered when selecting the wire material : the temperature/resistance coefficient (α_w) and the tensile strength (σ).

Constant temperature anemometer circuits are sensitive to temperature, and therefore to resistance, changes. Higher values of the α_w coefficient result in larger changes in wire resistance for a given variation in temperature. The tensile strength σ usually decreases when the temperature increases because of metallic grain growth. One way to improve the tensile strength is to use an alloy, by adding a small percentage of another metal such as iridium, rhodium, nickel, ... As this percentage increases, the sensitivity to temperature unfortunately decreases as is shown in the following table :

Material	T_{max} (°C)	α_w (K^{-1})	σ (MPa)
Platinum	950	0.00386	165
Pt-coated Tungsten	300	0.0034	1100
Pt - 10% Iridium	800	0.0017	379
Pt - 20% Iridium	800	0.0008	689
Pt - 10% Rhodium	950	0.0017	317
Pt - 20% Rhodium	950	0.0014	496
Platinum #851	950	0.0007	655
Pt - 10% Nickel	950	0.00135	813

(Note : all tensile strengths are given for wires under annealed form and for a diameter of 25 µm)

Pt-10%Ni wires with a diameter of 5 µm were finally selected. They were installed in a 1mm inner diameter aspiration probe. The latter was calibrated by means of the static method described in paragraph 5.2. A typical calibration curve is presented in Fig. 8 (Bigot, 1996). The definite advantage of the new material is clearly demonstrated.

An important remark needs finally to be made. Bigot (1996) recently observed that the resistance/temperature coefficient (α_w) and the resistance at ambient temperature are both modified when the wire temperature is gradually raised above 400°C. This "aging" phenomenon seems to be due to crystallographic reasons (passage through the Curie point in the Pt-Ni binary diagram). The present results indicate that the calibration procedure of both wire should take this behavior very carefully into account.

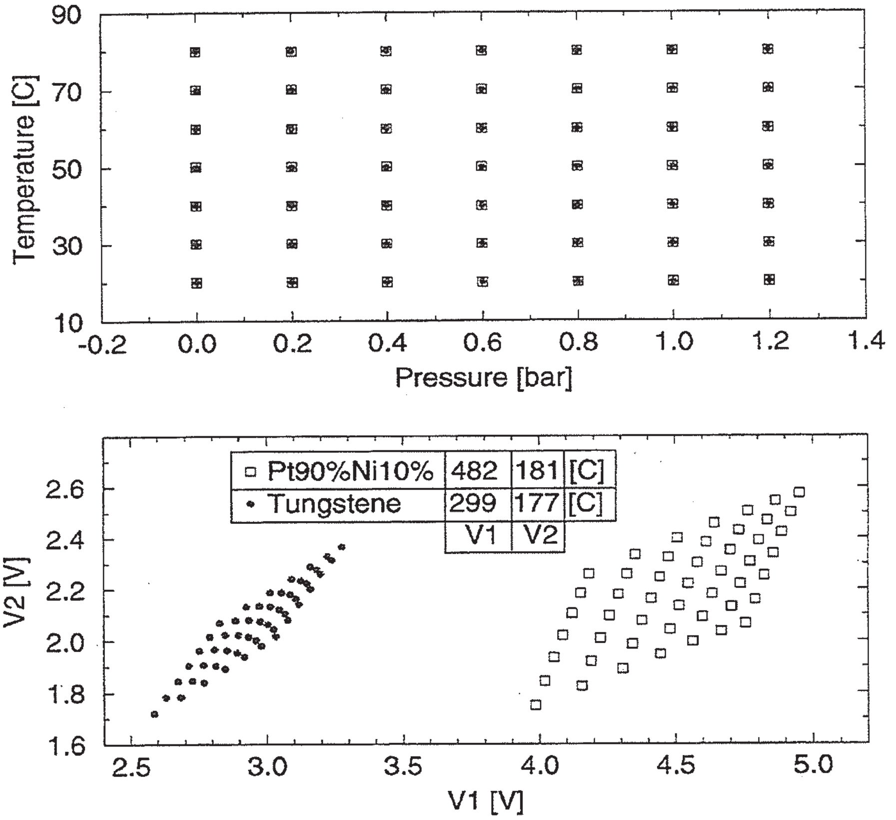


Fig. 8 - Effect of wire material (experimentally determined)

5.5 Effect of free stream Mach number

Based on the basic operating principles of the dual wire aspirating probe, this measuring device should be insensitive to dynamic pressure variations, or in other words, to variations of the surrounding free stream flow Mach number.

A typical example of this insensibility is presented in Fig. 9. The experiment was conducted in the second calibration nozzle (paragraph 5.2). The total pressure was maintained as constant as possible (1.790 ± 0.001 bar) at total ambient temperature. The free stream Mach number was then varied between 0.09 and 0.33. No significant changes in the output voltages V_1 and V_2 could be put in evidence. In more recent tests, Popp (1996) tried to characterize the noise level of the signal. His preliminary conclusions indicate that this noise level increases with the free stream flow velocity. The source of this noise seems to be related to the outer flow characteristics. The "electrical" and "aspiration" noises remain relatively small.

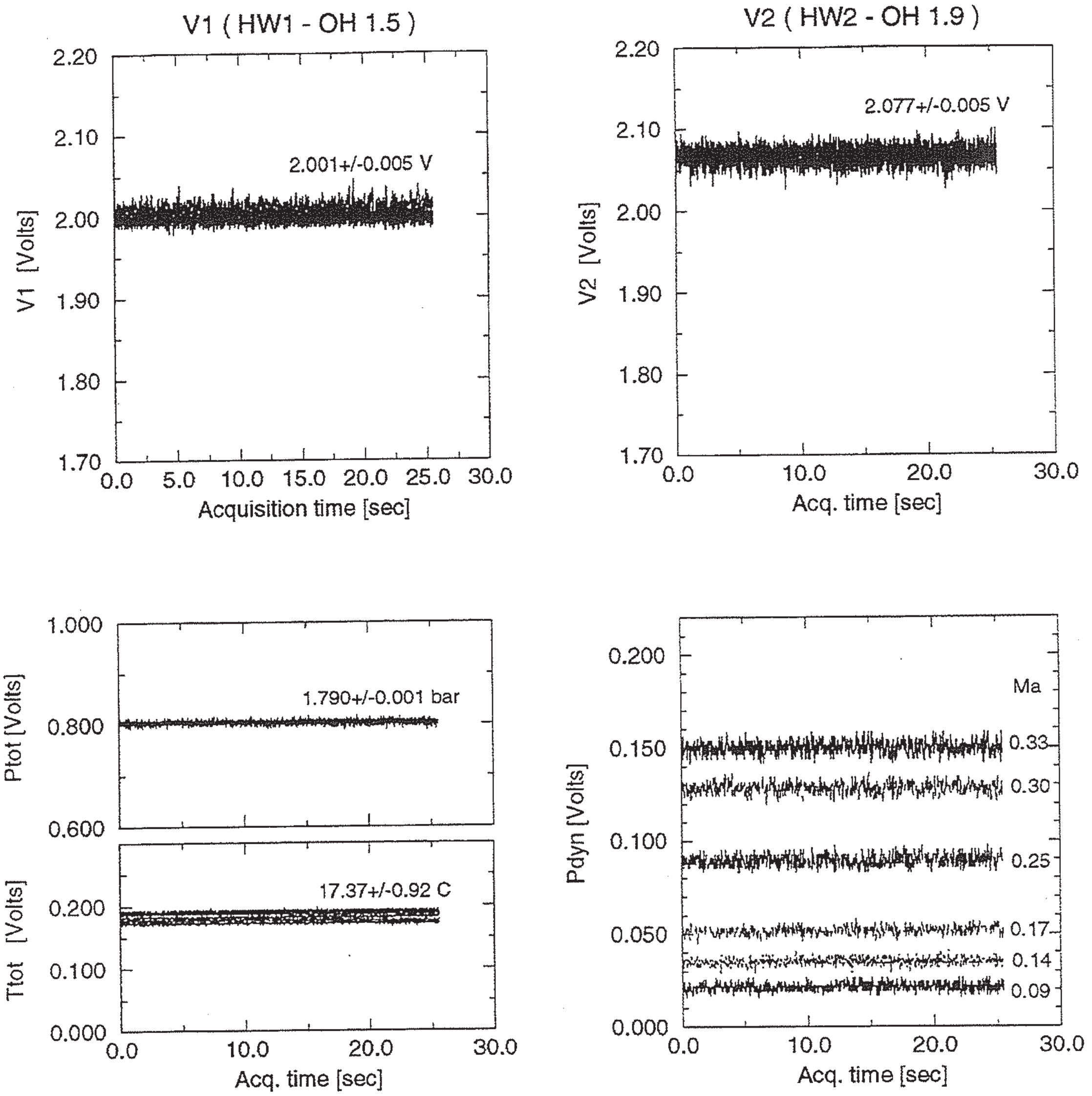


Fig. 9 - Response of the probe to free stream velocity variations

5.6 Effect of free stream incidence

When surveying the flow field downstream a turbine cascade, the flow angle is definitely not constant; it typically varies by a few degrees. The response of the probe with respect to incidence variations should therefore be considered. Ng and Epstein (1983) verified on their probes that the angle effects are insignificant below ± 15 deg. These tests were conducted at two different free stream Mach numbers; the insensibility of the probe output to velocity variations was again verified. The influence of incidence on the VKI probe was checked as well by Popp (1996). The probe was mounted on a mechanism allowing angular variations in yaw (in a plane parallel to both wires) and in pitch (in a plane perpendicular to both wires). These results demonstrate that there is no remarkable influence neither of pitch nor of yaw within a range of ± 20 deg.

6. BEHAVIOR OF THE PROBE IN A VERY STEEP GRADIENT

To investigate the response of the aspiration probe across a strong pressure gradient, a dynamic calibration setup has been assembled (Fig. 10). It consists of a rotating cylindrical settling chamber, equipped with 2 nozzles (Φ = 10 mm) installed at mid height. The temperature of the jets can be adjusted by means of a heat exchanger and the settling chamber is driven by a DC motor or an air turbine up to 4000 rpm. Results are shown here for a small probe (ϕ_{in} = 1 mm, ϕ_{out} = 2 mm), located at 8 mm from the nozzle exit. Ensemble averages of 20 passages through a jet at ambient temperature are presented in Fig. 11 for 3 different dynamic pressures. Two wire orientations were considered : parallel and perpendicular to the peripheral speed of the jet.

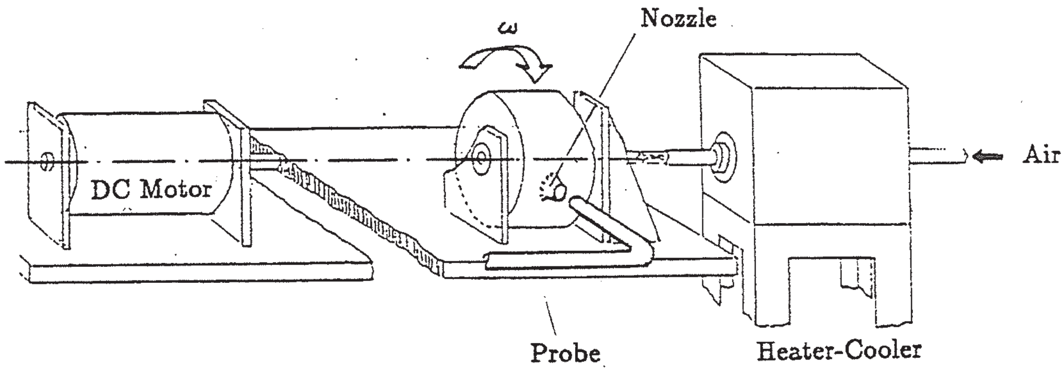


Fig. 10 - Rotating calibration setup for steep pressure gradients

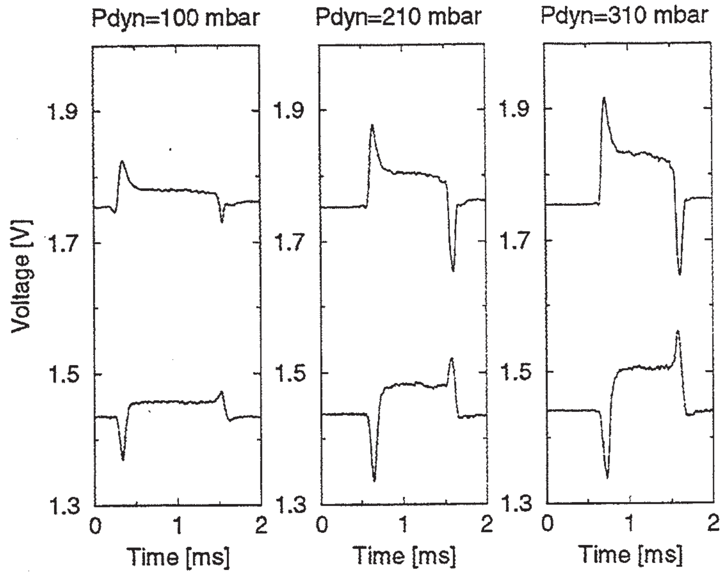


Fig. 11 - Response of the probe in a steep pressure gradient
(wires normal to the jet peripheral speed)

As expected, the mean level of both voltages increases with pressure. There are, however, unexpected peaks observed when the probe enters and leaves the jet flow. These peaks, obviously not justified by local pressure or temperature fluctuations within the shear layer, can be explained by looking at the successive positions of the latter with respect to the probe. Fig. 12 presents the idealized evolution of the 2 wire voltages as the jet moves from the bottom to the top. The wire orientation corresponds to Fig. 11

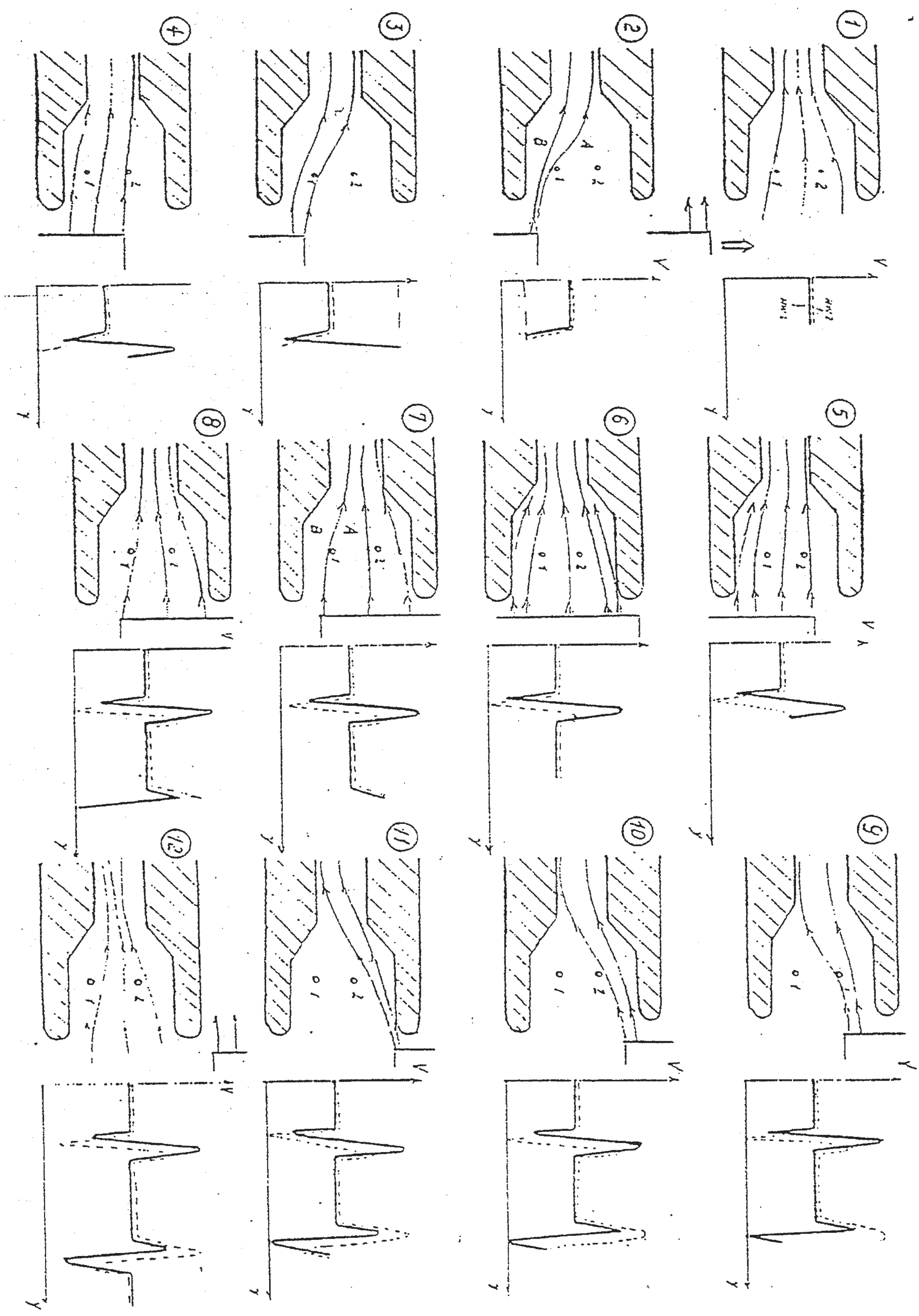


Fig. 12 - Idealized probe answer in a steep pressure gradient

At time (1) a uniform flow enters the probe. It results from the aspiration in an environment at rest. At time (2) the shear layer penetrates into the lower part of the probe head but wire 1 does not yet see it. One part of the mass flow (region B) through the throat (still choked, the total mass flow remains almost constant because the total pressure variations are quite low) now comes from the jet, at a slightly higher total pressure but much higher velocity. The other part of the mass flow (region A), around the wires, therefore decreases, resulting in a drop of voltages V_1 and V_2. When wire 1 feels the jet, at time (3), its voltage V_1 increases, as expected. This increase is more important than the one required by the actual pressure increase because of this local velocity gradient. The voltage V_2 continues to decrease for the same reason as observed at time (2). At time (5), wire 2 sees the jet and V_2 finally increases, but in a smaller proportion than for V_1 (the mass flow is uniform in a larger portion of the nozzle). At time (6) the jet entirely covers the nozzle. V_1 and V_2 finally reach their final and correct value with respect to the thermodynamic characteristics of the jet.

The reverse sequence is observed when the jet leaves the nozzle, from time (7) until time (12).

When the wires are rotated by 90 deg with respect to the peripheral speed of the jet, the spurious oscillations are still there, but smaller in amplitude. This is most probably due to the presence of the copper stubs, insensitive to these gradients..

This spurious behavior demonstrates the limitations of the probe with respect to its spatial extension, or resolution. It is however fair to remark that, with the exception of the passage of the probe through a shock wave, such strong pressure and temperature gradients do not exist in turbomachinery flows. In a wake, e.g., the gradients extend over a quite larger distance and are much closer to a sine than to a square wave.

7. CORRECTION FOR CONDUCTION EFFECTS

As already mentioned earlier, a constant heat flux due to conduction exists between each hot wire and the (cold) probe head when thermal equilibrium is obtained. As soon as the probe experiences a sudden temperature change, the wires immediately react whereas the probe head temperature changes much more slowly because of the large thermal inertia of this ceramic support. This behavior results in the transient conduction phenomenon already observed in section 5.1 It was studied, in a first approach, by submitting the probe to a temperature step.

The probe is placed on a linear displacement system driven by a pneumatic piston. This device allows to suddenly inject the probe from ambient (atmospheric) conditions into a 12 mm diameter jet of hot air. Considering a probe displacement speed of 0.5 m/s and a jet shear layer thickness of 1 mm, the highest analyzable frequency is about 125 Hz. Total pressure is also measured by means of a conventional pneumatic probe and temperature by a thermocouple, both placed in the settling chamber, upstream of the ejection nozzle.

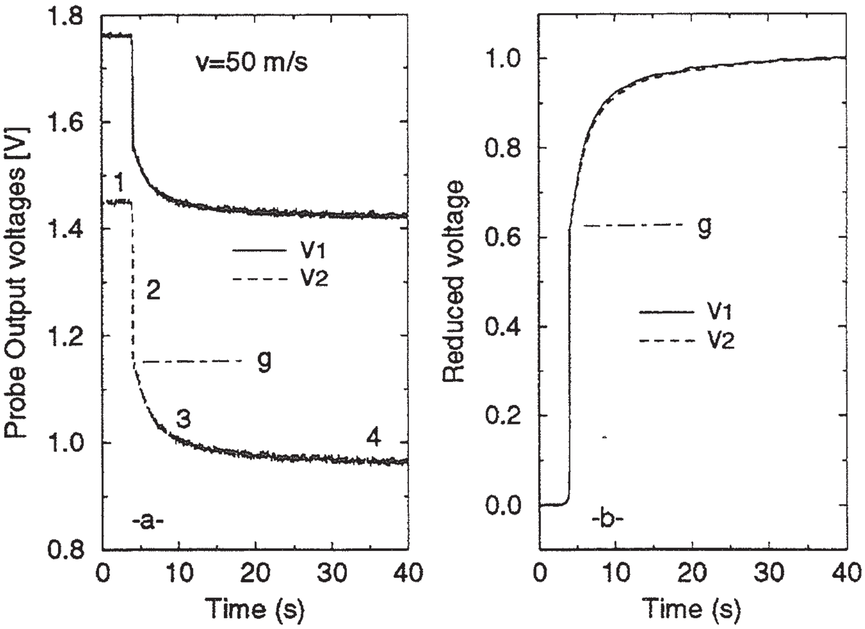


Fig. 13 - Probe response to a temperature step

Fig. 13 shows both output voltages V_1 and V_2 for a jet velocity and temperature respectively equal to 50 m/s and 80 °C. The test duration was 40 s. The response of the probe can be decomposed in 4 distinct areas :

1: the probe is located in uniform, steady conditions (air at rest). The conduction rate between the wire and the probe is constant.

2: the probe abruptly experiences the jet temperature. The frequency response of the wires and of servo-loops is high enough (≅ 20 kHz) that V_1 and V_2 immediately decrease to level *g* while the probe head temperature remains almost constant. As a result, the conduction rate is modified.

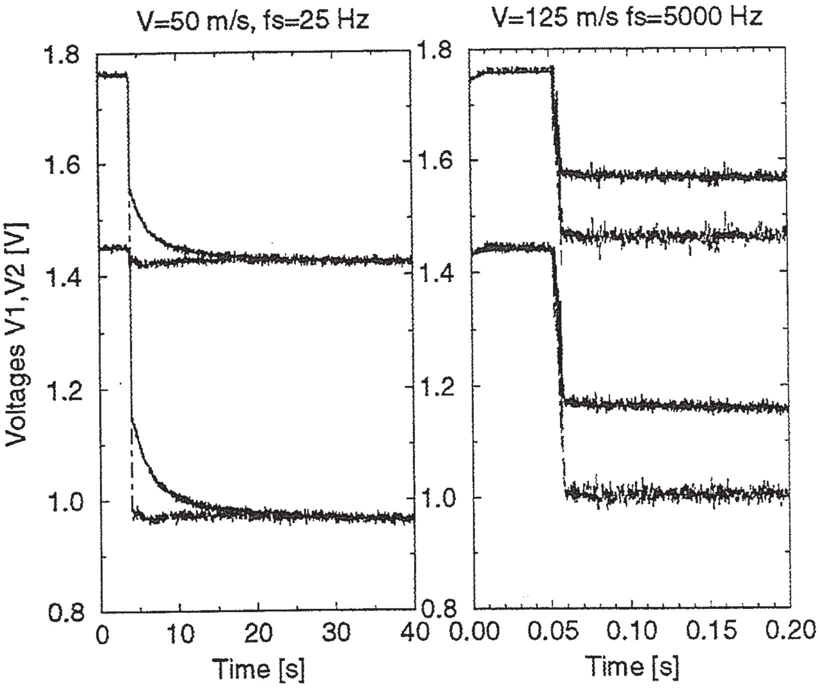
3: the ceramic head slowly heats up. A transient behavior in the conduction rate is, in such a way, imposed.

4: the probe head has now reached an equilibrium temperature. A new steady state is obtained; V_1 and V_2 are constant.

Let us first remark that the spurious effects described in paragraph 6 are not visible here. This is due to the much lower sampling rate applied for the present measurements. The time scale to consider is much larger. The V_1 and V_2 signals have first been smoothed, then reduced by the initial and final values to fit a range from 0 to 1. As seen in Fig. 13, both curves have exactly the same shape. Looking at 6 different step tests, the largest difference between V_1 and V_2 (at the same instant in time) has been maintained within ± 1 % of the step amplitude.

A simple modeling of the unsteady heat exchange by convection between the hot jet and the probe can be done by expressing the balance between the flux by convection Q_h and the flux allowed by the thermal inertia to enter the head Q_{sh}. The contribution of the flux from the hot wires is neglected because of their very small cross-sectional area. The mathematical details of this procedure have been described in details by Arts et al (1996).

Fig. 14 presents examples of compensated raw signals at different time scales and different free stream velocities. By comparing the converted voltages in pressure and temperature to reference values measured by thermocouples and classical pneumatic probes, an uncertainty of ± 1 K (20:1) has been attributed to the temperature whereas an uncertainty of ± 0.04 bar (20:1) has been associated to the pressure measurements



8. CONCLUSIONS

The dual wire aspirating probe operating principles have been presented in details. This probe is able to resolve time dependent pressure and temperature fluctuations. Several static and dynamic calibration procedures have been discussed and evaluated. The major advantages and difficulties or limitations associated with the use of the probe were clearly put in evidence. The size of the probe was reduced to its almost minimum. Sensitivities with respect to pressure and temperature were increased by using alternative materials for the hot wires.

Because of the need to use this measurement device in strongly variable temperature flow fields (short duration facilities), a spurious conduction effect within the probe head was put in evidence. To the best knowledge of the authors, it is the first time that this effect is reported in the open literature.

Measurements within variable flow fields, and comparison with alternative measurement techniques (thermocouples and pneumatic pressure probes) show very encouraging results for the use of this dual wire aspirating probe.

10. Acknowledgments

The VKI contribution in this field was realized by a number of undergraduate and graduate students. Their efforts were reported in paragraph 4. They all contributed in an important way to the development of the dual wire aspirating probe knowledge at the von Karman Institute. Special thanks are also due to the personnel of the Electronics laboratory and of the workshop of the VKI for the numerous probes manufactured, and repaired, over the last years.

List of references

Alansatan, S. :Measurement of high frequency pressure and temperature in turbomachinery flows. VKI Project Report 1992-07, June 1992

Arts, T., Dénos, R.; Brouckaert, J.F.: Hot wire thermometry. VKI Lecture Series on "Temperature Measurements", April 1996

Bigot, D. : Private communication (Industrial Engineering thesis, 1996, to be published)

Both, A. : High frequency response temperature measurements in turbines. VKI Stagiaire report 1992-12, February 1992

Brouckaert, J.-F. : Development of high frequency temperature and pressure measurements for use in a transonic turbine stage. VKI Project Report 1995-14, June 1995

Collis, D.C. & Williams, M.J. : Two dimensional convection from heated wires at low Reynolds number. *Journal of Fluid Mechanics*, Vol. 6, pp357-384, 1959

Dénos, R., Arts, T.; Sieverding, C.H. : Dual hot wire aspirating probe. IMT Area 3 Turbine Project Contract AER2-CT92-0044 Report, June 1994

Dénos, R.; Arts, T.; Sieverding, C.H. : Cold wire thermometry. VKI Lecture Series on "Temperature Measurements", April 1996

Doerr, T. : Fast response measurement of total temperature and total pressure in cascades. VKI Project Report 1988-14, June 1988

Epstein, A.H. : High frequency response measurements in Turbomachinery. VKI Lecture Series 1985-03 on *"Measurement Techniques in Turbomachines"*,February 1985

Kotidis, P.A. : Unsteady radial transport in a transonic compressor stage. Tech.Rep. 199, Gas Turbine Laboratory, MIT, USA, 1989

Lamonte, P. : High frequency measurements for turbomachinery applications - "Ontwerp, fabricage en test van een miniatuur aspiratie sonde". Afstudeerwerk, Vlaamse Interuniversitaire Raad, 1992

Martin, S. : Etude d'une sonde à aspiration pour la mesure de la pression et de la température d'un écoulement. Travail de fin d'étude, Université Libre de Bruxelles, Juin 1992

Neris, N.A. : An aspirating probe for fast response total pressure and total temperature measurements. VKI Project Report 1986-07, June 1986

Ng, W.F. & Epstein A.H. : High frequency temperature and pressure probe for unsteady compressible flows. Review for Scientific Instruments, Vol 54, No 12, December 1983

Ng, W.F. : Simultaneous measurements of stagnation temperature and pressure using an aspirating probe. International Symposium on Pressure and Temperature Measurement, ASME Winter Annual Meeting, Anaheim, California, December 1986

Patouraux, C. : Development of new calibration techniques for double hot wire aspiration probe. VKI Project Report 1993-19, June 1993

Popp, O. : High frequency total pressure and temperature measurements in a transonic turbine stage. VKI Project Report 1996-20, June 1996

Rheims, J. : Calibration measurements of a dual hot wire aspirating probe operated under very low overheat ratios. VKI Stagiaire Report 1992-37, September 1992

Richards, B.E. : Heat transfer measurements related to hot turbine components in the von Karman Institute hot cascade tunnel. in "Testing and Measurement Techniques in Heat Transfer and Combustion", AGARD CP 281, 1980

Sieverding, C.H. & Arts, T. : The VKI compression tube annular cascade facility CT3. ASME Paper 92-GT-336

Van Zante, D.E.; Suder, K.L; Strazisar,A.J. ; Okiishi, T.H. : An improved aspirating probe for total temperature and total pressure measurements in compressor flows. ASME Paper 94-GT-222, June 1994.