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Use of the Hot Wire Anemometry for Velocity and Temperature Measurements in a Turbomachine

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Résumé. — L'anémométrie à film chaud dans un écoulement instationnaire fortement hétérogène est une technique de mesure assez complexe. La vitesse est déterminée à partir de la mesure d'un flux de chaleur. La partie du signal concernant la vitesse doit être séparée de celle relative à la température et éventuellement la pression de l'écoulement. Après avoir rappelé le principe de l'anémométrie à fil chaud et les différents modèles d'échanges de chaleur entre un fil et un écoulement, on présente une formulation du flux de chaleur établie expérimentalement. Ce travail a été réalisé en vue de mesurer les champs de vitesse instantanée entre les rangées d'aubages fixes et mobiles d'un compresseur axial basse vitesse au moyen d'une sonde à deux films chauds croisés. Dans une telle machine, l'écoulement est fortement tridimensionnel et instationnaire. Bien que la vitesse de rotation du compresseur soit relativement faible (4500 tr/min), les fluctuations spatiales et temporelles de la température de l'écoulement ne sont pas négligeables. La connaissance de la température est donc un objectif important en elle même d'une part, et par son influence sur la mesure de la vitesse d'autre part. La mesure simultanée de ces deux paramètres serait donc une solution assez intéressante. A cet effet, un dispositif original utilisant un anémomètre à température constante d'un modèle standard, permettant cependant la commutation de la température de surchauffe de la sonde, a été mis en œuvre. Son principal avantage est de ne nécessiter que l'ajout d'un boîtier externe. Les limites d'utilisation du système, en fréquence notamment, ont été mises en évidence. Cette méthode de mesure a été utilisée pour explorer l'écoulement entre les rangées d'aubages dans un étage du compresseur. Le mode d'opération et les résultats obtenus sont présentés dans cet article.

Abstract. — The hot film anemometry in a highly heterogeneous unsteady flow is a quite complex measurement technique. The velocity is determined from the heat flux measurement. The part of the signal related to velocity must be kept apart from one related to temperature and to pressure of flow. After a brief return to the principle of hot wire anemometry and the different heat transfer models between hot wire and flow, an experimentally established heat flux expression is presented. This study was achieved in view to measure the instantaneous velocity fields between blade rows of a low speed axial compressor by means of a crossed hot film probe. In such a turbomachine, the flow is highly tri-dimensional and unsteady. Although compressor rotating speed is relatively low (4500 rpm), the spatio-temporal fluctuations of flow temperature are not negligible. Knowledge of temperature is then an important objective, for itself on the one hand, and by its influence on the measurement of velocity on the other hand. The simultaneous measurement of these two parameters would then be a quite interesting solution. For this

purpose, an original apparatus including a standard model constant temperature anemometer has been set out. Its main advantage is to require only the use of an external small cabinet which commutes the probe overheat temperature. System utilisation limits, especially in frequency, have been brought to the fore. The operating method and achieved results obtained in the compressor are presented in this paper.

Nomenclature

A, B, C, D	coefficients of Nusselt number
a, b, c, d	calibration coefficients of the hot film
C_{ax}	axial chord
d	hot film diameter
dR_s	resistance variation of the probe
F_c	frequency of temperature commutation
Gr	Grashof number
I_s	current through the film
Kn	Knudsen number
l	hot film length
Me	Mach number
Nu	Nusselt number
Pr	Prandtl number
P_∞	static pressure
R	bridge resistances
R_{ad}	additionnal resistance
R_c	cable resistance
Re	Reynolds number (based on the hot film diameter)
RG	gas constant
R_{op}	operational resistance
R_s	resistance of the film
T_r	reference temperature
T_s	probe temperature (°C)
T_∞	flow static temperature (°C)
$V_A - V_B$	difference of the voltage in the output of the bridge
V_{BN}	velocity component bi-normal to the film
V_{eff}	cooling velocity
V_N	velocity component normal to the film
V_T	velocity component tangential to the film
V_r	velocity radial component
V_u	velocity tangential component
V_z	velocity axial component
V_p	measured voltage
V_s	probe voltage
V_∞	local velocity
α	pitch angle or flow direction (10)
β	yaw angle
ΔT_s	temperature variation of the probe
κ	hot film resistivity

λ	coefficient of thermal conductivity of the gas
μ_r	dynamic viscosity of the flow at T_r
μ_∞	dynamic viscosity of the flow at T_∞
ρ_∞	flow density
θ	overheat ratio (T_s/T_∞)
ϕ_s	heat flux dissipated in the flow
ϕ_1, ϕ_2	angles of velocity vector relative to the probe axis

1. Introduction

The measurement of unsteady velocities between the blades rows in an axial flow compressor is quite critical, particularly when the axial spacing between these rows is low: the interactions between stationary and rotating flow fields lead to important fluctuations of velocity, temperature and pressure. Thus, hot film anemometry is quite an economical solution. However this measurement technique has two disadvantages. First, the presence of the probe induces perturbations in the flow. Secondly, the voltage supplied by the film is a function of both the velocity and the temperature of the flow. The last property can be considered as an advantage: other techniques of measurement, the laser Doppler velocimeter, for example, are not able to provide informations on the thermodynamic properties of the flow. Furthermore, with hot film anemometry, the frequency of measurement is independent of the density of a seeding: this property greatly simplifies the data analysis. However, if the hot film is convenient for measurements in turbomachines, an accurate knowledge of the response of the film is necessary to separate the respective influence of velocity, temperature and pressure of the flow.

The application reported in the present paper has been conducted in a low speed axial compressor. In this machine, the pressure fluctuations are low and then, have a negligible influence on the cooling of the hot film (see Ref. [7]). However, the temperature of the flow exerts a significant influence on the response of the probe even if the temperature of the film is kept high.

The experimental apparatus used in the present work include a standard constant temperature anemometer, adapted to measurements in a flow characterized by strong and rapid fluctuations of velocity. In a first part of the paper, the behaviour of the anemometer in the conditions of the tests in the compressor is analysed. In a second part, results of measurements of velocity and temperature, performed between the blades rows in the first stage of the compressor, are presented.

2. Basis of the Hot Film Anemometry

Hot wire anemometry uses very thin wires ($\cong 5 \mu\text{m}$), electrically heated. However, such a wire is not sufficiently strong to endure collisions with particles or sprays currently convected by the flow in turbomachines.

So, for applications requiring a durable sensor, hot films obtained by deposition of a thin platinum film at the surface of a quartz rod ($\cong 50 \mu\text{m}$) are generally used. The overall sensitivity and the cutting frequency of the hot films is quite high (200 kHz). The working modes of the hot wires and of the hot films are practically identical.

The electrical power supplied to the film is equal to the heat flux ϕ_s dissipated in the flow:

$$\phi_s = R_s I_s^2 \quad (1)$$

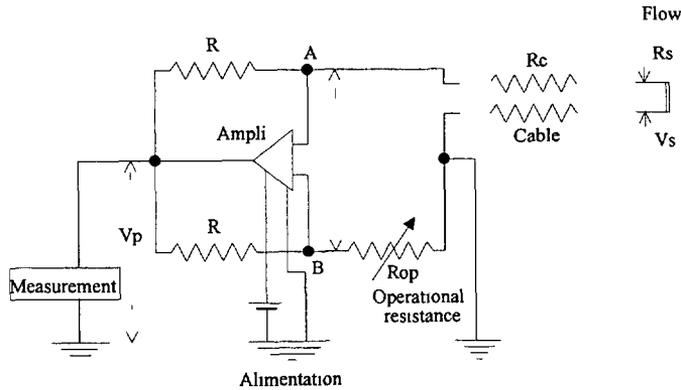


Fig. 1. — Constant Temperature Anemometer C.T.A.

Then, taking into account the voltage V_s between the pins of the probe:

$$\phi_s = \frac{V_s^2}{R_s} \quad (2)$$

Apparently, a simple relation exists between the voltage V_s and the heat flux ϕ_s . However, the resistance R_s of the film depends on its temperature T_s . Then to obtain ϕ_s as a function of V_s , it is necessary to impose one of the parameters involved in equations (1) and (2).

With the Constant Current Anemometer (CCA), the current I_s through the film is imposed. The heat flux is then proportional to the resistance R_s . This type of anemometer is suitable to velocity and particularly temperature measurements. However, the temperature T_s is not controlled and the film can be overheated and destroyed, if the flow velocity shows large fluctuations with time.

With the Constant Temperature Anemometer (CTA), an electronic device continuously adjusts the voltage V_s , so the temperature T_s is kept constant in time. The heat flux is then proportional to the square of the voltage V_s . This type of anemometer is reliable so far as the integrity of the probes is considered, but not well adapted to flow temperature measurements.

For the first reason, the CTA has been chosen for velocity measurements in turbomachines where the flow is strongly unsteady, despite the problems occurring from the interactions between velocity and temperature fluctuations.

3. The Constant Temperature Anemometer (CTA)

The probe is incorporated in a Wheatstone bridge balanced by a differential amplifier. This device continuously adjusts the bridge voltage as a function of the unbalance $V_A - V_B$ (Fig. 1).

When balanced, the bridge is symmetrical:

$$R_c + R_s = R_{op} \quad (3)$$

Then, the measured voltage V_p is proportional to the probe voltage V_s as:

$$V_p = \frac{R + R_c + R_s}{R_s} V_s \quad (4)$$

The heat flux ϕ_s is then:

$$\phi_s = R_s I_s^2 = \frac{R_s}{(R + R_c + R_s)^2} V_p^2 \quad (5)$$

4. Relation Between the Heat Flux and the Characteristics of the Flow

The convected heat flux ϕ_s through the wall of a cylinder with a diameter d and length l , heated to the temperature T_s is represented using the Nusselt number Nu :

$$\phi_s = \pi l d Nu \frac{\lambda}{d} (T_s - T_\infty) \quad (6)$$

The coefficient of thermal conductivity λ of the gas (air) is evaluated using a temperature T_f , average of T_s and T_∞ , $T_f = (T_s + T_\infty)/2$:

$$\lambda = \lambda(T_f) = 0.0242 \left(\frac{T_f + 273}{273} \right)^{0.885} \quad (7)$$

When $T_s \gg T_\infty$, λ depends mainly on T_s .

Taking equations (5), (6), (7), into account, Nu is written as a function of the measured voltage V_p :

$$Nu = K \frac{V_p^2}{(T_s - T_\infty)} \quad (8)$$

where:

$$K = \frac{1}{\lambda \pi l} \frac{R_s}{(R + R_{op})^2} \quad (9)$$

In general, the Nusselt number depends on seven parameters:

$$Nu = \mathcal{F}(Re, Me, Pr, Kn, Gr, \theta, \alpha) \quad (10)$$

It will be supposed later that:

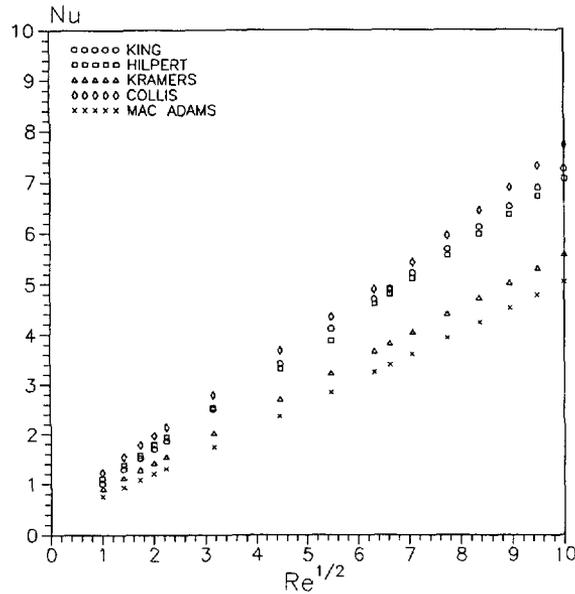
- The Reynolds number is high enough to cancel the natural convection effect, represented by Gr .
- The flow is incompressible ($Me < 0.2$).
- The Prandtl number is constant.
- The thermal inertia of the hot film is low.

Then, the Nusselt number depends on three parameters only:

$$Nu = \mathcal{F}(Re, \theta, \alpha) \quad (11)$$

4.1. INFLUENCES OF THE REYNOLDS NUMBER AND OF THE OVERHEAT RATIO. — Several authors studied the influence of these three parameters on the Nusselt number (Fig. 2). The formulas established by references [2] to [6] are given in Table of Figure 2.

The comparison of the previous formulas demonstrates the linear variation of the Nusselt



Authors	Formulation
KING [2]	$Nu = 0.318 + 0.696\sqrt{Re}$
HILPERT [3]	$Nu = C(Re \theta^{0.25})^n$
	$1 < Re < 4 \quad C=0.891 \quad n=0.33$
	$4 < Re < 40 \quad C=0.821 \quad n=0.385$
	$40 < Re < 4000 \quad C=0.615 \quad n=0.466$
KRAMERS [4]	$0.71 < Pr < 525 \quad 2 < Nu < 20$ $Nu = 0.42 Pr^{0.2} + 0.57 Pr^{0.33} \sqrt{Re}$
Mc ADAMS [5]	$0.1 < Re < 1000$ $Nu = 0.32 + 0.43 Re^{0.52}$
COLLIS [6]	$Nu = (A + B Re^n) \theta^{0.17}$
	$Re < 44 \quad A=0.24 \quad B=0.56 \quad n=0.45$
	$Re > 44 \quad A=0 \quad B=0.48 \quad n=0.51$

Fig. 2. — Comparison of the formulas of Nu in function of \sqrt{Re} established in bibliography.

number with the square root of the Reynolds number (King's law):

$$Nu = A + B\sqrt{Re} \tag{12}$$

These different formulas, are valid for airflows where pressure is constant or changes slightly. Otherwise, the coefficients A and B have to be corrected following the pressure changes [7]. In the first stage of the compressor, the spatial and temporal variations of pressure are below 3% of the atmospheric pressure. So, as indicated above, this influence of the pressure has been neglected in our work.

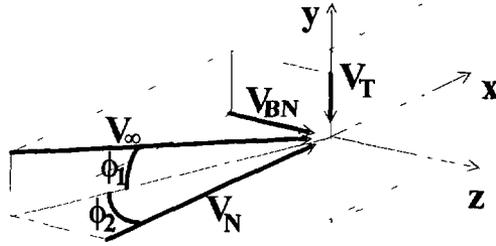


Fig. 3. — Velocity vector component's.

4.2. INFLUENCE OF THE DIRECTION OF THE FLOW WITH RESPECT TO THE HOT FILM

The approach used by the majority of the authors [8–11] consists to adapt the formula (12) as a function of the flow direction. A cooling velocity V_{eff} is defined, depending on the local velocity V_{∞} and the angles ϕ_1 and ϕ_2 of the velocity vector relative to the probe axis (Fig. 3):

$$V_{\text{eff}} = V_{\infty} f(\phi_1, \phi_2) \quad (13)$$

Then, the Nusselt number is defined, using the relations corresponding to the case where the velocity vector is orthogonal to the wire ($V = V_N$) where the effective Reynolds number is defined as:

$$Re(\phi_1, \phi_2) = Re(0, 0) f(\phi_1, \phi_2) \quad (14)$$

4.3. CONCLUSION. — From this short literature analysis, the following conclusions can be deduced:

- The heat flux is a linear function of the difference of the temperature between the flow and the hot film: $T_s - T_{\infty}$.
- If the Reynolds number Re is high enough, the effects of the natural convection can be neglected. Then the Nusselt number is a function of the square root of the Reynolds number.
- Nu depends obviously on the velocity vector direction with respect to the probe.

However, it is clear that the basic formulations proposed in references [2] to [6] are not accurately representative of the behaviour of the heat flux emitted by a hot wire or a hot film. More, thermal characteristics of this sensor installed in a probe, depends on several other components characteristics (pins, welding, electrical connections).

So, an experimental investigation is necessary to identify and then quantify the influence of the main parameters like Reynolds number, temperature of the sensor, direction of the flow.

5. Experimental Investigation of the Dependence of the Nusselt Number Relatively to the Reynolds Number, the Overheat Ratio and the Flow Direction

This investigation has been conducted in the calibration rig of L.E.M.F.I. The constant temperature anemometer was a TSI IFA-100. The probes used were standard "X" probes TSI 1240-20. The length and the diameter of the two sensors were 1 mm and $50.8 \mu\text{m}$ respectively.

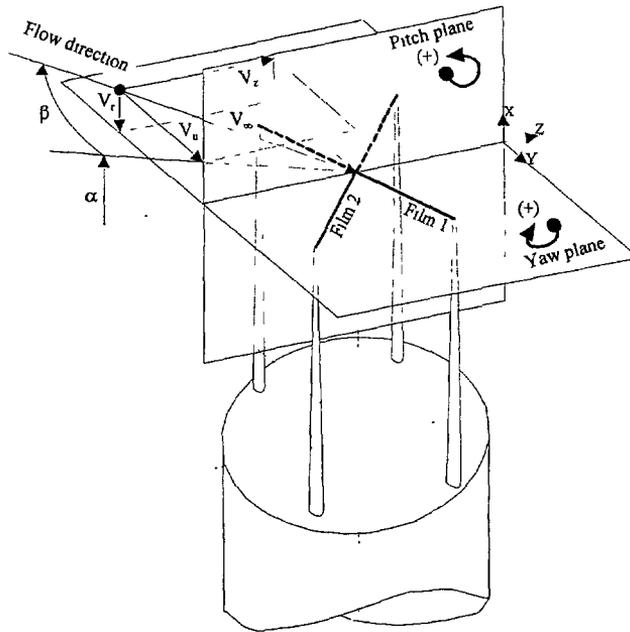


Fig. 4. — Probe localisation in the calibration rig.

In the calibration rig, the probe is fixed in the absolute reference frame. A movable nozzle gives a flow with variable incidence (α) and yaw (β) with respect to the probe (Fig. 4).

The influence of the following parameters on the twins sensors of the probe, has been tested:

- Probe temperature T_s (i.e. overheat ratio θ).
- Velocity of the flow (i.e. Reynolds number Re).
- Direction of the flow relatively to the probe (i.e. α , β).

In all these tests, the temperature of the flow T_∞ has been controlled and maintained equal to 23°C . The influence of the overheat ratio and the Reynolds number has been surveyed for a constant direction of the flow ($\alpha = \beta = 0$).

5.1. INFLUENCE OF THE TEMPERATURE OF THE HOT FILM (FIG. 5). — For temperature such as $23^\circ\text{C} \leq T_s \leq 120^\circ\text{C}$, the Nusselt number is a decreasing function of T_s . The relative derivatives of Nu with respect to T_s and T_∞ are equal and of opposite sign. For $T_s \geq 120^\circ\text{C}$, Nu becomes a quasi-linear function of T_s . A zoom performed on this part of the graph makes it appear that the slope of $Nu(T_s)$ is a smooth decreasing function of the Reynolds number (Fig. 6). In this range of T_s , the Nusselt number is practically independent of the temperature of the flow if T_∞ remain lower than 40°C .

5.2. INFLUENCE OF THE REYNOLDS NUMBER (FIG. 7). — The Nusselt number varies linearly with \sqrt{Re} for all values of T_s above 120°C . As example for $T_s = 250^\circ\text{C}$:

$$Nu = 0.94 \pm 0.32\sqrt{Re} \quad (15)$$

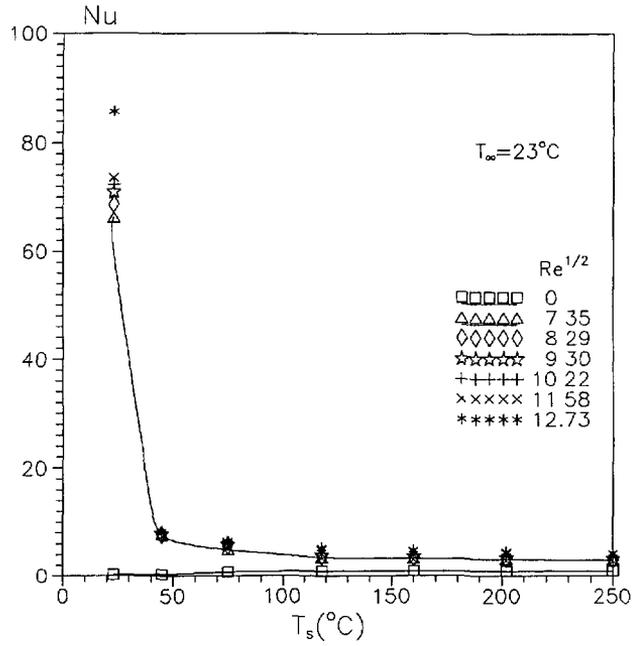


Fig. 5. — Influence of T_s on Nu .

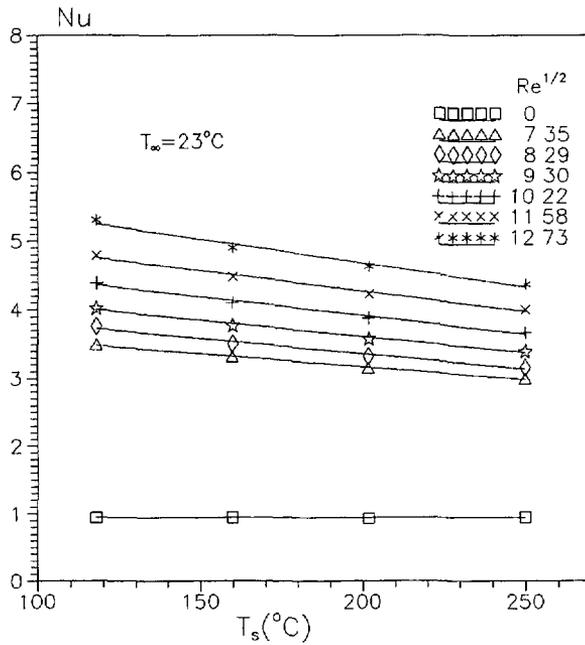


Fig. 6. — Variation of Nu in function of T_s .

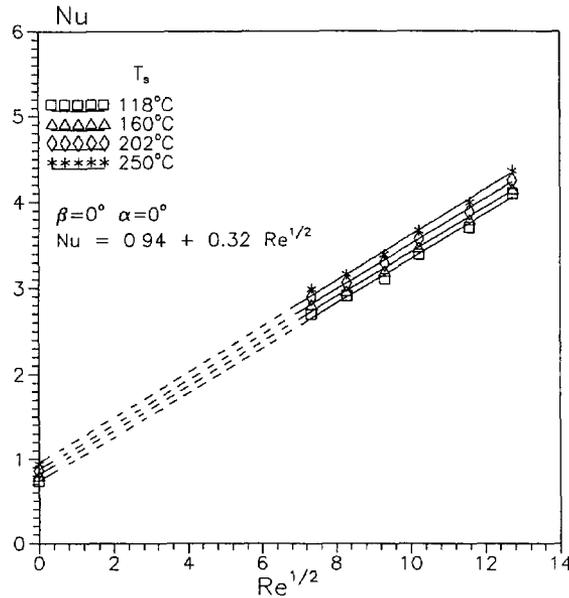


Fig. 7. — Variation of Nu in function of \sqrt{Re} .

Heat flux measurements has been realised for $Re = 0$. The corresponding results are shown in Figure 7. It can be observed that these points verify the relations obtained for $Re \neq 0$. Then, these relations can be extended down to the origin.

Figure 8 presents a comparison between the formulations of the Nusselt number found in references [2] to [6] for several sensors and probes types and the formulation represented in relation 14 for our probes. The Curves confirms that the variation of Nu with \sqrt{Re} is practically linear.

5.3. INFLUENCE OF THE DIRECTION OF THE FLOW (FIG. 9). — A first series of tests has been realised to investigate the influence of the angle β , the dominant parameter on the angular sensibility of the probe. The results of measurements, presented in Figure 9, prove that the linearity of the Nusselt number *versus* \sqrt{Re} is conserved in the domain $-45^\circ \leq \beta \leq 45^\circ$.

5.4. CONCLUSIONS. — The conclusions of this experimental investigation are given as: for the probes experimented and in the following test conditions, $T_s > 120^\circ C$, $T_\infty < 40^\circ C$, $Re > 50$, the Nusselt number can be formulated as:

$$Nu = \underbrace{A + BT_s}_1 + \underbrace{\{C(\beta, \alpha) + D(\beta, \alpha)T_s\}}_2 \sqrt{Re} \tag{16}$$

(typical values are $A = 0.48$, $B = 0.00084/^\circ C$). As for the group of terms (2), $C(\alpha, \beta)$, $D(\alpha, \beta)$ are drawn in Figure 10, first in function of β , then in function of α .

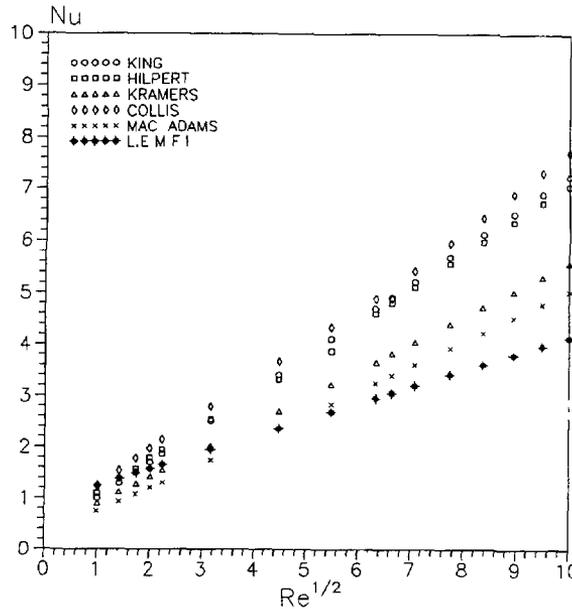


Fig. 8. — Comparison of the formula (15) with authors formulation's.

6. Velocity Measurement in a Tri-Dimensional Unsteady Flow

The constant temperature anemometer measures the heat flux (or the Nusselt number) relative to the hot film. Then, it is necessary to determine the local velocity V_∞ from the Nusselt number.

Relation (16) indicates that Nu is a bilinear function of \sqrt{Re} and T_s . The coefficients A, B, C, D are obtained from calibration. From equations (10) and (16), the output voltage of the anemometer, for each sensor, is written as:

$$V_p^2 = \left[a + bT_s + \{c(\beta, \alpha) + d(\beta, \alpha)T_s\} \sqrt{Re} \right] (T_s - T_\infty) \tag{17}$$

Four unknown quantities are present in equation (17): $Re, \alpha, \beta, T_\infty$. So, the knowledge of the three unsteady components of the velocity would require four independent sensors i.e. a probe incorporating four hot films. Unfortunately the volume of such probes is not compatible with measurements in narrowly spaced compressor blades. For this reason, we used two films probes in the present study, to obtain two components of the velocity vector. However, hypothesis are to be made about the influence of the temperature and the sensibility of the probes relatively to the third direction of the flow.

6.1. INFLUENCE OF THE STATIC TEMPERATURE OF THE FLOW. — A rough solution to the problem of velocity measurement is to suppose a constant temperature in the whole flow field. This hypothesis can be quite correct for very low speed machines. By differentiation of equations (6) and (15), it can be demonstrated that the relative uncertainty on the value of V_∞ is of the order of $1\% / ^\circ C$. However, in a axial compressor with a rotational speed higher than 4000 rpm, the temperature changes through one stage are not negligible. Furthermore, the unsteady fluctuations of T_∞ have been estimated between $5\ ^\circ C$ and $10\ ^\circ C$ in operating conditions close

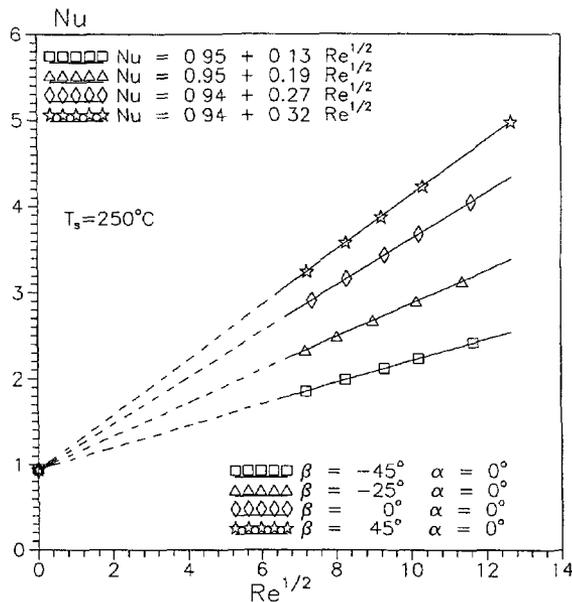


Fig. 9. — Variation of Nu in function of \sqrt{Re} and β .

to the surge line (see Ref. [12]). In these circumstances, neglecting the temperature influence can lead to an uncertainty close to 10% on velocity measurement.

Temperature must then be estimated simultaneously with velocity. A classical solution lies in the use of thermocouples; unfortunately it corresponds to an increase in the probe size. More, the response in time of a thermocouple is low. An alternative solution is proposed below.

6.2. INFLUENCE OF FLOW DIRECTION WITH RESPECT TO THE PROBE. — An additional hypothesis is to be made relatively to the flow direction: the probe is not sensitive to the angle of incidence α , in others words the coefficients C and D are not depending of α . It can be observed in Figure 10 that such a property is quite well respected if the yaw angle β is in the range: $-10^\circ < \beta < 10^\circ$. Then, if the probe is conveniently oriented in the flow, so as to equate the mean voltage of the two sensors, the probe can be supposed to be insensitive to α . The measured voltage (17) can then be written as:

$$V_p^2 = \left[a + bT_s + \{c(\beta) + d(\beta)T_s\} \sqrt{Re} \right] (T_s - T_\infty) \tag{18}$$

6.3. A SOLUTION IN VIEW OF SIMULTANEOUS MEASUREMENTS OF VELOCITY AND TEMPERATURE. — Use of a periodic current or voltage for temperature and velocity measurements has already be implemented [13,14]. However, the experimental devices included anemometer specially designed for this purpose.

In the present work, we followed a quite different approach: first, our main aim was to use a standard C.T. anemometer and secondly, we wished to limit the adjunction of additional devices.

Consider, first, a single hot film in a steady flow. The output voltage is represented by equation (18). Without any modification of the orientation of the film with respect to the flow, we introduce instantaneously a resistance R_{ad} serially with the film. This sudden increase of

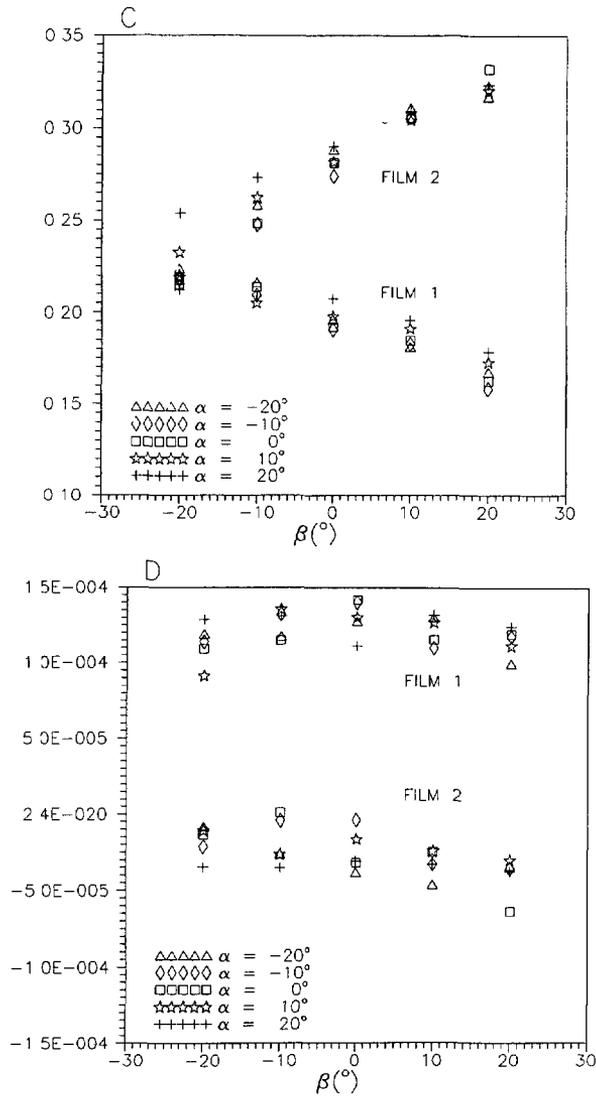


Fig. 10. — Variation of the coefficients C and D in function of α , β angles.

the resistance is seen from the anemometer as in an increase of the temperature T_s of the sensor. Then, the anemometer reduces the current to equilibrate the bridge again. As the operational resistance R_{op} is unchanged, the new values of the resistance and temperature of the sensor are:

$$R_s = R_s - R_{ad} \tag{19}$$

$$T_s = T_s - \frac{R_{ad}}{\kappa} \tag{20}$$

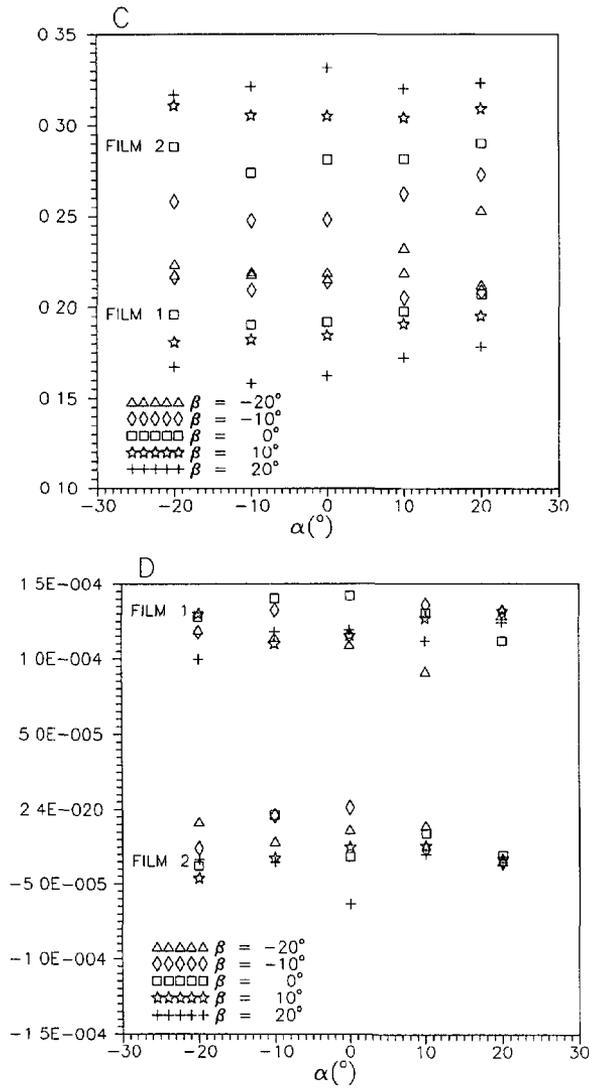


Fig. 10. — (Continued).

The measured voltages are then:

$$V_p^2 = \left[a + bT_s + \{c + dT_s\} \sqrt{Re} \right] (T_s - T_{\infty}) \quad (21)$$

(previously to the introduction of R_{ad})

$$V_p'^2 = \left[a + bT'_s + \{c + dT'_s\} \sqrt{Re} \right] (T'_s - T_{\infty}) \quad (22)$$

(after R_{ad} has been introduced)

If Re and β are independent of time, then the static temperature T_{∞} of the flow is obtain from:

$$X^2 - MX + N = 0 \quad (23)$$

where:

$$X = \frac{T_s - T_\infty}{T_s - T'_s} \quad (24)$$

$$M = 1 + \frac{V_p^2 (c + dT'_s) - V_p'^2 (c + dT_s)}{(bc - ad)(T_s - T'_s)^2} \quad (25)$$

$$N = \frac{V_p^2 (c + dT'_s)}{(bc - ad)(T_s - T'_s)^2} \quad (26)$$

Then from equation (24) to equation (26):

$$T_\infty = T_s - (T_s - T'_s) X (V_p, V'_p, T_s, T'_s, \beta) \quad (27)$$

So the static temperature T_∞ is known from two successive measurements of the voltage delivered by a single sensor as a function of the flow angle relative to the probe β . Obviously, it is necessary to introduce the second sensor of the probe to obtain the velocity vector (i.e. Re and β). The set of equations is then:

$$\begin{aligned} V_{p1}^2 &= \left\{ a_1 + b_1 T_{s1} + (C_1(\beta) + d_1(\beta) T_{s1}) \sqrt{Re} \right\} (T_{s1} - T_\infty) \\ T_\infty &= T_{s1} - (T_{s1} - T'_{s1}) X (V_{p1}, V'_{p1}, T_{s1}, T'_{s1}, \beta) \\ V_{p2}^2 &= \left\{ a_2 + b_2 T_{s2} + (C_2(\beta) + d_2(\beta) T_{s2}) \sqrt{Re} \right\} (T_{s2} - T_\infty) \end{aligned} \quad (28)$$

“1” and “2” corresponding to each crossed sensor of the probe.

A standard numerical iterative method is used to solve this system of three non linear equations with respect to the unknowns Re , T_∞ , β . Then, the components of the flow velocity can be deduced:

$$V_\infty = \frac{Re \mu_\infty}{\rho_\infty df} \quad (29)$$

$$V_z = V_\infty \cos(\beta) \quad (30)$$

$$V_u = V_\infty \sin(\beta) \quad (31)$$

where:

$$\rho_\infty = \frac{P_\infty}{RG T_\infty} \quad (32)$$

$$\mu_\infty = \mu_r \left(\frac{T_\infty}{T_r} \right)^{0.75} \quad (33)$$

$$(\mu_r = 15 \times 10^{-6} \text{ kg/m/s and } T_r = 273 \text{ K})$$

A number of tests have been performed in the calibration rig in view to validate the method. The experimental conditions are listed below:

$$\begin{aligned} V_\infty &= 30 \text{ m/s} \\ -30^\circ &\leq \beta \leq 30^\circ \\ -30^\circ &\leq \alpha \leq 30^\circ \\ T_\infty &= 23 \text{ }^\circ\text{C} \end{aligned}$$

Results are given in Figure 11. It is clear that, as long as the flow is steady, velocities and temperatures deduced from measurements are very close to their exact values. The ranges of error can be estimated as given below:

$$\begin{aligned} &\pm 0.5 \text{ }^\circ\text{C (4\%)} \text{ for temperature } (T_\infty) \\ &\pm 0.5 \text{ m/s (3\%)} \text{ for velocity } (V_\infty) \\ &\pm 0.5 \text{ }^\circ \text{ for velocity direction } (\beta) \end{aligned}$$

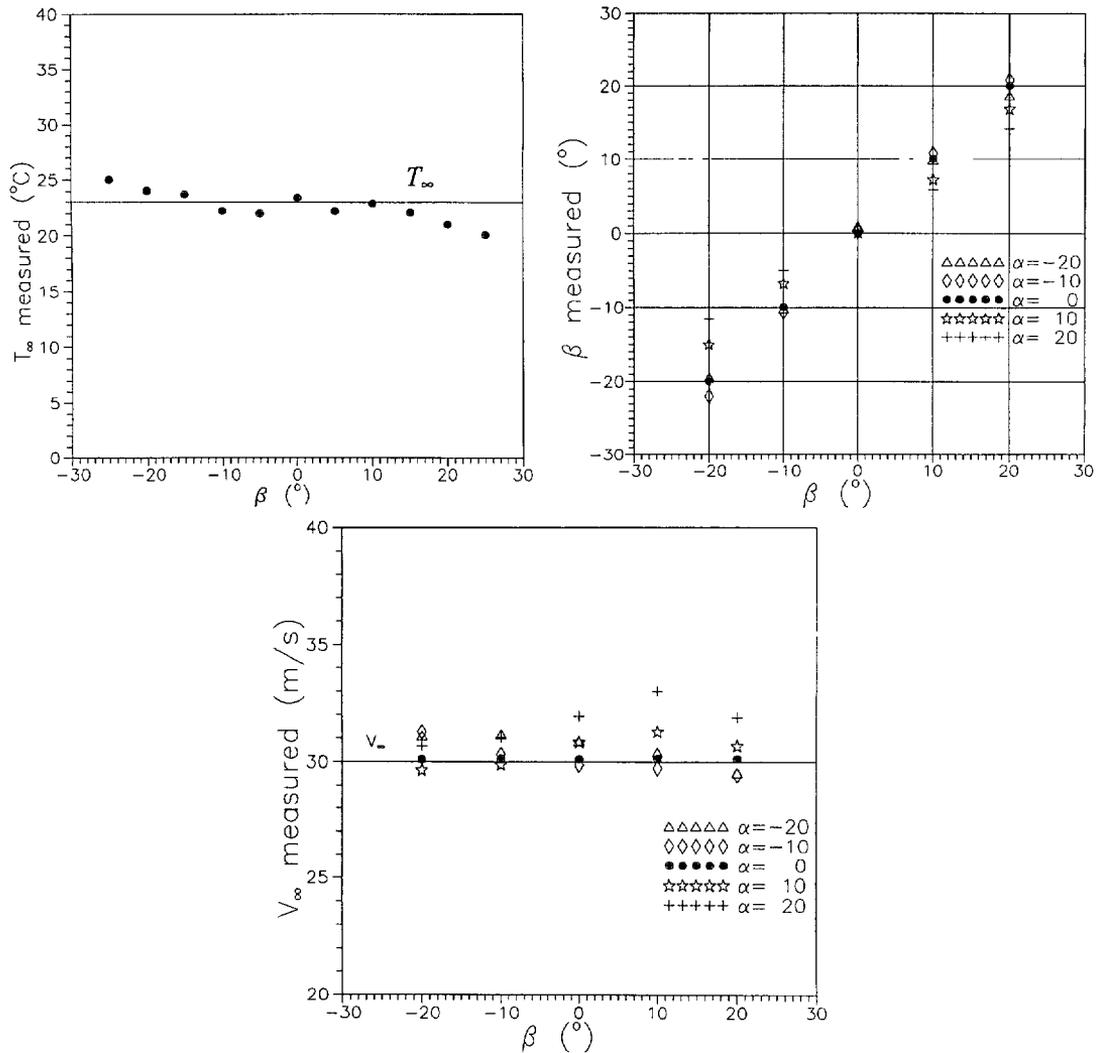


Fig. 11. — Comparison of T_∞ , β , et V_∞ values measured by the probe and those given by calibration rig.

6.4. APPLICATION TO UNSTEADY FLOW. — The previous procedure of temperature measurement is convenient if the flow remain steady. In unsteady periodic flow, the interval of time needed by the commutation of temperature of the sensor must be, at least, much lower than the fundamental period of the aerodynamic phenomena. Then, the set-up of a system suitable for velocity and temperature measurement require two main steps:

- Realisation of a device to commute the temperature of the hot film with a high frequency.
- Analysis of the dynamic response of the anemometer to rapid changes of the electrical resistance of the film.

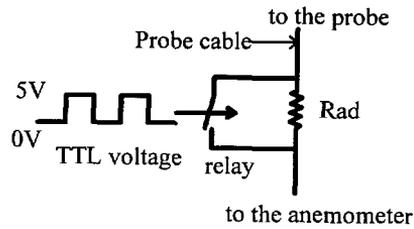


Fig. 12. — Device for commutation of the temperature of the hot film.

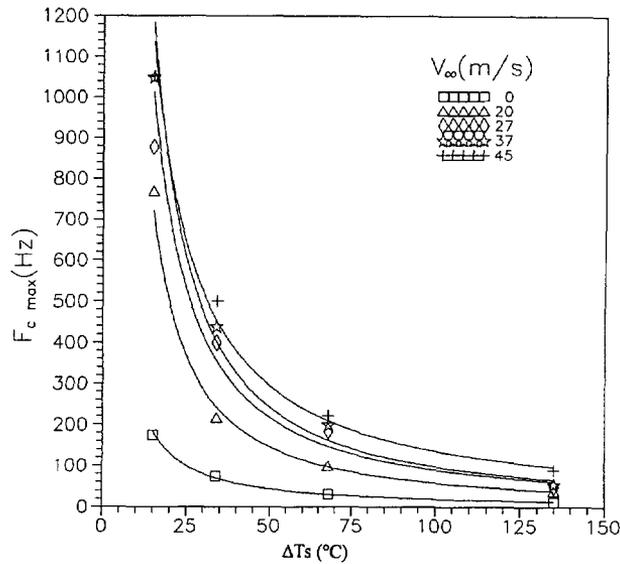


Fig. 13. — Frequency of temperature commutation F_c in function of T_s and V_∞ .

6.4.1. *Device for Commutation of the Temperature of the Hot Film.* — The sketch of the circuitry is given in Figure 12. A relay driven by a T.T.L. voltage (0/5 V) has been used. This input T.T.L. voltage is supplied by a small computer at a variable frequency. So the impedance of the circuit is periodically equal to 0 or R_{ad} . The critical frequency of the relay is close to 1 kHz.

6.4.2. *Dynamic Behaviour of the Anemometer to Rapid Changes of the Resistance of the Sensor.* — For a given sensor, the frequency response of the anemometer must be optimised by the user. A square voltage with adjustable level and frequency is provided to the sensor. The cutting frequency for hot films, defined in reference [14], depends on both the mean velocity and the amplitude of the velocity fluctuations. For example, for probes like those used in the present work, the cutting frequency is equal to 30 kHz in a flow of air with a mean velocity of 40 m/s and velocity fluctuations of 20 m/s. When the amplifier can no longer control the temperature of the sensor, the anemometer stop to feed it (automatic protection). From the anemometer, the introduction of R_{ad} is equivalent to a velocity or temperature fluctuation. Then it is necessary to analyse the transient behaviour of the bridge when the resistance R_{ad}

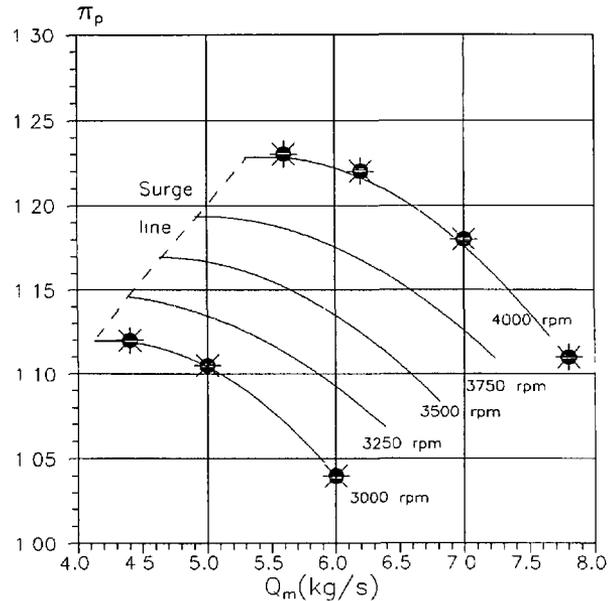


Fig. 14. — Compressor global performance.

is introduced in the circuit. These tests has been realised using a sensor with the following characteristics:

- resistance (0 °C): 6.21 Ω
- resistivity: 0.0148 $\Omega/^\circ\text{C}$
- cable resistance: 0.492 Ω
- sensor temperature: 250 °C

The results of the tests are represented in Figure 13.

The resistance R_{ad} is represented by the temperature variation ΔT_s of the sensor due to the introduction of R_{ad} . The curves indicate, for several velocities of the flow, the maximum frequency of commutation which can be obtained as a function of ΔT_s .

For example, if the flow velocity is equal to 40 m/s and ΔT_s to 30 °C, the maximum frequency of commutation is limited to 500 Hz.

6.4.3. Use of the Method for Measurements of Velocity and Temperature in an Axial Compressor. — The axial flow four stages compressor CME1 is described in references [1,16]. The pressure ratio *versus* mass flow rate chart for this compressor is illustrated Figure 14. Three axial locations of measurement are available in the first stage of the machine (Fig. 15):

- upstream of the rotor (1)
- downstream of the rotor (2)
- downstream of the stator (3)

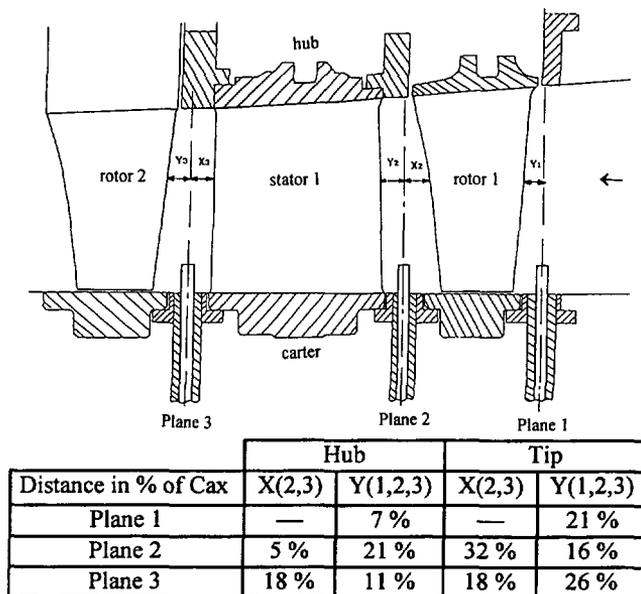


Fig. 15. — Axial locations of the probe.

The axial position of these locations with respect to the blades are represented in Figure 15.

The results presented in the present paper have been obtained in the following conditions:

- Rotational speed: 3000 rpm
- mass flow rate: 4.4 kg/s
- axial location of the probe: 2

The rotor of the first stage of this compressor has 17 blades. For a rotational speed of 4000 rpm, the frequency of the blades motion is close to 1 kHz. In view to obtain a quite accurate representation of the unsteady phenomena, a sampling frequency of 10 kHz has been used. Due, first, to the dynamic behaviour of the anemometer, this frequency is higher than the maximum possible frequency of commutation of the temperature of the sensor (500 kHz). So, when using directly the system described above, simultaneous measurement of flow velocity and temperature cannot be achieved. Then an alternative mode of operation has been implemented. The start of the acquisition is triggered by a transducer fitted in the casing of the compressor, delivering a T.T.L. pulse in response to the passing of a given blade. In a first step, a data acquisition of 4096 samples is performed with a temperature of the sensor equal to T_s . In a second step, 4096 samples are recorded with a temperature of the probe equal to T'_s (4096 samples correspond approximately to 25 revolutions of the rotor). Each homologous values in these two successive records correspond to the same position of the moving blades with respect to the probe. Using a F.F.T., the signals are reduced to their periodic components, leading to two series of data. It is assumed here that these two series of filtered data correspond to the same flow seen by the same probe, first at the temperature T_s , then at the temperature T'_s . The relations (29) are then applied to the corresponding samples.

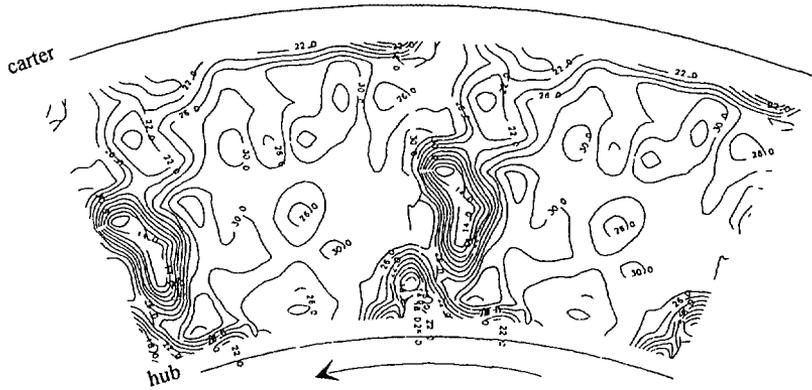


Fig. 16. — Axial velocities.

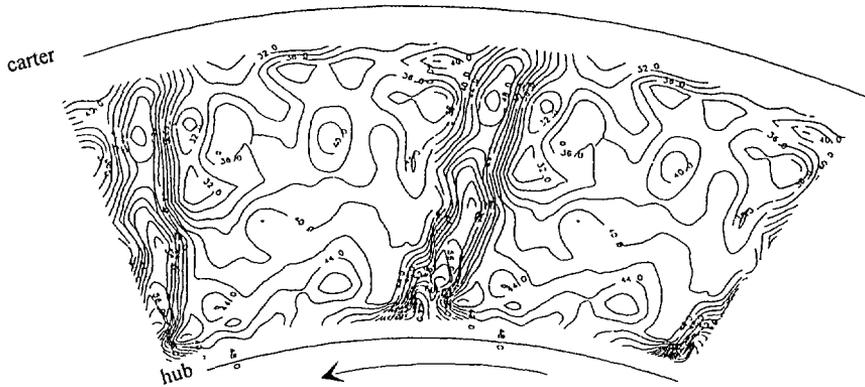


Fig. 17. — Tangential velocities.

6.4.4. *Analysis of Results Downstream the Rotor.* — Results of velocity and temperature measurements are represented in Figures 16 to 18.

The main phenomena can be observed clearly in the Figures: the wakes of the blades, the boundary layer along the casing whose thickness is close to 15 mm. In comparison, the boundary layer along the hub appear to be thin. Such a difference between the external and the internal boundary layers exists in the inlet plane of the compressor and so, is not mainly due to leakage effect or separation across the rotor blades.

Out of the wall regions and outside the wake regions, velocities and temperature are rather uniform. Axial velocities are contained between 26 m/s and 30 m/s, tangential velocities between 36 m/s and 40 m/s, temperature between 28 °C and 32 °C. The averaged temperature (30 °C) is close to the temperature measured with resistive platinum thermometer located at the same position that the hot film probe.

In the wake region, the axial velocities varies with radius as the axial distance of the probe to the trailing edge due to the twist angle of the blades. They are between 14 m/s at 30% of the blades height and 22m/s at the blade tip. Close to the hub, secondary flow phenomena

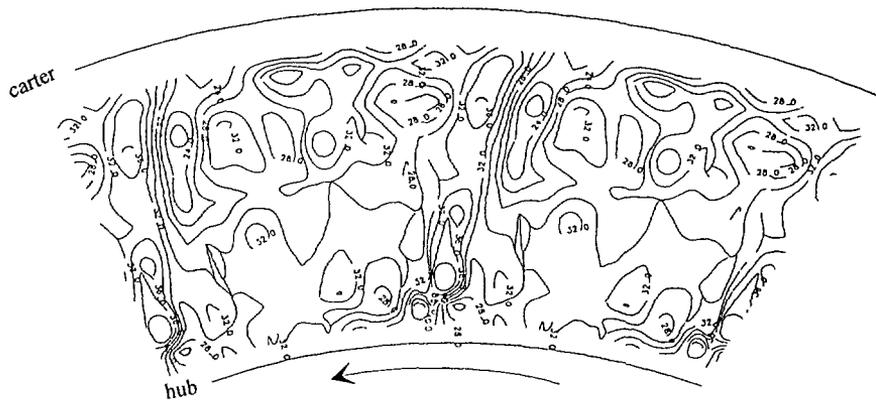


Fig. 18. — Temperatures.

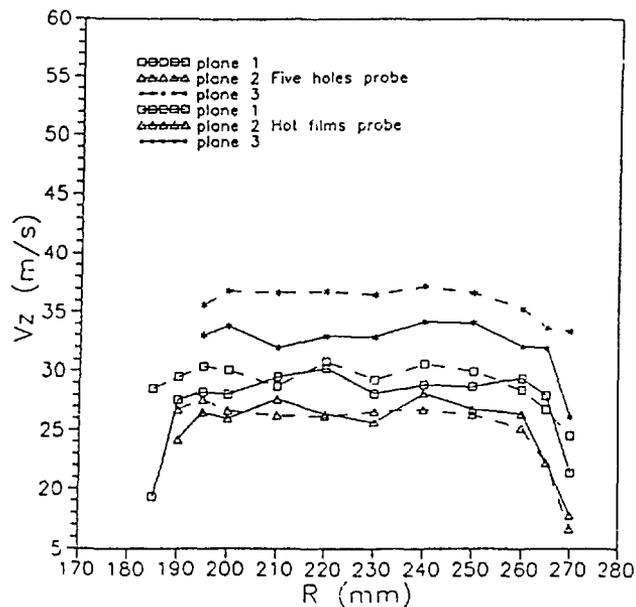


Fig. 19. — Comparison of axial velocities from cobra and hot films probes.

lead to higher axial velocity levels, up to 20 m/s. Tangential velocities increase in the wake are about 20 ms ($V_u \cong 57$ m/s) close to the hub, 10 m/s ($V_u \cong 45$ m/s), in the outer regions.

Temperatures show an increase of about 8 °C. Such a value is of the same order that those measured in reference [12].

The averaged velocities deduced from these measurements have been compared to the velocities obtained with a five holes pressure probe (“cobra probe”) located in the same position with respect to stator blades. Results are plotted in Figures 19 and 20. A quite satisfying agreement is observed between axial as like tangential velocities measurements.

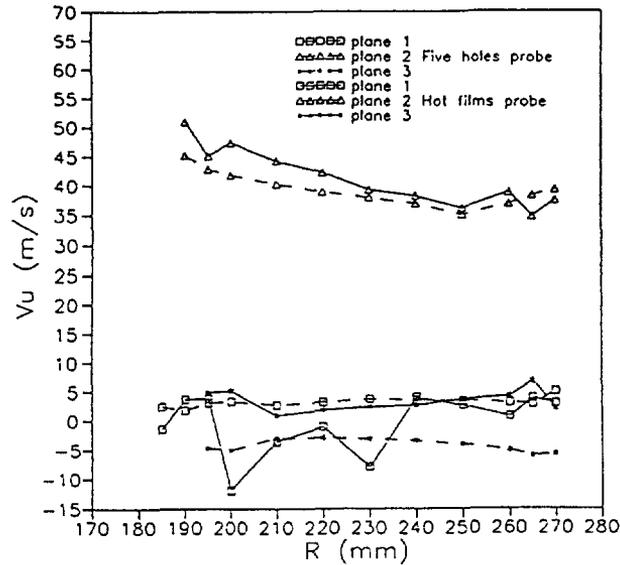


Fig. 20. — Comparison of tangential velocities from cobra and hot films probes.

7. Conclusion

A method to measure velocity and temperature in unsteady flow with hot film anemometry has been studied, and then tested, in a low speed axial compressor. The apparatus includes a standard constant temperature anemometer. An external device is used to commute the temperature of the probe at a given frequency and directly connected to this one.

Problems has been encountered to perform simultaneous measurements of velocity and temperature. The difficulties are mainly due to the anemometer which include a system protecting the probes from overheat. So, it is difficult to reach high frequencies of commutation of the temperature of the hot films unless to limit to a low level, -the step of temperature imposed by the additional resistance. However, such a way is quite critical to use in strongly turbulent flows currently encountered in turbomachines: it is then not easy to differentiate the signals corresponding to the two successive temperatures of the film.

In the present study, the difficulty has been overcome using the periodicity of the flow with respect to time. Obviously, such an approach is not compatible with measurements of the turbulent fluctuations of the temperature.

However averaged values of velocity and temperature deduced from these measurements are in satisfying agreement with steady measurements realised with pressure probe or resistive platinum thermometer.

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