MEASUREMENTS POSSIBILITIES ON TURBOMACHINES WITH THIN FILM TRANSDUCERS

by

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ABSTRACT

To carry out studies aiming at the improvement of turbomachine efficiency and the reduction of their acoustic nuisance it is necessary to implement, as well as conventional measuring devices, transducers which can be directly installed on fixed and mobile blades. To respond to this need, ONERA has developed new transducers of "thin-film" type, with an overall thickness not exceeding 80 μm. ONERA work in this field makes it possible to present several kinds of transducers in current use on test benches : pressure, temperature, heat transfer.

All these transducers are bonded on the walls to be instrumented, and thus do not require any machining for their integration.

These devices cover many fields of application, such as acoustics, energetics, aeroelastics, aerodynamics, hydrodynamics.

KEY WORDS. Thin film transducers -Pressure transducers - Temperature transducers - Heat flux transducers - Boundary layer analysis - Wall measurements - Turbomachine measurements.

1 - INTRODUCTION

With a view to approach the solution of two fundamental problems raised by turbomachines, viz. efficiency improvement and acoustic nuisance reduction, it is necessary to improve our knowledge on the physical phenomena developing at the interface between fixed and rotating aerofoils and the surrounding medium. This knowledge is based on various measurements : pressure, temperature, heat flux, turbulence, stresses, etc. Up till now, these measurements were performed with transducers located outside the machine : pressure and temperature probes, optical pyrometers, microphones, infrared radiometers, etc. Laboratories and manufacturers alike proved the necessity of complementing these measurements by information issued from other means, such as transducers directly installed on the fixed and mobile blades of the turbomachines.

Conventional transducers, even when miniaturized, require a machining of the part to be integrated to its surface, and such an operation is tricky, if not even impossible. It is the case near the leading edge or the trailing edge of the thin aerofoils involved in aeronautical turbomachines, whose maximum thickness may be of the order of 3 mm [1].

Furthermore, the aerodynamic, thermal and mechanical characteristics of the aerofoil may be modified by these machining, hence erroneous measurements. For these various reasons ONERA, supported by DRET (the Research Department of the Ministry of Defence) studied a new family of devices, called "thin-film transducers". The purpose of this paper is to present the various types of transducers which have been developed, to give examples of use, to define the possibilities of utilization and to list the principal fields of their application.

2 - GENERALITIES ON THIN FILM TRANSDUCERS

Three types of transducers have been developed at ONERA :

- pressure transducers with capacitance detection,
- temperature and convection heat flux transducers, which make use of the thermoelectric effect occurring between two metals or alloys deposited as thin films,
- transducers for analyzing the boundary layer of an aerodynamic flow, based on the variation of resistivity of metals as a function of temperature.

The properties common to all these transducers are as follows [2] :

- maximum overall thickness 80 μm ;
- integration on the wall to be instrumented, without machining, by bonding, hence preservation of the aerodynamic and mechanical qualities of the aerofoil, and very small modification of its thermal properties ;
- possibility of realizing several transducers on the same support, avoiding any disturbance of the flow, during aerodynamic tests, due to local bumps that would result from the bonding of several transducers along the profile ;
- dimensions, geometry of the sensitive elements, and their distribution over the substrate, adapted to the metrologic requirements.

The possibility of realizing these various types of thin film transducers results from :

- the existence of dielectric flexible foil, such as Kapton of Dupont de Nemours, chosen for its availability with thicknesses from 6 to 100 μm and for its good strength at high temperature (300°C) ;

- the implementation of vacuum evaporation or sputtering techniques to realize, as thin films (0.2 μm thick), the metallic parts of the sensitive elements and the conductors carrying the signal ;

- the possibility to obtain very thin glue films for assembling several kapton foils.

The technological study of all these types of thin film transducers required the development of several fabrication techniques. Let us mention, as examples, these concerning :

- the metal deposition as thin films fulfilling a large number of specific constraints ;
- the implementation of very thin films of glue, exempt of any inclusion, necessary for assembling the substrates and for integrating the transducers to the aerofoil walls ;

- the very accurate superposition, during piling up, of the metallic deposits on each kapton foil ;
- the integration of these transducers on aerofoils which, more often than not, present warped surfaces.

3 - THIN FILM PRESSURE TRANSDUCERS

3.1 Principle

This tranducer uses a capacitive type detector, whose sensitive element is made of a flexible dielectric foil metallized on both its faces, thus forming a capacitor of capacitance C [3] (fig. 1). Under the action of a pressure variation Δp, the thickness of this foil decreases of Δe ; there results a relative variation of the capacitance C proportional to the applied pressure variation.

$$\frac{\Delta C}{C} = - \frac{\Delta e}{e} = \frac{\Delta p}{K} , \qquad (1)$$

K is a coefficient defined later.

There exist three possibilities for measuring this capacitance variation :

- to include the capacitor in a capacitive bridge, supplied at a carrier frequency, this gives directly its measurement ;

- to polarize the capacitor by means of a source of continuous voltage V , and to measure the variations of the capacitor charge Q by means of a charge amplifier :

$$\frac{\Delta Q}{Q} = \frac{\Delta C}{C} = \frac{\Delta p}{K} \qquad (2)$$

- to supply the capacitor through a very high impedance, by the same source of continuous voltage V , and to measure the potential difference ΔV appearing at the terminals of this impedance ; it can be shown that :

$$\frac{\Delta V}{V} = \frac{\Delta C}{C} = \frac{\Delta p}{K} \qquad (3)$$

Among these three solutions, only the first one would provide the measurement of the continuous component of pressure.

For measurements in turbomachines, this parameter is not looked for. So, the third solution has been retained, in preference to the second one for technological reasons.

In practice, as shown on figure 2, guard circuits are arranged on either side of the "hot point" connexion which connects the sensitive element to the input of the measuring circuit made by an impedance converter. These guard circuits play several roles :

- to reduce the induced disturbances of electromagnetic origin,
- to avoid the accumulation of electric charges on the "hot point" connexion due to uncontrollable parasitic triboelectric effects, in the presence of aerodynamic flow,
- to reduce the spurious capacitances relative to the ground of the aerofoil ; these reduce the overall sensitivity of the transducer.

3.2 Description

Two types of transducers have been developed with a view to meet different specific requirements :

- transducers whose dielectric of the sensitive element is solid, and made of a kapton foil ; this type of dielectric allows very large static pressures ;

- transducers whose dielectric of the sensitive element is made by the air contained in cavities ; this type of transducer displays a greater sensitivity.

3.2.1 - Transducer with solid dielectric

The structure of this type of transducer corresponds to the representation of figure 2. The value of its sensitivity at crusching may be expressed in the form :

$$\frac{\frac{\Delta C}{C}}{\Delta p} = \frac{1}{K} = \frac{(1 + \sigma)\ (1 - 2\sigma)}{E(1 - \sigma)} \qquad (4)$$

with : E = elastic modulus of the material,

σ = Poisson coefficient of the material,

K = uniaxial compression modulus.

In fact, in gas medium and adiabatic regime, to the crushing response due to pressure fluctuations, in the low frequency range, a response to the gas temperature fluctuations induced by pressure, is added. This secondary effect makes it difficult to interpret the phase of the signal delivered by the transducer. Consequently this type of transducer is mainly used for providing the spectral distribution of the spectral beams of pressure fluctuation, by means of the sensitivity curve given on figure 3.

3.2.2 - Type of transducer with gaseous dielectric

This transducer is formed by multiple cavities bored in a kapton foil (figs. 4 and 5). These cavities, filled with air, are closed by two other kapton foils carrying electrodes, forming the capacitive sensitive element. The upper foil is used as deformable membrane.

For each cavity, the pressure sensitivity may be expressed by :

$$\frac{\frac{\Delta c}{c}}{\Delta p} \simeq \frac{(1 - \sigma^2)\ a^4}{16\ E h^3\ \ell} \qquad (5)$$

with a = cavity radius,
h = membrane thickness,
ℓ = cavity height,
c = capacitance of one cavity

To evaluate the overall sensitivity of the sensitive element, the capacitance C_K due to the presence of the kapton walls around the n cavities, must be taken into account. Hence :

$$\frac{\frac{\Delta C}{C}}{\Delta p} = \frac{(1 - \sigma^2)\ a^4}{16\ E.h^3\ \ell} \times \frac{nc}{C_K + n\,c} \qquad (6)$$

The transducer sensitivity may be fitted to the requirement by choosing the thickness of the kapton foil making up the deformable membrane.

This type of transducer provides the measurement of the amplitude and the phase of the pressure fluctuation.

3.3 Characteristics of the pressure transducers

Characteristics	Detectors with solid dielectric	Detectors with Membrane thickness 12 µm	gaseous dielectric Membrane thickness 25 µm
Sensitivity $\Delta C/C/Pa$	variable from 2.10^{-9} to 2.10^{-10}	3.10^{-7}	4.10^{-8}
Bandwidth (Hz)	1 to 10^5	1 to 10^5	1 to 10^5
Detectivity at 1kHz ($Pa - Hz^{-1/2}$)	2 (polarized under 100 V)	10^{-1} (polarized under 10 V)	6.10^{-1}
Transducer thickness (µm)	50	80	92
Thickness of metal deposits (µm)	0.2	0.2	0.2
Standard area of sensitive element (mm^2)	4 x 6	4 x 6	4 x 6
Width of thin film connections (mm)	0.6	0.6	0.6
Size of associated microelectronics (mm^3)	2 x 4 x 1	2 x 4 x 1	2 x 4 x 1
Temperature range (°C)	0 to 60	0 to 60	0 to 60

These detectors become operative only after installation on the aerofoil to be instrumented ; so their calibrations must be carried out after integration, by means, for instance, of a small cavity fitted with a reference transducer, of a shape adapted to the aerofoil and pneumatically supplied in an appropriate fashion.

3.4 Examples of use

Thin film pressure transducers with solid dielectric have already been used in several experiments of industrial type.

The out-fitting of a fixed, supersonic cascade blades (figs. 6 and 7) with these transducers made it possible to bring to light the flow instabilities as a function of the value of the counterpressure downstream of the blade-to-blade channels [4] (fig. 8).

Integration of thin film transducers on the mobile blades of a SNECMA compressor (figs. 9 and 10) enabled one to characterize noise sources [5]. In this experiment, the signals delivered by the transducers were amplified in high gain measuring units, located within the rotating part, before being transmitted to the acquisition system through a slip ring. At maximum rotating speed, the centrifugal accelerations applied to the measuring units and the transducers were respectively 20 000 and 75 000 g's. Figure 11 shows the spectrum of pressure fluctuations, calculated from the signal delivered by a transducer located on the suction side of the blade, near the leading edge.

Another cascade profile has been fitted with gaseous dielectric thin film transducers (fig. 12). It is being subjected to tests in a transonic wind tunnel, where a sine wave pitch motion is applied. The measurements collected in these conditions should enable us to calculate the unsteady pitching moment of the profile.

4 - TEMPERATURE, HEAT FLUX AND BOUNDARY LAYER ANALYSIS TRANSDUCERS

All these transducers detect thermal phenomena. They make use of two different principles.

4.1 Principles

4.1.1 - Temperature and heat flux

The temperature and heat flux transducers (figs. 13a, 13b) both make use of the thermoelectric effect existing at the junctions of two metals or alloys A and B [6] connected to a closed circuit. The electromotive force ξ appearing in the circuit is related, to the temperatures T_c of the hot junction and the temperature T_f of the cold junction, by the following polynomial relationship :

$$\xi = a(T_c - T_f) + \frac{1}{2} b(T_c^2 - T_f^2) + \ldots. \qquad (7)$$

As regards static heat flux ϕ, this is deduced from the measurement of the difference of the temperatures T_s and T_i on either side of a calorimetric element made of a kapton foil of thickness e and thermal conductivity λ :

$$\phi = \frac{\lambda}{e} (T_s - T_i) \qquad (8)$$

T_s and T_i are measured by two thermocouples, whose difference of electromotive forces is $\Delta \xi$.

The difference $(T_s - T_i)$ being small, one can use a quasi linear relationship for expressing the flux :

$$\phi = \frac{\lambda}{e} \cdot \frac{\Delta\xi}{k} \qquad (9)$$

k is the sensitivity coefficient of the thermocouples in the temperature range used.

4.1.2 - Boundary layer analysis

The transducers for analyzing the boundary layer of an aerodynamic flow are made of a resisting metallic thin film, deposited on a kapton dielectric foil and whose resistance R varies with the temperature T to which it is subjected (fig. 13c) :

$$R = R_0 \ (1 + \alpha T) \qquad (10)$$

α is the temperature coefficient of the resistance of the film.

This film is heated by Joule effect at an assigned temperature T . In the presence of flow, this film cools by convection, and the convective exchange decreases when the boundary layer thickness ε increases. Thus, the value of the power P_C, applied to the film to maintain it at the constant temperature T , gives an information on the boundary layer thickness above the film [7] :

$$P_C = f(\varepsilon) = P_V - P_0$$

with : P_V = power applied to the film in the presence of flow,

P_0 = power applied to the film without flow.

Furthermore, the r.m.s. value P_ε of the pressure fluctuations to the mean power P_V ratio makes it possible to evaluate the turbulence rate τ of this boundary layer.

To analyze the boundary layer around an aerofoil, a set of several transducers, made of hot films and realized on a single support, is integrated along the chord of this aerofoil.

4.2 Description of thermal thin film transducers

As for pressure transducers, the number of sensitive elements and their locations on the substrate are dictated by the metrologic requirements. The sensitive elements and their connections are realized from thin film metallic deposits ; their geometry is obtained either by masking during deposition or by chemical etching afterwards.

To realize these sensitive elements, two metallic materials A and B are successively deposited on the insulating substrate, the metallic junctions making up the thermocouples. The best couples of A and B materials have been looked for with a view to obtain at the same time, sensitive thermoelectric elements and deposits displaying good mechanical qualities. At present, two couples are retained :

- copper-nickel deposited by vacuum evaporation,
- chromel-constantan deposited by sputtering.

The Kapton foil making up the substrate is equipped with several thermocouple elements on one face or on both, whether we wish to measure temperatures or heat fluxes (figs. 14a, 14b). The voltages $\xi_1, \xi_2, ..$ available at the terminals of the connexions are representative of the temperatures T_1, T_2,... of the various junctions (fig. 14a). As regards the flux transducer, the knowledge of the surface temperature T_s , otbained from that of the e.m.f. ξ_s (fig. 14b) makes it possible to better evaluate the fluxmeter sensitivity which, for several reasons, varies with temperature (among others by variation of coefficient λ). The connexion with measuring instruments is ensured by means of wires : spurious thermocouples appear at the wire - thin film junctions. To avoid any error, the temperature of all these junctions must be the same, and stabilized at a known value.

The hot film type sensitive elements of boundary layer analysis transducers are realized from nickel deposits, and their connections are in gold (fig. 14c). To avoid thermal interactions between films, it is desirable to distribute over several chords of the profile under test the hot films used simultaneously in multitransducer sets.

4.3 Characteristics of thermal transducers

4.3.1 - Temperature and heat flux transducers

CHARACTERISTICS	Materials of deposited couples	
	Copper-nickel	Chromel-constantan
Temperature		
Thermoelectric sensitivty (V. K^{-1})	18.10^{-6}	45.10^{-6}
Sensitivity dispersion (%)	±10	±15
Resolving power (K. Hz $^{-1/2}$)	2.10^{-2}	7.10^{-3}
Transducer area (mm^2)	0,2 x 0,7	0,2 x 0,7
Transducer thickness (μm)	25	25
Metallic deposit thickness (μ m)	0,2	0,2
Connexion width (mm)	0,6	0,6
Operating temperature (°C)	0 to 200	0 to 200
Heat flux		
Sensitivity between 0 and 100°C (V.kW^{-1}.m^2)	$2.7.10^{-6}$	$7.5.10^{-6}$
Sensitivity dispersion (%)	±10	±15
Resolving power (W.m^{-2}.Hz$^{-1/2}$)	110	40
Transducer area (mm^2)	0,2 x 0,7	0,2 x 0,7
Transducer thickness (μm)	40	40
Metallic deposit thickness (μ m)	0,2	0,2
Connexion width (mm)	0,6	0,6
Operating temperature (°C)	0 to 200	0 to 200

To determine the transducer sensitivities at the various operating temperatures, and in particular to take into account the variation of thermal conductance of the Kapton calorimetric element, specific calibration benches have been realized.

4.3.2 - Boundary layer analysis transducers

CHARACTERISTICS	VALUES
Nature of sensitive material	nickel
Thermal sensitivity of film α : $(\frac{\Delta R}{R} K^{-1})$	$2.9.10^{-3}$
Sensitivity dispersion (%)	± 5
Admissible overheating ratio	1.6
Resistance of sensitive element at 20°C (Ω)	40
Resistance dispersion (%)	±10
Film dimensions : length (mm)	6
width (mm)	0.2
thickness (μm)	0.1
Operating temperatures (°C)	0 to 200

4.4 Examples of use

One of the first applications of thermal transducers consisted in equipping a NACA 65-012 symmetrical profile with 28 copper-nickel thin film fluxmeters (fig. 15) in order to know the chordwise distribution of the gas-aerofoil exchange coefficient h , or of the Stanton number related to it.

The comparison between the results obtained and computed ones shows a good agreement (fig. 16), especially in the zone of laminar flow.

In order to better know the boundary layer characteristics along a cascade blade profile, a set of 12 hot film transducers has been designed and fabricated by the DISA Company along ONERA specifications. Because of the small dimensions of the support (50 x 50 mm), only a part of the profile has been instrumented (fig. 17). Boundary layer characterizations were carried out for various flow velocities and various cascade deflections. Figure 18 shows the chordwise evolution of the convected power and turbulence ratio.

Later the implementation by ONERA of new technological means led to the study and development of sets of hot film multi-transducers of large dimensions. As an example, a set of 20 transducers planned to equip a 100 x 130 mm^2 airfoil is represented on figure 19.

5 - APPLICATION FIELDS OF THIN FILM TRANSDUCERS

The boundary layer analysis transducers met requirements specific to the aerodynamic field :

- characterization of the nature of the boundary layer, particularly determination of the transition zone along the profile,
- study of shock wave-boundary layer interactions occurring, in supersonic regime, in profile pile-ups : cascades, compressor wheel, etc.

On the other hand, the use of pressure temperature and heat flux thin-film transducers may be envisaged whenever a measurement at the wall is necessary:

- very thin wall,
- maintenance of the mechanical characteristics of the parts to be instrumented,
- respect of aerodynamic characteristics of a profile.

Moreover, the ease of adaptation of these transducers to metrologic needs, as regards the dimensions of sensitive elements, their number and their arrangement, constitutes an important advantage for their practical use.

Pressure thin-film transducers have been developed at ONERA to respond to aerodynamical needs and more particularly to perform measurements allowing to improve the knowledge upon the internal sound source of turbomachine.

The analysis of the signals delivered, associated by various processes with the signals of transducers placed on the fixed parts of the machine, makes it possible to locate the acoustic sources, to better know their origine and to evaluate the homogeneity of the flow upstream of the instrumented zone.

But the range of application of these transducers is broader. The fields of utilization of the two types of pressure transducers, as well as their metrological possibilities, are summarized in Table I.

		Solid dielectric		Gaseous dielectric	
Medium of utilization		Liquid	Gas	Liquid	Gas
Metrologic possibilities	Knowledge of fluctuation spectra	▨	▨	▨	▨
	Measurement of instantaneous pressure	▨		▨	▨
Operation at high static pressure		▨	▨		
Fields of application	Acoustics	▨	▨	▨	▨
	Energetics	▨	▨	▨	▨
	Aeroelastics			▨	▨
	Aerodynamics	▨	▨	▨	▨

▨ Possible ☐ Not possible

Table 1 : Possibilities of use and fields of application of pressure thin film transducers

Temperature and heat flux transducers are perfectly adapted to turbomachine studies, for measuring temperatures on the surface of blade profiles and evaluating gas-profile exchange coefficients. They should in particular allow the study of the blade cooling technique by injection of gaseous films, for which the equipment with conventional thermocouples is very tricky, if not altogether impossible. The metrologic sharpness and sensitivity of these thermal transducers enable one to envisage the generalization of their use in aerodynamics, hydrodynamics and energetics. In the last field, there exists a very broad domain of application, in relation with energy saving studies.

6 - CONCLUSION

The studies carried out at ONERA led to the development of thin film transducers for measuring pressure, temperature and heat flux and for analyzing boundary layers. These transducers, whose technology is acquired, meet the metrologic requirements expressed in many fields.

Present studies are pursued with a view to design thermal thin film transducers operating at high temperature (1400 K). The availability of such transducers is mandatory for characterizing the thermal operating conditions of the turbine stages and, in particular, for evaluating the cooling conditions of the blades.

In parallel, the characterization of the various types of thin film transducers already developed is extended towards low temperatures (120 K), in order to meet the metrological requirements related to the development of cryogenic wind tunnels.

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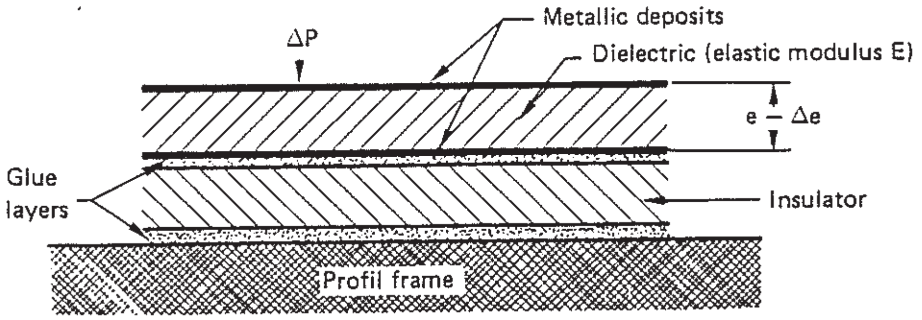


Fig. 1.: Simplified representation of a thin film pressure transducer, seen as a cross-section.

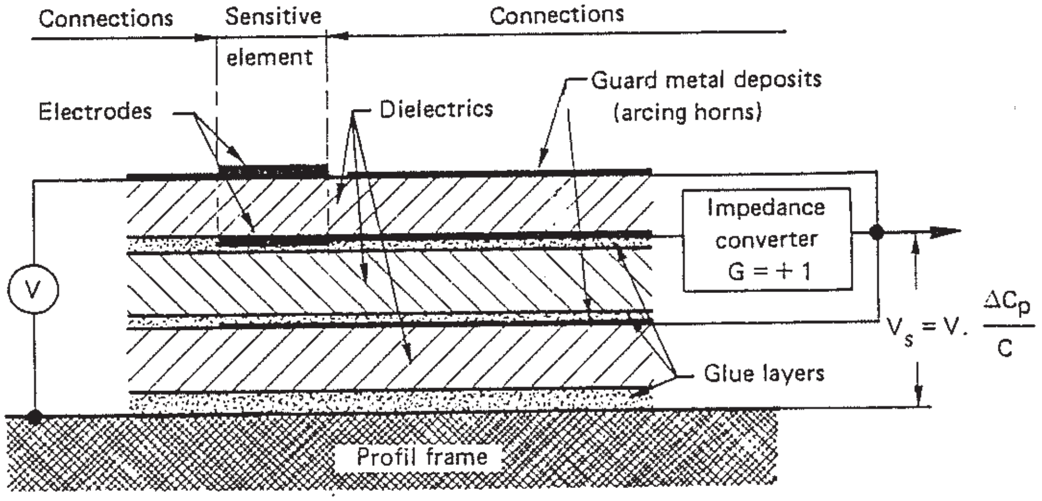


Fig. 2 : Schematic representation, seen as a cross-section, of a sensitive element equipped with its connexions, its arcing horns, and associated with an impedance converter.

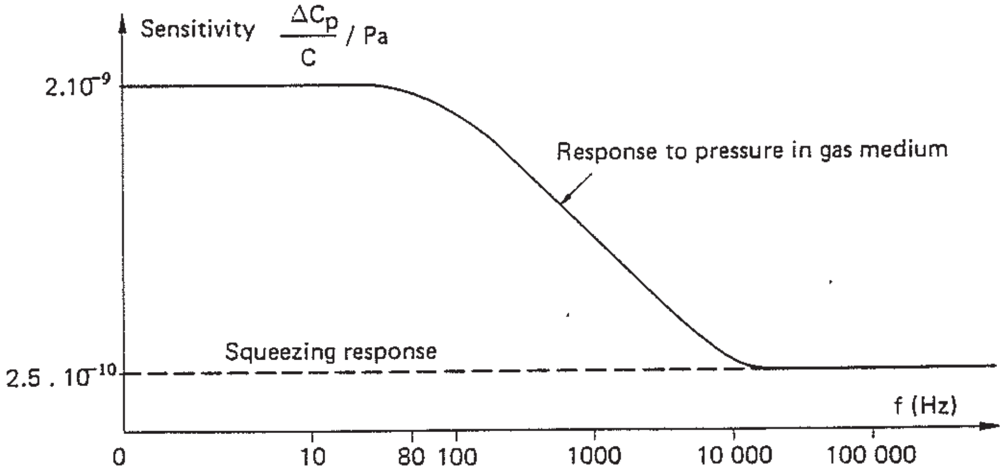


Fig. 3 : Evolution of the sensitivity as a function of frequency of a transducer with Kapton dielectric in gas medium.

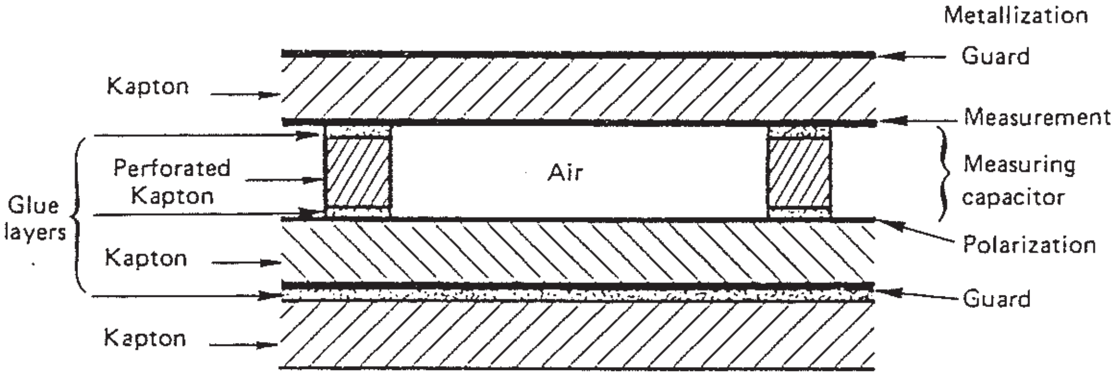


Fig. 4 : Principle of the thin-film pressure transducer with gaseous dielectric.

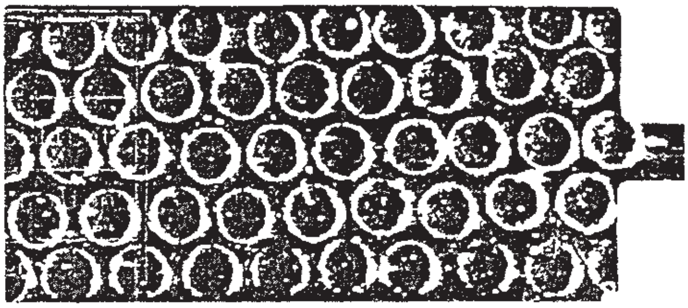


Fig. 5 : Examples of fabrication of cell transducer with insulating walls (700 - μm - dia. holes).

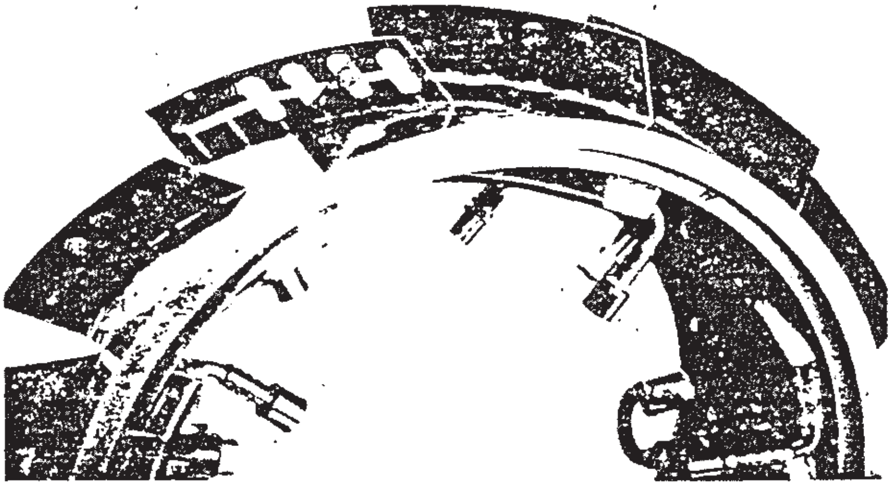
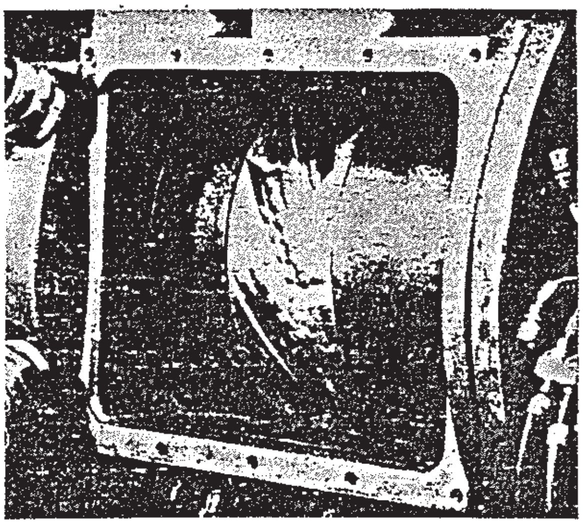


Fig. 6 : Blade fitted with transducers (annular cascade).

Fig. 7 : View of the supersonic, fixed, annular cascade.



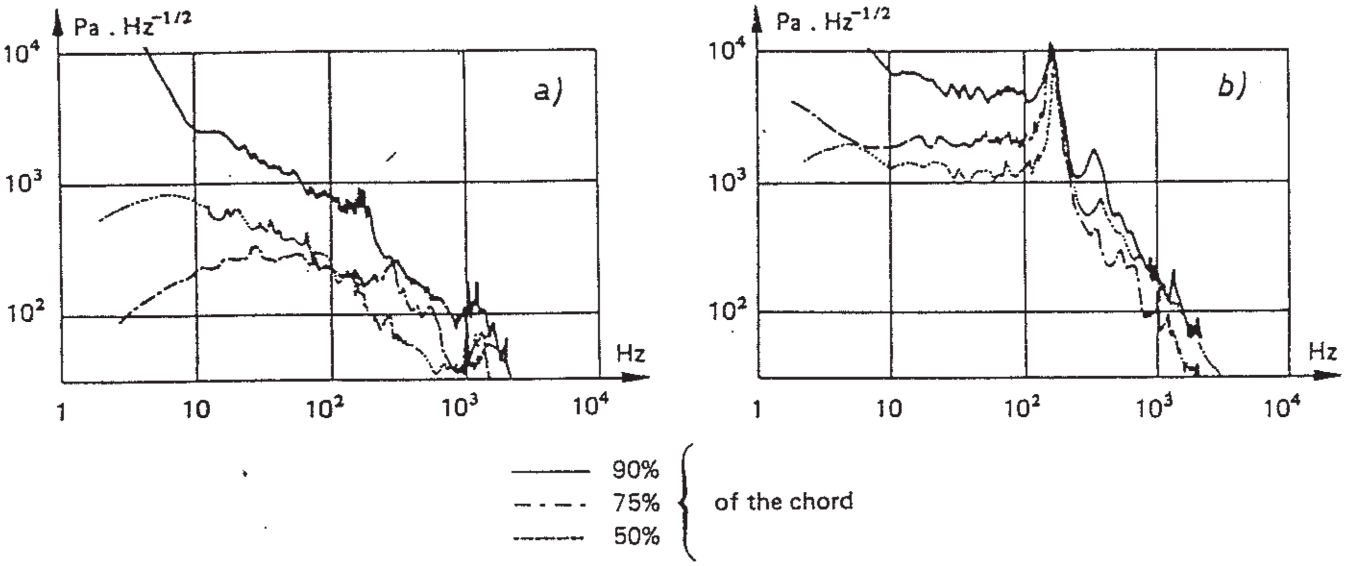


Fig. 8 : Influence of the back-pressure in the downstream flow on the response of thin-film pressure transducers placed on the suction side of a blade of fixed, supersonic, annular cascade.

a) absence of any marked privileged frequency in stable regime.
b) existence of pressure fluctuations when the back-pressure is sufficient for the complete unstarting of the cascade to appear.

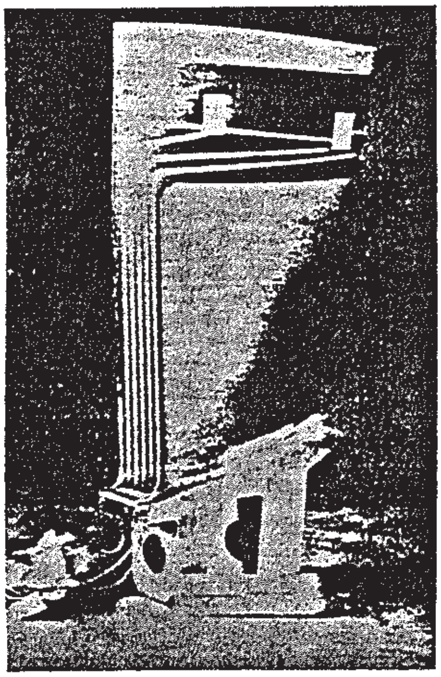


Fig. 9 : Blade equipped with pressure transducers thin-film

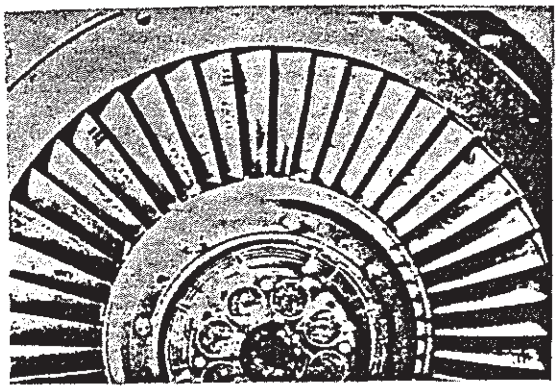


Fig. 10 : Mobile row with complete equipment.

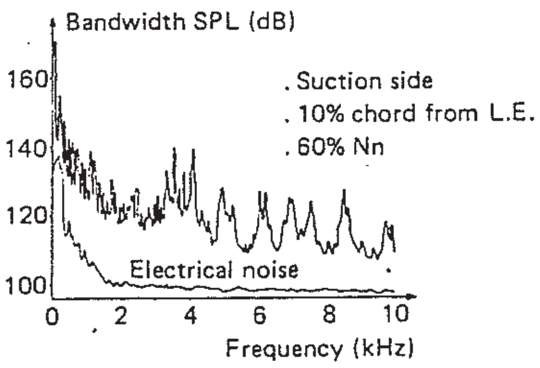


Fig. 11 : Spectrum deduced from unsteady pressure measurements.

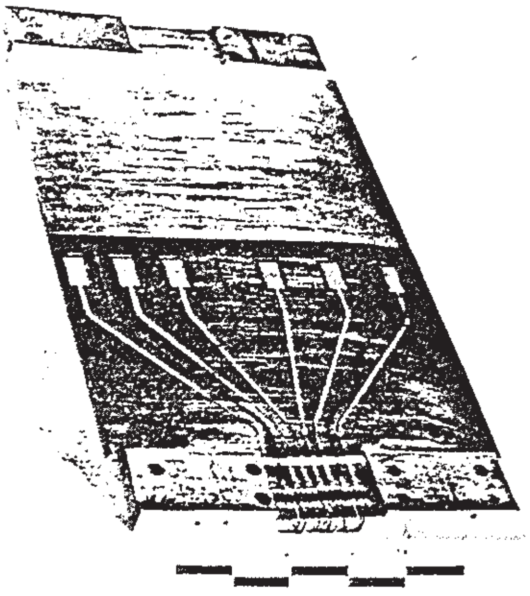


Fig. 12 : Blade fitted with dielectric gaseous transducers for aeroelastic measurements.

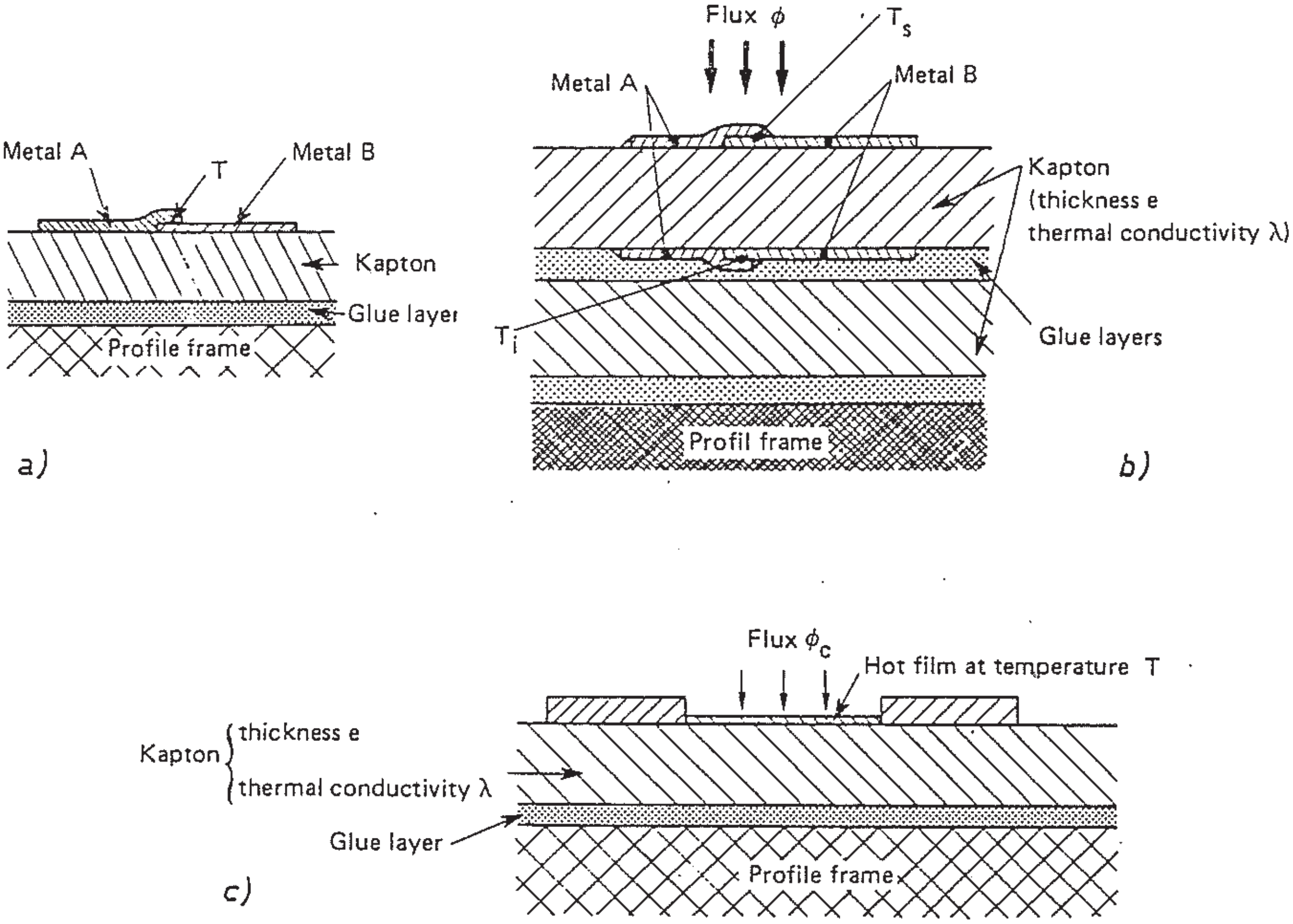


Fig. 13 : Principles of thin-film thermal transducers
a) thermometer
b) fluxmeter
c) boundary layer detector

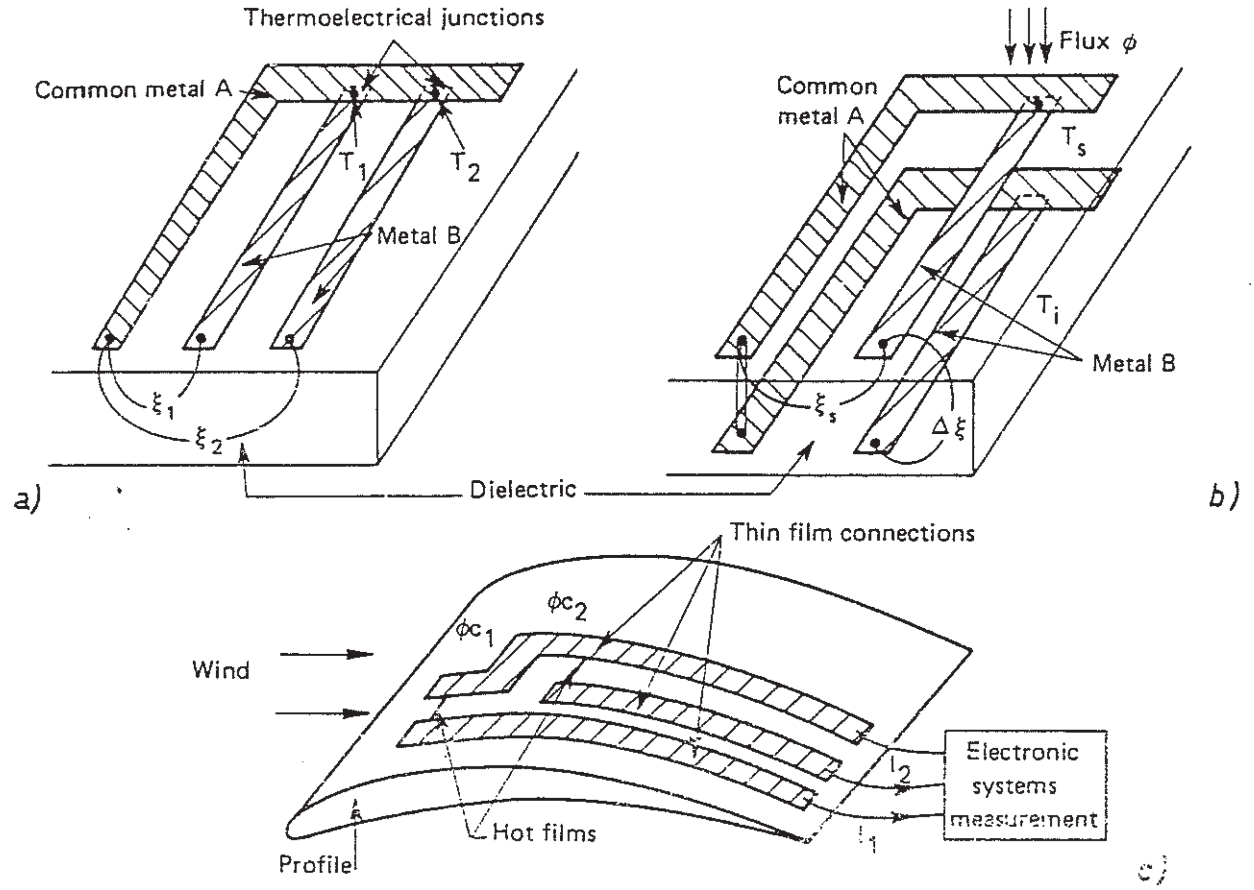


Fig. 14 : Schematic representation of thin-film thermal transducers-
a) thermometer
b) fluxmeter
c) boundary layer detector

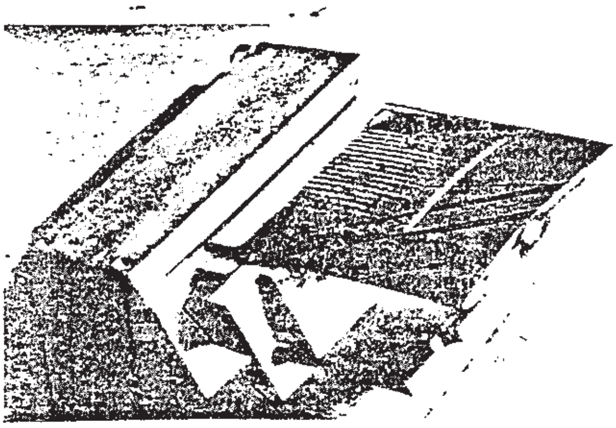


Fig. 15 : Mock-up profile NACA 65_1-012 fitted with fluxmeters.

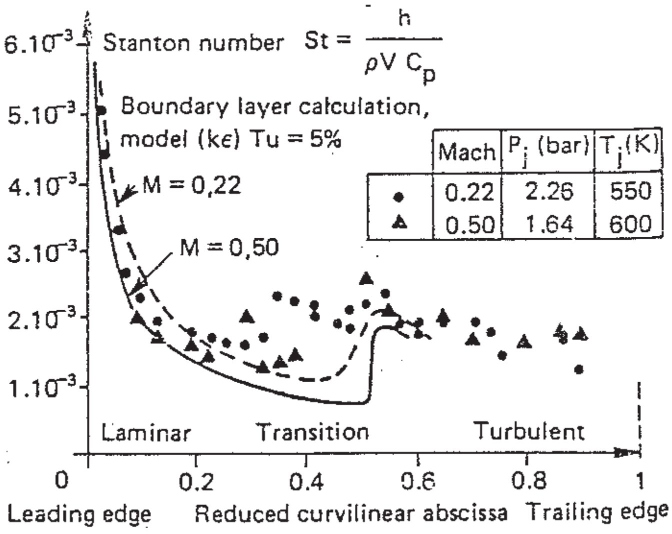


Fig. 16 : Measurement of the heat transfer coefficient on a symmetrical profile.

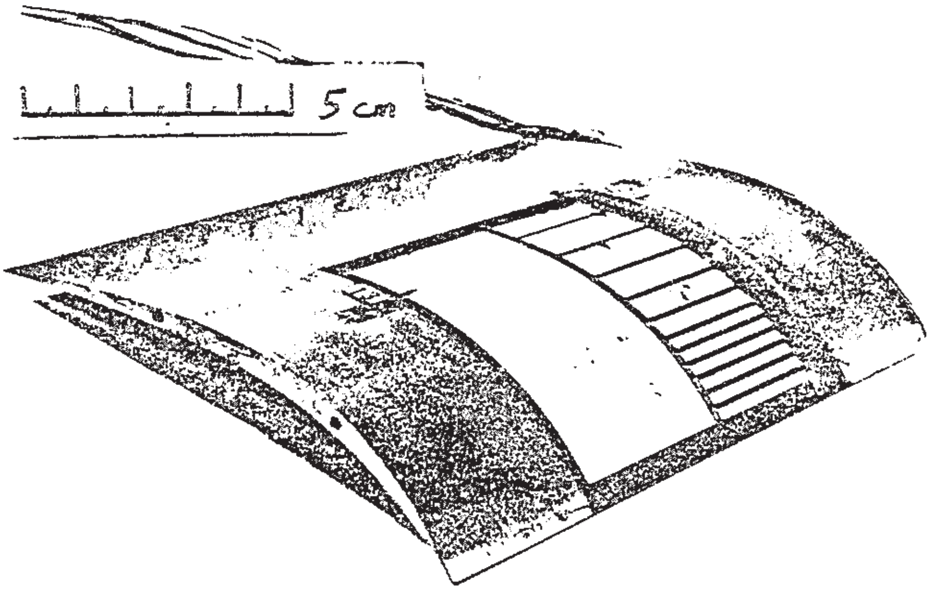


Fig. 17 : Blade of cascade fitted with DISA hot films.

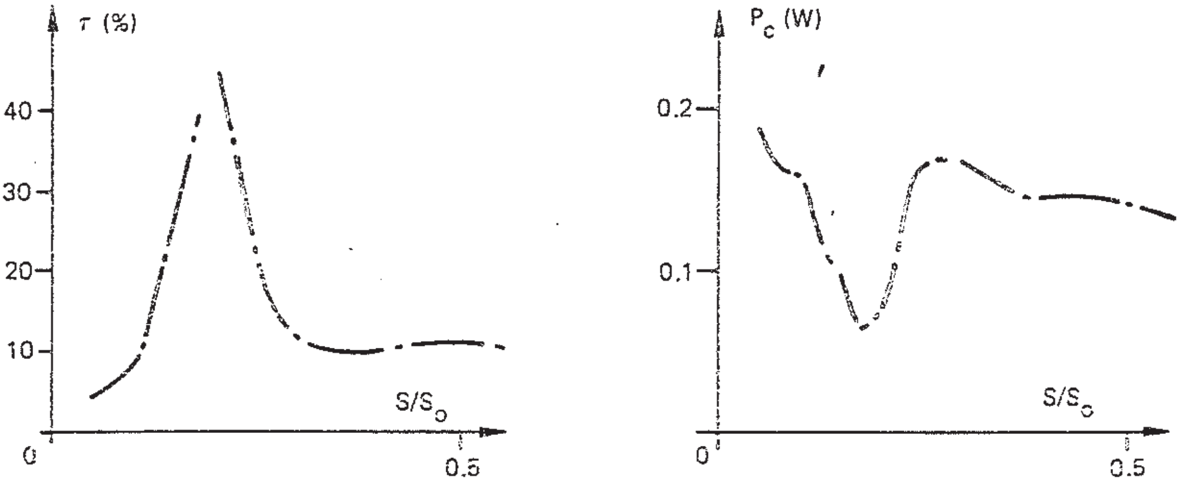


Fig. 18 : Evolution, along a chord of a blade, of the convected power P_c and the turbulence rate τ .

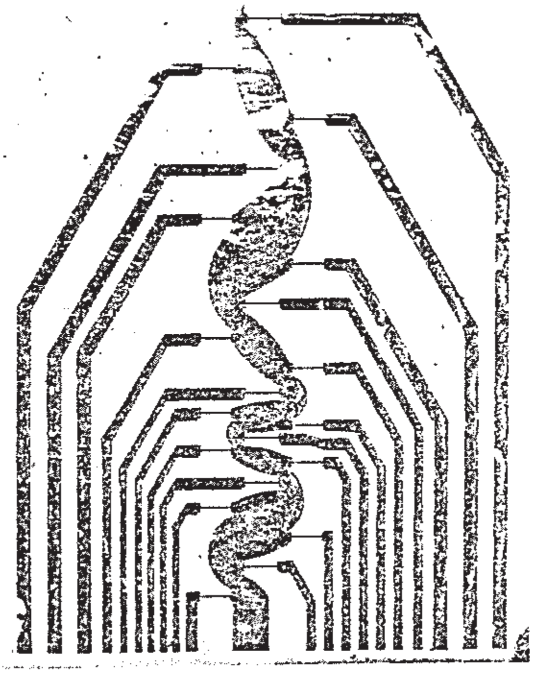


Fig. 19 : Achievement of 20 hot films substrate (100 x 130 mm^2).