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INVESTIGATIONS ON A PRESSURE SENSITIVE COATING MEASURING SYSTEM AT A STRAIGHT TURBINE CASCADE

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Investigations on a Pressure Sensitive Coating Measuring System at a Straight Turbine Cascade

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Abstract

A new optical measuring system, that is based on so called Pressure Sensitive Coating, was installed at the atmospheric wind tunnel for straight cascades of the Laboratorium für Strömungsmaschinen. It allows the quantitative monitoring of two-dimensional pressure distributions on blade and endwall surfaces. This paper reviews the physical basics and describes the experimental setup and the measuring procedure. The first results obtained from a turbine cascade are presented.

1 Introduction

Up to now static pressure information on the surface of an aerodynamic body are determined with pressure taps, which are drilled into the surface. A large number of pressure taps is required to map an entire surface. Since the orifices are usually separated by a significant distance, a continuous pressure map is not achieved.

Pressure Sensitive Coating (PSC) - or sometimes called Pressure Sensitive Paint - is an optical measuring technique for non-intrusive acquisition of static pressure maps with high spatial resolution. This technique uses a surface coating which contains organic probe molecules that luminesce when excited by an appropriate light source. Oxygen molecules interfere with this process, the drop of luminescence being a function of the partial pressure of oxygen. As a result the local static pressure on the coated surface can be evaluated from the recorded luminescence intensity.

PSC is relatively new for aerodynamic test purposes and it has been used mainly for airfoil and aircraft model investigations [2,5]. As measuring at flow passages with curved surfaces causes additional difficulties the application in cascades needs further investigation. So a PSC measuring system has been recently installed at the Laboratorium für Strömungsmaschinen for comprehensive testing and system optimization to achieve precise and reproducible measurements in an atmospheric cascade wind tunnel.

2 Fundamentals

The Pressure Sensitive Coating measuring system is based on the collisional deactivation of photo excited luminescent probe molecules embedded in the coating. This section briefly reviews luminescence, which includes fluorescence and phosphorescence, and quenching as it pertains to PSC. For this Fig. 1 schematically shows the energy transitions for a photoluminescent probe molecule.

Under normal conditions the molecules are in the ground state S_0. This ground state is a singlet state, i. e. all of the electrons in the molecule have their spins paired. In the case of one set of electron spins being unpaired the belonging state is called triplet state. From the ground state the probe molecules are promoted to one of many vibrational levels in an excited electronic state by absorbing a photon of appropriate energy. With only a few exclusions the molecules quickly fall in the lowest level of the first excited singlet state S_1 by partitioning the excess energy within the molecules. This state has the longest lifetime of any other excited singlet states. From here a spontaneous radiative transition can occur when the molecules return to the ground state. This radiative singlet-singlet transition is called fluorescence and it has an average lifetime of approximately 10^{-9} to 10^{-7} s.

Additionally a radiationless intersystem crossing from the first excited singlet state to the lowest excited triplet state T_1 can occur. This state has a relatively long lifetime because the return from here to the ground state S_0 involves a spin reversal. The radiative triplet-singlet transition with an emission rate of about 10^{-4} to 100 s is known as phosphorescence. It is evident that the luminescence emission energy is less than or equal to the light absorption energy, i. e. the emission light is red-shifted compared to the excitation light.

An alternate transition to the ground state is provided by collisional deactivation. This process is called "dynamic quenching". In this case the excited probe molecules transfer their excess energy to quencher molecules without light emission during a collision with this molecules. Oxygen is an excellent quencher compared with the other gases in atmospheric air. As the compound of air can be assumed as constant a constant quota of quencher molecules in the atmospheric test section flow can be presupposed, too. With increasing probability of collisional deactivation the luminescence life time and intensity decrease. The luminescence of a molecule when exposed to oxygen can be modelled simplified by a variation of the Stern-Volmer relation

$$\frac{p}{p_0} = A + B\frac{I_0}{I} \qquad (1)$$

where A and B are calibration constants, and I_0 and p_0 are luminescence intensity and pressure under reference conditions [3]. This relation presupposes that the dependence of luminescence on the surface temperature is negligible. Although all pressure sensitive coatings exhibit an inherent sensitivity to temperature the development and selection of the appropriate coating allows neglecting in certain temperature ranges [3].

According to the Stern-Volmer relation (1) the luminescence decreases with increasing pressure. Due to this non-linear relationship the sensitivity and pressure resolution are also decreased when the absolute pressure is increased. This yields to difficulties at measurements near to atmospheric conditions. In this case high and equally distributed excitation light intensities and data acquisition with high intensity resolution are necessary.

3 Experimental

The atmospheric wind tunnel of the Laboratorium für Strömungsmaschinen, shown in Fig. 2, is supplied with ambient air. Before entering the compressor the air is led through a dust filter. The total temperature of the compressed air can be hold constant by water cooling. This design of air supply allows a steady-state testing of subsonic and supersonic flow in the wind tunnel without time limits.

In the test section the blades are mounted with fixed geometrical parameters in a changeable frame establishing the sidewalls of the flow channel and containing apertures, e. g. for windows or measuring modules. For this investigations the VKI-1 turbine cascade is used that was proposed for comparison of experimental and computational results by Sieverding [9] in 1973 (see Fig. 3).

The setup of the Pressure Sensitive Coating measuring system itself consists of the three main components Pressure Sensitive Coating, Illumination system and Data acquisition and processing subsystem (see Fig. 4).

1.) Pressure Sensitive Coating:

The PSC with a film thickness of less than 20 µm is applied to the aluminium surface of the blade by means of an electrochemical process. The coating is homogeneous, smooth and hard. Due to the strong bonding to the surface high speed testing is possible. The response time of the coating is below 100 µs. Changes of the coating response due to surface temperature fluctuation are negligible between 15°C and 25°C [3]. The most efficient excitation of the probe molecules is between 430 nm to 480 nm. The red-shifted luminescence shows its maximum response around 600 nm.

Since direct calibration of the coated surfaces in the test section is not possible due to the impossibility of evacuating the wind tunnel, an external calibration chamber is used. With this calibration chamber the parameters A and B of the Stern-Volmer relation can be determined. The calibrations being executed till now verify that the surface temperature has no influence on the calibration constants A and B.

b) Illumination system:

The illumination source is a high power Xenon flashlamp with 5 µs pulse duration and a maximum flash rate of 200 Hz. A fibre optic cable transmits the light from the lamp to a projection lens system. This projection lens system contains the „blue“ excitation filter with highest transmission rate at the excitation range of the coating.

c) Data acquisition and processing subsystem:

For imaging the luminescence signals a slow scan ICCD camera with a resolution of nearly 384 x 286 pixels and 12 bit per pixel is used. The camera is equipped with an imaging lens and with a long-pass „red“ filter to block direct and reflected illumination light. The Personal Computer, forming part of the detection subsystem, controls the image acquisition and also the illumination system. The preparatory evaluation of the acquired CCD images is possible with this computer and the installed software, too.

Fig. 4 shows the setup of the PSC system for measuring endwall pressure maps. One endwall aperture is closed with a coated insert, the second one with a window. The coated section can be illuminated through this window and the luminescence light can be recorded. This configuration allows to take sidewall pressure maps in the rear area of one or more flow channels and behind the cascade.

Fig. 5 shows a sketch of the system configuration for measuring the pressure distribution on the suction side of a turbine blade. The setup and the geometrical parameters of the cascade allow to measure only on the rear half of the suction side.

4 Measurement Procedure

The measurement procedure arises from the Stern-Volmer correlation used above.

First a „wind-on“ image $I(x_i,y_j)$ is taken, i. e. during wind tunnel operation. Directly after the test run a „wind-off“ image $I_0(x_i,y_j)$ is taken at ambient conditions (p_0, T_0), i. e. across the whole field of view the pressure is on the same level and exactly known. Since the time interval between both recordings is short the room and surface temperatures stay constant. An alignment of the images is not necessary in most cases because the cascade displacement, due to the high pressure forces at wind tunnel operation, could be reduced significantly by an attached stabilizing construction. The pixelwise division yields the intensity ratio

$$F(x_i, y_j) = \frac{I_0(x_i, y_j)}{I(x_i, y_j)} . \qquad (2)$$

for each pixel. After calculating the intensity ratio the problems caused by non-uniform coating or illumination are eliminated. Using the calibration parameters A and B the pressure ratio

$$\frac{p}{p_0}(x_i, y_j) = A + B \cdot F(x_i, y_j) \qquad (3)$$

is determined. The absolute static pressure $p(x_i,y_j)$ can be calculated with the room pressure p_0 that was simultaneously recorded to „wind-off“ imaging. If the coated surface and the image plane in the camera are parallel the pressure map $p(x,y)$ is determined with the help of the known image scale. In the case of curved blade surfaces the image coordinates have to be converted to profile coordinates to finish the evaluation.

5 First Results

After installation of the system components the calibration constants of the existing coated surfaces were determined and measurements conducted at two different mach numbers. Some representative results are being presented subsequently.

For the isentropic outlet Mach numbers Ma_{2is} = 0,90 and 1,00 Fig. 6 and Fig. 7 show the pressure distribution at the sidewall of the VKI-1 turbine cascade, referring to the specific ambient pressure p_0. Pressure distribution and blade positions are presented in the coordinates x and y of the cascade which are related to the chord length l (see Fig. 3). The areas along the blade surfaces marked in white are representing areas which cannot be evaluated due to limited optical access by light source and camera.

Within the blade passages the isobars show a distinctive pressure drop caused by acceleration of the flow outside of the endwall boundary layer. Furthermore distinctive underpressure sections can be recognized in the rear part of the suction side indicating there high excess velocity. Remarkable structures are located behind the trailing edges. Circular areas are being formed there by the isobars at pressure above ambient.

At $Ma_{2is} = 1{,}00$ (Fig. 7) multiple isobars can be recognized originating from the trailing edge and leading along a straight line at an angle of about -25° to the x/l axis. These are the effect of the shock wave in the free flow which is being proved by a comparison with relating density measurements [4,8].

The irregularities in the course of the isobars at $x/l = 0.5$ and $y/l = -0.2$ or 0.5 respectively are caused by two pressure taps. Due to the concentration of the isobars an evaluation of the required preciseness is not feasible.

Whilst within the blade passages a good periodicity can be found, there are small differences behind the outlet plane. These differences result from the divergence of the flow behind the cascade and from slightly differing blade passages geometries due to manufacturing. This was proved by measurements with probes which were conducted at the lab.

An additional quantitative evaluation was performed by a comparison with conventional results. For doing this, the PSC plate was replaced with a plate being equipped with pressure taps. Eighteen of these pressure taps were located in the evaluation area of the PSC measurement. The differences in pressure which were found amount to approximately 2 %, related to the dynamic part of the total pressure, even less at low pressure.

The PSC results on the suction side of the turbine blade can appropriately be described by the isentropic contour Mach number

$$Ma_{is} = \sqrt{\frac{2}{\kappa-1}\left[\left(\frac{p_{tK}}{p}\right)^{\frac{\kappa-1}{\kappa}} - 1\right]} \,. \qquad (p_{tK}\text{: total pressure in upstream flow}) \quad (4)$$

Fig. 8 shows the contour Mach number for $Ma_{2is} = 0.90$ versus the x_b-coordinate of the bi-tangent referring to the chord length l. The contour Mach number was calculated from the pressure distribution at the suction side. This diagram additionally contains the results of a conventional comparison measurement. For this the coated blade was replaced with a blade with pressure taps. The area of evaluation of the PSC-measurement was adapted to the positions of the profile pressure taps.

It can be recognized that the results of the PSC measurement partly show higher values than those of the conventional measurements. One reason for that lies in the alternate use of different blades because in this field already the slightest variations of position and shape of the blade surface are changing the highly compressive flow. Furthermore the curve of the Mach number measured by PSC shows a small area of excess speed close to the trailing edge, resulting from the acceleration of the flow at the strongly bended surface. This area cannot be resolved by the conventional measurement, since at this place it was not possible to reduce the distance between the pressure taps for reason of manufacturing.

6 Summary and Outlook

The presented optical measuring system working with Pressure Sensitive Coating was used for taking measurements in an atmospheric cascade wind tunnel for the first time. This system allows to measure two-dimensional pressure fields within short time at high resolution. Already at the present development status of the system measurements at the endwall and the suction side of the profile could be conducted. A quantitative comparison with conventional measuring results in general showed a good agreement.

Further work is being planned with respect to optimizing the system. In detail the illumination of the coated surfaces has to be improved and calibration and measuring procedures have to be accelerated and optimized. Moreover more complex models for describing the luminescence intensities will be under investigation and new coatings will be tested. Other measuring techniques and also a 3D-Navier-Stokes computer program will be available to comment on the measuring results received by PSC.

References

[1] Bergmann-Schäfer: Lehrbuch der Experimentalphysik, Band IV: Aufbau der Materie, Walter de Gruyter & Co., Berlin, 1980

[2] Engler, R. H., Hartmann, K., Troyanovski, I., Vollan, A.: Description and assessment of a new optical pressure measurement system (OPMS) demonstrated in the high speed wind tunnel of DLR in Göttingen, DLR-Forschungsbericht 92-24, Göttingen, 1992

[3] LaVision: Surface Pressure Monitor, SPM-Manual, LaVision 2D-Messtechnik, Göttingen, 1996

[4] Miebach, F.: Beitrag zur dreidimensionalen Dichtemessung am ebenen Gitterwindkanal mit Rayleigh-Streulicht, Diplomarbeit, UniBw Hamburg, 1996

[5] Morris, M. J., Donovan, J. F., Kegelman, J. T., Schwab, S. D., Levy, R. L.: Aerodynamic Application of Pressure-Sensitive Paint, AIAA 92-0264, 30th Aerospace Sciences Meeting and Exhibit, Reno, 1992

[6] Oertel H. sen., Oertel H. jun.: Optische Strömungsmeßtechnik, G. Braun, Karlsruhe, 1989

[7] Riehl, N. (Hrsg.): Einführung in die Lumineszenz, K. Thiemig KG, München, 1971

[8] Sieber, O.: Quantitative Dichtefeldmessung mit Rayleigh-Streulicht am Laufschaufelprofil VKI-1 und Vergleich mit einer numerischen Simulation, VDI-Fortschrittsberichte, Reihe 7, Nr. 301, VDI Verlag, Düsseldorf 1996

[9] Sieverding C. H.: The Turbine Blade Definition, VKI Lecture Series 59, Transonic Flows in Turbomachinery, 1973

[10] Willard, H. H., Merritt, L. L. jr., Dean, J. A., Instrumental Methods of Analysis, D. Van Nostrand Company, 1974

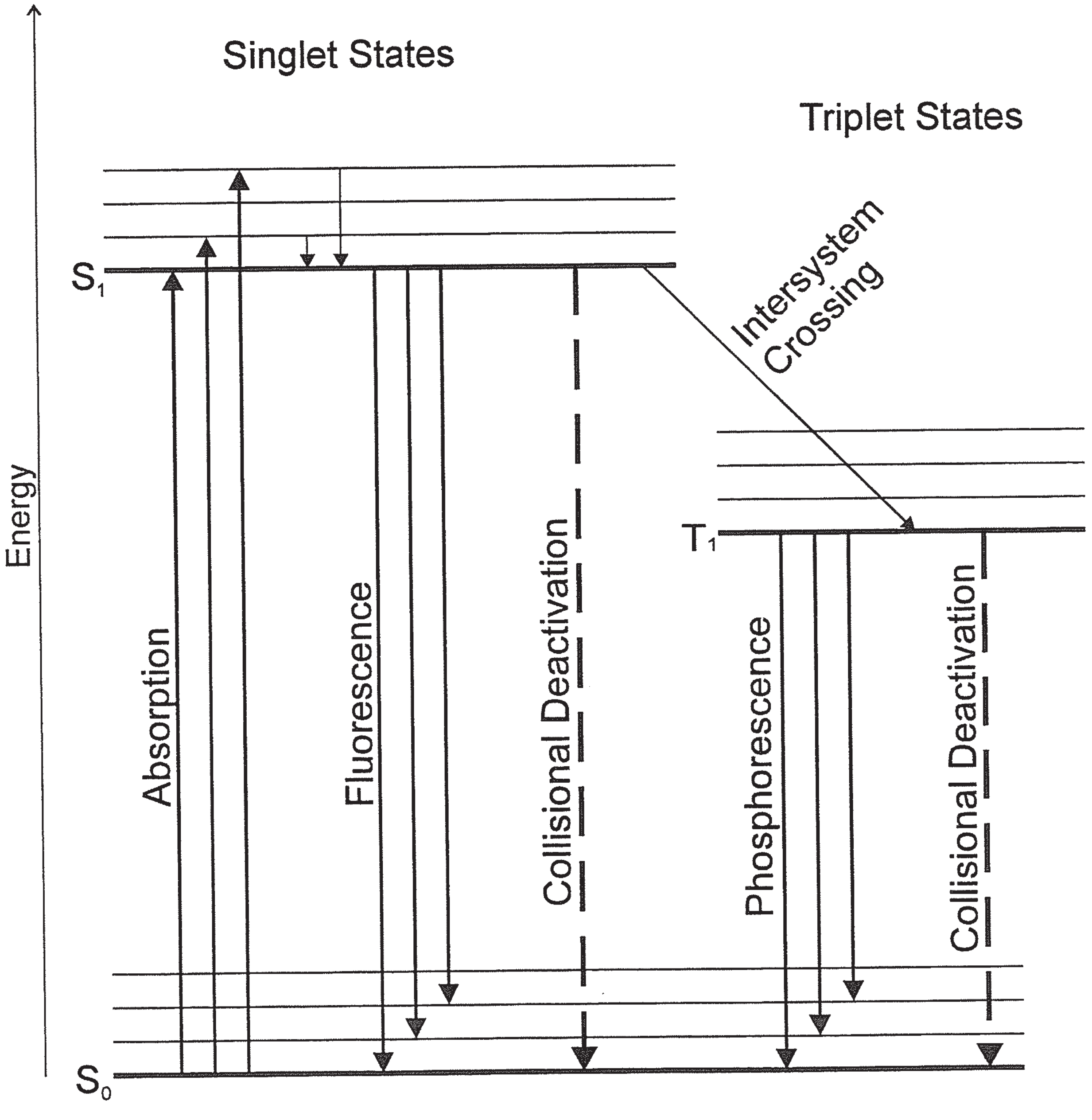


Fig. 1: Energy transitions for a photoluminescent molecule

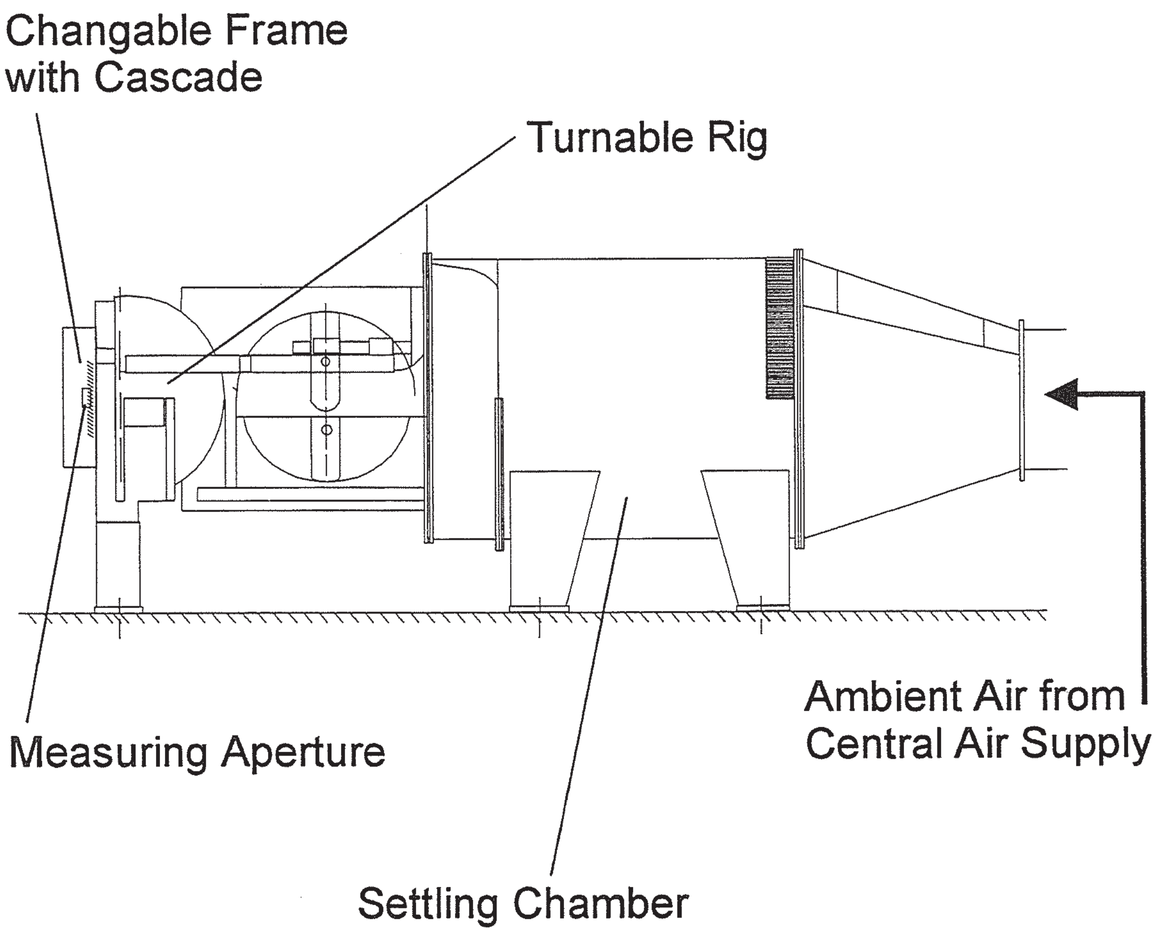
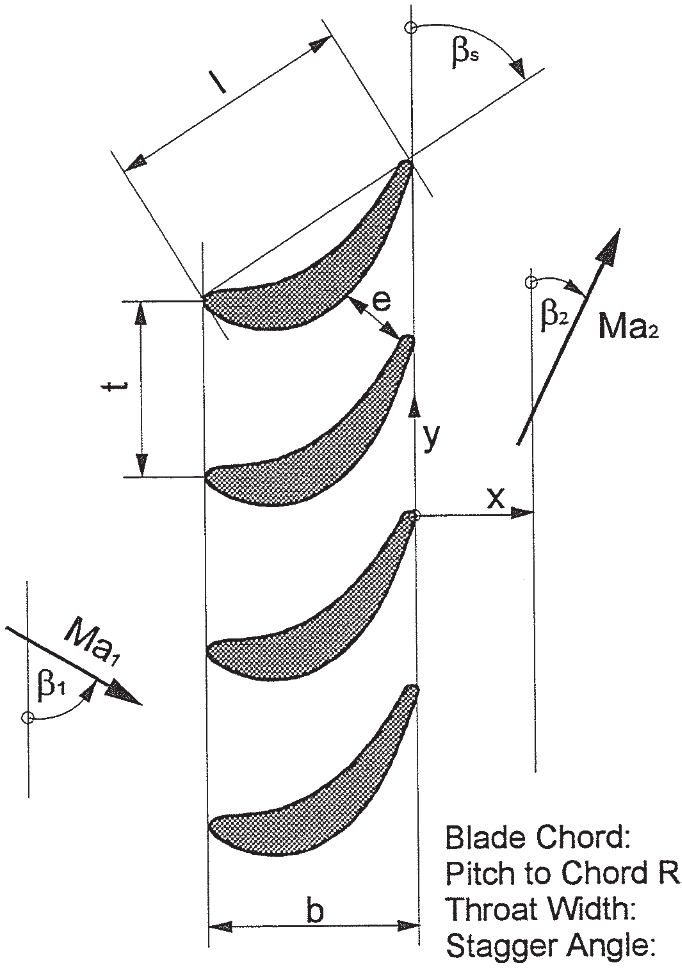


Fig. 2: Wind tunnel for straight cascades



Blade Chord: l = 65.2 mm
Pitch to Chord Ratio: t/l = 0.71
Throat Width: e = 17.5 mm
Stagger Angle: β_s = 56.7°

Fig. 3: VKI-1 cascade geometry

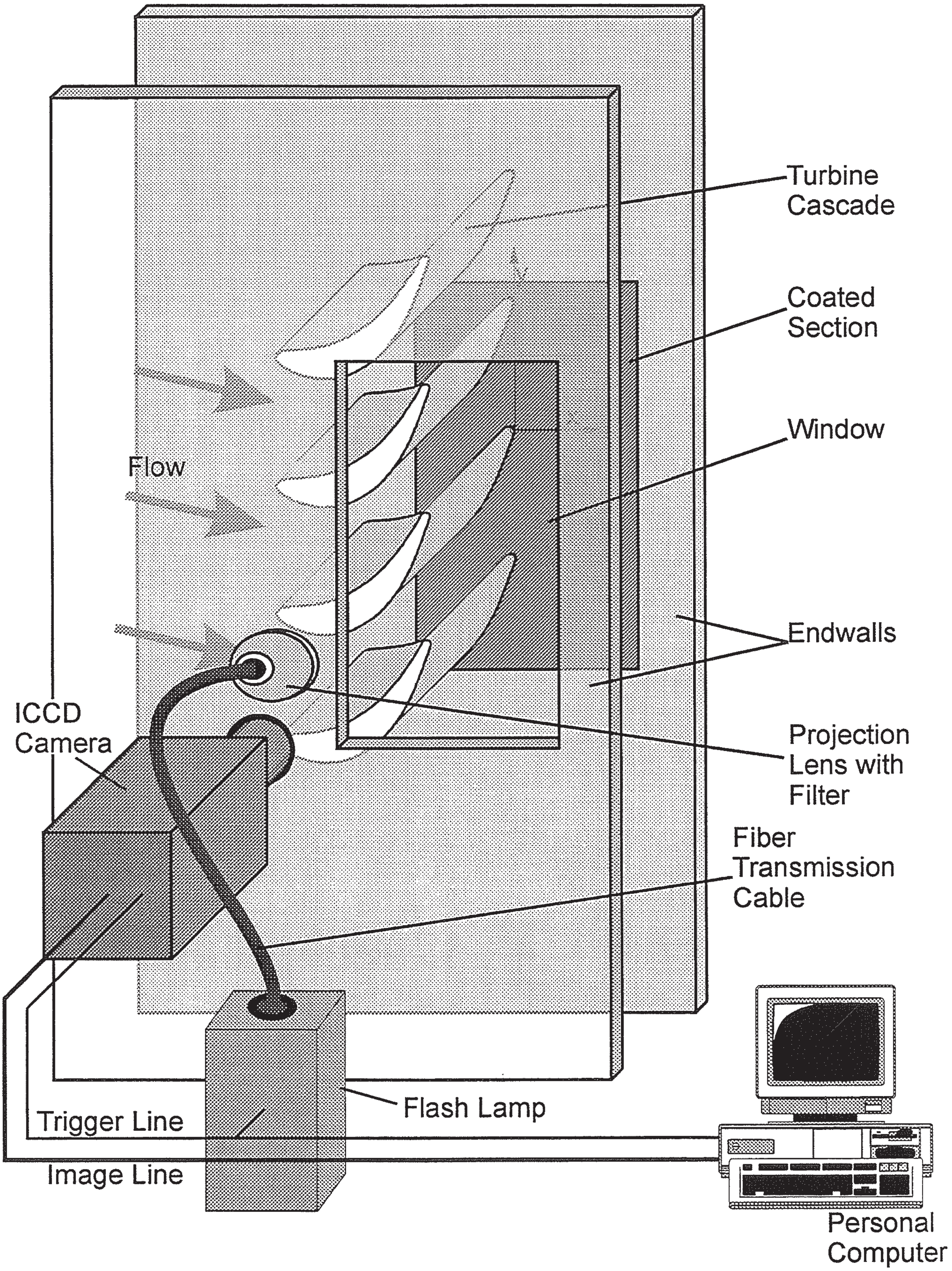


Fig. 4: Setup for endwall pressure measurements

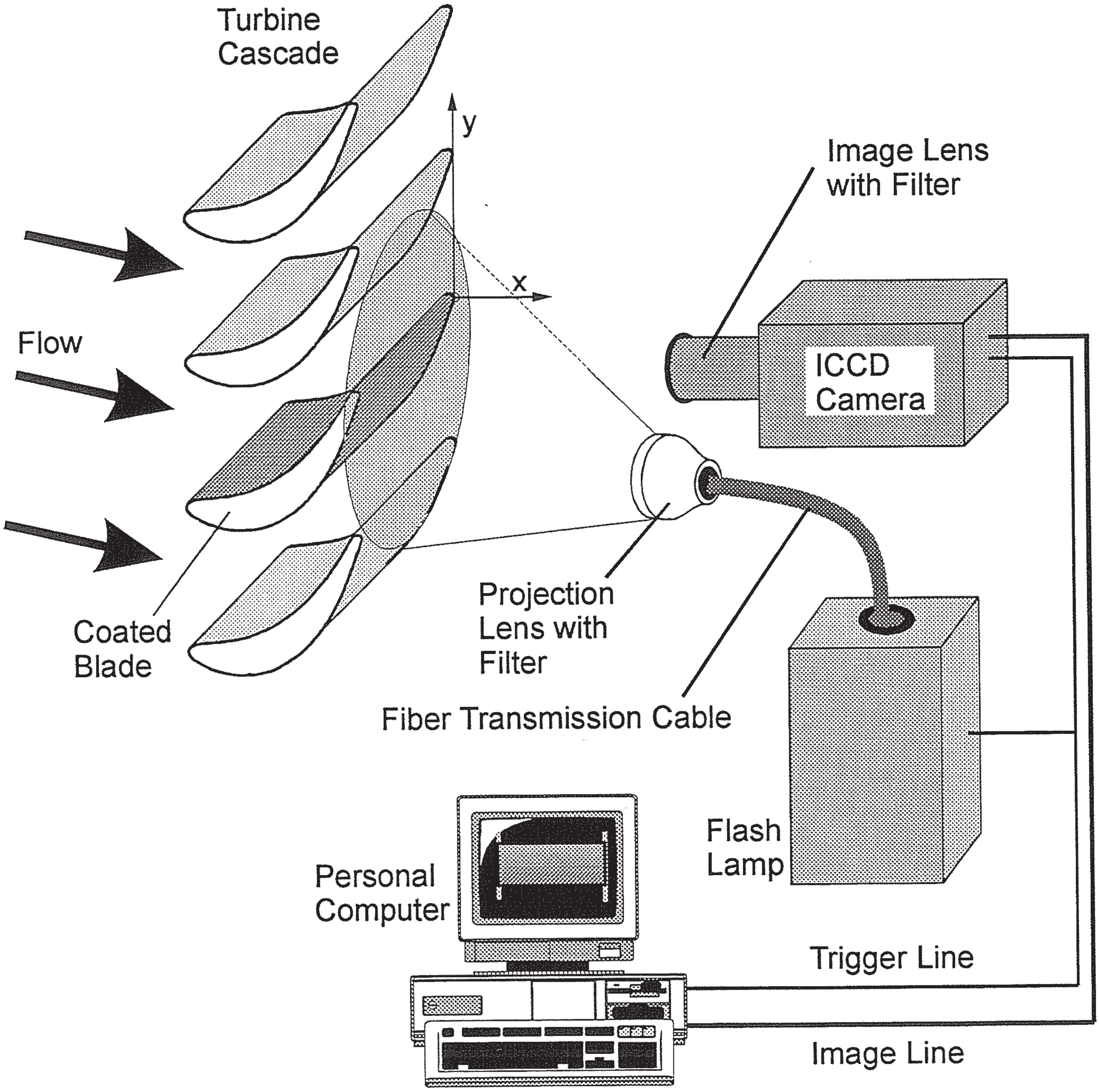


Fig. 5: Setup for pressure measurements on a turbine blade suction side

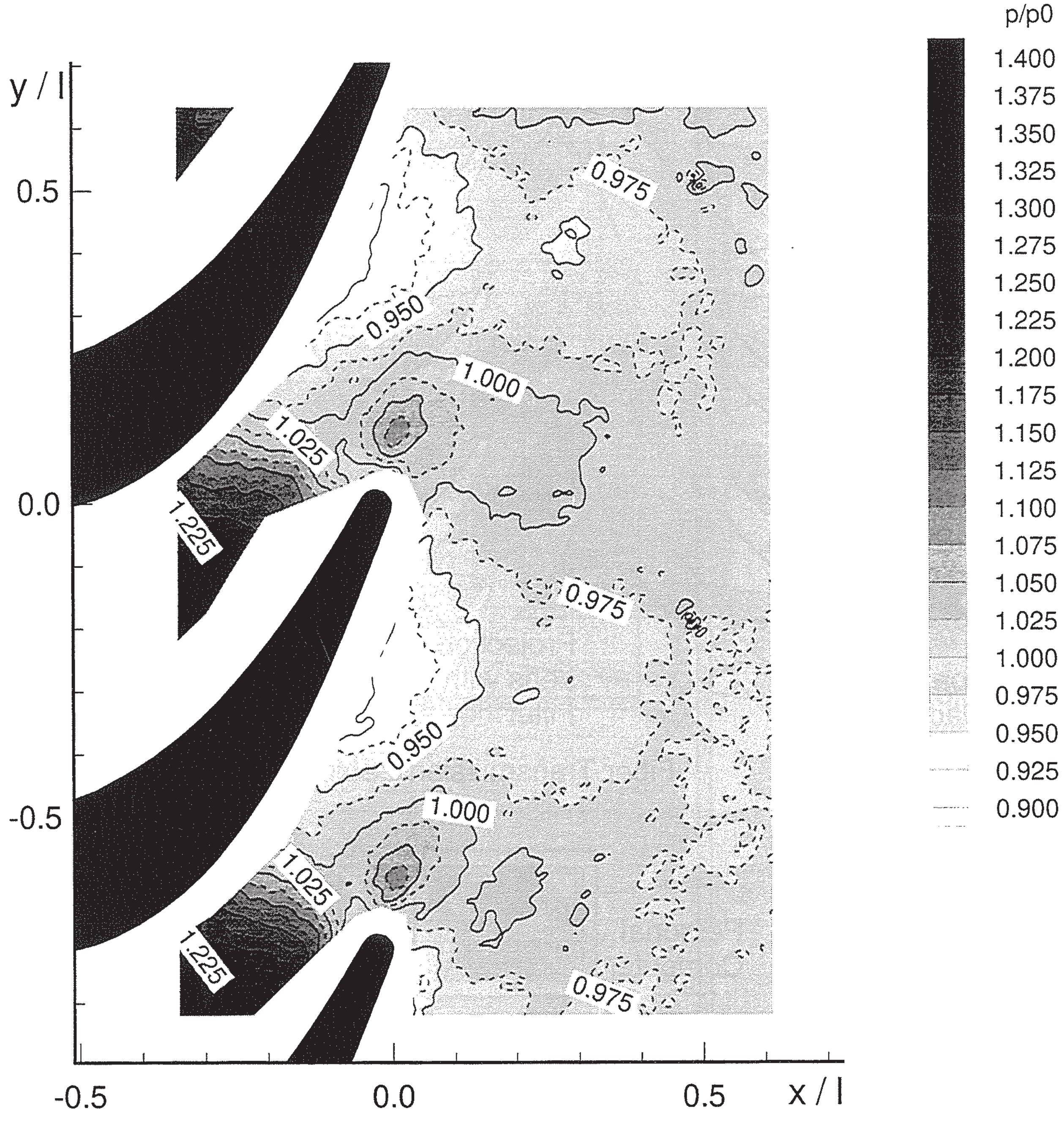


Fig. 6: Pressure distribution on endwall of VKI-1 cascade, $Ma_{2is} = 0,90$

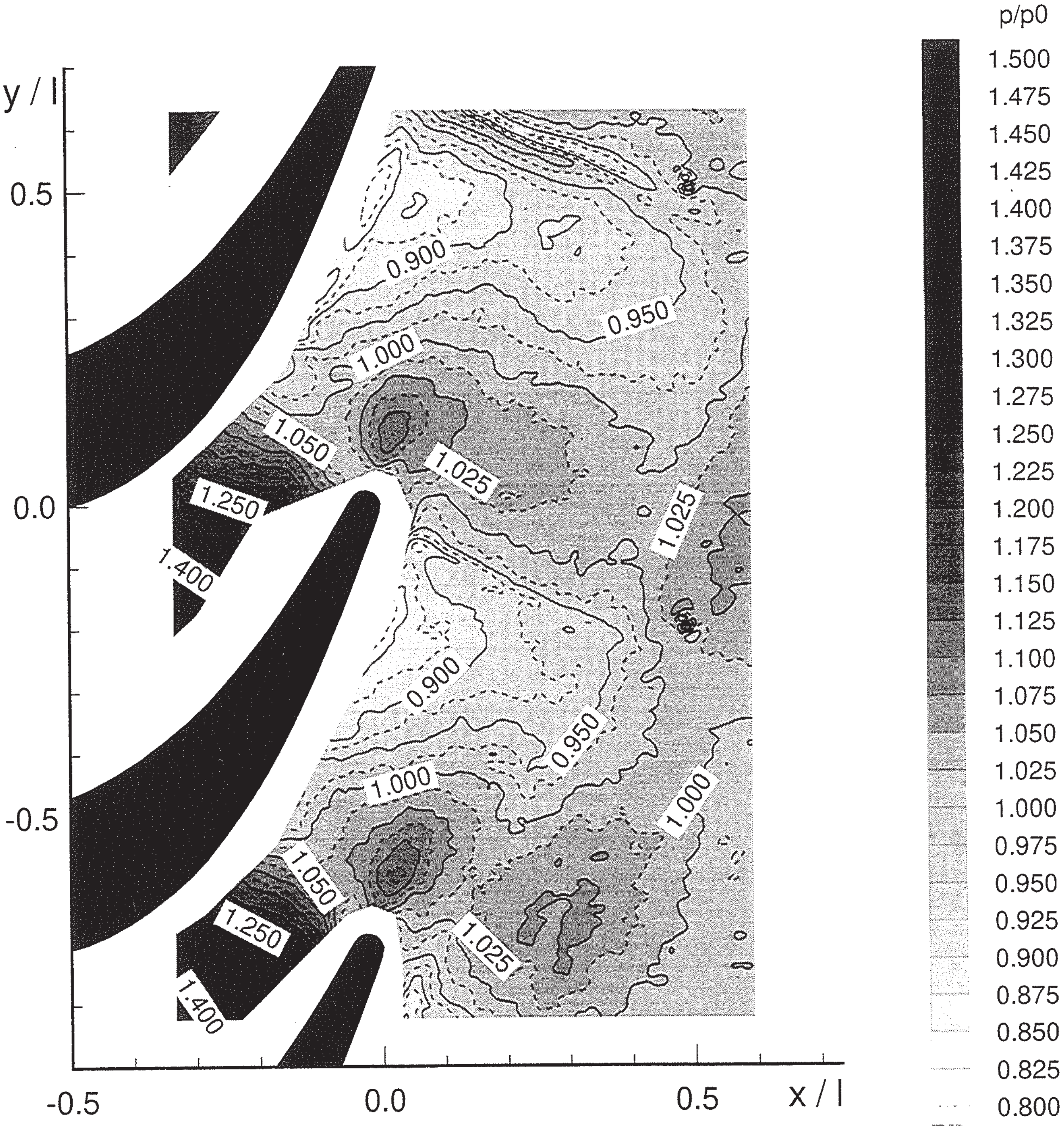


Fig. 7: Pressure distribution on endwall of VKI-1 cascade, Ma_{2is} = 1,00

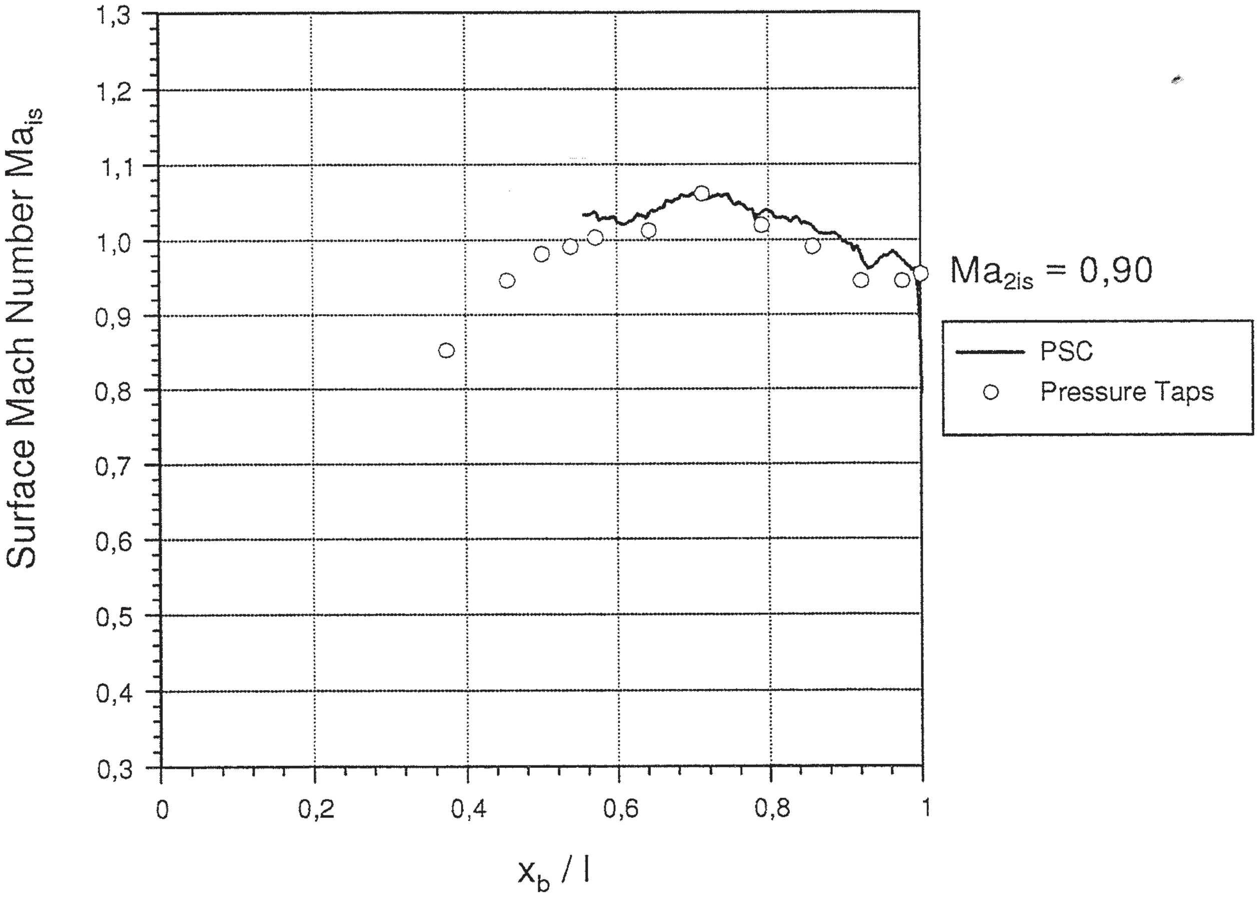


Fig. 8: Surface Mach Number distribution on the suction side of a VKI-1 turbine blade