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poświęcone są publikacjom naukowym z zakresu teorii i badań doświadczalnych w dziedzinie mechaniki i termodynamiki przepływów, ze szczególnym uwzględnieniem problematyki maszyn przepływowych

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exist for the publication of theoretical and experimental investigations of all aspects of the mechanics and thermodynamics of fluid-flow with special reference to fluid-flow machinery

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III НАУЧНАЯ КОНФЕРЕНЦИЯ

на тему

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A Contribution to the Problems of Turbulence Structure in a Flow Through the Turbine Cascade Blades

Introduction

The behaviour of turbulent boundary layer on the surface of turbine blades has been the subject of numerous (e.g. [1, 2, 3] etc.) papers. The complex nature of the phenomenon makes, however, this problem still open for further, intensive investigations.

The present results are the fragments of a more extensive work, dealing with aerodynamics of the fluid-flow-machinery blading, carried out at the Institute of Heat Machinery of the Technical University of Częstochowa. The report refers to experimental analysis of a boundary layer on the surface of stator blades under the conditions of variable inlet angle and different initial turbulence levels.

Experimental stand and procedure

The experiment has been carried out in an open-circuit, low-speed wind tunnel. The stator cascade blade under investigation (N12 profile) was mounted in the outlet channel of the wind tunnel by means of an exchangeable set of angular walls (Fig. 1 and 2), which allowed the inlet angle α_0 to be varied in the range $45 \div 135$ degrees.

The initial turbulence of an incoming flow was generated by a special grid installed in the channel in front of the cascade blades. Regulation of the distance between the grid and the inlet edges of the blades made it possible to obtain the variation of the initial turbulence intensity ε_0 within the limits of 2.8 to 10.9%.

In order to achieve the higher turbulence level and to stimulate, upstream of the tested cascade, the flow patterns similar to that occurring in actual turbomachines, it was decided to produce a turbulence by means of a moving grid or so called "eddy-generator", as shown schematically in Fig. 2.

The basic instruments applied during the experiment were DISA hot-wire anemometer and RFT 1/3-octave frequency analyser. The temperature sensors were mounted in a special support provided with a guide roll moved over the cam representing exactly the profile

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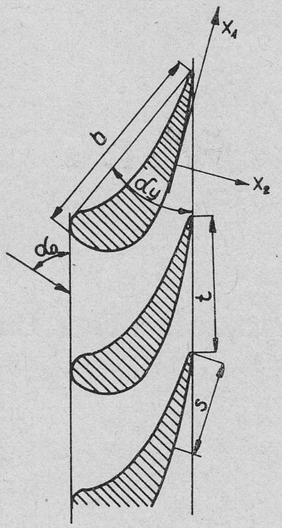

Fig. 1. The tested cascade blade

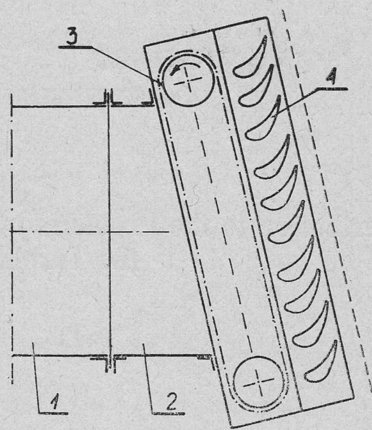

Fig. 2. The scheme of the experimental set-up
1 – outlet channel of the wind-tunnel, *2* – set of angular walls, *3* – eddy-generator, *4* – cascade blade

under investigation. The above device allowed, consequently, for continuous measurements of mean as well as fluctuating velocity distributionsalong lines parallel to the surface of the profile.

Experimental results

The reported investigations do not refer to the boundary layer over the whole surface of the profile. The experimental analysis has been limited only to the suction side near the

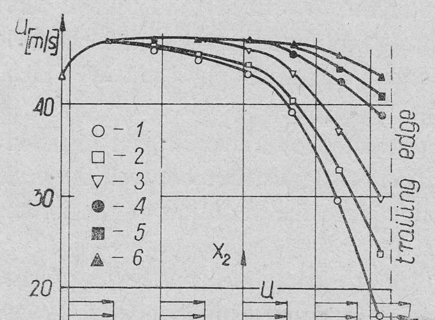

Fig. 3. Examples of the mean velocity distribution in a boundary layer on the suction side of the blade profile for $\alpha_0=90°$ and $\varepsilon_0=10.9\%$
1 – $x_2=0.5$ mm, *2* – $x_2=0.65$ mm, *3* – $x_2=0.8$ mm, *4* – $x_2=1.0$ mm, *5* – $x_2=1.5$ mm, *6* – $x_2=2.0$ mm, $\bar{s}=s/250$ – distance rom the trailing edge (see Fig. 1) referred the circumference of the whole profile (290 mm)

trailing edge of the blade where boundary layer, because of its considerable physical thickness, was the most suitable for detailed examination.

The examples of mean velocity distribution in several surfaces parallel to the blade

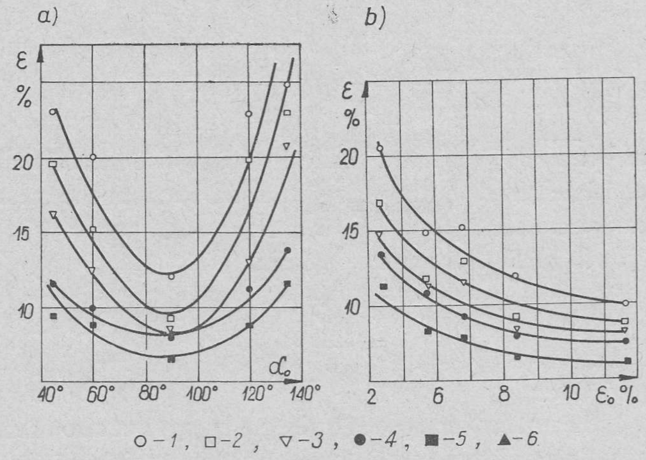

Fig. 4. The intensity of the turbulence of the boundary layer as a function of a) inlet angle α_0 for $\varepsilon_0=10.9\%$, b) initial intensity of the turbulence ε_0 for $\alpha_0=90°$
$1-x_2=0.5$ mm, $2-x_2=0.65$mm, $3-x_2=0.8$mm, $4-x_2=1.0$mm, $5-x_2=1.5$mm, $6-x_2=2.0$mm

profile have been presented in Fig. 3. As it could be expected one may observe a rapid increase of the boundary layer while approaching the trailing edges of the cascade blades.

Figures 4a and 4b show to what extent the longitudinal turbulence intensity at a fixed point of a boundary layer is influenced by the change of the inlet angle α_0 and the turbulence level of incoming flow. The first of the quoted figures points out an interesting feature, namely that the increase of ε_0 causes the decrease of the boundary layer turbulence level

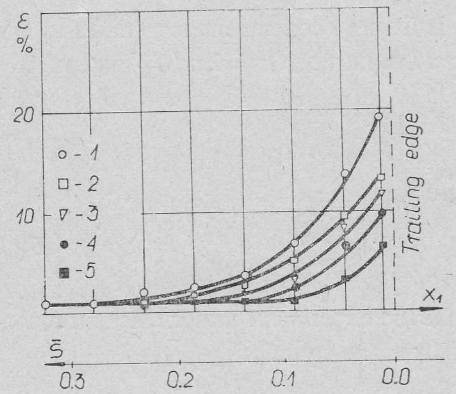

Fig. 5. Turbulence intensity distribution in the downstream direction for $\alpha_0=90°$ and $\varepsilon_0=10.9\%$
$1-x_2=0.5$mm, $2-x_2=0.65$mm, $3-x_2=0.8$mm, $4-x_2=1.0$mm, $5-x_2=1.5$mm

on the suction side of the cascade blades. The curves plotted in Fig. 4b show that the boundary layer becomes the more turbulent the more inlet angle differs from its nominal value.

In Fig. 5 the longitudinal turbulence intensity distribution is shown. A characteristic peculiarity of the results consist in an evident growth of the turbulence level in the downstream direction. This effect may be explained by the existence of a local positive static pressure gradient near the trailing edges of the blade profiles. As a result, in the equation of turbulent energy $\overline{q^2}$

$$\frac{d}{dt}\left(\frac{\overline{q^2}}{2}\right) = -\overline{u_i u_j}\,\frac{\partial U_i}{\partial x_j} + \ldots$$

the production term $-\overline{u_i u_j}\cdot\partial U_i/\partial x_j$ has a positive value, which means that the turbulent motion is carried and intensified by the energy transferred from the mean flow through the turbulence shear stresses.

The observed growth of the turbulence intensity

$$\varepsilon = \frac{\sqrt{\overline{u_1^2}}}{U}$$

is the result not only of the noticed increase of turbulent energy but also of the simultaneous decrease of the mean flow velocity in the outlet triangle region of the blade passage (see Fig. 3). It can be also seen that in the considered part of the blade passage the turbulence intensity in the outer flow, i.e. outside the boundary layer, becomes practically independent of the co-ordinate x_1.

A better insight into the microstructure of turbulent boundary layer may be obtained by the analysis of the kinetic energy distribution over the various frequencies n of turbulent fluctuations. If one assumes that the velocity field is quasi-steady, i.e. statistically homogeneous with respect to time, then energy distribution function $E_1(n)$ must satisfy the equation

$$\int_0^\infty E_1(n)\,dn = \overline{u_1^2}.$$

It is more convenient sometimes to consider the energy-spectrum function in terms of the wave-number $k_1 = 2\pi n/U_1$ instead of the frequency n. Then

$$E_1(k_1) = \frac{U_1}{2\pi}\,E_1(n)$$

while

$$\int_0^\infty E_1(k_1)\,dk_1 = \overline{u_1^2}.$$

In the experiment under discussion the distribution function $E_1(k_1)$ has been determined from the equation

$$E_1(k_1) = \frac{\overline{e_n^2}}{\Delta n\overline{e^2}}\,\frac{U_1}{2\pi}$$

using results of the measurements carried out with the aid of a hot-wire anemometer and a frequency analyser.

The results obtained, for two different inlet angles $\alpha_0 = 90°$ and $\alpha_0 = 60°$, have been presented in Figs. 6a and 6b. It can be easily seen that the shape of curves in question depends greatly on the choice of the observation point in the downstream direction.

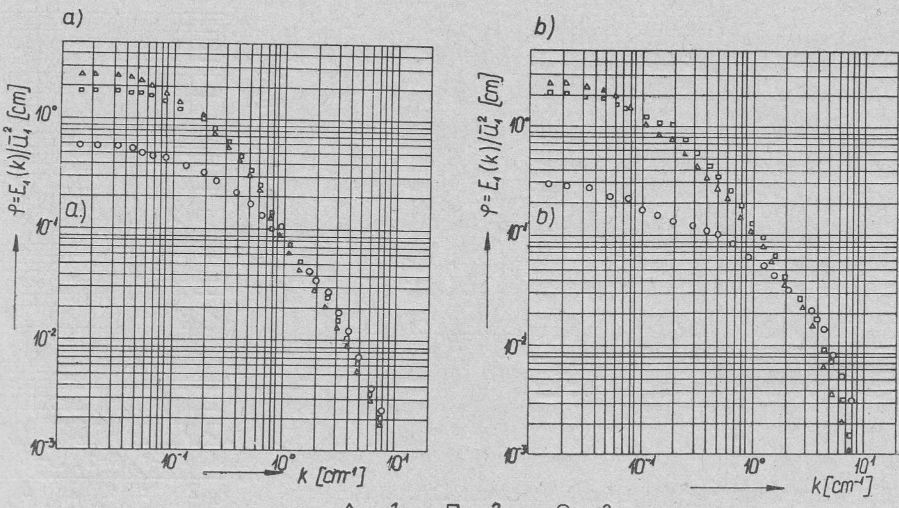

Fig. 6. Energy spectrum in a boundary-layer flow for $x_2=1.0$ mm and a) $\alpha_0=60°$, b) $\alpha_0=90°$
$1-\bar{s}=0.313$, $2-\bar{s}=0.14$, $3-\bar{s}=0.01$

The above mentioned experimental data illustrate the character of changes occurring in the turbulence structure of the boundary layer when approaching the trailing edge of the blade profile. Among other parameters the integral microscale Λ_f of the turbulent motion (a measure of the average dimension of the largest eddies) can be calculated on the ground of the relation

$$\Lambda_f = \frac{\pi}{2} \lim_{k_1 \to 0} \frac{E_1(k_1)}{\overline{u_1^2}}$$

The curves plotted in Fig. 7 indicate that Λ_f noticeably decreases when approaching the trailing edge. This fact means that in the turbulence structure the smaller eddies (corresponding to the higher wave-numbers) begin to prevail.

As a supplement to the previous conclusions, the evolution of the energy-spectrum function $E_1(k_1, t)$ in the downstream direction is shown in Fig. 8, for three given inlet angles $\alpha_0=60°$, 90° and 120° and for two different values of wave-number $k_1=1$ and $k_1=$ $=4$ cm^{-1}. In the both recently mentioned figures quantities Λ_f and E_1 are plotted against time t connected with a given point of the boundary layer by means of the equation.

$$x_1 - x_1^0 = \int_{t_0}^{t} U_1(t)\,dt.$$

The subscript 0 indicates the farthest boundary layer cross-section localized at the distance $x_1^0=91$ mm from the trailing edge of a blade.

Resigning from a more subtle quantitative description of the results it can be noticed that the curves plotted in Fig. 8 have approximately parabolic character. That allows to assume that in range of adequately high wave-numbers the energy spectrum function

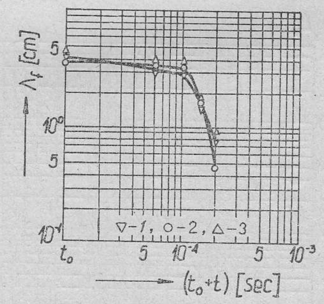

Fig. 7. The evolution of the turbulence macroscale Λ_f in the downstream direction, for
$1-\alpha_0=60°$, $2-\alpha_0=90°$, $3-\alpha_0=120°$

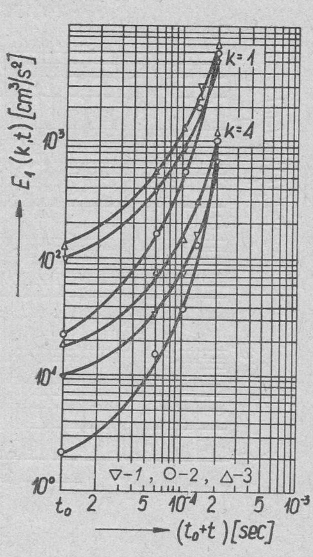

Fig. 8. Time-dependence of the energy spectrum function
$1-\alpha_0=60°$, $2-\alpha_0=90°$, $3-\alpha_0=120°$

$E_1(k_1, t)$ can be expressed by the relation of the type

$$E_1(k_1, t)=\text{const}\cdot E_1(k_1, t_0)\exp\left[C(t-t_*)^2\right],$$

where t_* refers to a suitably chosen value of the time-parameter. In Fig. 9 the ratio of the quantities $\varphi=[E_1(k_1)/u_1^2]_t$, calculated for the same wave-numbers but at two extreme points of the boundary layer, is presented. In spite of a certain irregularity of experimental data the area between the dashed lines confirms the previous conclusions and expresses the general tendency of changes occurring in the microstructure of a turbulent boundary layer. The

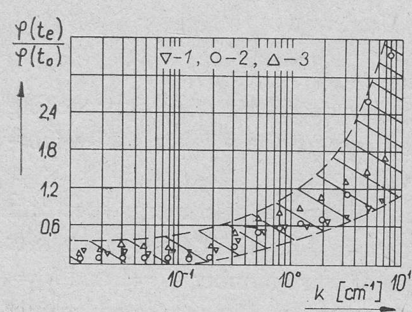

Fig. 9. The ratio of the relative energy spectrum functions, calculated in two extreme points ($\bar{s}=0.01\rightarrow t_e$, $\bar{s}=0.313\rightarrow t_0$) of the boundary layer for the initial turbulence level $\varepsilon_0=10.9\%$
$1-\alpha_0=60°$, $2-\alpha_0=90$, $3-\alpha_0=120°$

main feature of this tendency can be indentified with the fact that nearer to the trailing edge of the blade profile the contribution of big eddies in the kinetic energy of a turbulent motion noticeably decreases (see e.g. Fig. 8) whereas the contribution of the smallest eddies increases at the some time.

Final remarks

A certain caution in formulating general conclusions based on the results described above is needed because of the limited scope of the investigations. Even so, the experiment has shown that for a given cascade the kinetic energy of a turbulent motion in the boundary layer on the suction side of the blade profile increases noticeably in the downstream direction and simultaneously the energy spectrum distribution moves towards the range of higher wave-numbers.

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Przyczynek do problemu struktury turbulencji w przepływie przez palisadę łopatek turbinowych

Streszczenie

Przedstawiony w referacie materiał dotyczy wyników doświadczalnej analizy warstwy przyściennej w warunkach zmiennego kąta napływu oraz różnych poziomów wstępnej turbulencji strumienia.

Uzyskane wyniki wykazały, że charakterystyka turbulentnej warstwy przyściennej jest w znacznym stopniu zależna od kąta napływu strumienia, natomiast oddziaływanie turbulencji wstępnej jest mało znaczące. Odchylenie kąta napływu od jego wartości nominalnej powoduje wzrost turbulencji w warstwie przyściennej na profilu łopatki. Burzliwość warstwy przyściennej rośnie w miarę zbliżania się punktu obserwacji zarówno do powierzchni łopatki, jak również do krawędzi spływu profilu. W tym ostatnim przypadku obserwuje się również tendencję do przesuwania się widma energii turbulentnej w kierunku większych liczb falowych, co jest wyrazem zmian zachodzących w mikrostrukturze przepływu.

К проблеме структуры турбулентности в течении через решетку турбинных лопаток

Резюме

Представленный в докладе материал касается результатов экспериментального анализа пограничного слоя в условиях переменного входного угла и различных уровней предварительной турбулентности потока.

Из полученных результатов следует, что характеристика турбулентного пограничного слоя в значительной степени зависит от входного угла потока и в гораздо меньшей степени от предварительной турбулентности. Отклонение входного угла от его номинального значения способствует возрастанию турбулентности в пограничном слое на лопаточном профиле. Турбулентность пограничного слоя растет с уменьшающимся расстоянием точки наблюдения, как от поверхности лопатки, так и от выходной кромки профиля. В этом последнем случае наблюдается также стремление к перемещению спектра турбулентной энергии по направлению больших волновых чисел, что является обликом изменений, происходящих в микроструктуре течения.