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Transactions of the Institute of Fluid-Flow Machinery have primarily been established to publish papers from four disciplines represented at the Institute of Fluid-Flow Machinery of Polish Academy of Sciences, such as:

- Liquid flows in hydraulic machinery including exploitation problems,
- Gas and liquid flows with heat transport, particularly two-phase flows,
- Various aspects of development of plasma and laser engineering,
- Solid mechanics, machine mechanics including exploitation problems.

The periodical, where originally were published papers describing the research conducted at the Institute, has now appeared to be the place for publication of works by authors both from Poland and abroad. A traditional scope of topics has been preserved.

Only original and written in English works are published, which represent both theoretical and applied sciences. All papers are reviewed by two independent referees.

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Editorial

These Special Issues of the *Transactions of Fluid-Flow Machinery*, Nos. 113 and 114 contain selected papers from the International Conference on *Turbines of Large Output* devoted to commemorate 100$^{\text{th}}$ Birthday Anniversary of Prof. Robert Szewalski. The conference was held in Gdańsk, Poland on September 22-24, 2003.

The Conference is a continuation of previous conferences held at the Institute of Fluid-Flow Machinery PAS in former years dedicated to technology of steam turbines. Series of conferences bearing the same name took place in the years 1962, 1965, 1968, 1993. In 1997 organised has been a conference on steam turbines and related topics, but with a slightly amended title – *Problems of Fluid-Flow Machinery*. At present at the Institute of Fluid Flow Machinery there are conduced research of fundamental character encompassing both the issues related to steam turbines and fundamentals of power engineering.

Organisers of the present conference have returned to the traditional name, i.e. Conference on *Turbines of Large Output* to mark the respect to the memory of Professor Robert Szewalski (1903-1993), the founder and a director of the Institute of Fluid-Flow Machinery for several years, and initiator of the conference series devoted to the problems of steam turbines.

The Editors are very grateful to the referees of the papers presented in this issue of the *Transactions of Fluid-Flow Machinery*: J. Badur, W. Batko, E. S. Burka, J.T. Cieśliński, P. Doerffer, A. Gardzilewicz, B. Grochal, J. Kiciński, G. Kosman, T. Król, J. Krzyżanowski, J. Mikielewicz, A. Neyman, W. Ostachowicz, R. Puzyrewski, R Rządkowski, J. Świrydczuk, M. Trela, T. Uhl and Z. Walczyk.

We appreciate cordially the manifested authors interest in our conference. Special thanks are conveyed to Ms 'Maya' Bagińska, for her fruitful editorial help related to directing the papers to reviewers and correspondence with the authors of contributions.

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TRANSACTIONS OF THE INSTITUTE OF FLUID-FLOW MACHINERY

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ZYGMUNT WIERCIŃSKI*

Experimental investigation of laminar-turbulent transition at the Institute of Fluid-Flow Machinery, Gdańsk

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Abstract

It is well known that the flow in turbomachinery blade channels is inherently non-stationary. It is especially true for the multistage machines where periodic unsteady wakes generated by the preceding row of blades flow through the blade channels and influence strongly the development of the boundary layer causing premature transition and subsequently increase of the local shear stresses and the convective heat transfer rates. Since many years at the Institute of Fluid-Flow Machinery, Gdańsk, the investigations of laminar-turbulent transition have been carried out. These investigations have been made in the subsonic wind tunnel for the flat plate without and with heat transfer (cold and heated surface of the plate) for the case of natural and induced transition in the boundary layer on the plate (low level of turbulence in the outside flow and with wakes). The local skin friction and local Stanton number for these different flow conditions are determined and the velocity and temperature fluctuations in the boundary layer are measured. The non-stationary characteristics of flow in boundary layer are also determined. On the basis of these measurements the experimental correlation for natural and induced boundary layer transition is proposed and the three parameter Weibull distribution for the intermittency factor put forward. Furthermore, the Reynolds analogy for the induced and natural transition in the laminar and turbulent regions of boundary layer is stated.

Keywords: Natural and induced transition; Cold and heated boundary layer

Nomenclature

C_f	–	local shear stress coefficient
C_{nl}	–	nonisothermality coefficient
f	–	frequency
$H = \delta^*/\delta^{**}$	–	shape factor

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i	–	incidence angle
Pr	–	Prandtl number
$\mathrm{Re}_x = Ux/\nu$	–	local Reynolds number
$\mathrm{Re}^* = U\delta^*/\nu$	–	displacement thickness Reynolds number
$\mathrm{Re}^{**} = U\delta^{**}/\nu$	–	Reynolds number
$\mathrm{Re}_\delta = U\delta/\nu$	–	Reynolds number
s	–	Reynolds analogy factor
St	–	Stanton number
U	–	velocity
u'	–	velocity fluctuations
u^*	–	shear velocity
t	–	time
x	–	distance from the leading edge of the plate
y	–	coordinate, distance perpendicular (local Re)
$y^+ = yu^*/\nu$	–	wall coordinate
α	–	slope parameter of Weibull distribution
γ	–	intermittency factor
δ	–	boundary layer thickness
δ^*	–	displacement thickness
δ^{**}	–	momentum thickness
Θ	–	shape parameter of Weibull distribution
$\eta = y/\delta$	–	relative coordinate of boundary layer
ν	–	kinematic viscosity coefficient
ρ	–	density

Subscripts

B	–	begining of transition
e	–	outside of boundary layer
f	–	for given frequency
nj	–	negative jet
o	–	onflow condition
pj	–	positive jet
q	–	rms value
w	–	at wall

1 Introduction

The problem of turbulence inception in flows is one of the components of the more general problem of turbulence mechanics. In this context the turbulence inception problem in the laminar boundary layer is a minor, but significant for the technical applications, problem of fluid mechanics, which is the laminar-turbulent transition. For many years the problems of laminar-turbulent transition evoke great interest of scientists and engineers, which is connected with necessity of solution many practical tasks e.g. the control of boundary layer on the aircraft and its elements, the internal boundary in the turbomachinery, especially blades, and many others, aimed at the decrease of drag and fuel consumption. Despite the significant advances in our knowledge on the laminar-turbulent transitions there are many unknown issues e.g. the mechanism of momentum and heat transfer in induced boundary layer, to mention only this one. Moreover, the laminar-turbulent transition is not only observed in the technology and engineering but is also wide spread in nature, what additionally deepens our interest to this much more general problem.

The laminar-turbulent transition can be understood as a disintegration of the laminar state of flow and appearance of turbulent one and it is a set of many versatile and complex phenomena responsible for the break of the laminar flow. The laminar-turbulent transition can be divided into three or even four different phenomena depended on the reason causing it: natural, induced and separated, and sometimes apart from notion of induced transition additionally the by-pass transition is used. The natural transition refers to the transition caused by the very small natural disturbances and their initial development can be described by the linear stability theory. This transition can be observed when the turbulence level in the external flow is very small. The induced transition is caused by the external flow disturbances of different origin as e.g. enhanced turbulence level or wake in the external flow, etc. In turn, the separated transition is observed over the separation bubble, most frequently at the leading edge of plate or blade. So called by pass transition refers to the transition caused by the appropriate disturbance which is so high that the linear part of disturbance evolution is hidden i.e. not visible and sometimes immediately the turbulent spots are generated. In other words, the initial steps of disturbances evolution are by-passed. Most often the enhanced level of turbulence of external flow is responsible for it.

2 Experimental rig and program of investigation

The investigation is carried out in the subsonic (maximum velocity 100 m/s) wind tunnel of closed circuit at the IFFM, Gdańsk, [5]. In the investigation a flat plate with dimensions: plate length $L = 0.7$ m, width $W = 0.64$ m and thickness $d = 0.014$ m is used as a simple model for the blade. The leading edge of the blade was cut slantwise at 30° then made round at radius of 2 mm. The velocity range is subsonic but assuring the laminar - turbulent transition of the flow in the boundary layer, i.e. in the range $U_o = 10 \div 30$ m/s. The turbulence level in the oncoming flow is very small and equals $Tu = 0.0008$.

Two different flat plates of the same dimensions i.e. non-heated (cold) and heated are used in the experiment. The experiment is carried out for the three different disturbances conditions: the flow without any disturbances (only the external flow turbulence of level $Tu < 0.08\%$) and with two different wake generators: a single rod of $d = 4$ mm in the motion up and down, and a rotating drum with rods of diameter $d = 3$ mm on the circumference, so called squirrel cage. The frequency of both single rod and squirrel cage motion used in the experiment is $f = 4$ and 6 Hz.

The cold plate is placed at the incidence angle $i = -2.5^o$ to avoid the separation at the leading edge, while the heat transfer experiment is made for the heated plate arrangement at different incidence angles between $i = -2.5 \div 0^o$ (especially for the investigation of the transient behaviour of the transition).

For the cold plate the velocity and its fluctuations are measured across the boundary layer. On this base the local shear stress coefficient C_f is determined. Furthermore, the characteristics of boundary layer as its thickness δ, displacement thickness δ^*, momentum thickness δ^{**} and the shape factor H are determined.

For the heated flat plate the distribution of the Stanton number along the plate is measured, [7]. The measurements of temperature and its fluctuations across boundary layer are under way. It is also possible to measure the 2D distribution of the Stanton number. The velocity and temperature measurements in the boundary layer are made by means of hot-wire anemometry.

3 Aims of investigation

There are various aims of this investigation. First of all, the recognition of the mechanics of turbulence inception in the induced boundary layer is expected. The nature of the disturbances caused by wakes in the boundary layer is searched. It is expected that the boundary layer is a resonator for various disturbances and responds in different manner to different disturbance frequencies. On this base the model of the induced transition is elaborated. Furthermore, the influence of the positive and negative jet on the boundary layer is determined.

The investigation of flow about a heated flat plate is aimed at the confirmation (or not) of the Reynolds analogy between the heat momentum transfer i.e. between the local shear stress C_f and Stanton number St.

4 Results of measurements

4.1 Boundary layer induced by wake on the cold plate

In Fig. 1 the velocity distribution across boundary layer, expressed in the so called wall coordinates $u^* = f(y^+)$, is shown for the velocity $U_o = 15$ m/s for different Reynolds numbers, [6]. In this case the boundary layer is induced by the wake from the moving single cylinder with frequency $f = 4$ Hz. The first velocity distribution $\text{Re}_x = 2.02 \cdot 10^5$ lies at the edge between the laminar and transitional flow, the next velocity profile for $\text{Re}_x = 2.37 \cdot 10^5$ is already transitional and the last velocity distribution for $\mathrm{Re}_x = 6.47 \cdot 10^5$ is actually turbulent. In this figure the all transition is completely seen. The solid lines in the figure are: $u^* = y^+$ and $u^* = 2.5 \ln y^+ + 5.1$, linear and logarithmic low of velocity distribution, appropriately.

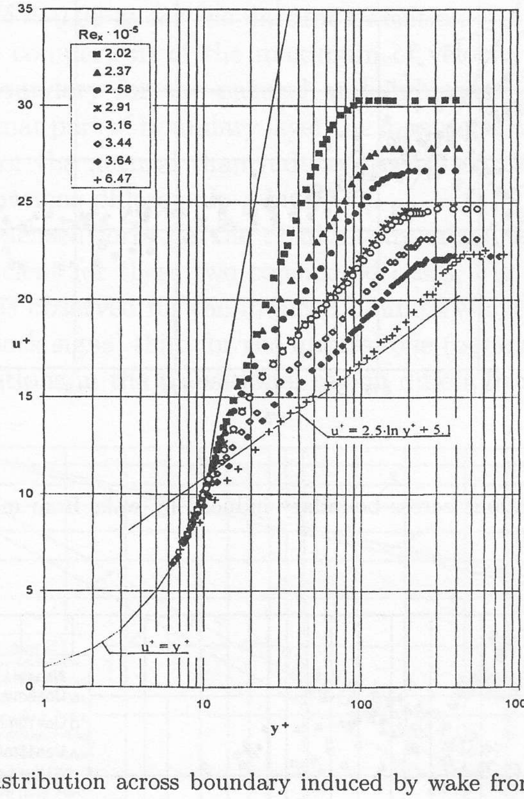

Figure 1. Velocity distribution across boundary induced by wake from moving single cylinder $u^* = f(y^+)$.

In Fig. 2 the velocity fluctuation distributions u'/U_e versus y/δ across boundary layer are shown for the velocity $U_o = 15$ m/s for different Reynolds numbers. As in the previous figure, the boundary layer is induced by wake from the moving single cylinder with frequency $f = 4$ Hz but for greater set of Reynolds numbers as before i.e. $\mathrm{Re}_x = (0.82 \div 6.47) \cdot 10^5$. For the laminar part of flow, i.e. for $\mathrm{Re}_x \leq 2.02 \cdot 10^5$ two peaks (indicated as MA the peak close to the surface and MB the peak near the outside edge of boundary layer) in this distribution can be seen and it is a special feature of the boundary layer induced by wakes when the external flow is of low turbulence. The velocity fluctuation level outside the boundary layer, $Tu = 4\%$, is caused here by the wakes flowing with external stream. For the low Reynolds number $\mathrm{Re}_x = 0.82 \cdot 10^5$ the velocity fluctuations of the peak MA are smaller than the velocity fluctuation in the external flow. It

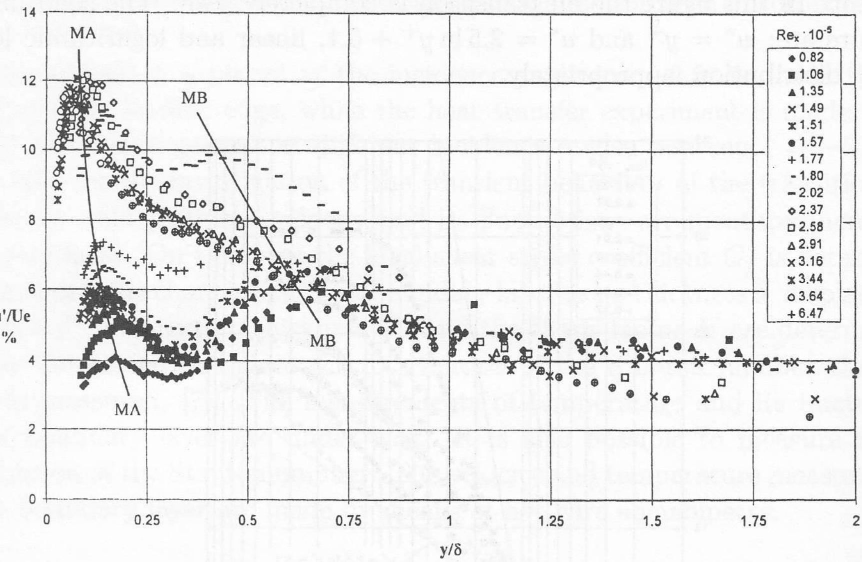

Figure 2. Velocity fluctuations across boundary induced by wake from moving single cylinder $u'/U_e = f(y/\delta)$.

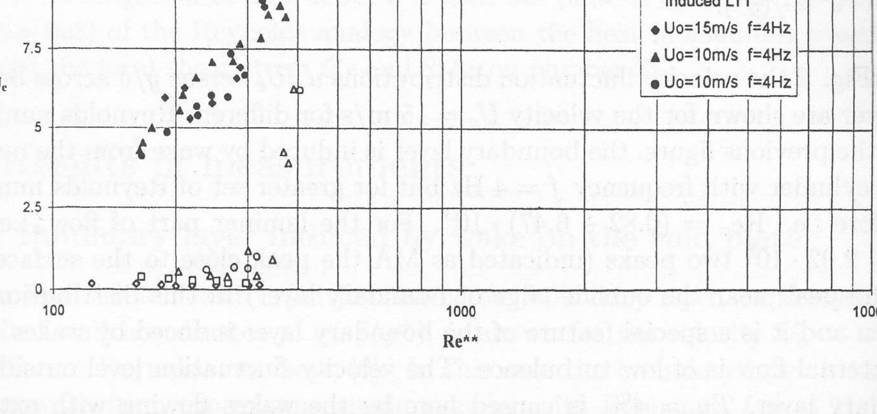

Figure 3. Velocity fluctuations in the boundary layer with natural and induced by wake transition.

is also the feature of induced by wake boundary layer that the peak MB placed approximately $y/\delta \approx 0.70$ is for the $\mathrm{Re} \leq 1.77 \cdot 10^5$ bigger than the peak signed MA near the wall i.e. at $y/\delta \approx 0.15 \div 0.20$. Next, the amplitude of the peak signed MA rises and finally is bigger than this of the peak signed MB. For the turbulent part of boundary layer $\mathrm{Re}_x > 2.02 \cdot 10^5$ there is only one peak in the distribution at $y/\delta \approx 0.08$ as for the natural transition.

In Fig. 3 the comparison of the maximum of velocity fluctuation $u'/U_e = f(\mathrm{Re}^{**})$ in the boundary for the natural and induced transition is presented. While for the laminar part of boundary layer the maximum of velocity fluctuations is much smaller for the natural than induced transition, for the turbulent part the velocity fluctuations differs only a little, [6].

The most condensed form for the results comparison is to present the local shear stress coefficient for these two considered cases, Fig. 4. In this figure the earlier transition is observed for the induced boundary layer by the wake from a single cylinder (black signs) than for the natural one (open signs). Also the slope of the C_f distributions in the transitional region differs from each other.

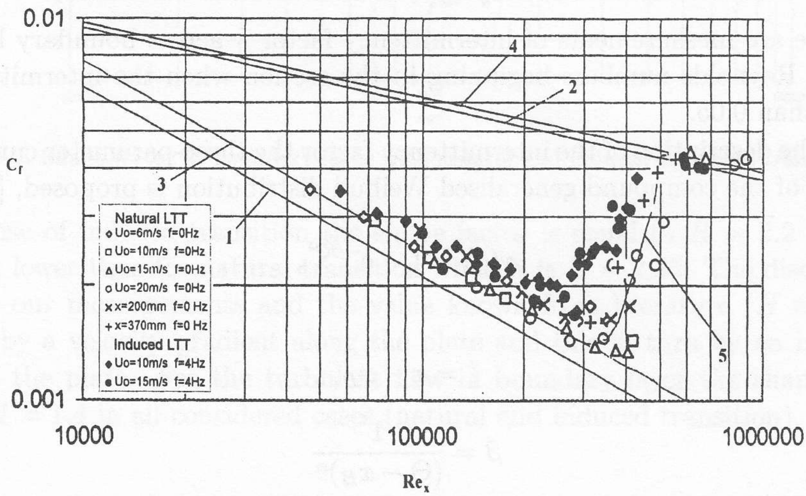

Figure 4. Local shear stress coefficient C_f versus Re_x for natural and induced transition.

Lines marked by numbers 1 to 5 refer to laminar (Blasius) and turbulent boundary layer, the laminar and turbulent boundary layer with small velocity gradient as used in the experiment, transition determined by using the formula (1) below with experimental measured intermittency factor γ, appropriately.

4.2 Intermittency factor

A very useful tool to present the transition is a intermittency factor γ defined as a ratio of time when the flow is turbulent to the whole time of observation.

Figure 5 below show the results of measurements of the intermittency factor in boundary layer for the natural transition.

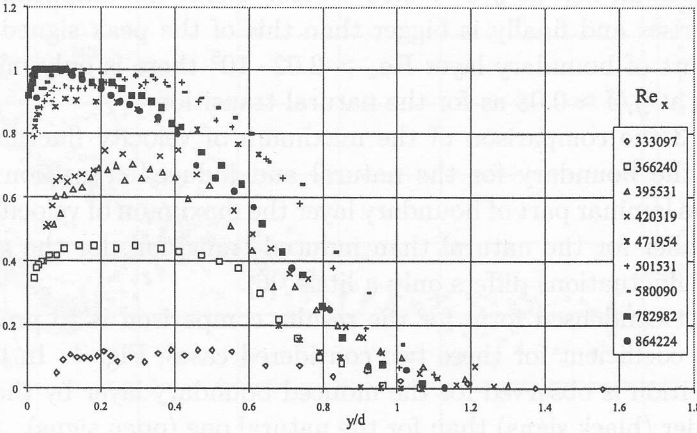

Figure 5. Intermittency factor across boundary layer versus Reynolds number Re_x.

These are measurements of intermittency factor γ across boundary layer for different Reynolds numbers beginning in the section when the intermittency is greater than 0.05.

For the description of the intermittency factor the three-parameter cumulative function of the compound generalised Weibull distribution is proposed, [6]:

$$\gamma(\zeta) = 1 - e^{-\beta\zeta^{\alpha}}, \tag{1}$$

where

$$\zeta = x - x_B, \tag{2}$$

$$\beta = \frac{1}{(\Theta - x_B)^{\alpha}} \tag{3}$$

and α, Θ and x_B are so called slope, scale and origin of the Weibull distribution.

For the natural transition observed in our experiments the following values for above defined parameters are determined: $\alpha = 3.5$, $\Theta = 0.395$, and the transition location $x_B = 0.22$ m.

It is possible to match the appropriate values for given above parameters for the transition induced by wakes. In our opinion the application of the Weibull distribution to describe the intermittency factor has its advantages to the known from the literature formula given by Narasimha, and others, which are most frequently two parameter formulea, because of the greater flexibility of three parameter Weibull distribution.

4.3 Shape factor

Shape factor as the ratio of displacement thickness δ^* to the momentum thickness δ^{**} of boundary layer is also a good indicator of the state of flow in the boundary layer. For the laminar boundary it is equal to approximately 2.5 and for turbulent boundary layer it is about 1.4. In Fig. 6 the measurements of shape factor H is displayed for natural and induced transition.

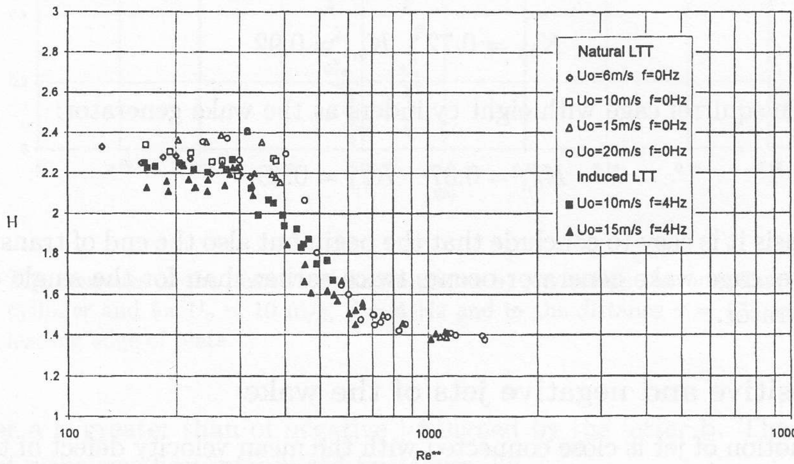

Figure 6. Shape factor in boundary layer with natural and induced by wakes transition.

In case of induced transition the shape factor is equal to $H = 2.2$ and is a little bit lower than for natural transition when it is $H = 2.35$. The discrepancy between our measurements and the value known from literature ($H \approx 2.5$) is created by a velocity gradient along the plate and this in turn by an incidence angle of the plate. For the turbulent flow in boundary layer the shape factor equals $H = 1.4$ in all considered cases (natural and induced transition).

4.4 Experimental correlation between the induced and natural transition

There are many different possible criteria for determination of the begin and end of transition based e.g. on the occurrence of high frequency velocity fluctuations, the appropriate value of intermittency factor, and a few others. Very often the Reynolds numbers determined by using different criteria differ a little. It is not to be astonishing, actually, because this criteria are not equivalent. However, one of the most popular criterion is based on the minimum and maximum of local shear coefficient C_f as begin and end of transition, appropriately. On the basis of the measurements of C_f for natural and induced transition it was possible to determine the experimental correlation in the form of simple formulae:

$$\mathrm{Re}_{b,i} = K_{b,i}\mathrm{Re}_{b,n} \quad \mathrm{Re}_{e,i} = K_{e,i}\mathrm{Re}_{e,n}, \tag{4}$$

where b and e stand for the begin and end of transition, i and n for the induced and natural transition. The Reynolds number can defined as Re_x or Re^{**} appropriately. The coefficient K was determined for different wake generators and for example for the single cylinder their values Re_x are:

$$K_{b,i} = 0.72 \quad K_{e,i} = 0.92 \tag{5}$$

and for the squirrel cage with eight cylinders as the wake generator:

$$K_{b,i} = 0.37 \quad K_{e,i} = 0.46. \tag{6}$$

On this basis it is easy to conclude that the begin but also the end of transition for the squirrel cage wake generator occurs twice earlier than for the single cylinder wake generator.

4.5 Positive and negative jets of the wake

The notion of jet is close connected with the mean velocity defect of the wake and, in turn, its sign: positive or negative is connected with its impact on the blade and especially with its direction relative to the surface, Fig. 7.

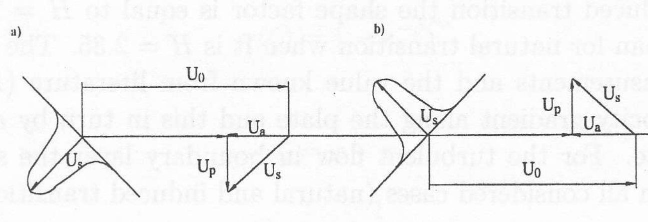

Figure 7. Positive a) and negative b) jet of the wake relative to the upper surface of plate, U_o, U_s, U_p, U_a – mean, defect, normal (slip) and tangential velocities.

The impact of the jet on the blade surface can be differentiated according to its sign and the side of the blade i.e. suction and pressure side, e.g positive jet – pressure side, and positive jet – suction side and so on. As expected, it is different for the compressor and turbine blade. Using the single rod in its motion up and down across the flow, it was possible to investigate the nature of the jet of the wake and its impact on the boundary layer. The measurement result of the shape of the jet in the boundary layer for the positive and negative jets are shown in Fig. 8. It is easy to notice that the width of the positive jet signed by

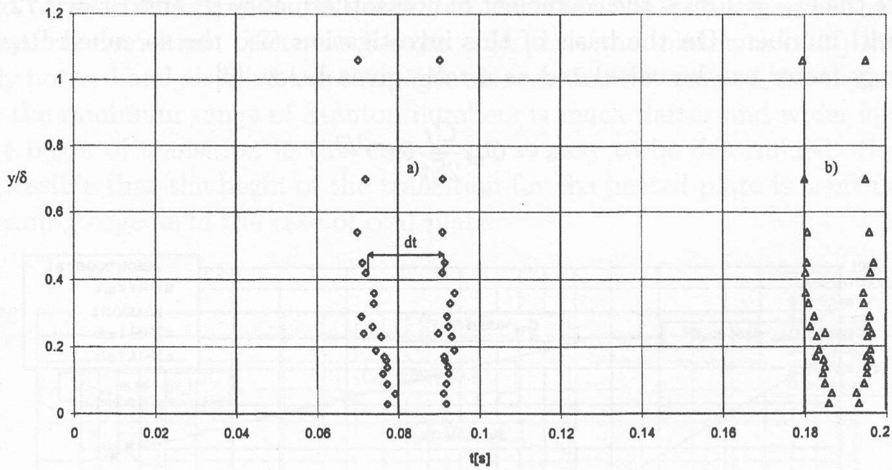

Figure 8. The contours of the positive a) and negative b) jets across the boundary for a single cylinder and for $U_o = 10$ m/s, $f = 4$ Hz and in the distance $x = 175$ mm from the leading edge of plate.

the letter a is greater than of negative jet signed by the letter b. The notion of the jet of wake was first introduced by Meyer, [2].

It is also clear that due to only this different shapes of jets across the boundary layer also the disturbances caused by positive or negative jets have to be different. It is also stated that the jet is narrower near the plate surface and wider at the boundary layer edge i.e. for $y/\delta \approx 1$.

4.6 Boundary layer on a heated flat plate

4.6.1 Natural transition

Besides the cold boundary layer measurements also the boundary layer on a heated plate has been tested. The special plate with heated sections was made. The details on the construction are given in [7], where the transient behaviour of heat transfer was analyzed. Here the results of the Stanton number measurements for the natural transition are shown and compared with the local shear stress coefficient C_f. In the reported experiment the heating of the plate is made for the condition of the constant heat stream, and not the isothermal plate.

The relationship between the local shear stress C_f and Stanton number St is well known and given by the formula below [3]:

$$\mathrm{St} = C_{nl}\frac{C_f}{2}\mathrm{Pr}^{-2/3}, \tag{7}$$

where the $C_{nl} = 1.35$ is the coefficient of nonisothermality [1] and $\mathrm{Pr} = 0.72$ is the Prandtl number. On the basis of this investigation also the so called Reynolds analogy factor can be calculated as a ratio given below [3]:

$$s = C_{nl}\frac{C_f}{2\mathrm{St}}\mathrm{Pr}^{-2/3}. \tag{8}$$

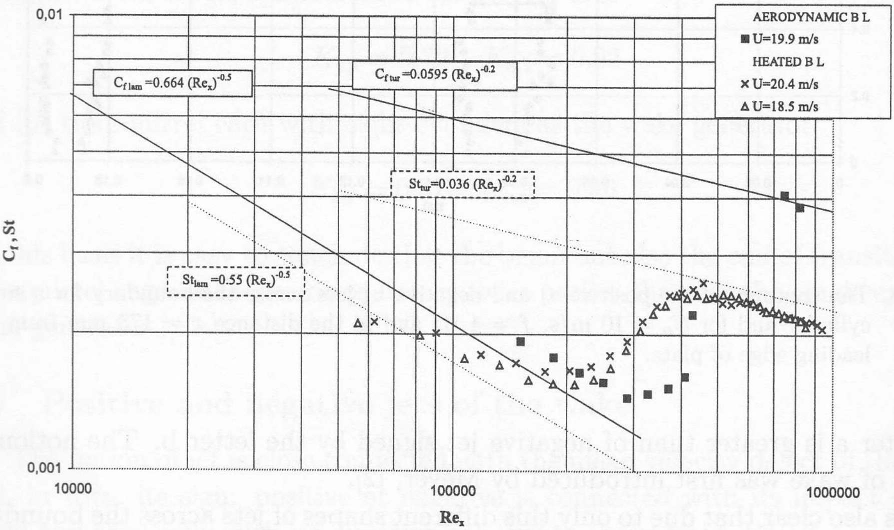

Figure 9. Local shear stress coefficient C_f and Stanton number for the natural transition

In Fig. 9 the local shear stress coefficient C_f measurements for the velocity $U_o = 19.9$ m/s are shown. Besides, in Fig. 9 the measurements of Stanton number St for two different velocities $U_o = 18.5$ and 20.4 m/s are presented. The Reynolds analogy is well observed for the laminar and turbulent flow. There are some differences in the location of the transition origin for the cold and heated flat plate. Transition for the heated flat plat begins a little bit earlier than in the case of the cold plate. The solid lines in this and next figures are denoting the theoretical C_f and St for isothermal flat plate, while the dashed lines are for the nonisothermal i.e. for the constant heat stream.

4.6.2 Transition induced by wakes

Next figure, Fig. 10, displays the local shear stress coefficient C_f and Stanton number for the case of transition induced by wakes. The measurements for the cold plate was made for two different oncoming velocities $U_o = 9.6$ and 17.6 m/s and for the heated flat plate for three velocities: $U_o = 9.16, 15.04$ and 20.46 m/s. In this case the squirrel cage wake generator was used with eight rods evenly placed on its circumferences. As expected the transition begins earlier than for the natural transition. Whereas for the cold plate the minimum of C_f can be clearly noticed and on this basis the begin of transition determined, for the heated plate the minimum range of Stanton numbers is much flatter and wider spread, so the begin of transition in this case is not so easy to be determined. So it is also possible that the begin of the transition for the heated plate is a bit nearer the leading edge as in the case of cold plate.

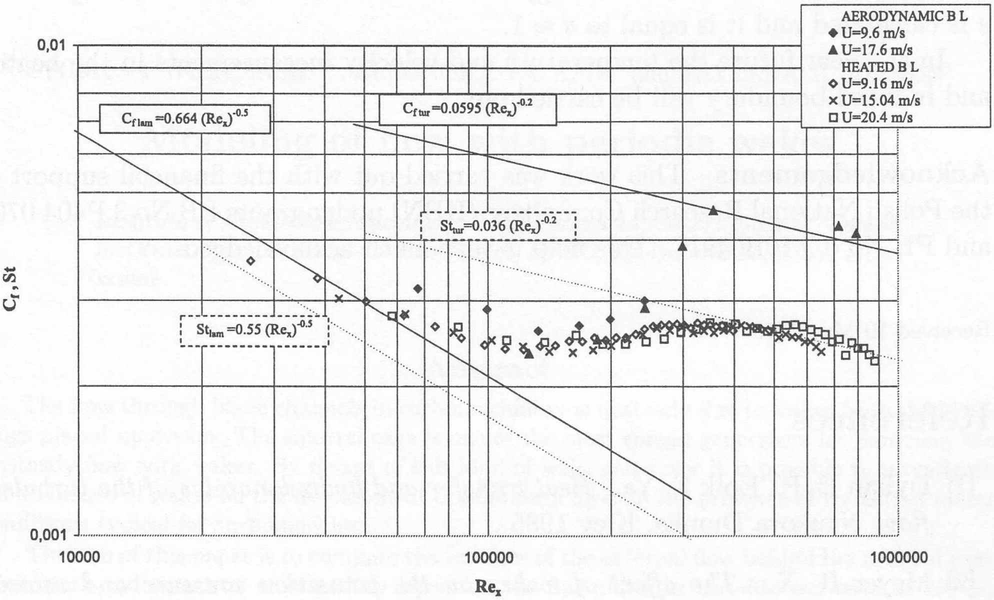

Figure 10. Local shear stress coefficient C_f and Stanton number for the transition induced by wakes.

The Reynolds analogy factor s according to the formula (8) can be calculated from this experiment and it is equal to $s \approx 1$ for the laminar flow as well as for the turbulent flow for two considered cases natural and induced by wakes transition.

5 Summary and conclusions

The transition is one of the most complicated phenomena in fluid dynamics and especially in the turbomachinery. Therefore its experimental investigation and modeling is needed. At the Institute of Fluid-Flow Machinery, PAS, Gdańsk, the investigation of the boundary layer transition from the laminar to turbulent flow has been performed. This investigation refers to both natural and induced by wakes transition on the cold and heated flat plate. The measurements velocity profiles, and velocity fluctuations for the cold flat plate are carried out. For the heated flat plate the heat transfer and then Stanton number St calculated by means of calorymetry are performed.

On this basis the different characteristics of boundary layer were calculated and compared with known data. Furthermore, the new formula for the intermittency factor in form of the Weibull distribution is proposed. The experimental correlation between the begin of transition for the induced and natural transition was established. The same was done for the end of the transition. For the heated boundary layer the Reynolds analogy is confirmed. The Reynolds analogy factor s is calculated and it is equal to $s \approx 1$.

In the near future the temperature and velocity measurements in the heated and induced boundary will be carried out.

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