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POLISH ACADEMY OF SCIENCES

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- 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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TRANSACTIONS OF THE INSTITUTE OF FLUID-FLOW MACHINERY

No. 114, 2003, 3-4

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$^{\mathrm{th}}$ 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.

Prof. Jarosław Mikielewicz
Editor-in-Chief

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TRANSACTIONS OF THE INSTITUTE OF FLUID-FLOW MACHINERY

No. 114, 2003, 237-252

ZYGMUNT WIERCIŃSKI*and MACIEJ KAISER

Transient laminar-turbulent transition of thermal boundary layer after the change of incidence angle

Institute of Fluid-Flow Machinery, PAS, Fiszera 14, 80-952 Gdańsk, Poland

Abstract

Convective heat transfer problems occur in many technical application. Unsteady transition in the heated boundary layer is one of them. Heat transfer investigation of a flat plate in a low subsonic wind tunnel for flow velocity $U_o = 15$ and 20 m/s was performed. The changes in time of the Stanton number distribution along the plate were observed after the incidence angle had been changed from - 0.8 to 0°. While for the incidence angle $i = -0.8°$ the flow in boundary layer was laminar, for the angle $-0.6°$ the transition was observed, and for the angle $-0.23°$ the flow was turbulent. After the sudden change of angle the transient behaviour of the heat transfer between these three states were observed, e.g. for the change from -0.8 to $-0.6°$ from laminar to transitional, so after the time of about 30 min the transition was perfect. This time is needed to achieve a new internal thermal balance of the plate and transition in thermal boundary is established.

Keywords: Convective heat transfer; Laminar-turbulent transition; Thermal boundary layer

Nomenclature

C_f	–	local shear stress, –
C_p	–	specific heat, kJ/(kg K)
C_{ni}	–	coefficient of nonisothermality, –
d	–	thickness, m
E	–	voltage difference of the heated section, V
F	–	surface of heated section, m^2

*Corresponding autor. E-mail address: zw@imp.gda.pl

q	–	density of heat flux, W/m^2
i	–	incidence angle, °
I	–	current intensity, A
Nu	–	Nusselt number, –
St	–	Stanton number, –
T	–	temperature, °K
Tu	–	turbulence level, –
t	–	temperature in external flow, °C
U_o	–	velocity of oncoming flow, m/s
(x, y)	–	coordinates, m
α	–	local heat transfer coefficient, W/(m^{2}K)
ε	–	emissivity coefficient, –
λ	–	specific heat conductivity, W/(m K)
Pr	–	Prandtl number
R	–	resistivity of foil section, Ω
Re	–	Reynolds number, –
ρ	–	density; specific resistivity, kg/m^3, Ωm
σ	–	Stefan-Boltzmann constant, W/(m^{2}K^4)
τ	–	time, s

Subscripts

d	–	across plate; lower surface of plate
$foil$	–	refers to heated foil
l	–	along plate
$loss$	–	refers to heat losses
m	–	mean value
pl	–	refers to plate
rad	–	refers to radiation losses
u	–	upper surface of plate
w	–	refers to plate surface

1 Introduction

The convective heat transfer problems are very important for many different power engineering elements and equipment, e.g. steam and gas turbines, heat exchangers and many others. It is well known that the flow in turbomachinery blade channels is inherently unsteady due to the rotor-stator interaction, the potential-theoretic influence of blade rows, the secondary flow (three-dimensionalities), coherent vortical structures and turbulence. It is especially true for the multistage machines. Periodic unsteady wakes generated by the preceding row of blades onflow the blades and change the incidence angle of flow. Furthermore, the passing wakes may give rise to instantaneous flow separation on the blade surface and influence strongly the development of the boundary layer causing premature transition and subsequently increase the local shear stresses and the convective heat transfer rates.

In the past, the investigations of boundary layer over the flat plate under the influence of unsteady wakes generated by means of two different wake generators: single rod in up and down motion and rotating squirrel cage of rods were performed by Wierciński [5]. These simplified flow configurations allowed detailed studies of the different states of boundary layer from laminar to full turbulent and revealed a number of interesting characteristics. First, the non-disturbed flow around flat plate was examined, than the boundary layer affected by the wakes generated by two above mentioned wake generators.

The investigation described in this paper represents a continuation of the investigation of the flow around the non-heated flat plate [5] and designed to obtain detailed data about the heat-flux and the aerothermal characteristics of the boundary layer induced by wakes. So at this step of investigation, the heat transfer experiment is carried out with very low turbulence in the outside flow and for the case when the incidence angle of flow is changed giving appropriately laminar, transitional and turbulent flow. Finally, the turbulent flow prevailing in the whole boundary layer along the plate is caused by the separation at the leading edge.

This investigation is aimed at gaining knowledge about transient behaviour of the heat transfer of the flat plate after the change of the incidence angle. After the change of the incidence angle laminar – turbulent transition in the boundary layer takes place. We also observe the changes of the temperature field in the flat plate after the incidence angle change. This information can be of significance for the determination of the instationary thermal stresses in the plate.

2 Experimental stand

The experimental investigation was carried out in a subsonic wind tunnel featuring with the low level of turbulence, $Tu < 0.08\%$, at the Institute of Fluid Flow Machinery, Gdańsk. This tunnel, Fig. 1, and its measuring apparatus as well as data acquisition system was described by Wiercinski, [5]. In the working section of the wind tunnel a heat transfer flat plate of dimensions: 0.7 m long, 0.6 m wide and 0.013 m thick is mounted. The leading edge of the plate was cut slantwise at 30° then made round at a radius of 2 mm.

In Fig. 2 the drawing of the heated flat plate is shown. The flat plate is made of policarbonate. The heating of the plate surface is realized by the six heated sections made of foil glued on the plate. The foil is made of ferrite steel of type 00H20Ju5 of specific resistivity $\rho_{foil} = 137\,\mu\Omega$ m, specific heat conductivity $\lambda = 13.5$ W/(m K), specific heat $C_{foil} = 460$ J/(kg K), density $\rho = 7000$ kg/m^3 and of thickness $d_{foil} = 0.00005$ m. Whole surface of the plate is heated i.e. there are three sections on the upper and three sections on the lower part of

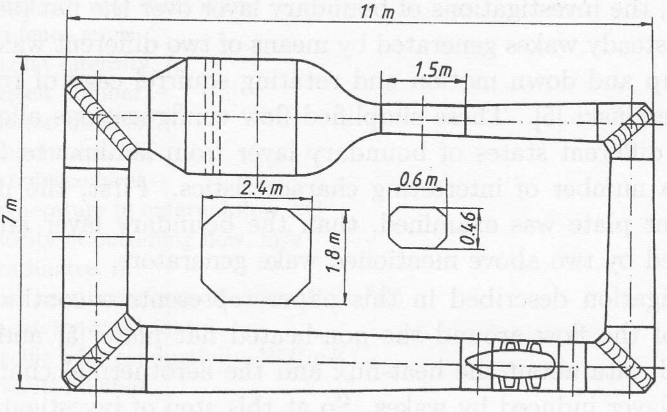

Figure 1. Subsonic wind tunnel.

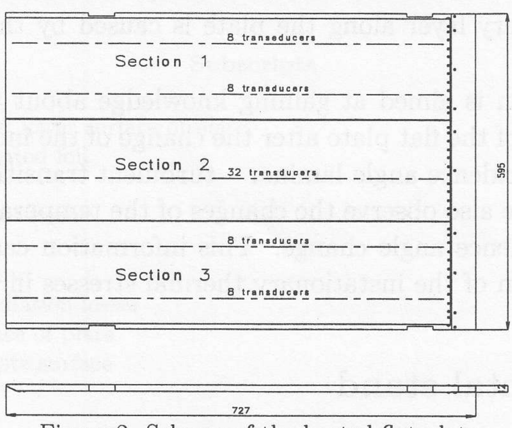

Figure 2. Scheme of the heated flat plate.

plate. Each of the heated sections consists of six foil strips of 31 mm width connected electrically in series. The foils on the upper side pass the leading edge of the plate ending on the lower side. That is why the length of foils are different: upper foils are 714 mm whereas lower foils only 689 mm long.

The resistivity of the upper sections is equal to $R_u = 4.06 \pm 0.02\ \Omega$ each, whereas of the lower section $R_d = 3.80 \pm 0.02\ \Omega$. There are six electrical alternating current suppliers of low voltage up to 24 V and up to maximum current intensity of 10 A; one for each heated section. There are two modes possible to heat the plate. The impulse heating with controlled temperature in chosen point of the plate. The temperature in point of the plate can be controlled within the temperature difference range of $T + \Delta T$ where $\Delta T = \pm 0.1°\mathrm{C}$. In other words, the heating of the plate is switched off only if the temperature difference in the controlled point is in the range given above. The other possible mode of heating is the continuous heating when the heated plate is in heat balance with the oncoming flow i.e heat supplied to the plate is transferred to the flow and temperature of the plate does not increase. In this case the maximum temperature is also limited and controlled not to overheat the plate.

Temperature of the plate surface is measured by means of the semiconductor temperature transducers (digital thermometer and thermostat) of type DS1621 Dallas Semiconductor located in the plate underneath the heated foil in such a way that the transducers almost contact the foil. The transducers are located in five rows on the upper and lower side of the surface.

In the central rows 32 transducers are located: the first in the distance of 44 mm from the leading edge and the last at the distance of 34 mm from the trailing edge, i.e. at the distance 20 mm each. In two rows located on the both sides of the central row there are eight temperature transducers in equidistance of 80 mm each. The resolution of the temperature transducer is equal to 0.1°C.

3 Program of investigation

All measurements were made for the flow of low turbulence level i.e. $Tu = 0.08\%$.

First of all, the investigation of the non-heated boundary layer on the plate was made for three different flow velocities: $U_o = 10, 15$ and 20 m/s. This investigation is a repetition of the investigation made for the cold flat plate without heated sections [7]. The velocity profiles in the boundary layer were measured by means of hot wire and then the local shear stress coefficient was determined.

Next part of investigation concerns the heated flat plate, for which the local heat transfer coefficient α was measured and than the Stanton number along the plate determined and compared with the C_f measurements for the cold plate. This part of investigation was made for a few oncoming velocities in the range $U_o = 15$ and 20 m/s and for the incidence angle equal to $i = -0.6^o$.

Investigation of transient heat transfer of the flat plate was carried out for the incidence angle range $i = 0 \div -0.8^o$ for two velocities $U_o = 15$ and 20 m/s. In this range the three different types of flow were observed: the laminar flow for the incidence angle equal to $i = -0.8^o$, the transient flow for $i = -0.6^o$, and turbulent for $i = -0.35^o$ to 0^o. This turbulent flow along the whole plate was due to separation at the leading edge.

4 Heat transfer measurements

The method of electrocalorymetry was used for the determination of local heat transfer coefficient α as given below:

$$\alpha = \frac{q_{foil} - q_{loss}}{t_w - t_\infty}, \tag{1}$$

where t_w – local temperature of the surface (wall), t_∞ – free stream temperature, q_{foil} – density of heat flux generated by alternating electrical current,

$$q_{foil} = \frac{\sqrt{3}IE}{F}, \tag{2}$$

where I – current intensity of the foil (heated section), E – voltage difference of the heated section, F – surface of the heated section.
Heat losses q_{loss} are calculated as a sum of three components according to the formula

$$q_{loss} = q_{rad} + q_l + q_d \tag{3}$$

here radiation losses q_{rad} are given as:

$$q_{rad} = \varepsilon\sigma(T_w^4 - T_\infty^4). \tag{4}$$

The emissivity of the painting is equal to $\varepsilon = 0.3$ and σ is the Stefan-Boltzman constant.

The heat losses caused by heat transfer along the plate can be calculated from the heat balance of the infinitesimal section along the plate and depend on the conductivity of materials composing the plate and their respective thicknesses:

$$q_l = (\lambda_{pl} d_{pl} + 2\lambda_{foil} d_{foil}) \frac{\partial^2 T_m}{\partial x^2}, \tag{5}$$

where λ_{pl}, d_{pl} and λ_{foil}, d_{foil} are the thermal conductivity coefficients and thicknesses of the plate and heat foil, and T_m is average temperature across the plate $T_m = (T_u + T_d)/2$ where T_u and T_d are temperatures on the upper and lower surface (foil) of the plate. The losses q_l are actually neglected in the calculations of heat flux basing on the assumption that they are small in comparison to the losses q_d considered below.
The heat losses across the plate is given by the following formula:

$$q_d = \lambda_{pl} \frac{\partial T}{\partial y}. \tag{6}$$

Assuming that the temperature gradient of the plate is constant this formula can be presented in a simple form:

$$q_d = \lambda_{pl} \frac{\Delta T_d}{d_{pl}}, \tag{7}$$

where d_{pl} – is the plate thickness and $\Delta T_d = (T_u - T_d)/2$ – temperature difference across the plate. This time the assumption is made that the temperature across the foil is rather steady because of its very small thickness and the foil is the heat source.
Finally, the Stanton number is defined by the following formula:

$$\mathrm{St} = \frac{\alpha}{\rho C_p U_o}. \tag{8}$$

According to the Reynolds analogy, the following formula expresses the relation between local shear stress C_f and the Stanton number St for the laminar boundary layer, where Pr is the Prandtl number and C_{si} is non-isothermality coefficient which for the case of constant heat flux is equal to $C_{si} = 1.35$ [1].

$$\mathrm{St} = C_{ni} \frac{C_f}{2} \mathrm{Pr}^{-2/3}. \tag{9}$$

Applying the well known formula for the local shear stress coefficient C_f for the laminar boundary layer:

$$C_f = 0.644\, \mathrm{Re}_x^{-1/2} \tag{10}$$

and than the formula for Stanton number can be given as below (where the Prandtl number for air $\mathrm{Pr} = 0.72$):

$$\mathrm{St} = 0.55\, \mathrm{Re}_x^{-1/2}. \tag{11}$$

The formula for the local shear stress C_f in the case of turbulent flow is given below:

$$C_f = 0.0595\, \mathrm{Re}_x^{-1/5}. \tag{12}$$

The formula for the Stanton number St in the case of turbulent flow is also well known:

$$\mathrm{St} = 0.036\, \mathrm{Re}_x^{-1/5}. \tag{13}$$

The above given formulae for local shear stress C_f and heat transfer St can be found in monographs by e.g. Schlichting and Gersten, [4] and also in Schetz and Fuhs [3].

5 Results and discussion

5.1 Calibration of plate – Reynolds analogy

The first results of measurements are presented in Fig. 3 where besides the results of the local shear stress C_f measurements by means of hot wire for the cold plate also the local heat transfer coefficient represented by Stanton number St along the plate, i.e versus Reynolds number are shown. While the Stanton number measurements are made for six different velocities in the range from 16 to 20 m/s, the local shear stress coefficient C_f measurements are made for the cold plate and only for three velocities $U_o = 10, 15$ and 20 m/s. The shear stress measurements are compared with the measurement of C_f made previous in [5] and very close similarity and equivalence has been found. This part of investigation is made for the purpose of plate calibration and confirmation of existence of the Reynolds analogy.

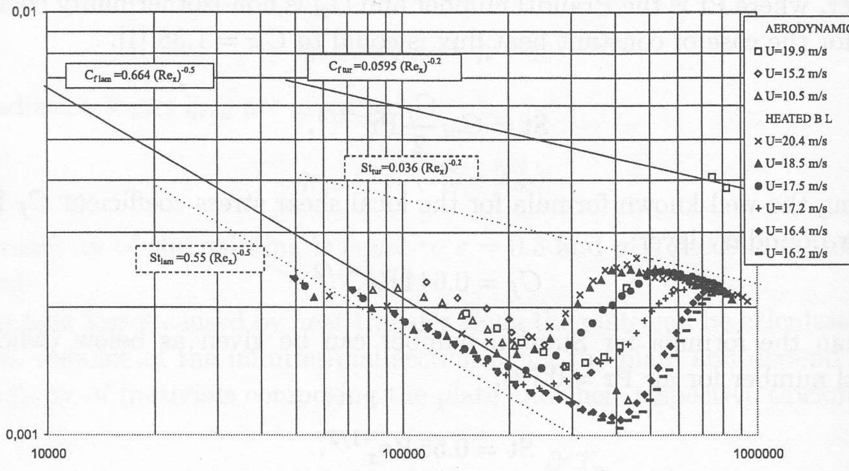

Figure 3. Local Stanton number St and shear stress coefficient C_f versus Reynolds number along the cold and heated flat plate for the angle $i = -0.6°$ and different velocities from 10 to 20 m/s.

It is easy to see that Reynolds analogy according to formulae (9) exists especially for the laminar but also for turbulent flow although the turbulent flow is presented only by two points for the velocity $U_o = 19.9$ m/s (open square). The steady lines correspond to C_f values according to (10) and (12) and broken lines correspond to the Stanton number St according to (12) and (14) for laminar and turbulent flow, appropriately.

5.2 Results of temperature and local heat transfer coefficient measurements

In the figures below the example of temperature and local heat transfer coefficient measurements are presented. Figure 4 presents the temperature distribution along the plate for three different incidence angle. For the $i = -0.8^o$ the temperature rises steadily along the plate, for the incidence $i = 0.0^o$ the temperature also rises steadily but is a few degree lower than for the case of $i = -0.8^o$. For the incidence angle $i = -0.6^o$ we observe the maximum in the temperature distribution as the indication of the laminar-turbulent transition. For the incidence angle $i = -0.8^o$ the state of the boundary layer is laminar, and for the incidence $i = -0.0^o$ the flow in the boundary layer is fully turbulent thanks of the separation at the leading edge, and for the incidence angle $i = -0.6^o$ at the leading edge the laminar flow can be observed, than transitional where the fall of the temperature is seen, and finally turbulent flow where the temperature distribution lies on the same line as for the incidence angle $i = -0.0^o$. So do the temperature changes between the laminar and turbulent distribution.

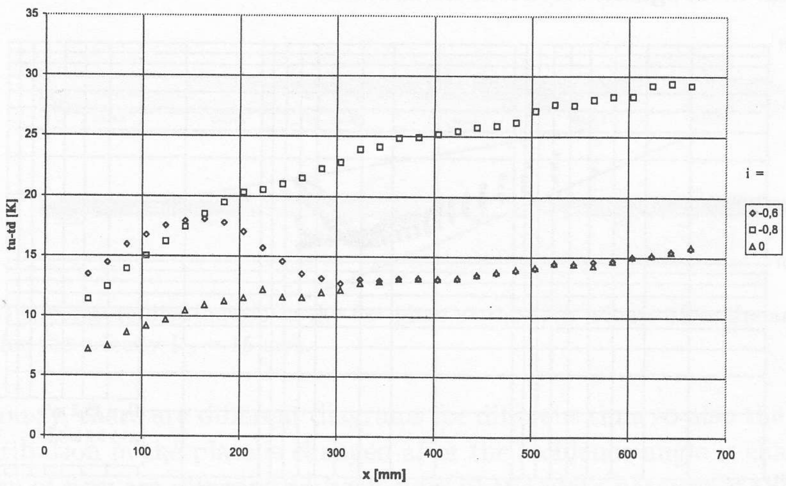

Figure 4. Temperature distribution along the plate for three different incidence angle.

According to the formulae given in the section 4, the local heat transfer coefficient α can be determined which is shown for different incidence angle as in the figure shown before, Fig. 5. For these distributions the same three different states of the boundary layer can be observed, i.e. laminar, turbulent and transitional.

5.3 Transient heat transfer

Next figure, Fig. 6, shows the changes in time of the Stanton number along the flat plate after the incidence angle change from -0.8^o to -0.6. For the angle

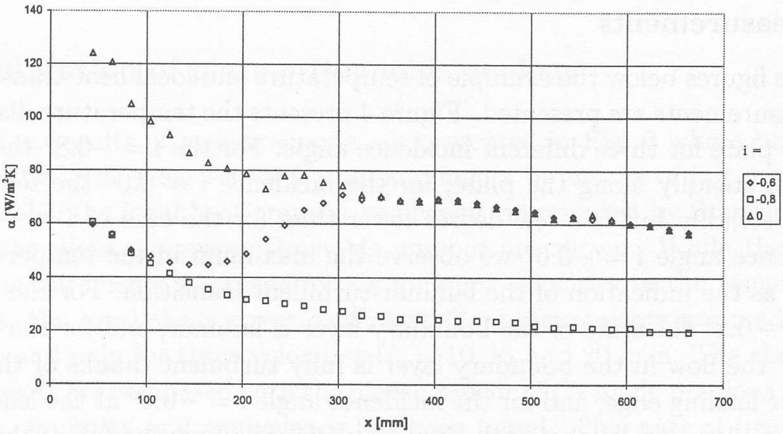

Figure 5. Local heat transfer coefficient along the plate.

-0.8° the heat transfer is almost parallel to laminar state of the flow in boundary layer for all investigated Reynolds numbers.

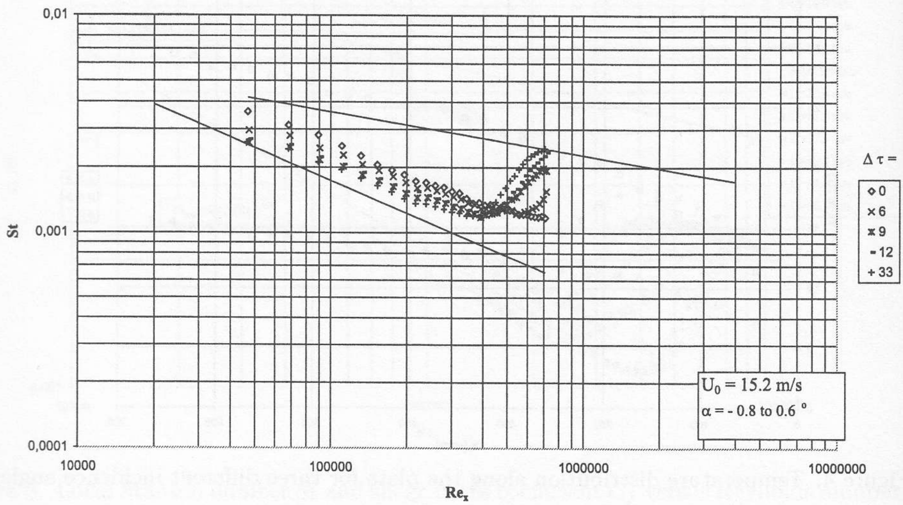

Figure 6. The Stanton number St distribution after the incidence angle change from -0.8° to -0.6° in the course of time $t = 0$ to 33 min.

In Fig. 6 the Stanton number distribution at six different time stamps: 0, 6, 9, 12 and 33 minutes are shown. In the first six minutes, after the angle change, small changes in the Stanton number distribution at the trailing edge of the plate are seen. In the next three minutes the boundary layer transition is better recognized showing the deeper valley in the Stanton number distribution. In the course of time the signs of the transition are more and more apparent. At the end, after 33 minutes the transition in the boundary layer is clearly seen. The Stanton number distribution begins at the laminar line and ends at the turbulent one. So after 33 minutes the transition in the boundary layer of the heated flat plate after the change of the incidence angle is finished. In the presented case the process of heat transfer is the interaction between the heat transfer in the boundary layer and the heat transfer in the plate. After the new heat balance in the plate is reached also the new state of flow in the thermal boundary layer i.e. transition is finished. Apparently some time is required to achieve a new heat balance and finish the process of transition. The process of achieving the new balance in the plate is much longer than that connected with external processes in the flow e.g. wake passing or the plate characteristic time $\tau = L/U_o$. The temperature measurements on both sides of plate enable presentation of temperature distribution in the flat plate, Fig. 7 (upper part of picture, lower part gives the colour temperature scale). Laminar-turbulent transition is shown as the region of higher temperature on the upper surface of plate. The leading edge of the plate is not shown on the diagram. The first point corresponds to the first point of temperature measurements, i.e. 44 mm from the leading edge.

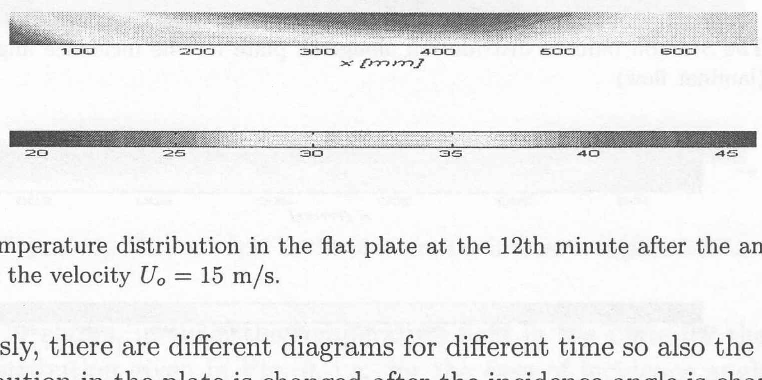

Figure 7. Temperature distribution in the flat plate at the 12th minute after the angle change for the velocity $U_o = 15$ m/s.

Obviously, there are different diagrams for different time so also the temperature distribution in the plate is changed after the incidence angle is changed The conditions of flow are different on both sides of the plate because of the shape of the leading edge of plate and the not positive incidence angle. All the time on the lower side of plate the turbulent boundary layer exists.

5.4 Transient temperature field on the plate

Next the results of Stanton number distribution along the plate with the temperature field in the plate are shown for the oncoming velocity $U_o = 20$ m/s and for different flow condition in the boundary layer. First, the Stanton number distribution, Fig. 8, for the laminar flow in boundary, i.e. for the incidence angle equal to $-0.8°$, will be discussed.

The Stanton number distribution versus Reynolds number is parallel to the steady line according to the formula (12) for the laminar flow. The discrepancy is due to the velocity gradient along the plate caused by the negative incidence angle.

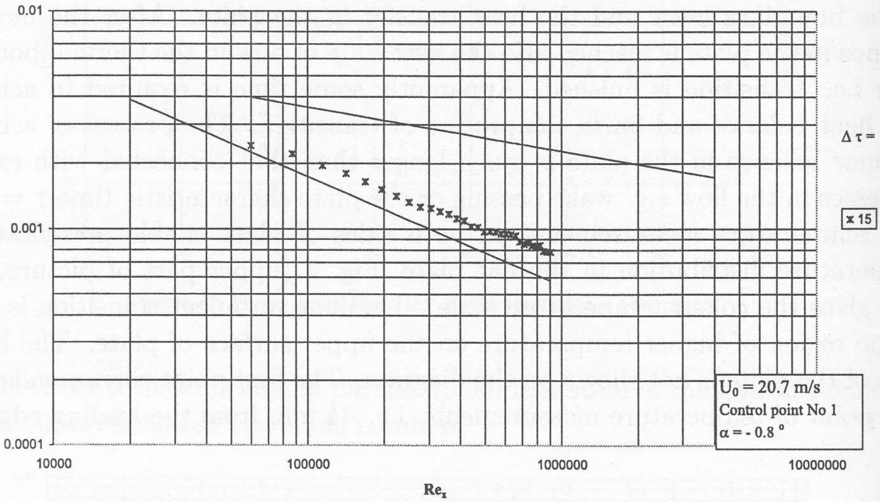

Figure 8. The Stanton number distribution along the plate for the incidence angle $i = -0.8°$ (laminar flow).

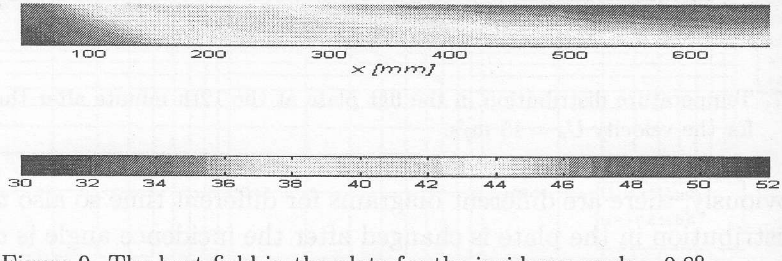

Figure 9. The heat field in the plate for the incidence angle $-0.8°$.

Figure 9 shows the appropriate temperature field in the flat plate. On the upper surface the continuous increase of temperature is seen according to the steady decrease of the Stanton number.

In Fig. 10, the transitional distribution of the Stanton number can be seen. This measurement is made for the incidence angle equal to $i = -0.64°$. For this case at the end of the plate the transitional character of the flow is observed and the Stanton number distribution has a minimum of St $= 0.0009$ for the $Re_x = 7 \cdot 10^5$, but the fully turbulent flow on the upper side of plate is not achieved.

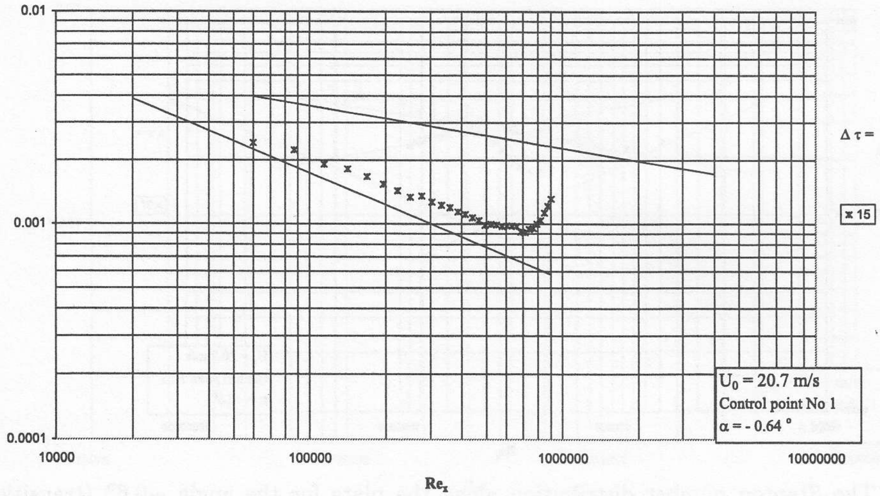

Figure 10. The Stanton number distribution along the plate for the angle -0.64° (transition at the end of plate).

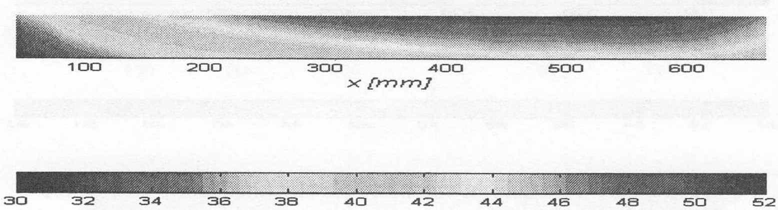

Figure 11. The heat field in the plate for the incidence angle -0.64°.

Figure 11 shows, in turn, the temperature field in the plate for the Stanton number distribution given in Fig. 9, i.e. for the case of incidence angle -0.64°. Here, the decrease of the temperature at the end of plate is clearly seen.

Two subsequent figures, Figs. 12 and 13, show the distribution of the Stanton number and thermal field for the transition passing towards the leading edge of the plate when the decrease of temperature of the upper surface of plate in comparison to the former case is easy to notice. This time the transition is much closer to the leading edge than in case shown in Figs. 9 and 10, and also the slight increase of the temperature near the leading edge is observed.

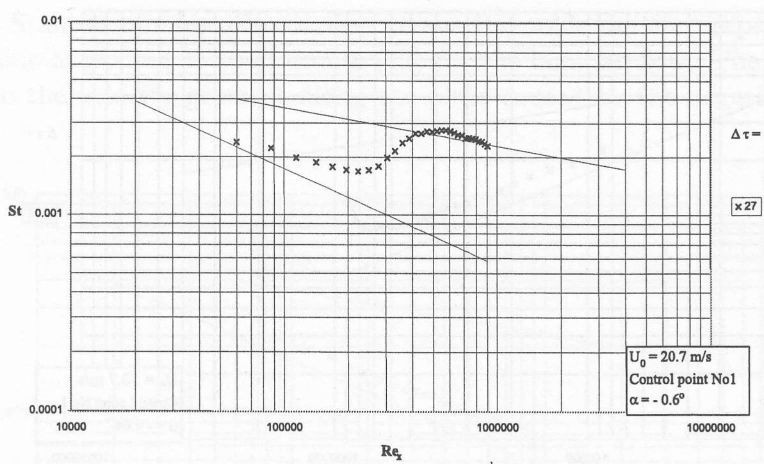

Figure 12. The Stanton number distribution along the plate for the angle $-0.6°$ (transition passing to the leading edge).

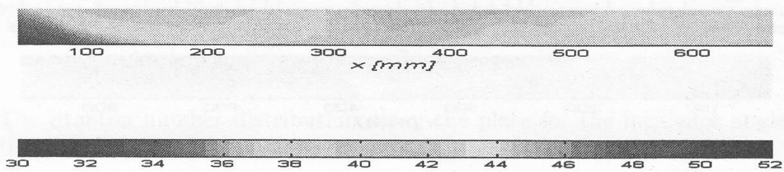

Figure 13. The heat field in the plate for the incidence angle $-0.60°$.

The minimum of Stanton number is St $= 0.0018$ for Reynolds number $\mathrm{Re}_x = 2.3 \cdot 10^5$ whereas at the end of plate fully turbulent flow conditions exist.

Finally, the case of the turbulent flow on the upper side of the plate is shown, i.e. for the case of the incidence angle equal to $i = -0.24°$. This time the separation at the leading edge caused the turbulent behaviour of the boundary layer along the whole plate. This case is presented in Figs 14 and 15. As expected, for the turbulent boundary layer, the temperature of the upper surface of the plate is much lower than for cases presented before due to greater heat transfer to the flow.

6 Conclusions

In this paper investigation of heat transfer on a flat plate in a low turbulence, $Tu < 0.08\%$, subsonic wind tunnel facility for two different oncoming velocities $U_o = 15$ and 20 m/s is reported. It is supposed that the condition of constant

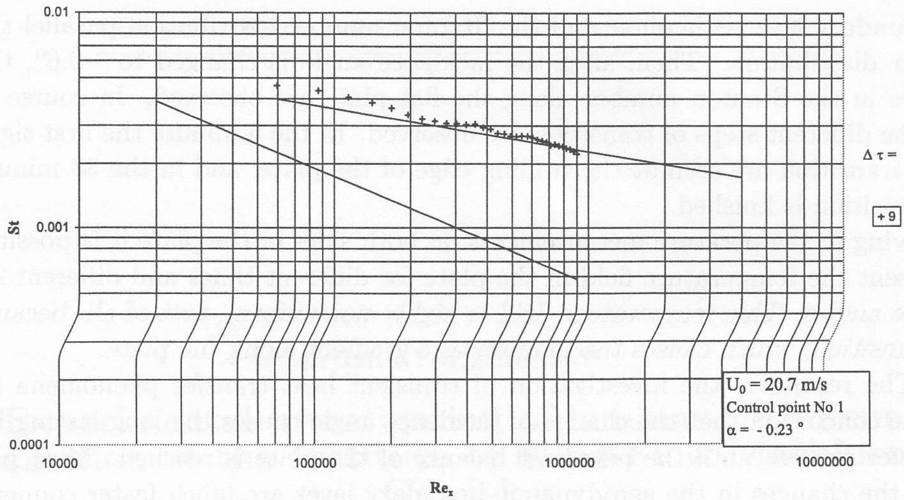

Figure 14. The Stanton number distribution along the plate for the angle $-0.23°$ (fully turbulent boundary layer).

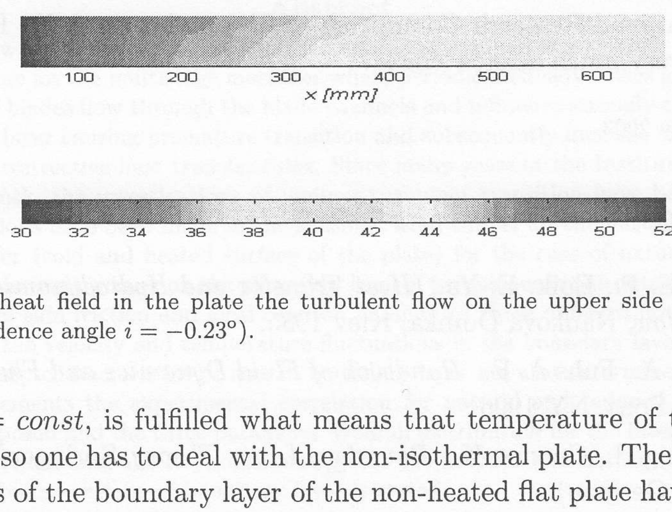

Figure 15. The heat field in the plate the turbulent flow on the upper side boundary layer (incidence angle $i = -0.23°$).

heat-flux, $q = const$, is fulfilled what means that temperature of the plate was not constant, so one has to deal with the non-isothermal plate. The aerodynamic measurements of the boundary layer of the non-heated flat plate have been made previously. The measurements of steady temperature were taken on the surface of the flat plate and the local heat transfer coefficient distribution along the plate were determined on that basis. First, the local shear stress coefficient C_f for cold plate and Stanton number St measurements for different flow velocities are presented. The Reynolds analogy between Stanton number and shear stress C_f is well confirmed.

Next, the transient behaviour of heat transfer after the incidence angle change is presented, i.e. the Stanton number distribution along the flat plate after the change of the incidence angle is investigated. At the angle $-0.8°$ the flow in the boundary layer is laminar and the Stanton number distribution parallel the laminar distribution. Then, after the incidence angle is changed to -0.6°, the changes in the Stanton number along the flat plate are observed. In course of time the different steps of transition are observed. In the 6 minute the first signs of the transition are seen at the trailing edge of the plate, and in the 33 minute the transition is finished.

Owing to temperature measurements on both sides of the plate it is possible to present the temperature field in the plate for different times and different incidence angles. This temperature field is highly nonuniform, first of all, because of transition, which causes the temperature gradient along the plate.

The results of the investigation of transient heat transfer phenomena lead to the conclusion that the change of incidence angle causes the long-lasting heat transfer process until the new heat balance of the plate is reached. Most probably the changes in the aerodynamic boundary layer are much faster connected with the characteristic time of plate $\tau = L/U_o$ than the changes in the thermal boundary layer connected with temperature (heat) field in the plate.

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