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Temperature boundary layer on a rotating surface - the problem of the constant temperature wall

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This paper is dedicated to the memory of my late professor Dr Viktor N. Saljnikov.

Abstract

Introducing the group of Loitskanskii [1] form-parameters and transformations of Saljnikov [2], the set of governing equations of the incompressible laminar temperature boundary layer was transformed in the universal form, with Prandtl number as parameter, for the case of the constant wall temperature. Using the universal results for air ($Pr = 0.72$) the procedure for calculation of the Nusselt number (dimensionless heat transfer coefficient) on the particular contour (airfoil NACA 0010-34) was developed. The dimensionless temperature profiles within the boundary layer were presented also. The parameter of rotation Ω_0, as well as Eckert number, was varied, and their influences on the heat transfer from the surface to the working fluid were presented and analyzed.

Keywords: laminar temperature boundary layer, 2-D flow, rotating contour, heat transfer, local Nusselt number distribution.

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Nomenclature

$a_0; b_0$	constants
A_0	dimensionless displacement thickness
B_0	dimensionless momentum thickness
c	coefficient of thermal conductivity
Ec	Eckert number
f_1	first form parameter
f_k	set of form parameters
F	characteristic boundary layer function
H	displacement/momentum thickness ratio
h	heat transfer coefficient
Nu	Nusselt number
Pr	Prandtl number
P	function determining the influence of friction on the boundary layer temperature
R	function determining the influence of the given wall temperature on the boundary layer temperature
S_v	transforming function
T	temperature
T_w	wall temperature (constant)
T_∞	temperature of the outer flow (constant)
$u; v$	velocity components
$U; V$	velocities of the outer potential flow
U_∞	velocity far afore the body (constant)
$x'; y$	coordinates
x	dimensionless coordinate
δ^*	displacement thickness
δ^{**}	momentum thickness
ζ	dimensionless friction factor
η	dimensionless transversal coordinate
θ_k	recurrent function
θ	dimensionless temperature
ν	kinematics viscosity
ψ	stream function
Φ	universal dimensionless stream function
Ω	parameter of rotation

1 Introduction

Development of technology and resources for scientific computation in recent years offers a solution of numerous problems in fluid mechanics. Using CFD (Computational Fluid Dynamics) ready-made programs, solutions of many certain problems can be obtained. The problem with solutions obtained in this manner is their particularity – they belong to certain particular problem and even a minor variation of governing parameters demands an entirely new numerical treatment of the problem concerned. More theoretical approach to the treated problem, on the other hand, leads to the more general solution that covers, at least, a class or a group of the particular cases. In the laminar boundary layer theory, the method of Loitskianskii [1], improved by Saljnikov [2] and his school, seems to be very promising approach for theoretical treatment of various problems – Boricic et al [3], Saljnikov et al [4], Miric-Milosavljevic, Pavlovic [5], Obrovic et al [6] and Ivanovic D., Ivanovic V. [7].

The boundary layer flow on a rotating surface of arbitrary shape, such as rotating radial impeller blade on the Fig.1, was intensively studied in fluid mechanics due to its practical application in turbo machines. Papers of Jungclaus [8], Li [9], Glauert [10] and Saljnikov, Djordjevic [11], demonstrating the interest for the treated problem, were the results of discussion on the problem of linearization of the influence of rotation. Using the multi-parametric method of Loitskianskii [1], and transformations proposed by Saljnikov [2] the solutions for the dynamic boundary layer on the rotating surface were obtained and applied to different practical problems in Saljnikov, Pavlovic [12].

The appropriate study of the heat transfer process is certainly of the particular interest in order to understand better heating or cooling of the rotating surface. In this paper method of determining the Nusselt number is exposed. The procedure is based on the universal solutions of temperature boundary layer on the rotating surface obtained in the paper [13].

2 Universal equations of the boundary layer

When the influence of rotation is present in the stream field, the governing equations of the dynamic and temperature boundary layers on the rotating

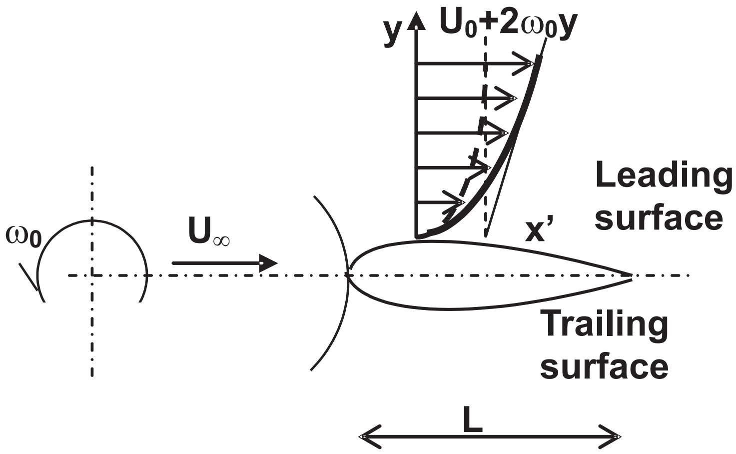

Figure 1: Boundary layer on the rotating surface.

surface can be obtained in the following form:

$$u\frac{\partial u}{\partial x}+v\frac{\partial v}{\partial y}=\nu\frac{\partial^2 u}{\partial y^2}+\left(U\frac{\partial U}{\partial x}+V\frac{\partial U}{\partial y}\right)_{y=\infty} \tag{1}$$

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0, \tag{2}$$

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\frac{\nu}{c}\left(\frac{\partial U}{\partial x}\right)^2+\frac{\nu}{\mathrm{Pr}}\frac{\partial^2 u}{\partial y^2}, \tag{3}$$

where U, V are velocities of the outer potential flow. It is important to notice that the equations (1-3) are relevant to the dynamic and thermal plane boundary layers on the rotating surface of an incompressible fluid. The corresponding boundary conditions are:

$$y=0: u=v=0,\ T=T_w; \quad y\to\pm\infty: u=U_0\pm 2\omega_0 y,\ T=T_\infty \tag{4}$$

where: ω_0 - angular velocity of the rotating surface, Fig.1. In (4) and further sign '+' corresponds to the leading surface and sign '-' to the trailing surf ace of the blade impeller. The influence of rotation was analyzed and introduced in the form (4) by Jungclaus [8].

Instead of velocity, as usually for the incompressible flows, the stream function ψ is introduced:

$$u = \frac{\partial \psi}{\partial x}; \quad v = \frac{\partial \psi}{\partial y} \tag{5}$$

In order to universalize the governing equations (1-3) Lotskianskii's method [1], improved by Saljnikov [2] is used. A new transversal coordinate η and universal stream function Φ are involved:

$$S_v = \left(a_0 \nu \int_0^x U_0^{b_o - 1} dx \right)^{-\frac{1}{2}}; \; a_0 = 0.4408; \; b_0 = 5.714 \tag{6}$$

$$\eta = \frac{U_0^{\frac{b_0}{2}}}{S_v} y, \quad \Phi(x, \eta, \Omega) = \frac{U_0^{\frac{b_0}{2}-1}}{S_v} \psi(x, y\omega_0). \tag{7}$$

The influence of rotation is defined by the means of particular parameter:

$$\Omega = \frac{2\omega_0 S_v}{U_0^{\frac{b}{2}+1}}. \tag{8}$$

Considering the boundary condition (4), temperature can be assumed as a sum of two functions:

$$T = T_\infty + \frac{U_0^2}{2c} P\left(x, \eta, \mathrm{Pr}, \Omega\right) + \left(T_w - T_\infty\right) R\left(x, \eta, \mathrm{Pr}, \Omega\right). \tag{9}$$

Function P determines the influence of friction, and R the influence of the given wall temperature.

Assuming that the rotational parameter Ω (8) is small, functions Φ, P and R can be used in a linear form:

$$\Phi(x, \eta, \Omega) = \Phi_0(x, \eta) + \Omega \Phi_1(x, \eta) + ... \cong \Phi_0(x, \eta) + \Omega \Phi_1(x, \eta), \tag{10}$$

$$\begin{aligned} P\left(x, \eta, \mathrm{Pr}, \Omega\right) &= P_0\left(x, \eta, \mathrm{Pr}\right) + \Omega P_1\left(x, \eta, \mathrm{Pr}\right) + ... \cong \\ & P_0\left(x, \eta, \mathrm{Pr}\right) + \Omega P_1\left(x, \eta, \mathrm{Pr}\right), \end{aligned}$$

$$R\left(x,\eta,\Pr,\Omega\right) = R_0\left(x,\eta,\Pr\right)+\Omega R_1\left(x,\eta,\Pr\right)+...\cong R_0\left(x,\eta,\Pr\right)+\Omega R_1\left(x,\eta,\Pr\right).$$

On the development of the dynamic and temperature boundary layer, there is strong influence of the change of the shape in longitudinal direction. Instead of the longitudinal coordinate x the group of Lotskianskii's form parameters f_k, like in [1], can be introduced:

$$f_k = U_0^{k-1}\frac{d^kU_0}{dx^k}\left(\frac{\delta_0^{**2}}{\nu}\right)^k;\ k=1,2,3...\infty. \tag{11}$$

In this way derivatives in x are transformed in derivatives in f_k using the operator:

$$\frac{\partial}{\partial x}=\sum_1^\infty \frac{df_k}{dx}\frac{\partial}{\partial f_k}=\frac{U_0'}{U_0 f_1}\sum_1^\infty \theta_k\frac{\partial}{\partial f_k},$$
$$\theta_k=\left[k\left(f_1+F\right)-f_1\right]f_k+f_{k+1}. \tag{12}$$

New universal functions F, H and ξ are used in this transformation:

$$F=2\left[\xi-\left(2+H\right)f_1\right]\quad;\quad H=\frac{A_0}{B_0}\quad;\quad \xi=B_0(\Phi_{0\eta\eta})_{\eta=0}. \tag{13}$$

Also, dimensionless displacement thickness A_0 and momentum thickness B_0 are introduced:

$$A_0=\int_0^\infty(1-\Phi_{0\eta})d\eta=U_0^{\frac{b}{2}}\delta_0^*\left(a_0\nu\int_0^x U_0^{b_o-1}dx\right)^{-\frac{1}{2}}, \tag{14}$$

$$B_0=\int_0^\infty\Phi_{0\eta}\left(1-\Phi_{0\eta}\right)d\eta=U_0^{\frac{b}{2}}\delta_0^{**}\left(a_0\nu\int_0^x U_0^{b_o-1}dx\right)^{-\frac{1}{2}}. \tag{15}$$

When the system of governing equations for the dynamic boundary layer (1-2) is transformed, by the means of shown transforming procedure, the system of partial differential equations is obtained for universal stream functions Φ_0 and Φ_1. These results were presented in the paper [12]. For the functions P_0 and P_1, and R_0 and R_1 two independent systems of partial differential equations with corresponding boundary conditions are obtained:

$$\frac{1}{\Pr}P_{0\eta\eta} + \frac{1}{2B_0^2}\left[aB_0^2 + (2-b)f_1\right]\Phi_0 K_{1\eta} - 2\frac{f_1}{B_0^2}\Phi_{0\eta}P_0 + 2\Phi_{0\eta\eta}^2 =$$

$$\frac{1}{B_0^2}\sum_1^\infty \theta_k\left(\Phi_{0\eta}P_{0f_k} - \Phi_{0f_k}P_{0\eta}\right)$$

$$\eta = 0 : P_0 = 0;\ \eta \to \infty : P_0 = 0 \tag{16}$$

$$\frac{1}{\Pr}P_{1\eta\eta} + \frac{1}{2B_0^2}\left[aB_0^2 + (2-b)f_1\right]\left(\Phi_0 P_{1\eta} - \Phi_{0\eta}P_1\right) + \frac{1}{B_0^2}\left[aB_0^2 - bf_1\right]\Phi_1 P_{0\eta} -$$

$$2\frac{f_1}{B_0^2}\Phi_{1\eta}P_0 + 4\Phi_{0\eta\eta}\Phi_{1\eta\eta} = \frac{1}{B_0^2}\sum_1^\infty \theta_k\left(\Phi_{0\eta}P_{1fk} + \Phi_{1\eta}P_{0fk} - \Phi_{0fk}P_{1\eta} - \Phi_{1fk}P_{0\eta}\right)$$

$$\eta = 0 : P_1 = 0;\ \eta \to \infty : P_1 = 0 \tag{17}$$

$$\frac{1}{\Pr}R_{0\eta\eta} + \frac{1}{2B_0^2}\left[aB_0^2 + (2-b)f_1\right]\Phi_0 R_{0\eta} = \frac{1}{B_0^2}\sum_1^\infty \theta_k\left(\Phi_{0\eta}R_{0f_k} - \Phi_{0f_k}R_{0\eta}\right)$$

$$\eta = 0 : R_0 = 1;\ \eta \to \infty : R_0 = 0 \tag{18}$$

$$\frac{1}{\Pr}R_{1\eta\eta} + \frac{1}{2B_0^2}\left[aB_0^2 + (2-b)f_1\right]\Phi_0 R_{1\eta} - \frac{1}{2B_0^2}\left[aB_0^2 + (2+b)f_1\right]\Phi_{0\eta}R_1 +$$

$$\frac{1}{B_0^2}\left[aB_0^2 - bf_1\right]\Phi_1 R_{0\eta} = \frac{1}{B_0^2}\sum_1^\infty \theta_k\left(\Phi_{0\eta}R_{1f_k} + \Phi_{1\eta}R_{0f_k} - \Phi_{0f_k}R_{1\eta} - \Phi_{1f_k}R_{0\eta}\right)$$

$$\eta = 0 : R_1 = 0;\ \eta \to \infty : R_1 = 0 \tag{19}$$

Differential equations (19-22) are not strictly universal, since Prantdl number remains as parameter. First equation in each system, equations (16) and (18), determines the solution of the basic flow, and the second one, equations (17) and (18), gives the solutions that represents the influence of rotation.

3 The results and their application

Since in paper [1], as well as in numerous other applications, were confirmed that first parameter f_1 of the group of parameters f_k is "strong", that means that the practical influence of the parameters of orders higher than one is feeble, the equations (16) were derived in so-called one-parametric approximation. That means: $f_1 \neq 0, f_2 = f_3 = ... = 0$. One-parametric solutions were obtained numerically using finite difference method in the paper [13] for two values of the Prandtl number, $Pr = 0,72$ and $Pr = 1$, since the incompressible fluid is treated.

In the case of constant wall temperature it is important to determine heat transfer process in boundary layer, between the surface and fluid. For such purpose the values of second derivation on the surface of the treated functions P_0,P_1, R_0 and R_1 were calculated and presented on the Fig.2. It is evident that the basic influence of friction, expressed by the function $(P_{0\eta})_{\eta=0}$, is relatively feeble, since it decreases slowly along the boundary layer. On the other hand, the influence of the given wall temperature, expressed by the function $(R_{0\eta})_{\eta=0}$ is strong, particularly approaching the separation point. The influence of rotation on frictional part of heat transfer process, expressed by the function $(P_{1\eta})_{\eta=0}$ is also strong, rising along the boundary layer. From Fig. 2 it is obvious that the rotation has feeble influence on the part of heat transfer process due to given constant wall temperature, since the function $(R_{1\eta})_{\eta=0}$ along the boundary layer is almost constant.

To study heat transfer process on a rotating surface the obtained universal results were applied on the NACA 0010-34 airfoil. Using from [14] dimensionless velocity distribution $\tilde{U}_0 = U_0/U_\infty$ as a function of dimensionless coordinate $x = x'/L$ for this foil characteristic function $(f_1/B_0^2)_p$:

$$\left(\frac{f_1}{B_0^2}\right)_p = a_0 \frac{\tilde{U}_0'}{\tilde{U}_0^{b_0}} \int_0^x \tilde{U}_0^{b_0-1} dx = \left(\frac{f_1}{B_0^2}\right)_u , \tag{20}$$

was calculated and compared with its value obtained from the universal solution: $(f_1/B_0^2)_u$, in order to find the section on the foil to apply the universal solutions. In that way correlation between local coordinate of the contour x and form parameter f_1 is established.

Heat transfer process within the boundary layer is characterized by local heat transfer coefficient. In dimensionless form it is known as Nusselt

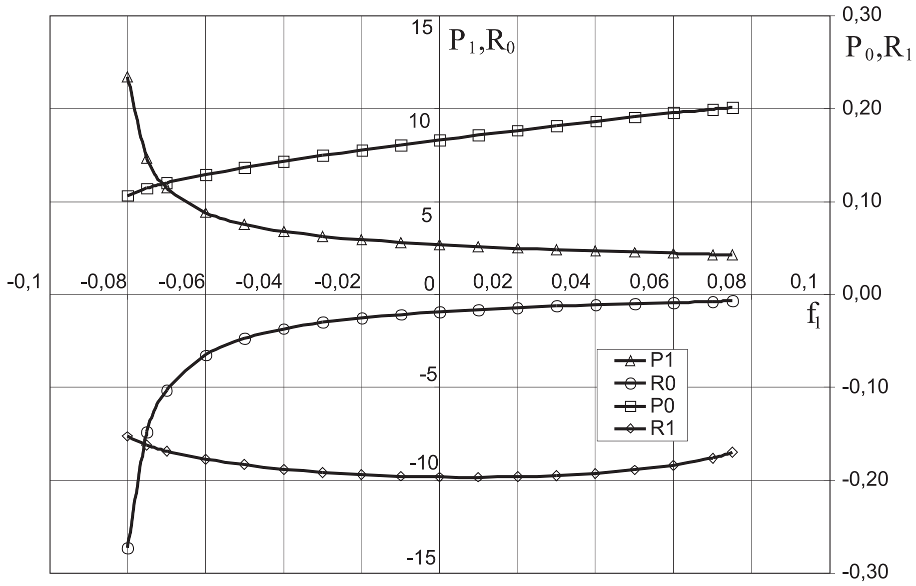

Figure 2: Distribution of parietal values $(P_0\eta)_{\eta=0}$, $(R_0\eta)_{\eta=0}$, $(P_{1\eta})_{\eta=0}$, $(R_{1\eta})_{\eta=0}$ for $Pr = 0.72$.

number, and can be defined as:

$$Nu = \frac{h\,(x)\,L}{c} = \frac{1}{T_w - T_\infty}\left(\frac{\partial T}{\partial \eta}\right)_{\eta=0} =$$

$$\left[\frac{1}{2}EcP_\eta(x,0,\mathrm{Pr}) + \Omega R_\eta(x,0,\mathrm{Pr})\right] =$$

$$= -\left\{\left[\frac{1}{2}EcP_{0\eta}(x,0,\mathrm{Pr}) + R_{0\eta}(x,0,\mathrm{Pr})\right] + \right. \tag{21}$$

$$\left.\tilde{\Omega}\Omega_0\left[\frac{1}{2}EcP_{1\eta}(x,0,\mathrm{Pr}) + R_{1\eta}(x,0,\mathrm{Pr})\right]\right\}$$

Eckert number, manifesting the ratio of the functions P and R, is defined as:

$$Ec = \frac{U_\infty^2}{2c\,(T_w - T_\infty)}. \tag{22}$$

The influence of rotation (8) can be presented as:

$$\Omega = \Omega_0 \tilde{\Omega}, \tag{23}$$

where:

$$\Omega_0 = \frac{2\omega_0 L}{U_\infty \sqrt{Re_\infty}} \tag{24}$$

is specific rotational parameter, depending on particular flow conditions;

$$\tilde{\Omega} = \frac{\left(a_0 \nu \int\limits_0^x \tilde{U}_0^{b_o - 1} dx \right)^{-\frac{1}{2}}}{\tilde{U}_0^{1+b_o/2}} \tag{25}$$

is local rotational parameter depending on velocity distribution, i.e. contour form.

On the Fig. 3 the Nusselt number distribution along the foil contour is shown, with Eckert number as parameter, for the case without rotation ($\Omega_0 = 0$). It is obvious that heat transfer process increases along the boundary layer approaching the separation point. Decreasing the Eckert number also intensifies the heat process.

The Fig. 4 shows the influence of rotation on heat transfer process in boundary layer. In general, this influence is feeble, rising with the growth of the Eckert number.

Although the main practical interest in the treated case is to determine local heat transfer coefficient along the boundary layer, the results obtained can be also used to study how the process develops in normal to surface direction - y. For this reason dimensionless temperature profiles, defined as:

$$\begin{aligned} \tilde{\theta} = \frac{T - T_\infty}{T_w - T_\infty} &= \tfrac{1}{2} EcP(f_1, \eta, 0.72) + R(f_1, \eta, 0.72) = \\ &\left[\frac{1}{2} EcP_0(f_1, \eta, 0.72) + R_0(f_1, \eta, 0.72) \right] + \\ &\Omega_0 \tilde{\Omega} \left[\frac{1}{2} EcP_0(f_1, \eta, 0.72) + R_0(f_1, \eta, 0.72) \right] \end{aligned} \tag{26}$$

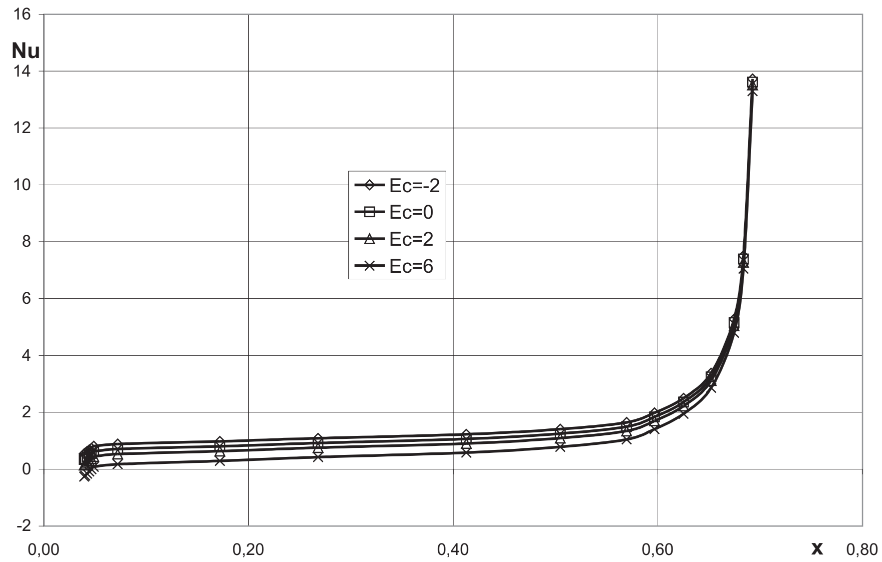

Figure 3: Nuselt number distribution along the aerofoil NACA $0010 - 34$ for $Pr = 0.72$ without rotation ($\Omega_0 = 0$) with Eckert number as parameter.

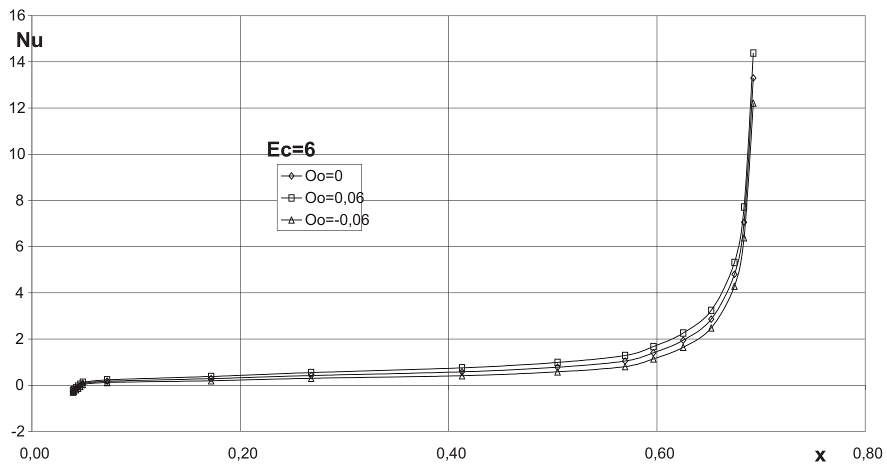

Figure 4: Infuence of rotation ($\Omega_0 = Oo$) on Nuselt number distribution along the aerofoil $NACA0010 - 34$ for s$Pr = 0.72\,(Ec = 6)$.

were calculated for the air, $Pr = 0.72$, for the section where $f_1 = 0$. This section, corresponding to the point of maximal velocity/minimal pressure, is quite suitable, since boundary layer is fully developed.

On the Fig. 5 the influence of the Eckert number is presented, for the case without rotation. It is evident that the growth of Eckert number leads to the increase of temperature within the boundary layer.

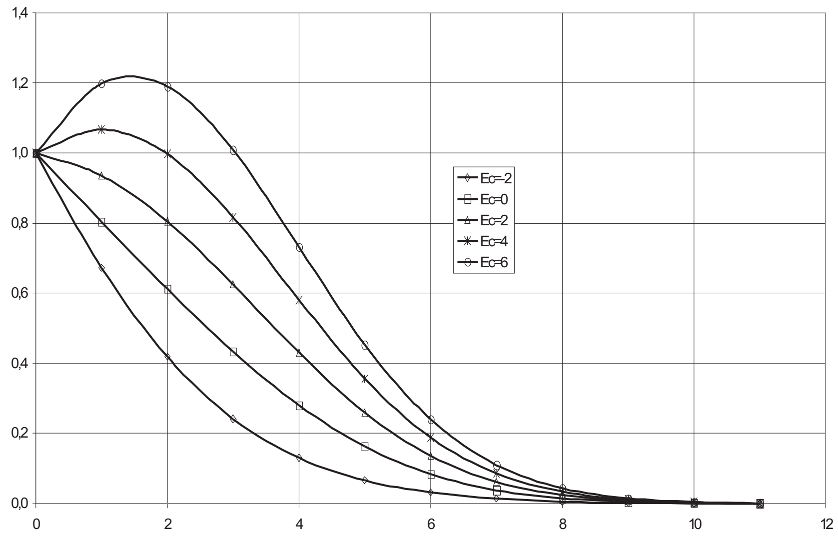

Figure 5: Infuence of the Eckert number on temperature profiles for $Pr = 0.72$, $f_1 = 0$, $\Omega_0 = 0$.

The influence of rotation is presented on the Fig. 6, for the Eckert number $Ec = 2$. The weak influence of rotation is obvious, particularly near to the surface, in the inner part of the boundary layer, increasing the temperature on the leading surface and lessening it on the trailing surface. In the outer part of the boundary layer the influence of the rotation is a little stronger, decreasing the temperature on the leading surface and rising it on the trailing surface.

4 Conclusions

Procedure presented in this paper, showing the method for calculating distinctive features of the temperature boundary layer for the case of constant

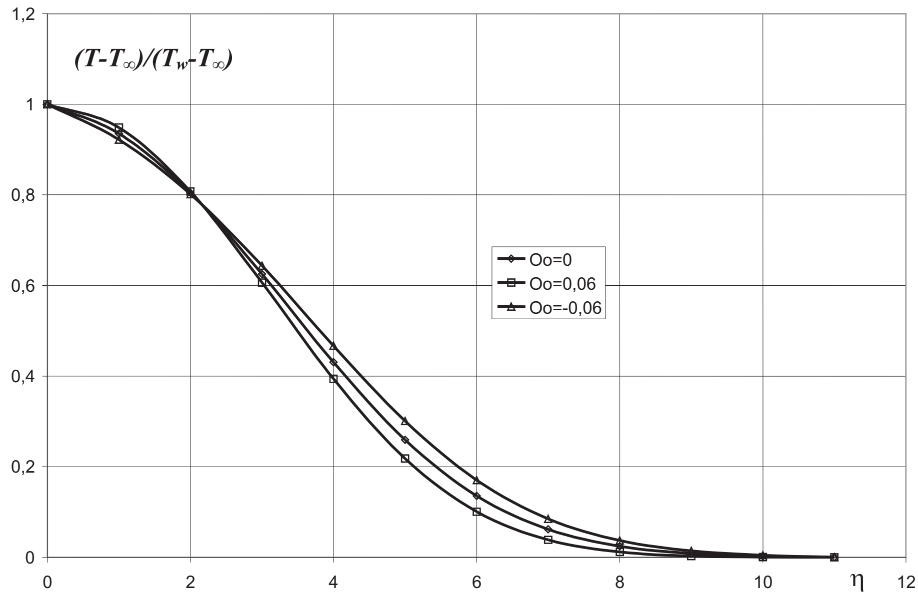

Figure 6: Infuence of rotation ($\Omega_0 = Oo$) on temperature profiles for $Pr = 0.72$, $f_1 = 0$, $Ec = 2$.

wall temperature, seems to be quite suitable for application in technical practice. Proceeding from the solutions of the universal functions for particular Prandtl number, heat transfer process between the surface and a working fluid can be defined, calculating the Nusselt number on the particular contour (here aerofoil NACA 0010-34 was chosen). If necessary, for certain section of the aerofoil, profiles of the dimensionless temperature can be calculated in order to clarify the heat transfer process within the boundary layer. Procedure is rather simple and can be completed using standard programs for spreadsheet calculations (EXCEL for example). Precision of the calculations is very high, what is not evident, since the results are shown graphically.

Presented results enable the estimation of working parameters, significant in the treated case of the constant wall temperature. It is evident that heat transfer between the surface and a working fluid, defined by the Nusselt number, rises along the contour from the stagnation point towards the separation point. Decreasing of the Eckert number results in growth of the Nusselt number. From the presented results it seems that the influence of rotation is particularly feeble, particularly in the inner part of the boundary layer, near to wall.

The principal limitations of the presented model of the temperature boundary layer lie in the assumption of incompressibility. In order to avoid these restrictions more realistic model of the compressible boundary layer has to be taken in further work.

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Temperaturski granični sloj na rotirajućoj konturi - slučaj konstantne temperature zida

UDC 532.526, 536.24

Za slučaj konstantne temperature konture jednačine nestišljivog laminarnog temperaturskog graničnog sloja transformisane su u univerzalni oblik uvodjenjem grupe parametara Lojscjanskog [1] i transformacijama Saljnikova [2], sa Prantlovim brojem kao parametrom. Koristeći univerzalne rezultate za vazduh ($Pr = 0.72$) razvijen je postupak za proračun Nuseltovog broja (bezdimenzionog koeficijenta prelaza toplote) na odredjenoj konturi (aeroprofil NACA 0010-34). Takodje su dati bezdimenzioni profili temperature u graničnom sloju. Variran je parametar obrtanja 0, kao i Ekertov broj, i prikazan je i analiziran njihov uticaj na prelaz toplote sa površine na radni fluid.