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THE EFFECT OF VARIABLE PROPERTIES OF AIR ON THE BOUNDARY LAYER FOR A MOVING CONTINUOUS CYLINDER

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Abstract—The laminar boundary layer flow on an isothermal moving flat sheet and moving cylinder was analyzed by finite differences including variation of air properties in the range 66°C $\le T_w \le$ 1093°C. As to the constant property case, the moving cylinder problem was solved also by an integral method to test the accuracy of the finite difference scheme that was employed. The constant property solutions for both moving flat sheet and moving cylinder are in good agreement with other reported findings. The effect of air property variations is manifested in the increase of C_{fx} and Nu_x with increasing T_w. The results are presented in a practical range of Re_x.

NOMENCLATURE

- C_p, specific heat;
- C_{fr}, local skin friction coefficient, equation (19);
- C_{fx}, local skin friction coefficient, equation (20);
- f, dimensionless stream function, equation (12);
- h_x, local heat transfer coefficient, equation (23);
- k, thermal conductivity;
- r, radial coordinate from the axis of the cylinder;
- Nu_r, local Nusselt number, equation (21);
- Nu_x, local Nusselt number, equation (22);
- Pr, $= \mu C_p/k$ Prandtl number;
- R, cylinder radius;
- Re_x, Reynolds number, equation (18);
- T, temperature of air;
- u, axial component of air velocity;
- U, cylinder velocity;
- v, radial component of air velocity;
- x, axial coordinate;
- y, normal distance from cylinder surface;
- Y, a parameter, equation (15).

Greek symbols

- δ, boundary layer thickness;
- η, transformed r-coordinate, equation (11);
- θ, non-dimensional temperature, equation (12);
- μ, viscosity;
- ν, kinematic viscosity;
- ξ, transformed x-coordinate, equation (11);
- ρ, density;
- ψ, stream function, equation (12).

Subscripts

- w, properties at cylinder surface temperature;
- ∞, properties at ambient temperature.

1. INTRODUCTION

THIS PAPER deals with the axisymmetric boundary layer flow generated by a continuous hot cylinder of infinite length issuing from a slot into stagnant air at uniform temperature. The temperature difference between the cylinder and ambient air can be arbitrary, but it is supposed to be sufficiently large so that the variation of air properties across the boundary layer can be significant. It is with the effect of these air property variations on the air drag and heat transfer rate that this paper is concerned.

In the absence of air property variations, the boundary layer flow on a moving cylinder can be effectively analyzed by an integral method. Sakiadis [1] showed that the various boundary layer parameters can be determined as functions of a single dimensionless group $\nu x/UR^2$ where ν is the kinematic viscosity of air, x, the distance from the slot exit, U, cylinder velocity and R, cylinder radius. However, his investigation was restricted to the momentum transfer in the boundary layer. Bourne and Elliston [2] have extended the problem by including thermal boundary layer equation. The Kármán–Pohlhausen integral technique was used with the assumption that both velocity and temperature profile in the boundary layer can be expressed in a logarithmic form similar to the one used by Sakiadis. The results indicate that Nusselt number, Nu_r, can be approximated, again, by the parameter $\nu x/UR^2$ in the Prandtl number range $0 \le Pr \le 1$. The accuracy of their integral solutions was tested by Karniš and Pechoč [3], who obtained exact solutions for small $\nu x/UR^2$ by power series expansion. According to their study, the Kármán–Pohlhausen method underestimates Nu_r by 8–10% in the range $0.7 \le Pr \le 10$. From these results, it appears that the integral method yields fairly accurate solutions if proper correction factors are used. However, its use is limited to the case where the fluid property variations are negligible.

In most engineering practice, the boundary layer flow on a moving cylinder is closely related to the extrusion process of hot raw material through a slot into ambient air. As such, the temperature difference between the solid surface and ambient air is bound to be large. Typically, the temperature difference can be as high as 1000°C. In this temperature range, the variation of air properties is substantial. For instance, the ratio of air density change from 60 to 1000°C is in the order of 4. Therefore, it can be expected that the solutions obtained taking into account the variation of air properties can deviate significantly from the constant property predictions when a large temperature difference exists in the boundary layer (see, e.g. [4].)

In this paper, the axisymmetric boundary layer equations for a moving, continuous cylinder are solved numerically by finite differences. Assuming that atmospheric pressure prevails throughout the flow field, all the air properties are treated as functions of temperature only. The air property data in [5] were taken and interpolated in the temperature range $66 \leq T \leq 1093$°C by using 4th-order polynomials.

2. FORMULATION

The equations of continuity, momentum and energy for an axisymmetric, laminar boundary layer flow on a moving, continuous cylinder can be written as:

$$\frac{\partial}{\partial x}(\rho r u) + \frac{\partial}{\partial y}(\rho r v) = 0, \tag{1}$$

$$u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = \frac{1}{\rho r}\frac{\partial}{\partial y}\left(r\mu\frac{\partial u}{\partial y}\right), \tag{2}$$

$$u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} = \frac{1}{\rho C_p r}\frac{\partial}{\partial y}\left(rk\frac{\partial T}{\partial y}\right), \tag{3}$$

with boundary conditions for $x > 0$

$$u(x,0) = U;\, v(x,0) = 0;\, T(x,0) = T_w, \tag{4}$$

$$\lim_{y\to\infty} u(x,y)\to 0;\, \lim_{y\to 0} T(x,y)\to T_\infty. \tag{5}$$

Here y signifies normal distance from the solid boundary and $r = R + y$ is the normal distance from the cylinder axis. The two velocity components in the axial and normal direction are denoted by u, v and the temperature by T, with T_w and T_∞ being the boundary temperature at the solid surface and ambient.

Introducing

$$\bar{x} = x;\, \bar{y} = y + \frac{y^2}{2R} \tag{6}$$

and

$$\bar{u} = u;\, \bar{v} = \frac{r}{R}v, \tag{7}$$

the equation of continuity is satisfied if the stream function, ψ, is defined as

$$\bar{u} = \frac{1}{R}\left(\frac{\rho_w}{\rho}\right)\frac{\partial\psi}{\partial\bar{y}};\, \bar{v} = -\frac{1}{R}\left(\frac{\rho_w}{\rho}\right)\frac{\partial\psi}{\partial\bar{x}}. \tag{8}$$

Equations (2) and (3) can be cast into quasi-2-dim. form

$$\bar{u}\frac{\partial\bar{u}}{\partial\bar{x}} + \bar{v}\frac{\partial\bar{u}}{\partial\bar{y}} = \frac{1}{\rho}\frac{\partial}{\partial\bar{y}}\left[\left(1 + \frac{2}{R}\bar{y}\right)\mu\frac{\partial\bar{u}}{\partial\bar{y}}\right], \tag{9}$$

$$\bar{u}\frac{\partial T}{\partial\bar{x}} + \bar{v}\frac{\partial T}{\partial\bar{y}} = \frac{1}{\rho C_p}\frac{\partial}{\partial\bar{y}}\left[\left(1 + \frac{2}{R}\bar{y}\right)k\frac{\partial T}{\partial\bar{y}}\right]. \tag{10}$$

Equations (9) and (10) are now recast into non-dimensional forms by an additional transformation. This transformation is carried out with usual similarity variables for two reasons; firstly, the non-dimensional solution is quite often only a mild perturbation of the similar solution in many boundary layer problems encountered in practice; and secondly, a suitable choice of scaling and dependent variables allows each incorporation of similar solution to the starting point.

Introducing

$$\xi = \bar{x};\, \eta = \sqrt{\left(\frac{U}{\nu_w\bar{x}}\right)}\int_0^{\bar{y}}\frac{\rho}{\rho_w}\,d\bar{y} \tag{11}$$

and

$$f(\xi,\eta) = \frac{1}{R}(\nu_w U\xi)^{-1/2}\psi;\, \theta = \frac{T - T_\infty}{T_w - T_\infty}, \tag{12}$$

the equations (9) and (10) reduce to

$$\frac{\partial}{\partial\eta}\left[\left(1 + \frac{2}{R}Y\right)(\overline{\rho\mu})\left(\frac{\partial^2 f}{\partial\eta^2}\right)\right] + \frac{1}{2}(f)\left(\frac{\partial^2 f}{\partial\eta^2}\right) = \xi\left[\left(\frac{\partial f}{\partial\eta}\right)\left(\frac{\partial^2 f}{\partial\xi\partial\eta}\right) - \left(\frac{\partial^2 f}{\partial\eta^2}\right)\left(\frac{\partial f}{\partial\xi}\right)\right], \tag{13}$$

$$\frac{\partial}{\partial\eta}\left[\left(1 + \frac{2}{R}Y\right)(\overline{\rho k})\left(\frac{\partial^2\theta}{\partial\eta^2}\right)\right] + \frac{1}{2}(Pr_w\bar{C}_p)\left(f\frac{\partial\theta}{\partial\eta}\right) = (Pr_w\bar{C}_p)\xi\left[\left(\frac{\partial f}{\partial\eta}\right)\left(\frac{\partial\theta}{\partial\xi}\right) - \left(\frac{\partial\theta}{\partial\eta}\right)\left(\frac{\partial f}{\partial\xi}\right)\right], \tag{14}$$

$$Y = \left(\frac{\nu_w}{U}\xi\right)^{1/2}\int_0^\eta\frac{d\eta}{\bar{\rho}}. \tag{15}$$

The corresponding boundary conditions are

$$f = 0;\, \theta = \frac{\partial f}{\partial\eta} = 1 \text{ at } \eta = 0 \tag{16}$$

and

$$\frac{\partial f}{\partial \eta} \to 0; \theta \to 0 \text{ as } \eta \to \infty. \tag{17}$$

The equations (13) and (14) can be reduced to two limiting cases; (i) constant property formulation is obtained if $\bar{\rho} = \bar{\mu} = \bar{k} = \bar{C}_p = 1$, (ii) 2-dim. formulation is yielded if $2Y/R = 0$. The latter case can be realized physically if $\delta/R \ll 1$ which is equivalent to the condition $\xi \to 0$, where δ is boundary layer thickness. Thus, by taking sufficiently small ξ, the solutions for a moving cylinder problem can be matched to its two dimensional counterpart. This limiting case is characterized by the boundary layer flow on a moving flat sheet and has been treated by many authors [6–8].

Equations (13) and (14) were reduced to a 1st-order system at the expense of introducing additional equations and then finite differencing was carried out. The resulting system involves two adjacent streamwise stations, one station having known solutions and the other unknowns; hence the solution scheme requires iteration. The non-linear terms in the system were linearized by introducing residuals, defined as the differences between two successive iterations, for each dependent variable. The coupling term functions (variable properties) were not decoupled. Rather, they were treated as lump products to the other dependent variables so that no derivatives of properties had to be used.

The resulting system of equations can be expressed as two matrix equations whose coefficients are tri-diagonal. The matrix inversion was carried out by the standard inversion technique known as Crout or Choleski method of matrix decomposition into upper and lower triangular factors.

The solutions for equations (13) and (14) were calculated first by setting $2Y/R = 0$ and eliminating the right-hand terms assuming that similarity solutions exist. The resulting solutions were then used as initial conditions at small $2Y/R$ for equations (13) and (14). Preliminary study revealed that this initialization procedure is adequate provided that $2Y/R < 0.1$.

3. BOUNDARY LAYER PARAMETERS

The boundary layer parameters of interest can be expressed in non-dimensional forms in terms of f, θ and air properties.

The Reynolds number is defined as

$$Re_x = \frac{Ux}{\nu_w}; \tag{18}$$

the local skin friction coefficient either as

$$C_{fr} = \frac{-2\pi R\mu_w \left(\frac{\partial u}{\partial y}\right)_{y=0}}{\mu_w U} = -2\pi \left(\frac{\nu x}{UR^2}\right)^{-1/2} \left(\frac{\partial^2 f}{\partial \eta^2}\right)_{\eta=0} \tag{19}$$

or as

$$C_{fx} = \frac{-\mu_w \left(\frac{\partial u}{\partial y}\right)_{y=0}}{\frac{1}{2}\rho_w U^2} = -2(Re_x)^{-1/2} \left(\frac{\partial^2 f}{\partial \eta^2}\right)_{\eta=0}; \tag{20}$$

the local Nusselt number as

$$Nu_r = \frac{-2\pi R k_w \left(\frac{\partial T}{\partial y}\right)_{y=0}}{k_w (T_w - T_\infty)} = -2\pi \left(\frac{\nu x}{UR^2}\right)^{-1/2} \left(\frac{\partial \theta}{\partial \eta}\right)_{\eta=0} \tag{21}$$

$$Nu_x = \frac{-k_w \left(\frac{\partial T}{\partial y}\right)_{y=0} x}{k_w (T_w - T_\infty)} = -(Re_x)^{-1/2} \left(\frac{\partial \theta}{\partial \eta}\right)_{\eta=0}; \tag{22}$$

and the local heat transfer coefficient as

$$h_x = \frac{-k_w \left(\frac{\partial T}{\partial y}\right)_{y=0}}{T_w - T_\infty} = Nu_x \left(\frac{k_w}{x}\right). \tag{23}$$

4. RESULTS

All the computations here were carried out in the range $10 \le x/R \le 100$. Since the cylinder radius is in the range $R < 2.5 \times 10^{-3}$ cm in most applications for extrusion process such as fiberization, the Reynolds number of interest in this range is not large. As such, the results are presented here only for $Re_x \le 10^4$.

The effect of variable properties of air on the velocity and temperature profiles is shown in Fig. 1. The inclusion of air property variations increases both the velocity and thermal boundary layer thickness significantly. This increase is the direct indication that the

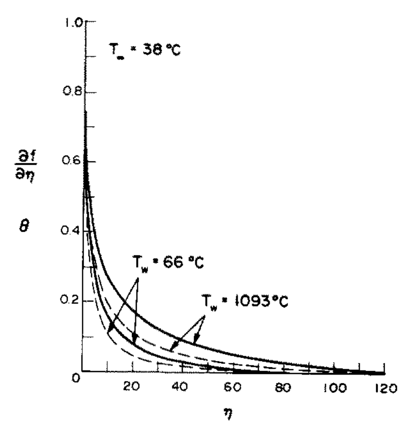

FIG. 1. Effect of variable air properties on velocity and temperature profile ($\xi = 20 \times R$): ---- velocity, —— temperature.

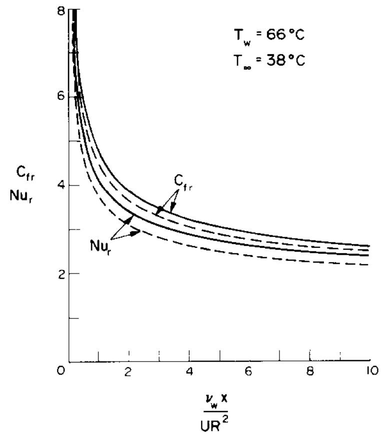

FIG. 2. Comparison of skin friction coefficient and Nusselt number calculated by: ---- integral method, —— finite difference method.

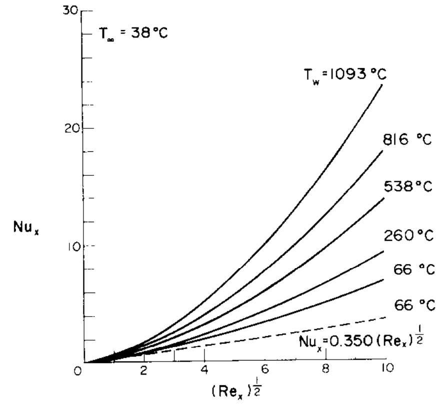

FIG. 4. Effect of variable properties of air on local Nusselt number: ---- moving flat sheet, —— moving cylinder.

surface velocity and temperature gradient are also increased. The boundary layer thickness for a moving flat sheet at the same ξ location was found to be in the range $10 \leq \eta_\infty \leq 20$. As such, it can be inferred that the transverse curvature $(2Y/R)$ exerts a dominant influence upon the boundary layer growth.

In order to test the accuracy of the present solution scheme, the constant property solutions were calculated also by an integral method for comparison. This integral method is basically the same as the one used by [2] and a detailed description of the calculation procedure can be found there. The results are displayed in Fig. 2. The integral solutions agree with those obtained by [2] and [3] within 1%. The percentage increase predicted by the finite difference procedure over integral solutions is about 5% and 9% for the skin friction coefficient, C_{fr}, and Nusselt number, Nu_r, respectively. Following the study by Karniš and Pechoč [3], it can be estimated that the finite difference solutions converge to the exact solutions within 2% with improved accuracy for smaller $\nu x/UR^2$.

The effect of variable properties of air on the local skin friction coefficient, C_{fx}, and the local Nusselt number, Nu_x, is shown in Figs. 3 and 4, respectively. For a moderate temperature difference between the solid surface and ambient air (T_w < 66°C), the constant property approximation is acceptable. When the surface temperature increases, both C_{fx} and Nu_x increase substantially, the increase being more pronounced with increasing $(Re)^{1/2}$. For $Re_x = 10^4$, the increase of C_{fx} and Nu_x, when T_w changes from 66 to 1093°C, is in the order of 5. Since the definition of Reynolds number, Re_x, in Figs. 3 and 4 is based on the kinematic viscosity evaluated at surface temperature, this increase is largely due to air property change at the surface. In order to find the changes of C_{fx} and Nu_x with increasing T_w at the same axial location, therefore, the property effects should be considered. For instance, the following relations:

$$\frac{C_{fx,w}}{C_{fx,\infty}} = \left(\frac{\nu_\infty}{\nu_w}\right)^{1/2} \frac{\left(\dfrac{\partial^2 f}{\partial \eta^2}\right)_{\eta=0,w}}{\left(\dfrac{\partial^2 f}{\partial \eta^2}\right)_{\eta=0,\infty}} \tag{24}$$

$$\frac{Nu_{x,w}}{Nu_{x,\infty}} = \left(\frac{\nu_\infty}{\nu_w}\right)^{1/2} \frac{\left(\dfrac{\partial \theta}{\partial \eta}\right)_{\eta=0,w}}{\left(\dfrac{\partial \theta}{\partial \eta}\right)_{\eta=0,\infty}} \tag{25}$$

can be used for this purpose. The ambient condition can be approximated if $T_w \leq 66$°C. The change of local heat transfer rate at the same location can be more realistically represented in terms of heat transfer coefficient, h_x. In this case, the following relationship applies:

$$\frac{h_{x,w}}{h_{x,\infty}} = \left(\frac{k_w}{k_\infty}\right)\left(\frac{\nu_\infty}{\nu_w}\right)^{1/2} \frac{\left(\dfrac{\partial \theta}{\partial \eta}\right)_{\eta=0,w}}{\left(\dfrac{\partial \theta}{\partial \eta}\right)_{\eta=0,\infty}}. \tag{26}$$

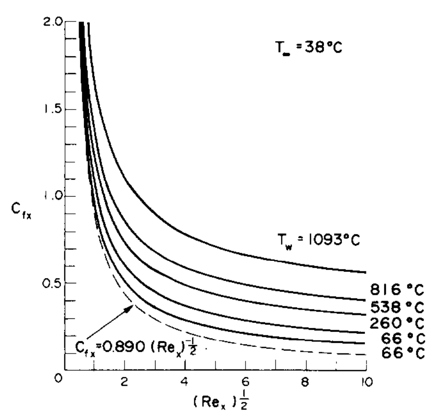

FIG. 3. Effect of variable properties of air on local skin friction coefficient: ---- moving flat sheet; —— moving cylinder.

Table 1. Non-dimensional velocity and temperature gradient at cylinder surface, $T_\infty = 38°C$

T_w	66°C		538°C		1093°C	
$(Re_x)^{1/2}$	$-\left(\frac{\partial^2 f}{\partial \eta^2}\right)_{\eta=0}$	$-\left(\frac{\partial \theta}{\partial \eta}\right)_{\eta=0}$	$-\left(\frac{\partial^2 f}{\partial \eta^2}\right)_{\eta=0}$	$-\left(\frac{\partial \theta}{\partial \eta}\right)_{\eta=0}$	$-\left(\frac{\partial^2 f}{\partial \eta^2}\right)_{\eta=0}$	$-\left(\frac{\partial \theta}{\partial \eta}\right)_{\eta=0}$
0.01	0.445	0.349	0.457	0.351	0.474	0.355
0.1	0.449	0.352	0.471	0.364	0.506	0.384
1.0	0.483	0.384	0.606	0.475	0.784	0.631
5.0	0.623	0.520	1.090	0.913	1.711	1.470
10.0	0.782	0.673	1.596	1.379	2.668	2.355
100.0	2.922	2.783	8.335	7.813	15.76	14.87

Table 1 provides the velocity and temperature gradients on the surface needed to utilize equations (24)–(26). Using this table along with equation (26), it can be found that the increase of h_x at $Re_x = 10^4$ when T_w increases from 66 to 1093°C, is in the order of 7. This increase attributes to the interaction of air properties in the boundary layer rather than to the individual role played by each property.

In Figs. 3 and 4, the results for a moving flat sheet are also displayed for comparison. As previously mentioned, the solutions for a moving cylinder can be matched to that for a moving flat sheet if $2Y/R < 0.1$. This condition is attained if $Re_x < 10^{-4}$. Thus, the role of transverse curvature starts to appear when $Re_x \geq 10^{-4}$. The C_{fx} and Nu_x for a moving flat sheet was found to be

$$C_{fx}(Re_x)^{+1/2} = 0.890 \quad (27)$$

$$Nu_x(Re_x)^{-1/2} = 0.350 \quad (28)$$

respectively. These correlations show an excellent agreement with the results obtained by Sakiadis [9] for C_{fx} and Tsou *et al.* [7] for Nu_x when $Pr = 0.70$ is used.

5. CONCLUSIONS

The effect of air property variations in the boundary layer is manifested in the increase of boundary layer thickness. The direct consequence of this increase is the enhanced C_{fx} and Nu_x for large T_w. The increase of C_{fx} and Nu_x with increasing T_w becomes more substantial with increasing Re_x. The deviation of variable property solutions against constant property case is believed to be the result of air property interactions rather than the contribution of each individual property.

REFERENCES

1. B. C. Sakiadis, Boundary layer behavior on continuous surfaces: III. The boundary layer on a continuous cylindrical surface, *A.I.Ch.E. Jl* **7**, 467–470 (1961).
2. D. E. Bourne and D. G. Elliston, Heat transfer through the axially symmetric boundary layer on a moving circular fibre, *Int. J. Heat Mass Transfer* **13**, 583–593 (1970).
3. J. Karniš and V. Pechoč, The thermal laminar boundary layer on a continuous cylinder, *Int. J. Heat Mass Transfer* **21**, 43–47 (1978).
4. D. E. Bourne and H. Dixon, The Cooling of Fibres in the Formation Process, *Int. J. Heat Mass Transfer* **24**, 1323–1332 (1971).
5. E. R. G. Eckert and R. M. Drake, Jr., *Heat and Mass Transfer*, p. 504. McGraw-Hill, New York (1959).
6. J. W. Rotte and W. J. Beek, Some Models for the Calculation of Heat Transfer Coefficients to a Moving Continuous Cylinder, *Chem. Engng Sci.* **24**, 705–716 (1969).
7. F. K. Tsou, E. M. Sparrow and R. G. Goldstein, Flow and Heat Transfer in the Boundary Layer on a Continuous Moving Surface, *Int. J. Heat Mass Transfer* **10**, 219–235 (1967).
8. L. E. Erikson, L. C. Cha and L. T. Fan, The Cooling of a Moving Continuous Flat Sheet, 8th Natn. Heat Transfer Conf., Los Angeles, Calif., Vol. 62, No. 64, pp. 157–165 (1965).
9. B. C. Sakiadis, Boundary Layer Behavior on Continuous Solid Surfaces: II.–The Boundary Layer on a Continuous Flat Surface, *A.I.Ch.E. Jl* **7**, 221–225 (1961).

EFFET DES PROPRIETES VARIABLES DE L'AIR SUR LA COUCHE LIMITE D'UN CYLINDRE EN DEPLACEMENT CONTINU

Résumé—L'écoulement à couche limite sur une plaque plane mobile isotherme et sur un cylindre mobile est étudié par des différences finies incluant la variation des propriétés de l'air dans le domaine $66 \leq T_w \leq 1093°C$. Comme pour le cas des propriétés constantes, le problème du cylindre mobile est résolu par une méthode intégrale pour tester la précision du schéma aux différences finies qui est employé. Les solutions pour les propriétés constantes dans les deux cas sont en bon accord avec d'autres résultats connus. L'effet de la variation des propriétés de l'air est d'augmenter $C_{f\alpha}$ et Nu_x quand T_w augmente. Les résultats sont présentés dans un domaine pratique de Re_x.

DER EINFLUSS VERÄNDERLICHER STOFFWERTE VON LUFT AUF DIE GRENZSCHICHT EINES BEWEGTEN ZYLINDERS

Zusammenfassung—Die laminare Grenzschichtströmung an einer bewegten ebenen Fläche und an einem bewegten Zylinder wurde mittels finiter Differenzenverfahren unter Berücksichtigung von Änderungen der Stoffwerte der Luft im Bereich von $66 \leqslant T_w \leqslant 1093°C$ untersucht. Für den Fall konstanter Stoffwerte wurde das Zylinderproblem auch nach einem Integralverfahren gelöst, um die Genauigkeit des verwendeten Differenzenverfahrens zu testen. Die Lösungen bei konstanten Stoffwerten sowohl für die bewegte ebene Fläche als auch für den Zylinder befinden sich in guter Übereinstimmung mit anderen bekannten Ergebnissen. Der Einfluß von Änderungen der Stoffwerte der Luft zeigt sich in einer Zunahme von c_{fx} und Nu_x mit wachsendem T_w. Die Ergebnisse werden für den praktisch bedeutenden Bereich von Re_x dargestellt.

ВЛИЯНИЕ ПЕРЕМЕННЫХ СВОЙСТВ ВОЗДУХА НА ПОГРАНИЧНЫЙ СЛОЙ У ДВИЖУЩЕГОСЯ БЕСКОНЕЧНОГО ЦИЛИНДРА

Аннотация — Методом конечных разностей анализируется ламинарное течение в пограничном слое на изотермической движущейся плоской пластине и движущемся цилиндре с учетом изменения свойств воздуха при изменении температуры в диапазоне $66°C \leq T_w \leq 1093°C$. Для случая с постоянными свойствами задача о движущемся цилиндре решена также интегральным методом с целью проверки точности конечно-разностной схемы. Результаты решения для случая с постоянными свойствами как для движущейся плоской пластины, так и движущегося цилиндра хорошо согласуются с другими имеющимися данными. Влияние переменных свойств воздуха проявляется в увеличении C_{fx} и Nu_x с ростом T_w. Приведены результаты для реального диапазона значений числа Re_x.