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A new type of boundary condition in convective heat transfer problems

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Abstract—Earlier, by solving the boundary-layer equations, a new type of boundary condition was obtained [A. Sh. Dorfman, *Heat Transfer of Flow Past Nonisothermal Bodies*. Izd Mashinostroenie, Moscow (1982)] which makes the boundary condition of the third kind more precise and which allows a conjugate problem to be reduced to an equivalent problem for the heat conduction equation. In this paper a procedure is given for the solution of problems with the use of the new kind of boundary conditions and the specific features of the procedure are discussed.

1. INTRODUCTION

IN THE majority of problems associated with heat transfer calculations, the boundary condition of the third kind is used, i.e.

$$q_w = \alpha(T_w - T_\infty). \quad (1)$$

The heat transfer coefficient α in this equation can be found from the relations obtained either theoretically or experimentally by solving a particular heat transfer problem. That this approach is an approximate one is seen from the following. Experimental or theoretical determination of the heat transfer coefficient involves certain boundary conditions. Usually, these are the most simple conditions: T_w = const. or q_w = const. The resulting relations for the heat transfer coefficients are then used in all cases irrespective of the actual temperature or heat flux distribution over the body surface in the problem considered. In other words, this approach is based on the supposition that the heat transfer coefficients are independent of the conditions at the body–heat agent interface.

In some problems this assumption closely approximates the real situation, so that the use of the conventional approach, based on the third-kind boundary condition and heat transfer coefficients for isothermal surfaces, does not entail substantial errors. However, as has been frequently indicated over the past 30 years (beginning with ref. [2]), there are a number of problems in which the neglect of the heat transfer coefficients being the functions of the boundary conditions leads not only to appreciable errors, but also to qualitatively erroneous results.

The above and ever-increasing requirements on the accuracy of thermal calculations, which sharply reduce the range of problems admitting approximate formulation, resulted in a situation that in recent years one has begun to consider the convective heat transfer problems as conjugate ones, i.e. to use the boundary conditions of the fourth kind instead of the third-kind boundary conditions.

2. BASIC RELATIONS

Conjugate formulation considerably complicates the problem, since instead of the heat conduction equation for a body with boundary condition (1) one has to consider a system consisting of the heat conduction equation for a body and boundary-layer equations for a heat agent, and to seek such solutions of this system which would satisfy the conditions of conjugation at the interface. The solution of conjugate problems might be markedly simplified if boundary condition (1) could be refined in such a way that it could be valid for any temperature distribution of the body in flow. Then the solution of the conjugate problem might be reduced again to the solution of one heat conduction equation for a body but with a refined, and not usual, boundary condition. Not only could the solution of conjugate problems thus be simplified considerably, but one could use the background of experience gained for many years in the solution of the heat conduction equation.

In ref. [1], by solving the boundary-layer equations, it was shown that this kind of boundary condition, which would be valid for arbitrary surface temperature distribution over a streamlined body, can be presented in the form

$$q_w = \alpha_*\left(t_w + g_1\Phi\frac{dt_w}{d\Phi} + g_2\Phi^2\frac{d^2t_w}{d\Phi^2} + \cdots + g_k\Phi^k\frac{d^kt_w}{d\Phi^k} + \cdots\right). \quad (2)$$

Equation (2) is valid for a separation-free flow around an arbitrarily shaped body. For a non-gradient flow past a plate $U(x) = U_\infty$ = const., $\Phi = U_\infty x/\nu$, and equation (2) simplifies to

$$q_w = \alpha_*\left(t_w + g_1x\frac{dt_w}{dx} + g_2x^2\frac{d^2t_w}{dx^2} + \cdots + g_kx^k\frac{d^kt_w}{dx^k} + \cdots\right). \quad (3)$$

NOMENCLATURE

a	thermal diffusivity
c_1, c_2	exponents in the expression for the function of influence
c_p	specific heat
$f(\xi/\Phi)$	function of influence of unheated length
Fo	Fourier number
g_k	coefficients of series determining heat flux density
L	length of a body
Pr	Prandtl number
Q	heat flux
q	heat flux density
q_v	strength of volumetric heat release by inner sources
R	parameter determining the ratio between body and heat transfer agent thermal resistances
r/s	exponent at Reynolds number in similarity equation for the Nusselt number on isothermal plate
T	temperature
t_w	temperature difference, $T_w - T_\infty$
$U(x)$	velocity distribution at the boundary layer outer edge
U_w	speed of flat plate pulling
x, y	coordinates reckoned along body surface and along the normal to it.

Greek symbols

α	heat transfer coefficient
β	parameter characterizing longitudinal change of pressure gradient
Δ	plate thickness
ζ	dimensionless longitudinal coordinate, x/L
θ	dimensionless temperature
λ	thermal conductivity
Λ	parameter characterizing the ratio between body and heat transfer agent thermal resistances
ν	kinematic viscosity
ρ	density
τ	time
Φ	Görtler variable, $\frac{1}{\nu}\int_0^x U(\xi)\,d\xi$.

Subscripts

*	isothermal surface
w	wall
∞	far from a body
in	initial
f	final
av	average
L	at the end of the body of length L.

In the case of laminar flow the coefficients g_k are defined by the formula

$$g_k = \frac{(-1)^{k+1}}{k!(2k-1)}.$$

When $Pr \to 0$, this formula defines all the coefficients g_k; for $Pr \neq 0$, it defines these coefficients beginning only from the third term. The first two coefficients turn out to be dependent on Pr number and on the parameter

$$\beta = 2\left(1 - \frac{\nu\Phi}{xU}\right),$$

which depicts a change of the pressure gradient in the flow. The coefficients g_1 and g_2 can be found from the graphs given in ref. [1] and obtained by numerical integration of appropriate ordinary differential equations. Also given in that reference are the values of the coefficients g_k for turbulent flow past bodies and other cases as, e.g., flows of non-Newtonian power-law fluids, compressible gases, etc.

It follows from equations (2) and (3) that the relationship between the heat flux and temperature difference can be represented by a sum whose number of terms depends on the temperature difference distribution. For an isothermal surface, t_w = const. In this case only the first term is retained in equations (2) and (3) and, as in the third-kind boundary condition (1), the heat flux density turns out to be proportional to the temperature difference. When the temperature difference varies linearly, the heat flux density is represented by the sum of two terms the first of which is proportional to the temperature difference and the second, to its first derivative with respect to the longitudinal coordinate (in general, with respect to the variable Φ). When the temperature difference varies parabolically, $t_w(x)$, the heat flux density starts already to depend on the temperature difference and its first two derivatives, so that generally, when the temperature difference undergoes an arbitrary variation, the heat flux is governed by the temperature difference and, strictly speaking, by all its derivatives. Therefore, in the general case, the third-kind boundary condition can be looked upon only as the first approximation obtainable from equation (2) or (3) when all the terms, except the first one, are neglected. It is clear that when the importance of the subsequent terms is small, this approach will not entail significant errors. Otherwise, the errors turn out to be appreciable.

Equation (2) establishes the relationship between the heat flux density and the temperature difference in differential form, which is not always convenient, since it contains higher-order derivatives. It can be shown [1] that the following integral relation is equivalent to series (2)

$$q_w = \alpha_*\left[t_w(0)+\int_0^{\Phi} f\left(\frac{\xi}{\Phi}\right)\frac{dt_w}{d\xi}\,d\xi\right]. \quad (4)$$

The function of influence of the unheated surface length can be taken in the form

$$f\left(\frac{\xi}{\Phi}\right) = \left[1-\left(\frac{\xi}{\Phi}\right)^{c_1}\right]^{-c_2}.$$

The exponents c_1 and c_2 are connected with the coefficients g_k of series (2). Their values are given elsewhere [1].

3. SOLUTION PROCEDURE FOR CONJUGATE PROBLEMS

Equation (2) is obtained by solving the boundary-layer equations. It establishes the relationship between q_w and t_w on the surface of a body in a flow for any surface temperature distribution. It follows from the above and the conditions of conjugation that the solution of the heat conduction equation on the body surface should transform into equation (2). In other words, with this approach the solution of the conjugate problem reduces to the integration of the heat conduction equation with the boundary condition on a streamlined surface in the form of equation (2).

Disregarding all the terms after the first one in equation (2), one can obtain the relation coincident with the third-kind boundary condition. From this it follows that the solution of the heat conduction equation with the third-kind boundary condition can be regarded as a first approximation to the solution of a conjugate problem. By retaining the first two terms in equation (2) and solving the heat conduction equation with the two-term boundary condition, a more accurate solution of the problem can be obtained. The process of refinement can be continued by retaining a larger number of terms in equation (2). However, this entails difficulties posed by the calculation of higher-order derivatives and, therefore, the integral form of boundary condition (4) should be used for further approximations.

In practical calculations it is convenient to retain the first few terms of the series and to calculate the error term from the results of the previous approximation. When, in this case, the first three terms of the series are retained, the boundary condition takes the form

$$q_w = \alpha_*\left[t_w+g_1\Phi\frac{dt_w}{d\Phi}+g_2\Phi^2\frac{d^2t_w}{d\Phi^2}+\varepsilon(\Phi)\right] \quad (5)$$

$$\varepsilon(\Phi) = \frac{1}{\alpha_*}\left(q_w^{\text{int}}-q_w^{\text{diff}}\right), \quad (6)$$

where q_w^{int} is defined by integral equation (4) and q_w^{diff}, by differential equation (5) without the error term. The first approximation is found by assuming to a first approximation that $\varepsilon(\Phi) = 0$. Having calculated the error term from the results of the first approximation, it can be introduced into boundary condition (5) and the second approximation can be found. By continuing this process it is possible to obtain the solution of the conjugate problem with the desired accuracy. If the effect of conjugation in the problem considered is known to be not very large, one may retain only the first two terms in boundary condition (5) or only the first term, having included the remaining terms into the error term $\varepsilon(\Phi)$. In the latter case the boundary condition of the third kind is obtained with the correction in the form of the error term.

Thus, as a boundary condition for the heat conduction equation it is possible to use the differential, equation (2), or combined equation (5), forms of relations with one, two, or three terms involving the derivatives, or the integral form of the relation, equation (4). However, the use of the integral form entails additional difficulties. Normally, therefore, ruling out the cases when the effect of conjugation is obvious, one should start from the use of most simple forms and, after each approximation, to assess the error either by comparing the results of successive approximations or by evaluating the error term from equation (6).

4. EXAMPLES

Example 1

A thin plate is streamlined on two sides by heat agents with different temperatures. The flow is laminar. It is required to find the distribution of temperatures and heat fluxes along the plate surfaces. By assuming, as usual, the temperature distribution over the thickness of a thin plate to be linear, it is possible to obtain

$$-q_{w_1} = q_{w_2} = (\lambda_w/\Delta)(T_{w_1}-T_{w_2}).$$

The substitution into these equations of the values of heat fluxes calculated from equation (3) yields two equations to determine the plate surface temperatures

$$\begin{aligned}
&-g_{01}\lambda_1\sqrt{U_{\infty 1}/\nu_1}(T_{w_1}-T_{\infty 1}+g_{11}xT'_{w_1} \\
&\quad +g_{21}x^2T''_{w_1}+\cdots) \\
&= g_{02}\lambda_2\sqrt{U_{\infty 2}/\nu_2}(T_{w_2}-T_{\infty 2}+g_{12}xT'_{w_2} \\
&\quad +g_{22}x^2T''_{w_2}+\cdots) \\
&T_{w_2}-T_{w_1} = g_{01}\frac{\lambda_1\Delta}{\lambda_w}(T_{w_1}-T_{\infty 1} \\
&\quad +g_{11}xT'_{w_1}+g_{21}x^2T''_{w_1}+\cdots).
\end{aligned} \quad (7)$$

A detailed analysis of these equations, their solution with the retainment in the series of one, two and three terms, and the assessment of the accuracy by comparing the results of successive approximations can be found in refs. [1, 3, 4]. Figure 1 presents the relative differences, $\Delta q_w/q_w^*$, of heat fluxes calculated in a conventional

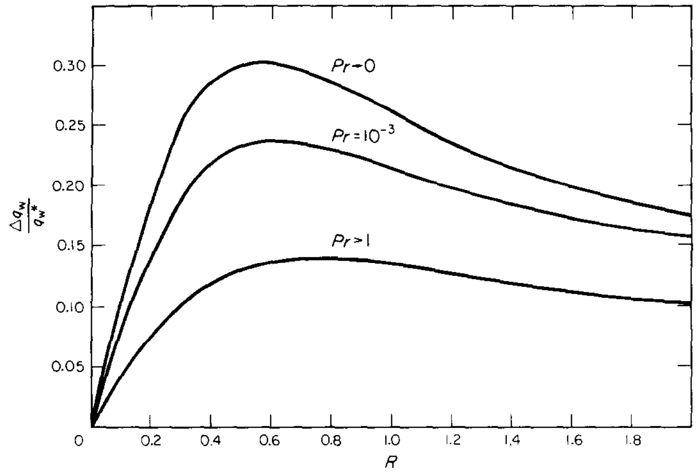

FIG. 1. Relative error in the local heat flux due to the disregard of the conjugate nature of the problem.

manner (q_w^*) with the aid of the formula for the heat transfer coefficient and in a conjugate problem by solving the system of equations (7). On the abscissa the quantity

$$R = \frac{\lambda_w/\Delta}{1/\alpha_{*_1} + 1/\alpha_{*_2}} \tag{8}$$

is plotted, this characterizes the relationship between the thermal resistances of the plate and of heat agents under the isothermal plate conditions. It is seen from Fig. 1 that the error introduced as a result of the disregard of conjugation in the problem considered does not exceed 20–25%. The plot simply allows one to introduce corrections into the results of calculations by the formula usually used for the heat transfer coefficient. For this it is sufficient to calculate the value of R by formula (8) and, having found in Fig. 1 the correction $\Delta q_w/q_w^*$, to adjust the value of q_w^* obtained by a conventional technique. A similar problem for the turbulent flow of a heat agent is considered in ref. [5]. In this case the error does not exceed 7%.

Example 2

It is required to calculate the heat transfer between a metal plate, heated on one end face with the other insulated, and a heat agent flowing past it. By assuming the plate to be thermally thin and neglecting the change of temperature across it, it is possible to use the heat conduction equation averaged over the plate thickness

$$\frac{d^2 T_w}{dx^2} - \frac{2q_w}{\lambda_w \Delta} = 0. \tag{9}$$

The replacement of q_w by its value from equation (3) will yield the equation

$$T_w'' - \frac{2\alpha_*}{\lambda_w \Delta}(T_w - T_\infty + g_1 x T_w' + g_2 x^2 T_w'' + \cdots) = 0,$$

which will determine the plate temperature distribution. The solution of this equation with the retainment of the first three terms of the series for laminar and turbulent flows, the analysis of this solution and the evaluation of the error term by equation (6) are presented in ref. [1]. In the case of the conjugate formulation of the problem the results depend substantially on the direction of flow past the plate. When the flow arrives at the heated end face of the plate, the temperature difference decreases, but when the flow arrives at the insulated end face, it increases in the flow direction. It is known [1] that in the case of the increasing temperature difference the heat transfer coefficients are higher, and with decreasing lower, than on an isothermal surface. As a result, the heat transfer characteristics and, in particular, the heat flux distributions differ substantially in the two cases. In the first case, when the flow arrives at the heated end face, the local heat fluxes decrease quickly and become nearly zero at the end of the plate, while in the second case the heat flux decreases only over a portion of the plate and then, having reached its minimum, starts to increase. For all that, it turns out ultimately that, at the given temperature of the heated end face, the total quantity of the heat released from the plate is larger in the first case than in the second. The explanation is that in the first case large temperature differences are present over the plate starting length with high heat transfer coefficients, while in the second case there are small temperature differences over the plate starting length. Quantitative results depend on the relationship between the thermal resistances of the plate and heat agent which in this problem is conveniently characterized by the parameter $\Lambda = \alpha_{L*} L^2/\lambda_w \Delta$, where α_{L*} is the heat transfer coefficient at the end of an isothermal plate of length L. It is seen from Fig. 2 that in the case of laminar flow the quantities of the total heat flux Q_w can differ markedly. It should be noted that had the calculations been made in a conventional manner with the length-averaged heat transfer coefficient, the

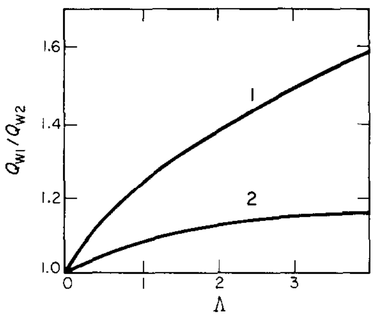

FIG. 2. Relationship between the heat fluxes released from the plate in a flow arriving at the heated or insulated end face. 1, laminar flow; 2, turbulent flow.

heat transfer characteristics would have been independent at all of the flow direction.

Example 3

It is required to calculate the heat transfer characteristics for the flow around an elliptical cylinder with uniformly distributed heat sources of strength q_v. The solution of this problem is given in ref. [6]. The heat conduction equation, expressed in terms of the elliptical coordinates, was solved in series by the method of separation of variables. For the determination of the series coefficients the boundary condition in the integral form was used, equation (4). The results of calculation in conjugate and ordinary formulations are compared in Fig. 3.

Example 4

An infinite flat plate (tape) of temperature T_0 is brought forward from a die and is pulled at velocity U_w through a heat agent with the temperature T_∞. It is required to calculate the temperature distribution along the plate. In ref. [7], this problem was solved numerically using a finite difference method. The heat conduction equation for the moving tape,

$$U_w \frac{\partial T}{\partial x} = a_w \frac{\partial^2 T}{\partial y^2},$$

was solved with the combined boundary condition (5) with two terms and the error term $\varepsilon(\Phi)$ which was calculated by equation (6) from the results of the preceding approximation. Three approximations were sufficient in the above examples. Figure 4 presents the results of calculations for a polymer film cooled by water in the process of moulding. It is seen that in this problem the effect of conjugation is appreciable. The reason for this is that for continuously moving bodies the effect of surface non-isothermicity of the heat transfer rate is much more substantial than for general streamlined bodies [8].

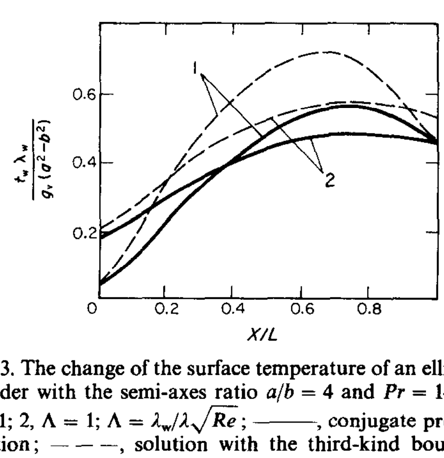

FIG. 3. The change of the surface temperature of an elliptical cylinder with the semi-axes ratio $a/b = 4$ and $Pr = 1$; 1, $\Lambda = 0.1$; 2, $\Lambda = 1$; $\Lambda = \lambda_w/\lambda\sqrt{Re}$; ———, conjugate problem solution; — — —, solution with the third-kind boundary condition.

Example 5

A thermally thin plate with the heat sources $q_v(x, y)$, to the end faces of which the heat fluxes $q_{in}(0)$ and $q_f(L)$ are supplied, is streamlined on two sides by heat agents with temperatures $T_{\infty 1}(0)$ and $T_{\infty 2}(0)$; at $\tau < 0$ a steady-state regime takes place. When $\tau = 0$, the sources begin to vary in time as $q_v(x, y, \tau)$, the heat fluxes at the end faces as $q_{in}(0, \tau)$ and $q_f(L, \tau)$, and the temperatures of the heat agents as $T_{\infty 1}(\tau)$ and $T_{\infty 2}(\tau)$. It is required to find the laws governing the change of the plate temperature, $T_w(x, \tau)$, and of the heat flux density $q_w(x, \tau)$. For the case at hand the plate thickness-averaged heat conduction equation, analogous to equation (9) for the steady-state regime, is

$$\frac{1}{a_w}\frac{\partial T}{\partial \tau} - \frac{\partial^2 T}{\partial x^2} + \frac{q_{w_1}+q_{w_2}}{\lambda_w \Delta} - \frac{(q_v)_{av}}{\lambda_w} = 0.$$

By assuming, as usual, [10] that the heat transfer in heat agents is quasi-steady, it is possible to use the integral form of the boundary conditions on the streamlined plate surfaces. Then the following equation for the plate temperature will be obtained

$$\frac{\partial \theta}{\partial Fo} - \frac{\partial^2 \theta}{\partial \zeta^2} + (\Lambda_1 + \Lambda_2)\zeta^{-r/s}$$

$$\times \left[\int_0^\zeta f(\xi/\zeta)\, d\theta + \theta(0, Fo) \right]$$

$$- \frac{\Lambda_2}{\Lambda_1 + \Lambda_2}\theta_\infty(Fo) + T'_{\infty 1}(Fo) - \bar{q}_v = 0$$

$$\theta = \frac{T_w - T_{\infty 1}(\tau)}{T_{\infty 2}(0) - T_{\infty 1}(0)}; \quad \theta_\infty = \frac{T_{\infty 2}(\tau) - T_{\infty 1}(\tau)}{T_{\infty 2}(0) - T_{\infty 1}(0)}$$

$$\zeta = \frac{x}{L}; \quad \bar{q}_v = \frac{(q_v)_{av} L^2}{\lambda_w [T_{\infty 2}(0) - T_{\infty 1}(0)]}; \quad Fo = \frac{a_w \tau}{L^2},$$

$r/s = 1/2$ for a laminar flow and $r/s = 1/5$ for a turbulent one. The solution of this equation in eigenfunction series is given in ref. [1]. The first four eigenvalues and eigenfunctions were calculated for laminar and turbulent regimes of flow. The examples of calculations are presented.

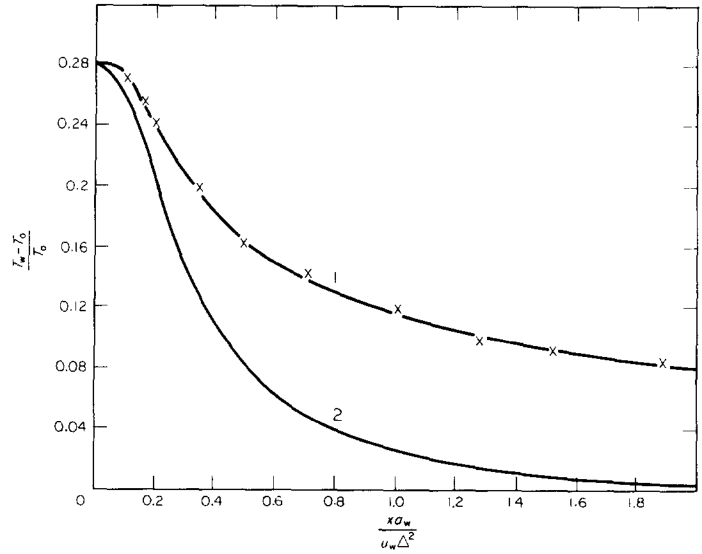

FIG. 4. Temperature distribution along a polymer film cooled while moving through water: $Pr = 6$; $[(\lambda c_p \rho)_w / \lambda c_p \rho] = 8.5$; 1, conjugate problem solution; 2, solution with the third-kind boundary condition; ×, experimental data [9].

CONCLUSIONS

The proposed form of the boundary condition determines the functional relationship between the heat flux density and temperature difference on an arbitrarily non-isothermal surface. This boundary condition coincides with the boundary condition of the third kind only for an isothermal surface. Generally, the third-kind boundary condition turns out to be only a first approximation which can be obtained only in the case when the first term of the series is retained in a generalized boundary condition. Therefore, the results of problem solution subject to the third-kind boundary conditions can be satisfactory only in the case of the relative insignificance of subsequent series terms allowing for the non-isothermicity of the heat transfer surface. Then it is possible to restrict ourselves to the solution of the heat conduction equation subject to the third-kind boundary condition which in the method suggested can be regarded as a first approximation to the conjugate problem solution. Subsequent approximations are constructed as the solution of the heat-conduction equation with an improved boundary condition in which a large number of terms are retained or to the boundary condition taken in integral, equation (4), or combined, equation (5), form. By comparing successive approximations it is possible to judge the accuracy of each of these and the necessity of further refinements.

The above examples show that the proposed method of conjugate problem reduction to the heat conduction equation with a generalized boundary condition can be applied to a wide range of conjugate problems and can allow substantial simplification of their solution. It is seen from the examples given that the effect of conjugation can be either small or great. This depends on many factors the main of which are the character of change of the temperature difference along a streamlined body and the ratio between the thermal resistances of the body and heat agent. A detailed analysis of the effect of different factors on the degree of problem conjugation is given elsewhere [1].

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UN NOUVEAU TYPE DE CONDITIONS LIMITES DANS LES PROBLEMES DE CONVECTION THERMIQUE

Résumé—En résolvant les équations de couche limite, un nouveau type de conditions limites avait été obtenu [1]. Il rendait la condition limite de troisième espèce plus précise et il permettait la réduction d'un problème conjugué à un problème équivalent à un problème de conduction thermique. Ce texte donne une procédure pour la résolution de problèmes en utilisant un nouveau type de conditions et on discute les aspects spécifiques de la procédure.

EINE NEUARTIGE RANDBEDINGUNG BEI KONVEKTIVEN WÄRMEÜBERGANGSPROBLEMEN

Zusammenfassung—Durch Lösen der Grenzschichtgleichungen wurde bereits früher eine neuartige Randbedingung gefunden [1], welche die Randbedingung dritter Art präzisiert und es erlaubt, ein gekoppeltes Problem auf ein gleichwertiges Wärmeleitproblem zurückzuführen. In diesem Bericht wird ein Verfahren zum Lösen von Problemstellungen unter Zuhilfenahme der neuen Randbedingung mitgeteilt und die spezifischen Eigenschaften des Verfahrens untersucht.

НОВЫЙ ВИД ГРАНИЧНОГО УСЛОВИЯ В ЗАДАЧАХ КОНВЕКТИВНОГО ТЕПЛООБМЕНА

Аннотация—В монографии [1] путем решения уравнений пограничного слоя получен новый вид граничных условий, уточняющий граничное условие третьего рода и позволяющий свести сопряженную задачу к эквивалентной задаче для уравнения теплопроводности. В настоящей статье излагается методика решения задач с использованием нового вида граничных условий и обсуждаются особенности этой методики.