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THE POSSIBILITY OF DETERMINING AND USING A NEW LOCAL HEAT TRANSFER COEFFICIENT

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Abstract—A new parameter named the physical heat transfer coefficient, h_{ph}, can be used for characterizing the relation between heat flux and wall temperature. The concept of h_{ph} and its definition with the necessary restrictions given in a local, differential form are presented. In order to apply h_{ph} in a possible way, a relation to the conventional heat transfer coefficient is derived for fully developed turbulent flow in a pipe or along a flat plate. Conclusions regarding h_{ph} measurability are also discussed.

NOMENCLATURE

a	molecular thermal diffusivity, $k/\rho c_p$
c_f	local coefficient of skin friction, $2\tau_w/\rho u_\infty^2$
c_p	specific heat capacity at constant pressure
D	diameter of tube
g	gravitational constant
h_t, h_{ph}	technical and physical local heat transfer coefficients
k	heat conductivity
K	constant, equation (22)
l	thickness of laminar sublayer
Pr	molecular Prandtl number, ν/a
Pr_t	turbulent Prandtl number, $\varepsilon_M/\varepsilon_T$
q	heat flux (per unit area)
q_w	wall heat flux
Re	Reynolds number, $u_\infty D/\nu$ or $u_\infty x/\nu$
T	temperature
T_w	wall temperature
T_∞	temperature affected to a negligible extent by heat transport. Temperature outside the boundary layer for a flat plate, mean temperature in a pipe
u	velocity component in x direction
u_∞	velocity component at T_∞
u^*	friction velocity, $\sqrt{(\tau_w/\rho)}$
v	velocity component in y direction
x, y	coordinates, x in axis direction

Greek symbols

δ	minimum distance in y direction, in equation (13)
$\varepsilon_M, \varepsilon_T$	diffusivity for momentum and heat, respectively
μ	absolute viscosity
ν	kinematic viscosity, μ/ρ
ρ	fluid density
τ	shear stress
θ	temperature in coordinates (ξ, η)
ϕ	arbitrary functional, equation (10)
ξ, η	transformed coordinates of x, y

Subscripts and superscripts

l	value at the edge of the laminar sublayer
ph	physical value
t	technical value
w	value at the wall
δ	value at distance δ
+	dimensionless value: for velocity $(\ )^+ = (\ )/u^*$; for distance $(\ )^+ = (\ )\cdot u^*/\nu$
‾	averaged quantity
′	fluctuating part of a scalar quantity or of a vector in turbulent flow
*	transformed values in coordinates (ξ, η)

INTRODUCTION

THE PRESENT study introduces the concept of a local heat transport parameter, h_{ph}, defined by equation (2); this parameter might be called the local physical heat transfer coefficient. Its introduction is strongly motivated by its independence of the temperature T_∞, which cannot be stated for the conventional heat transfer coefficient, h_t. The latter is defined by equation (1) and described by the adjective 'technical' to make the distinction clear. Although h_t and h_{ph} are rather independent of each other, their relation in a given boundary layer structure is unambiguously determined by the processes governing the heat transfer. This relation can serve an application of h_{ph}. At first glance it is easy to assume equivalence between h_t and h_{ph}; this can be supposed by the result obtained for h_t by differentiating equation (1) with respect to T_w. Such a formal equalization was made, e.g. in ref. [1]. The difference between the two parameters, however, is essential. To elucidate this their different behaviour towards the T_∞ temperature can serve as a good example. The conventional basic equation with the technical heat transfer coefficient is

$$q_w = h_t(T_w - T_\infty). \tag{1}$$

As for the choice of the above temperature T_∞, there may be, in principle, several possibilities, and thus differing values of h_t will pertain to the different values of T_∞. The formal differential quotient dq_w/dT_w derived from equation (1) agrees with h_t, i.e. it may have differing values. Let us examine now the process of heat transfer. At each point of the surface such a differential quotient can be assigned to the heat transfer that can be interpreted as the heat transfer reactivity or sensitivity with the notation h_{ph}:

$$h_{ph} = \frac{dq_w}{dT_w}. \quad (2)$$

The value of h_{ph} can be determined from the response given to a minute steady-state change either of T_w or of q_w. The differential quotient dq_w/dT_w obtained in this way is not sensitive to the choice of T_∞. However, the variations of both q_w and T_w must be of zero-order and the additional heat penetration dq_w into the boundary layer must have a direction identical to that of q_w.

This paper is intended to determine the relationship between h_t and h_{ph} for the case of a turbulent flow of air along a flat plate or in a pipe.

PRELIMINARY EQUATIONS

The Prandtl–Taylor analogy will be used to relate h_{ph} and h_t. In its further use let us recall the derivation of the interrelation between the velocity and temperature distributions [2]. For parallel flow over an isothermal flat plate heat flux, q, and shear stress, τ, can be expressed as

$$\begin{aligned} q &= \rho c_p(a+\varepsilon_T)\frac{d\bar{T}}{dy}, \\ \tau &= \frac{\rho}{g}(\nu+\varepsilon_M)\frac{d\bar{u}}{dy}, \end{aligned} \quad (3)$$

where ε_T and ε_M can be neglected in the laminar sublayer, while a and ν can be neglected in the turbulent layer.

According to the Prandtl analogy, the relation q/τ remains constant in the whole width of the boundary layer. Integration of equations (3)—neglecting ε_M and ε_T in the laminar sublayer and a and ν in the turbulent layer, and assuming $Pr_t = \varepsilon_M/\varepsilon_T = 1$, and omitting the buffer layer, will yield

$$\frac{q}{\tau} = \frac{kg}{\mu}\frac{T_l - T_w}{u_l}, \quad (4)$$

$$\frac{q}{\tau} = c_p g\frac{\bar{T}_l - \bar{T}_\infty}{\bar{u}_l - \bar{u}_\infty}. \quad (5)$$

Equalizing the RHS of equations (4) and (5), and applying $T_l = \bar{T}_l$, $u_l = \bar{u}_l$, some reduction will give

$$\frac{T_w - \bar{T}_l}{T_w - \bar{T}_\infty} = \frac{Pr}{(\bar{u}_\infty/\bar{u}_l)+Pr-1}. \quad (6)$$

Although the above equation has been obtained for a distance l, it is convenient to apply it to an arbitrary coordinate y:

$$\frac{T_w - \bar{T}(y)}{T_w - \bar{T}_\infty} = \frac{Pr}{[\bar{u}_\infty/\bar{u}(y)]+Pr-1}. \quad (7)$$

In fact, the above relationship, as can be seen from the experimental results of ref. [3], is valid with a discrepancy of 8% for air in a fully developed turbulent pipe flow from the laminar sublayer ($y^+ = 10$) through the buffer layer to the turbulent core ($y^+ = 200$). For a flat plate in fully developed turbulent flow, equation (7) with the Fulachier temperature profile [4] and the Blasius-Nikuradze universal velocity law [2] will be satisfied within 5% from $y^+ = 10$ to 200. In the developing area with the temperature and velocity profiles of ref. [5] the deviation is about 9% between $y^+ = 30$ and 200. The above deviations are acceptable, thus equation (7) will be accepted in the interval from the laminar sublayer to the turbulent core.

After this preparation integrate equations (3) from 0 to y:

$$\int_0^y \frac{q(y)}{a+\varepsilon_T(y)}\,d(y) = \rho c_p(\bar{T}-T_w), \quad (8)$$

$$\int_0^y \frac{\tau(y)q(y)}{[\nu+\varepsilon_M(y)]q(y)}\,dy = \frac{\rho}{g}\bar{u}. \quad (9)$$

Applying again the hypothesis of Prandtl to the constancy of τ/q, a coefficient τ_w/q_w can be factored from the LHS of equation (9). Divide now equation (8) by equation (9) and denote the quotient of the integrals obtained in this way by the functional $1/\phi(y)$. The reduction will yield

$$\frac{q_w}{\tau_w} = \phi(y)\frac{T_w - \bar{T}(y)}{\bar{u}(y)}. \quad (10)$$

Based on the reasoning made with equation (3), the functional $\phi(y)$ can be characterized by the following relationship:

$$\phi(y) = \begin{cases} \dfrac{kg}{\mu} & \text{if } y \ll l, \\ f(y) & \text{if } y \text{ is in the buffer layer,} \\ c_p g & \text{if } y \gg l \text{ and } Pr_t = 1, \\ \dfrac{kg}{\mu} = c_p g & \text{if } Pr = 1 \text{ and } Pr_t = 1, \end{cases} \quad (11)$$

(y is arbitrary).

From equation (10), by formal differentiation, regarding T as a function of T_w, the following expression can be obtained:

$$\frac{dq_w}{dT_w} = \frac{\phi(y)\tau_w}{\bar{u}(y)}\left(1 - \frac{d\bar{T}(y)}{dT_w}\right). \quad (12)$$

The above equation can be a bridge between h_t and h_{ph}. The differential quotient $d\bar{T}/dT_w$ appearing on the RHS of equation (12) can be given a physical interpretation, namely in a place y it means the relative sensitivity of the temperature to the change of the surface temperature. In other words, dT/dT_w characterizes the penetration of the disturbance coming from the surface. It has to be stipulated that the heat penetration in question starts from the surface in the direction identical with that of q_w. δ shall mean the minimum y for which $\mathrm{d}T/\mathrm{d}\bar{T}_w = 0$, i.e.

$$\delta = \min y, \quad \left\{\frac{\mathrm{d}\bar{T}(y)}{\mathrm{d}T_w} = 0\right\}. \tag{13}$$

With the above y, which is the penetration depth of the local heat transfer, the LHS of equation (12) can be regarded as equal to the physical heat transfer coefficient h_{ph}, i.e.

$$h_{ph} = \frac{\phi(\delta)\tau_w}{\bar{u}(\delta)}. \tag{14}$$

With the use of equations (1), (10), (12) and (14), and applying relationship (7), two different forms of the equation expressing the relationship between h_t and h_{ph} will be obtained:

$$\frac{h_t}{h_{ph}} = \frac{T_w - \bar{T}_\delta}{T_w - \bar{T}_\infty} = \frac{Pr}{(\bar{u}_\infty/\bar{u}_\delta) + Pr - 1}. \tag{15}$$

PENETRATION DEPTH OF THE LOCAL HEAT TRANSFER

The question to be answered is how deep the heat penetrates from a surface point into the boundary layer? It is reasonable to consider the case of the isothermal flat plate when the penetration is perpendicular to the surface. The problem differs from the examination of scalar dispersion of point or line sources (e.g. ref. [6]), since in the present case strictly isothermal conditions have been stipulated. It is desirable, in addition, to reckon with heat conduction in the streamwise direction in the laminar sublayer, since definition (2) includes only heat penetration in the direction perpendicular to the wall. In the turbulent sublayer, however, the heat flux in the x direction is permitted, as the heat transport there is not governed by the temperature gradient.

The object is to find estimation limits for the penetration depth δ. To estimate the maximum value, one may examine the effect of a line source in a direction crossing the flow instead of a point source, for in this way the problem is reduced to a two-dimensional one. The examination of the solution of the differential equations governing the phenomenon may lead to a result. The different sections of the boundary layer must be handled separately, and it is practical to start from outside the turbulent layer.

With the usual simplifications, for two dimensions, the time-smoothed heat balance equation will be [7]:

$$\bar{u}\frac{\partial \bar{T}}{\partial x} + \bar{v}\frac{\partial \bar{T}}{\partial y} = \underset{(a)}{-\frac{\partial}{\partial x}\overline{u'T'}} \underset{(b)}{-\frac{\partial}{\partial y}\overline{v'T'}} + \underset{(c)}{\frac{k}{c_p\rho}\frac{\partial^2 \bar{T}}{\partial x^2}} + \underset{(d)}{\frac{k}{c_p\rho}\frac{\partial^2 \bar{T}}{\partial y^2}}. \tag{16}$$

Terms (a) and (c) are neglected even when the temperature is a step-change function, e.g. ref. [3]. Thus term (c) can be omitted. The partial derivative of the turbulent heat flux in term (a) does not appear even in the heat balance equation of ref. [6] examining the dispersion of a point source, and thus it can presumably be neglected as well. In the present case, however, it is favourable to keep term (a) for the penetration to be estimated without the numerical solution of the differential equation. In term (b) the turbulent heat flux $\overline{v'T'}$, expressed by the eddy diffusivity, equals $-\varepsilon_T\, \partial\bar{T}/\partial y$. It is practical to express the heat flux $\overline{u'T'}$ by using the ratio of the streamwise and the cross-stream heat flux $\overline{u'T'}/\overline{v'T'}$. According to the experimental result of ref. [4] this quotient in the vicinity of the wall can be predicted between -1.5 and -2.2. Both for homogeneous shear flow and near-wall turbulence according to ref. [8], the quotient in question is about -1.8. Accepting this latter value and considering its constancy in the turbulent layer, one obtains for the turbulent flux in term (a)

$$\overline{u'T'} = -1.8\varepsilon_T\, \partial\bar{T}/\partial y. \tag{17}$$

After substitution and reductions, neglecting the molecular heat transport in the turbulent zone, one will obtain for equation (16):

$$\bar{u}\frac{\partial \bar{T}}{\partial x} + \left(\bar{v} - \frac{\partial \varepsilon_T}{\partial y}\right)\frac{\partial \bar{T}}{\partial y} = -1.8\varepsilon_T\frac{\partial^2 \bar{T}}{\partial x\,\partial y} + \varepsilon_T\frac{\partial^2 \bar{T}}{\partial y^2}. \tag{18}$$

The above equation can be brought to canonic form by the characteristic transformation below:

$$\xi = x, \quad \eta = y + \frac{1}{1.8}x. \tag{19}$$

The transformation of $\bar{T}(x, y)$ into $\Theta(x, y)$ results in a second-order partial differential equation of hyperbolic type (HPDE).

Turning to the dimensionless values of temperature, velocity and distance:

$$\frac{\partial^2 \Theta^+}{\partial \xi^+\,\partial \eta^+} + \left[\frac{\bar{u}^+}{1.8\varepsilon_T/\nu}\right]^* \frac{\partial \Theta^+}{\partial \xi^+} + \left[\frac{1}{1.8\varepsilon_T/\nu}\left(\frac{\bar{u}^+}{1.8} + \bar{v}^+ - \frac{\partial \varepsilon_T}{\partial y^+}\right)\right]^* \frac{\partial \Theta^+}{\partial \eta^+} = 0. \tag{20}$$

When estimating the penetration into the turbulent boundary layer, it is practical to give, as a boundary condition of HPDE equation (20), temperature $\bar{T}$ and the derivative $\partial\bar{T}/\partial y$ on a section parallel to the x axis. This derivative can be calculated from the heat flux in the y direction, provided that no heat flux in the x direction is supposed.

The coordinate system ξ, η should be displaced into the turbulent boundary layer, keeping the ξ axis parallel to the wall. The boundary condition in this case means prescription of Θ^+ and $\partial\Theta^+/\partial\eta^+$ on an X-length section of line $\xi^+ = 1.8\eta^+$ (see Fig. 1). This is exactly the Cauchy problem relating to equation (20), which, according to the theory of HPDE, has a unique solution within the hatched area of Fig. 1. Thus, the disturbance starting from bound X penetrates to the depth of y

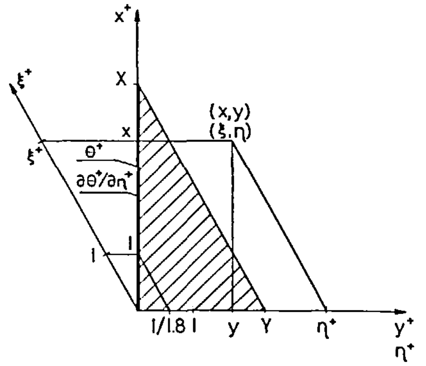

FIG. 1. The transformed coordinate system and the area (hatched) within which the unique solution is ensured by the boundary conditions stated for section X.

$= Y$; it follows that from a section of size dx the penetration is of zero order.

In the laminar boundary layer the penetration is governed by physical processes and equations of quite another type. After omission of terms (a) and (c) in equation (16), the equation of the conservation of heat will be of the parabolic type. Accordingly, the penetration is infinite, although its intensity may strongly decrease with the distance increasing from the wall. In accordance with all that has been discussed in connection with equation (20), only the y-direction disturbance and not the x-direction dispersion has to be considered. The penetration depth of this must be larger than the laminar sublayer thickness. Continuing this idea, it will be found that the penetration may run at most to the remaining traces of molecular heat transport, i.e. to the outermost edge of the buffer layer. Thus, the limits of the buffer layer can be stated as an estimation for δ^+. For turbulent flow both over a flat plate and in a circular pipe, according to the usual choice for the buffer layer limits found in ref. [9], one can write

$$5 < \delta^+ < 30. \tag{21}$$

FORMULA OF THE RELATION h_t/h_{ph}

In turbulent flow in a pipe or along a flat plate, for hydraulically smooth surfaces, the velocity relationship of equation (15) can be connected to the local skin friction coefficient c_f. For both cases the result can be obtained in a similar way, according to the procedure presented in Chapter XX of ref. [2], with the assumption of Blasius' velocity profile and utilization of relationship (21). The final result of both cases will be

$$\frac{h_t}{h_{ph}} = \frac{Pr}{[1/K\sqrt{(1/2\,c_f)}]+Pr-1}, \tag{22}$$

where $11 < K < 14$, belonging to the estimation limits of δ^+ in equation (21).

DISCUSSION

The following sections will deal with the importance of distinguishing between h_t and h_{ph} by using equation (22), and with the interpretation and explanation of the definition of h_{ph} from the viewpoint of applications. A few words will be said also about earlier spontaneous applications of h_{ph} hidden in the disguise of h_t.

(1) According to relationship (22), as an example with a Reynolds number $Re = 10^5$, for a smooth pipe and air ($Pr = 0.73$), the relation h_t/h_{ph} is 0.51 ± 0.07. Thus, h_t and h_{ph} may considerably differ from each other. Owing to the wide estimation interval for K in equation (22) relationship (22) has an uncertainty around 10%. This error, however, does not appear very serious considering that a difference of about 100% between the two heat transfer coefficients was obtained in the above example.

(2) The dq_w in definition (2) is not identical with the total additional heat flux originating from a point heat source on the surface, since no dispersion is permitted. Such a choice of the definition appeared to be practical, for in this way the difference between the mean value relative to a small finite surface element and a local value of h_{ph} is not very large. With simplification to two dimensions again, the mean value of h_{ph} relative to a surface element of size Δx gets modified only because of the change of the penetration, provided that the relation $\bar{u}_\infty/\bar{u}_\delta$ in the x direction is constant. Through the derivation of relationship (22), provided that the penetration depth changes with the increase of Δx according to Fig. 1, one can obtain the relation $h_{ph}/\overline{h_{ph}(\Delta x)}$, i.e. the ratio of a local and a mean physical heat transfer coefficient; the latter relates to a finite surface element Δx around the local point. Choosing the lower and upper limits of δ^+ in equation (21), the functions (curves a and b, respectively) shown in Fig. 2 can be obtained, e.g. for three different Re numbers. The maximum increase of penetration together with the increase of Δx on the basis of Fig. 1, is possible, but it is not inevitable, in fact not even likely. In the other

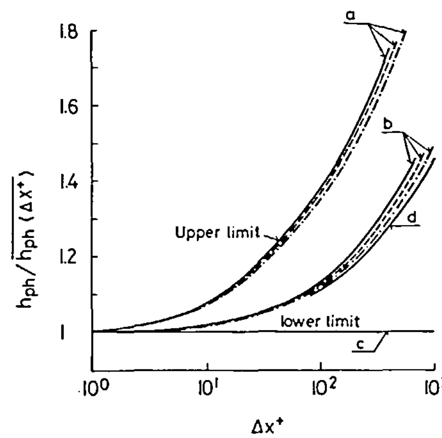

FIG. 2. The lower and upper estimation limits of the ratio of h_{ph} to the average $\overline{h_{ph}(\Delta x^+)}$ relative to section Δx^+ containing the point. Curves a, $\delta^+ = 5$; curves b, $\delta^+ = 30$ and with the change of penetration depth (PD) according to Fig. 1; curve c, with constant PD; curve d, with the change of PD identical with the development of the thermal boundary layer measured by Antonia *et al.* [4].

extreme case penetration depth can be considered constant, so the ratio in question is a unit also drawn in Fig. 2 (curve c). To look for some agreement in literature the change of penetration depth should be considered identical with the change of turbulent thermal boundary layer thickness obtained for step change boundary condition, e.g. by ref. [4]. The ratio in question can be calculated by the procedure mentioned before; when calculating the local h_{ph} and the average $\overline{h_{ph}(\Delta x)}$, $\delta^+ = 5$ and δ^+ converted from the above mentioned ref. [4] were considered, respectively. The ratio is also drawn in Fig. 2 (curve d). This latter curve convincingly falls between the marked lower and upper limits.

(3) Concerning the measurement of the local h_{ph}, the result given in Fig. 2 has a convenient consequence. On a finite surface element of size Δx, i.e. of the same order as the thickness l of the laminar boundary layer, $dq_w(x)$ can probably be manipulated to have only a perpendicular heat flux component in the centre of the surface element. Of course, the heat penetration can be decisively influenced in the laminar boundary layer only, where the heat penetration is governed by the temperature gradient. In the turbulent layer the penetration with the assumed conditions is not affected by the prehistory of the flow approaching the place in question, and the dispersion will be restricted to the hatched area of Fig. 1.

Thus in the centre of a compensating surface element of size Δx, the local h_{ph} can be obtained, according to Fig. 2, with a probably overestimated uncertainty of about 7% caused by a possible increased penetration at the value of $\Delta x^+ = 10$. This paper cannot deal with the techniques of measurement and with further refinements possible in principle.

(4) The h_{ph} as a boundary condition does not appear very convenient with the precise application of the assumed conditions. Practice and further theoretical examinations are needed to decide what simplifications can be permitted. It is possible, e.g. to neglect the dispersion of edges in the mean $\overline{h_{ph}}$ relative to a certain finite surface element, to suppose a constancy of the penetration depth δ^+ or to relax the prescription that dq_w and dT_w be of zero-order.

(5) Finally, a few words on earlier spontaneous applications. In addition to ref. [1] mentioned in the Introduction, it is possible that the results of several local heat transfer measurements furnished, in fact, not the expected h_t but—with the concessions mentioned in (4)—the values of h_{ph}. A h_{ph}-like result instead of the expected h_t must have been obtained by ref. [10], although its results cannot be regarded as local physical heat transfer coefficients, because the results may be distorted, owing to the surface dimensions of the probe.

In addition to the foregoing, measurements of any forced heat transfer in so-called unheated systems using a small-size measuring area (electrical gauge or some other device) are very likely to be measurements of the physical heat transfer coefficient.

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LA POSSIBILITE DE DETERMINER ET D'UTILISER UN NOUVEAU COEFFICIENT DE TRANSFERT THERMIQUE LOCAL

Résumé—Un nouveau paramètre appelé coefficient physique de transfert thermique h_{ph}, peut être utilisé pour caractériser la relation entre le flux de chaleur et la température pariétale. Le concept h_{ph} et sa définition avec les restrictions nécessaires sont présentés dans une forme différentielle locale. De façon à appliquer h_{ph} on établit une relation avec le coefficient de transfert conventionnel pour l'écoulement turbulent pleinement établi dans un tube ou le long d'une plaque plane. Des conclusions sur l'accès à la mesure de h_{ph} sont aussi présentées.

DIE MÖGLICHKEIT EINEN NEUEN ÖRTLICHEN WÄRMEÜBERGANGSKOEFFIZIENTEN ZU BESTIMMEN UND ZU VERWENDEN

Zusammenfassung—Ein neuer Parameter mit der Bezeichnung "physikalischer Wärmeübergangskoeffizient", h_{ph}, kann zur Charakterisierung des Zusammenhanges zwischen Wärmestromdichte und Wandtemperatur verwendet werden. Das Konzept und die Definition von h_{ph} unter Berücksichtigung der erforderlichen Einschränkungen in lokaler, differentieller Form werden dargestellt.

Um eine Möglichkeit der Anwendung von h_{ph} zu veranschaulichen, wird eine Beziehung zu dem konventionellen Wärmeübergangskoeffizienten für voll ausgebildete turbulente Strömung in einem Rohr bzw. an einer ebenen Platte abgeleitet. Schlußfolgerungen bezüglich der Meßbarkeit werden ebenfalls diskutiert.

ВОЗМОЖНОСТЬ ОПРЕДЕЛЕНИЯ И ИСПОЛЬЗОВАНИЯ НОВОГО ЛОКАЛЬНОГО КОЭФФИЦИЕНТА ТЕПЛОПЕРЕНОСА

Аннотация—Новый параметр, получивший название физического коэффициента теплопереноса, h_{ph}, можно использовать для определения соотношения между величиной теплового потока и температурой стенки. Дано определение понятия h_{ph} и в локальном дифференциальном виде приведены присущие этому параметру ограничения. Для использования коэффициента h_{ph} выведено его соотношение с обычным коэффициентом теплопереноса для полностью развитого турбулентного течения в трубе или вдоль плоской пластины. Рассмотрены также способы измерения h_{ph}.