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AN EXPERIMENTAL DETERMINATION OF THE TURBULENT PRANDTL NUMBER IN THE INNER BOUNDARY LAYER FOR AIR FLOW OVER A FLAT PLATE

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Abstract—Results are presented of measurements of velocity and temperature profiles and of turbulent momentum and heat fluxes for air flow over a flat plate, part of which was kept at a temperature of about 11 K above ambient temperature. Flow measurements were performed by hot-wire anemometry, using single wire and X-wire probes, and temperature measurements by resistance thermometry, using small sensors of a special construction. From the experimental data, values of the eddy diffusivities for momentum and heat, and of the turbulent Prandtl number were derived. For a developing turbulent boundary layer, velocity and temperature profiles for $z^+ < 300$ could be well represented by the equations

$$z^+ = U^+ + 0.1342\,[\exp(0.41U^+) - \textstyle\sum_{n=0}^{4}(0.41U^+)^n/n!],$$

$$z^+ = Pr^{-1}T^+ + 0.1342\,[\exp(0.48T^+) - \textstyle\sum_{n=0}^{4}(0.48T^+)^n/n!].$$

For the region $30 < z^+ < 100$ the value found for Pr_t is 0.9 ± 0.1. The relation between Pr_t and z^+ for $40 < z^+ < 300$ is in agreement with the results of Fulachier. There is less agreement with the results of Antonia *et al.* given for a developing thermal boundary layer.

NOMENCLATURE

B, B_1,	parameters in equations (11) and (12);
b, b_1,	parameters in equations (11) and (12);
c_p,	specific heat capacity [J kg^{-1} K^{-1}];
L,	length of the unheated part of the plate [m];
m,	integer;
n,	integer;
p,	static pressure [Pa];
Pr,	Prandtl number;
q,	heat flux density [W m^{-2}];
S,	boundary layer thickness (0.99 criterion) [m];
S^+,	Su_τ/ν;
T,	temperature [K];
T',	temperature fluctuation [K];
T_τ,	friction temperature, $q_w/\rho c_p u_\tau$ [K];
T^+,	$(T_w - \bar{T})/T_\tau$;
U, V, W,	velocity components in x, y, z-directions [m s^{-1}];
U^+,	$\bar{U}/u_\tau$;
u, v, w,	fluctuations of U, V, W [m s^{-1}];
u_τ,	friction velocity $(\tau_w/\rho)^{1/2}$ [m s^{-1}];
x, y, z,	Cartesian coordinates [m];
z^+,	$u_\tau z/\nu$.

Greek symbols

κ,	thermal diffusivity [m^2 s^{-1}];
ν,	kinematic viscosity [m^2 s^{-1}];
ρ,	mass density [kg m^{-3}];
τ,	shear stress [Pa].

Dimensionless number

Pr,	Prandtl number, ν/κ.

Subscripts

0,	free stream condition;
t,	turbulent;
u,	velocity;
T,	temperature;
w,	wall condition;
$\bar{\ }$,	time average.

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1. INTRODUCTION

THE RESPONSE of a turbulent boundary layer to a stepwise change in surface conditions has received special attention, both experimentally and theoretically, mainly because of its relevance to the atmospheric situation. As no general solution of the boundary layer equations is known, accurate measurements can support hypotheses on the turbulent shear stress and heat flux density in these boundary layers.

Earlier measurements of shear stresses and heat fluxes made by others show different results. The aim of this work is to provide accurate data on the combined transport of momentum and heat in a turbulent boundary layer over a smooth horizontal surface with a stepwise change in temperature. The present work represents data achieved by advanced measuring and data handling techniques. It is a continuation of that presented by D. A. de Vries at the Sixth International Heat Transfer Conference in Toronto [1], and can be considered as a final report on the determination of the turbulent Prandtl number performed in our laboratory.

2. STATEMENT OF PROBLEM

The fundamental problem of heat transfer from a flat plate with a stepwise discontinuity in the wall temperature was chosen for our experimental study of heat transfer in a turbulent boundary layer. A sketch of the velocity and temperature boundary layers and the associated velocity and temperature profiles is given in Fig. 1. The boundary layer equations for a stationary, 2-dim., incompressible, turbulent flow, neglecting buoyancy and dissipation are

$$\partial\bar{U}/\partial x + \partial\bar{W}/\partial z = 0, \quad (1)$$

$$\bar{U}\partial\bar{U}/\partial x + \bar{W}\partial\bar{U}/\partial z = -\rho^{-1}\partial\bar{p}/\partial x - \rho^{-1}\partial\tau/\partial z, \quad (2)$$

$$\bar{U}\partial\bar{T}/\partial x + \bar{W}\partial\bar{T}/\partial z = -(\rho c_p)^{-1}\partial q/\partial z, \quad (3)$$

with

$$\tau = -\rho\nu\partial\bar{U}/\partial z + \rho\overline{uw}, \quad (4)$$

$$q = -\rho c_p \kappa \partial\bar{T}/\partial z + \rho c_p \overline{T'w}. \quad (5)$$

All air properties have been considered constant. Introducing eddy diffusivities, we write, for the turbulent terms,

$$\tau_t = \rho\overline{uw} = -\rho\nu_t\partial\bar{U}/\partial z, \quad (6)$$

$$q_t = \rho c_p \overline{T'w} = -\rho c_p \kappa_t \partial\bar{T}/\partial z. \quad (7)$$

With the turbulent Prandtl number

$$Pr_t = \nu_t/\kappa_t, \quad (8)$$

equation (3) can be rewritten as

$$\bar{U}\partial\bar{T}/\partial x + \bar{W}\partial\bar{T}/\partial z = \frac{\partial}{\partial z}\left[(\kappa + \nu_t/Pr_t)\frac{\partial\bar{T}}{\partial z}\right]. \quad (9)$$

The eddy diffusivities, and hence Pr_t, can be determined from experimental data in the following ways:

(a) The integration method: From measured values of $\bar{U}(z)$, $\bar{T}(z)$, $\partial\bar{p}/\partial x$, τ_w and q_w at different stations (x values) along the plate. First $\tau(z)$ and $q(z)$ are found by integration of equations (2) and (3); next are calculated ν_t and κ_t by application of equations (4)–(7).

(b) The eddy correlation method: From measured values of $\bar{U}(z)$, $\bar{T}(z)$, $\overline{uw}(z)$ and $\overline{T'w}(z)$ by application of equations (6) and (7).

3. EQUIPMENT AND MEASURING TECHNIQUES

The measurements reported here were performed in a "low-turbulence", closed-circuit wind tunnel. A sketch of the test section is given in Fig. 2: full details are presented in refs. [1, 2].

The heated part of the plate was kept at a constant temperature (± 0.2 K), whilst guard elements secured heat flow in a vertical direction. The temperature was measured with thermocouples situated just below the plate surface. Two rows of water cooled blades, located in corners of the wind tunnel, kept the free stream air temperature at a constant value.

The wall shear stress, τ_w, was measured with Preston tubes [3, 4]. The accuracy of the τ_w values is about 2%. The wall heat flux density, q_w, could be determined within 3% from the power supplied to the central heated part.

Velocity measurements were performed by constant temperature hot-wire anemometry. $\bar{U}$ values were measured by a single wire, with its axis in the y direction, having a diameter of 3 μm and an effective length of 1.90 mm.

The $\overline{uw}$ values were determined with an X-wire probe. The wires of this probe were located in x, z-planes; they made angles of about $\pm 30°$ with the x-axis. Their diameter was 3μm and they had effective lengths of 1.96 mm and 1.68 mm. A method described by Bradshaw [5] was used to examine the validity of the 'cosine law' for the X-wire probe. Corrections were made for deviations from this law.

All hot wires were carefully calibrated and the calibration was corrected for variation of the average air temperature, as described by Koppius and Trines [6].

Temperatures were measured by electrical resistance thermometry, as described by Nieuwvelt *et al.* [7]. This includes compensation for the thermal inertia of the sensor. This sensor consists of a thin quartz wire, with a diameter of 5.5 μm and a platinum coating of about 0.1 μm thickness.

A probe with an effective length of 1.90 mm, with its axis in the y direction, was used to measure $\bar{T}$.

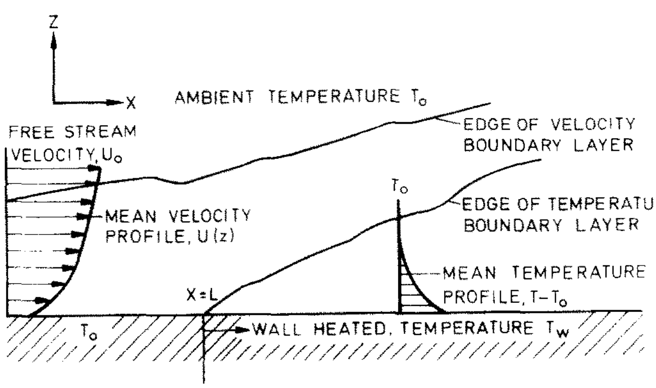

FIG. 1. Sketch of configuration investigated.

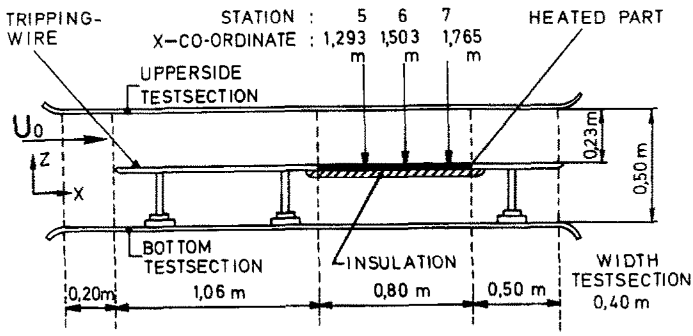

FIG. 2. Test section of the wind tunnel, showing plate with heated part and relevant dimensions.

A second probe (with an effective length of 1.56 mm) was combined with the X-wire probe for determining $\overline{T'w}$. A correction was made for axial heat conduction to the (isothermal) prongs (5% for T' values) analogous to the correction described by Maye [8].

All probes were constructed so as to minimize aerodynamic disturbances, according to the recommendations of Strohl [9].

The electrical signals from the probes were recorded on a 14 track Honeywell 7600 analogue instrumental tape recorder. All anemometer signals were linearised by analogue equipment before processing. Correlations were obtained by means of a Federal Scientific UC-201c two-channel correlator.

An electronically controlled transversing mechanism, designed at our laboratory, was used to move the probes vertically through the boundary layer. It allowed an accuracy of 15 μm in the determination of absolute z-values and of 2 μm in the probe displacements.

4. EXPERIMENTAL RESULTS

Care was taken to keep the free stream velocity, U_0, and the difference between the wall and free stream temperatures, $T_w - T_0$, constant.

Because the measurements extended over a period of about 6 months, conditions changed slightly due to variations of barometric pressure and ambient temperature. All air properties (ρ, ν, c_p, κ) were taken at the relevant film temperature, $\frac{1}{2}(T_w + T_0)$, and pressure. Some of the flow measurements were carried out both under isothermal ($T = T_0$) and non-isothermal conditions. No influence of buoyancy was observed.

Velocity and temperature profiles were measured at stations 5, 6 and 7 (Fig. 2). Measurements of $\overline{uw}$ and $\overline{T'w}$ were performed at stations 6 and 7 only. The results for station 6 are presented, those for the stations 5 and 7 being similar.

Typical conditions, pertaining to the measurements with the combined X-wire and temperature probe, are given in Table 1.

The velocity profile is given in Fig. 3 in the usual dimensionless form. For $z^+ > 30$ our profile approaches the logarithmic law, with parameters as given by Hinze [10]

$$U^+ = 2.44 \ln z^+ + 4.90. \tag{10}$$

For $z^+ < 300$ the data show an excellent agreement

Table 1. Values of various quantities for station 6 during measurements with the combined probe

Quantity	Value	Quantity	Value
U_0	10.8 m s^{-1}	S_u	35 mm
T_0	300.4 K	τ_w	0.25 Pa
$T_w - T_0$	11.4 K	q_w	362 W m^{-2}
$\frac{1}{2}(T_w + T_0)$	306.1 K	$d\bar{p}/dx$	−4.8 Pa m^{-1}
p_0	101.4 kPa	dq_w/dx	−140 W m^{-3}

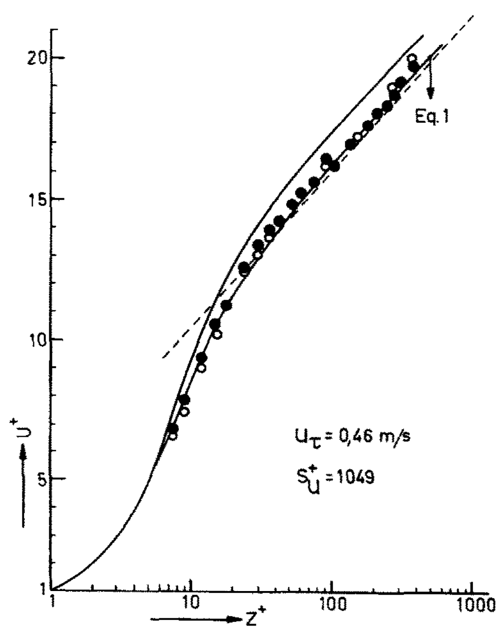

FIG. 3. Dimensionless velocity profile at station 6. Broken line, logarithmic profile [equation (10)]. Upper curve, [equation (11), with $B = 0.1108$, $b = 0.40$ and $m = 5$]. Lower curve, [equation (11), with $B = 0.1342$, $b = 0.41$ and $m = 4$]. ●, Linearized signals; ○, non-linearized signals.

with the Spalding formula [11]

$$z^+ = U^+ + B\left[\exp(bU^+) - \sum_{n=0}^{m} (bU^+)^n/n!\right] \quad (11)$$

with $B = 0.1342$, $b = 0.41$ and $m = 4$.

These values of B and b correspond with the values of the parameters in ref. [10].

These results are slightly different from those of Spalding, who found a best fit with $B = 0.1108$, $b = 0.40$ and $m = 3$ or $m = 4$. They are also different from those of Blom [2], who found a best fit with the values of B and b given by Spalding, but with $m = 5$ (modified Spalding profile). Figure 3 shows that the effect of linearization is small.

The temperature profile is presented in Fig. 4. The experiments show a logarithmic temperature profile for $30 < z^+ < 300$. Assuming a linear profile for $z^+ < 7$, analogous to the velocity profile, the whole temperature profile can be well represented by a Spalding-like formula given by

$$z^+ = Pr^{-1}T^+ + B_1\left[\exp(b_1T^+) - \sum_{n=0}^{m} (b_1T^+)^n/n!\right] \quad (12)$$

with $Pr = 0.71$.

In the logarithmic region one obtains from the experimental data the following simple relation between T^+ and U^+:

$$T^+ = (0.86 \pm 0.02)U^+, \ 30 < z^+ < 300. \quad (13)$$

Combining equations (10), (12) and (13) results in $B_1 = 0.1342$, $b_1 = 0.48$ and $m = 4$.

From the values of S_u^+ and S_T^+ given in Figs. 3 and 4, it can be seen that the thickness of the temperature boundary layer is about half that of the velocity boundary layer at station 6.

It should be noted that the temperature data obtained with the combined probe agree well with those given by the single probe. The former could not be used for $z^+ < 20$, because of the vertical extension of the X-wire probe.

Results of both methods for determining the turbulent shear stress profile are given in Fig. 5. The values found by the eddy correlation method appear to be much smaller than those derived from the integration method. The reason for this discrepancy is not clear as yet. Probably it has to do with the fact that the X-wire probe does not give a true point measurement.

Results of both methods for determining the turbulent heat flux density are given in Fig. 6. The broken line indicates that the values obtained from the integration method become less reliable because the edge of the thermal boundary layer is approached, so T^+ becomes independent of z^+ and x. Here also the eddy correlation method gives lower results than the integration method. In addition the profile obtained by the former is shifted towards higher z^+ values. The

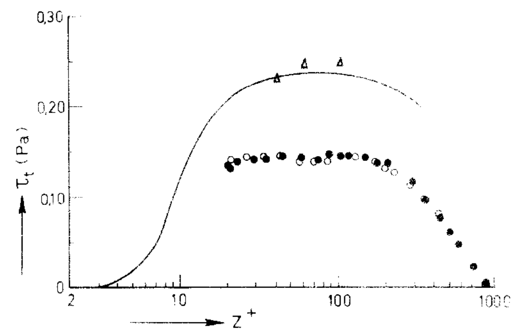

FIG. 5. Turbulent shear stress profile at station 6. —— derived from equation (2). ●, Eddy correlation, isothermal condition; ○, eddy correlation, non-isothermal condition; △, see Discussion and Conclusions.

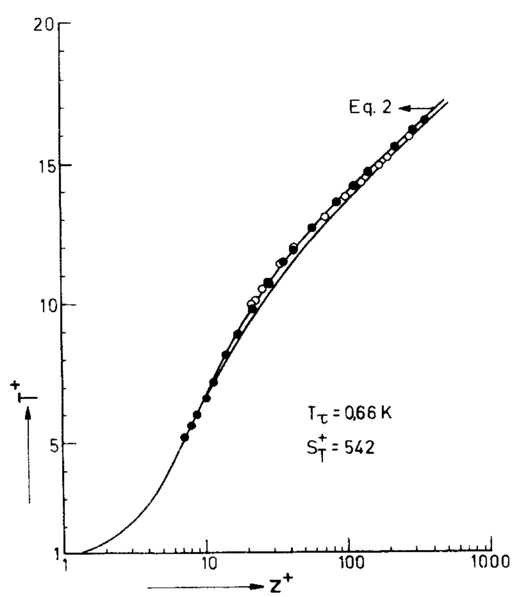

FIG. 4. Dimensionless temperature profile at station 6. Upper curve, equation (12) with $m = 4$. Lower curve, equation (12) with $m = 3$. ●, Single temperature probe; ○, combined temperature and X-wire probe.

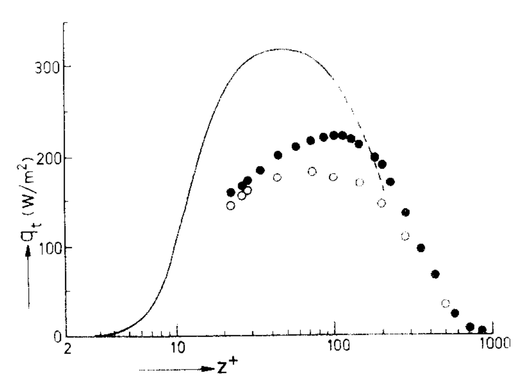

FIG. 6. Turbulent heat flux density at station 6. —— derived from equation (3). ●, Eddy correlation, linearized, temperature corrected; ○, eddy correlation, non-linearized, temperature not corrected.

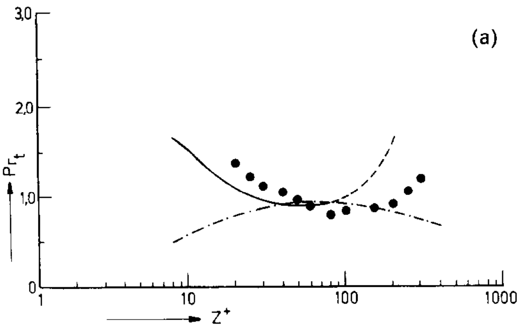

FIG. 7(a). Profile of the turbulent Prandtl number at station 6. —— obtained from integration method; ●, obtained from eddy correlation method; —·—·— results of Blom [2].

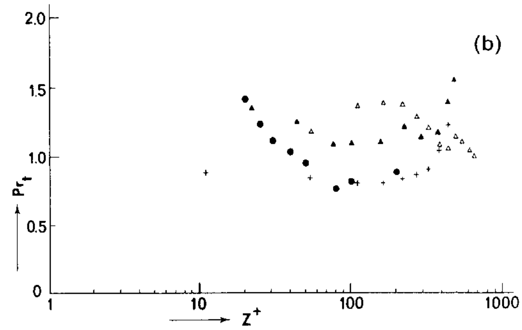

FIG. 7(b). Turbulent Prandtl number across the inner boundary layer obtained by the eddy correlation method: +, results of Fulachier *et al.*; $(x-L)/S_u(L) = 10.3$; △, results of Antonia *et al.*; $(x-L)/S_u(L) = 11.4$; ▲, results of Antonia *et al.*; $(x-L)/S_u(L) = 42.9$; ●, present results; $(x-L)/S_u(L) = 13.2$.

effects of linearization and temperature correction are quite marked here.

Finally the profiles of Pr_t are presented in Fig. 7(a), together with the results of Blom. The shift between the results of the two methods, shown in Fig. 6, recurs here. However, the values obtained from the eddy correlation method do not differ markedly from those derived from the integration method. This indicates that the same systematic error arises in both $\overline{uw}$ and $\overline{T'w}$. Contrary to the findings of Blom, Pr_t appears to increase with decreasing z^+ in the transition layer $(7 < z^+ < 30)$. For $30 < z^+ < 300$, equation (13) would imply $Pr_t = 0.86$, provided that $\tau(z)/\tau_w = -1$ and $q(z)/q_w = 1$.

5. DISCUSSION AND CONCLUSIONS

The velocity profile found in the present work can be well represented for $z^+ < 300$ by the Spalding formula with $m = 4$, equation (11), with the values of the parameters derived from the logarithmic profile [equation (10)]. The values of the parameters in equation (10) are chosen as the best in the literature. Other values of these parameters, also in use, will influence strongly the values of the corresponding constants in equation (11). We have to keep in mind that our experiments were performed in a developing velocity boundary layer, while equation (10) is given for a fully-developed boundary layer. Figure 3 suggests that a somewhat higher value than 2.44 is acceptable. This implies a somewhat lower value of the Von Kármàn constant, as was also found by other authors [10, 12]. The temperature profile can be well described by a Spalding-like formula [cf. equation (12)].

To construct the dimensionless temperature profiles the value of q_w is needed, which here is derived from the electrical power input to the heated elements. Another possibility would be to use the slope of the temperature profile near the wall $(0 < z^+ < 5)$. Later experiments show that in this case, due to the temperature gradient in this region $(1.5 \times 10^4 \text{ K m}^{-1})$, corrections have to be made for the heat conduction along the prongs in this non-isothermal field. (Zarič's correction modified to our probe shape [13] was used.) Small differences in the temperature between adjacent elements (0.2–0.3 K) lead to a considerable scatter in the measured values due to the presence of local internal thermal boundary layers.

The deviation between the shear stress results derived from the integral method and the eddy correlation method can be explained by the effect of the lengths of the X-wires on the latter method, as described by Willmarth and Bogar [14]. Afterwards some shear stress measurements were made with effective lengths of the X-wires of 0.8 mm.

After special attention was paid to the application of the 'cosine law' [5], the measured shear stress values agreed within 6% with the values of the integral method down to $z^+ = 40$ (marked Δ in Fig. 5).

To test the analogue data processing for determining shear stress values the recorded X-wire signals were fed into a B 7700 Burroughs computer. After digital processing including linearization the values of the shear stress agreed within 2% with the presented values (marked Δ in Fig. 5). For the region $30 < z^+ < 100$ the value found for Pr_t is 0.9 ± 0.1.

This is also the region in which the maximum values for the turbulent fluxes of momentum and heat occur. Figure 7(a) shows that for $z^+ < 30$ and $z^+ > 100$, Pr_t is increasing in contradiction to earlier results of Blom [2]. Figure 7(b) represents the results of Pr_t determined by the eddy correlation method by different authors [12]. The shape of our curve shows agreement with the results of Antonia *et al.* for the fully developed thermal layer $[(x-L)/S_u(L) = 42.9]$. For $40 < z^+ < 300$ there seems to be agreement with the results of Fulachier *et al.* [15]. There is less agreement with the results of Antonia *et al.* for a developing thermal boundary layer.

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DETERMINATION EXPERIMENTALE DU NOMBRE DE PRANDTL TURBULENT A L'INTERIEUR DE LA COUCHE LIMITE POUR UN ECOULEMENT D'AIR SUR UNE PLAQUE PLANE

Résumé—On présente des résultats sur la mesure de vitesse et de température, de flux turbulent de quantité de mouvement et de chaleur pour l'air en écoulement sur une plaque plane dont une partie est maintenue à 11 K au-dessus de la température ambiante. Ce travail poursuit ce qui a été présenté à la Sixième Conférence Internationale sur le Transfert de Chaleur.

Des mesures de vitesse sont faites par anémométrie à fil chaud, utilisant un fil unique et des sondes en X ; les mesures de température par thermométrie à résistance avec des petits capteurs spéciaux.

Des expériences sont déduites les valeurs des diffusivités turbulentes pour la quantité de mouvement et la chaleur et celles du nombre de Prandtl turbulent. Pour une couche limite turbulente en développement, les profils de vitesse et de température pour $z < 300$ peuvent être bien représentés par les formules

$$z^+ = U^+ + 0{,}1342\left[\exp(0{,}41\,U^+) - \sum_{n=0}^{4} (0{,}41\,U^+)^n/n!\right],$$

$$z^+ = Pr^{-1}T^+ + 0{,}1342\left[\exp(0{,}48\,T^+) - \sum_{n=0}^{4} (0{,}48\,T^+)^n/n!\right].$$

Pour la région $30 < z^+ < 100$ la valeur trouvée pour Pr_t est $0{,}9 \pm 0{,}1$. La relation entre Pr_t et z^+ pour $40 < z^+ < 300$ est en accord avec les résultats de Fulachier. Il y a moins d'accord avec les résultats d'Antonia donnés pour une couche limite thermique en développement.

EXPERIMENTELLE BESTIMMUNG DER TURBULENTEN PRANDTL-ZAHL IN DER INNEREN GRENZSCHICHT DER LUFTSTRÖMUNG AN EINER EBENEN PLATTE

Zusammenfassung—Es werden Meßergebnisse von Geschwindigkeits-und Temperaturprofilen sowie des turbulenten Transports von Impuls und Wärme in der Luftströmung an einer ebenen Platte mitgeteilt, von der ein Teil auf einer Temperatur von 11 K über Umgebungstemperatur gehalten wurde. Es handelt sich um eine Fortsetzung der Arbeit, über die auf der 6. Internationalen Konferenz für Wärmeübertragung vorgetragen wurde.

Die Strömungsmessungen wurden mit Hitzdrahtanemometern unter Verwendung von Einzeldraht- und X-Draht-Sonden durchgeführt. Für die Temperaturmessung wurden speziell konstruierte Widerstandsthermometer eingesetzt. Aus den experimentellen Daten konnten die turbulenten Transportgrößen für Impuls und Wärme sowie die turbulente Prandtl-Zahl abgeleitet werden. Für eine sich ausbildende turbulente Grenzschicht lassen sich das Geschwindigkeits- und Temperaturprofil für $z^+ < 300$ durch folgende Gleichungen gut beschreiben

$$z^+ = U^+ + 0{,}1342\left[\exp(0{,}41\,U^+) - \sum_{n=0}^{4} (0{,}41\,U^+)^n/n!\right],$$

$$z^+ = Pr^{-1}T^+ + 0{,}1342\left[\exp(0{,}48\,T^+) - \sum_{n=0}^{4} (0{,}48\,T^+)^n/n!\right].$$

Für den Bereich $30 < z^+ < 100$ ergab sich als Wert für die turbulente Prandtl-Zahl $Pr_t = 0{,}9 \pm 0{,}1$. Die Beziehung zwischen Pr_t und z^+ für $40 < z^+ < 300$ ist in guter Übereinstimmung mit den Ergebnissen von Fulachier. Eine weniger gute Übereinstimmung besteht mit den Ergebnissen von Antonia, welche für eine sich ausbildende thermische Grenzschicht gelten.

ЭКСПЕРИМЕНТАЛЬНОЕ ОПРЕДЕЛЕНИЕ ТУРБУЛЕНТНОГО ЧИСЛА ПРАНДТЛЯ ВО ВНУТРЕННЕМ ПОГРАНИЧНОМ СЛОЕ ПОТОКА ВОЗДУХА НАД ПЛОСКОЙ ПЛАСТИНОЙ

Аннотация— Представлены результаты по измерению профилей скорости и температуры, а также турбулентных потоков импульса и тепла при течении воздуха над плоской пластиной, на части которой поддерживается температура, примерно на II K превышающая температуру окружающей среды. Приведенные результаты являются продолжением работы, представленной на 6-й Международной конференции по теплообмену.

Измерения скоростей проводились по методу тепловой анемометрии одножильными и X-образными зондами, а температуры методом термометрии сопротивления с использованием малых датчиков особой конструкции.

На основе экспериментальных данных были получены значения турбулентной вязкости и температуропроводности, а также турбулентного числа Прандтля. Для развивающегося турбулентного пограничного слоя профили скорости и температуры при $z^+ < 300$ можно хорошо описать следующими уравнениями:

$$z^+ = U^+ + 0{,}1342\left[\exp(0{,}41U^+) - \sum_{n=0}^{4}(0{,}41U^+)^n/n!\right],$$

$$z^+ = Pr^{-1}T^+ + 0{,}1342\left[\exp(0{,}48T^+) - \sum_{n=0}^{4}(0{,}48T^+)^n/n!\right].$$

Для области $30 < z^+ < 100$, значение Pr_t составило $0{,}9 \pm 0{,}1$. Соотношение между Pr_t и z^+ при $40 < z^+ < 300$ согласуется с результатами, полученными фулакье. Совпадение с результатами Антониа для развивающегося теплового пограничного слоя несколько хуже.