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An Experimental Study of Turbulent Free Convection Boundary Layer
in Air along a Vertical Plate using LDV*

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Local heat transfer data were obtained for turbulent free convection on a vertical surface with uniform heat generation in air and are correlated well by the relation:

$$Nux = 0.175 (Grx \cdot Pr)^{0.256} \quad \text{for } 8 \times 10^{12} < Grx \cdot Pr < 2 \times 10^{14}$$

An LDV and a thermocouple were used to measure the longitudinal and normal components of velocity, u and v , and the temperature, t , in a fully developed turbulent boundary layer. Appreciable differences of turbulence quantity distributions, $(u'^2)^{1/2}$, $u'v'$ and $v't'$, between the present and the previously obtained results using hot wire sensors, have been found. Present LDV results of $(u'^2)^{1/2}$ and $u'v'$ have a tendency to be more similar to the previously calculated results by the mean turbulent energy method.

Key Words: turbulence, free convection, boundary layer, vertical plate, laser doppler velocimeter

1. Introduction

There are many publications on experimental investigation of turbulent free convection heat transfer along a vertical flat plate. These include early research with measurements of local heat transfer coefficient, mean temperature profiles and mean velocity profiles across the boundary layer, and recent research with measurements of turbulence structure in the boundary layer. Fujii⁽¹⁾ reviewed all experiments up to 1973 and pointed out that these experimental results were deficient in measuring accuracy and concluded that much more experimental data were necessary.

In experiments with air since 1973, turbulence structures of the boundary layer were fully investigated by Smith.⁽²⁾ Also, Hoogendoorn and Euser⁽³⁾ measured streamwise mean velocity profiles which cast doubt on profiles previously measured by Cheesewright⁽⁴⁾. Furthermore, Vliet and Ross⁽⁵⁾ measured the local heat transfer coefficients along an inclined flat plate including a vertical flat plate. Cheesewright and Doan⁽⁶⁾ measured space-time correlation in a turbulent boundary layer along a vertical plate and Hishida et al.⁽⁷⁾ investigated turbulence structures of the boundary layer along a vertical plate.

In all these recent investigations, a hot wire anemometer was used to measure velocities in the boundary layer, and the tested vertical flat plate was maintained

at uniform temperature except in the experiment by Vliet and Ross. It is very difficult to use a hot wire to accurately measure velocities in the turbulent free convection boundary layer because velocities in it are very low and intensively fluctuate along with violent temperature fluctuations. There are still problems in the accuracy of measurements by a hot wire in the case of the turbulent free convection boundary layer.

This paper describes the results of an experiment in which an LDV and a fine thermocouple were used to measure velocities and temperature in the free convection boundary layer along a vertical flat plate with uniform-heat-generation in air. The vertical heated flat plate was thinner than 0.7 mm and was constructed in plane symmetry about the plane at the center of its thickness. Also the convection room was arranged in plane symmetry about the vertical heated plate. These constructions of the experimental apparatus made it possible to determine accurately the local heat transfer rate by the measurements of the surface temperature and the heat-generation-rate. The estimation of thermal radiation from the heated plate was made in due consideration of the local convective heat transfer rate in the laminar region.⁽⁸⁾ In the turbulent region, variation of radiation heat flux along a vertical plate was insignificant.⁽¹⁾ Further, considering that the difference of thermal boundary conditions has a slight influence on characteristics of turbulent heat transfer, the present experimental results can be compared with previous results in the case of the uniform-temperature vertical plate, by using a simple transformation equation.

Publications concerning velocity measurements by an LDV in the turbulent boundary layer are few even in the field of forced convection and fewer in the field of turbulent free convection. Appropriateness of

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experimental apparatus, measuring method and accuracy were examined by measurements of temperature and velocities in the laminar boundary layer. Results of these measurements agreed well with the numerical solution in the case of the uniform-heat-flux, vertical plate without thermal radiation.

In this paper, experimental studies of lateral profiles of turbulence quantities in a fully turbulent free convection boundary layer will be described mainly, comparing the present results with theoretical results⁽⁹⁾⁽¹⁰⁾ by the mean turbulent energy method and with the previous experimental results⁽²⁾⁽⁷⁾ using a hot wire.

2. Nomenclature

E	: turbulent kinetic energy, $= (\overline{u'^2} + \overline{v'^2} + \overline{w'^2}) / 2$.
f	: frequency.
Ft, Fv	: flatness factor of temperature and streamwise velocity, $Ft = \frac{1}{N} \sum_{i=0}^{N-1} ti'^4 / [\frac{1}{N} \sum_{i=0}^{N-1} ti'^2]^2.$
g	: acceleration of gravity.
i	: time number of data sequence.
Grx	: Grashof number, $= g\beta(T_w - T_\infty)X^3/\nu^2$.
Grx*	: modified Grashof number, $= g\beta qcX^4/\lambda\nu^2$.
N	: total number of data points.
Nux	: local Nusselt number, $= \alpha X/\lambda$.
Pr, Prt	: Prandtl number and turbulent Prandtl number.
Px'x'(f)	: power spectra density distribution.
q, qc, qr	: heat generation rate, convective heat flux and radiation heat flux, $q = qc + qr$, qr defined by Eq.(1).
St, Sv	: skewness factors of temperature and streamwise velocity, $St = \frac{1}{N} \sum_{i=0}^{N-1} ti'^3 / [\frac{1}{N} \sum_{i=0}^{N-1} ti'^2]^{3/2}.$
t, $\bar{T}$, t'	: temperature, mean temperature and fluctuating component of temperature, $t = \bar{T} + t'$.
T _w	: temperature on the heated plate.
u, $\bar{U}$, u'	: streamwise velocity, mean streamwise velocity and fluctuating component of streamwise velocity, $u = \bar{U} + u'$.
v, $\bar{V}$, v'	: velocity in Y direction, mean velocity in Y direction and fluctuating component of velocity in Y direction, $v = \bar{V} + v'$.
U, V	: dimensionless forms of u and v, $U = (\lambda/g\beta qc\nu^2)^{1/4} u$.
w'	: fluctuating component of velocity in Z direction.
X	: vertical distance from leading edge along a plate or in Fig.8 only dimensionless form of X, $= Grx^{1/4}$.
Y	: horizontal distance from a plate or in Fig.8 only dimensionless form of Y, $= (g\beta qc/\lambda\nu^2)^{1/4} Y$.
Z	: horizontal distance in parallel with a plate.
α	: local heat transfer coefficient, $= qc/(T_w - T_\infty)$.
β	: volumetric expansion.
ϵ	: emissivity on a heated plate.

ζ	: dimensionless form of Y, $= Nux(Y/X)$.
θ	: dimensionless temperature, $= (\bar{T} - T_\infty)/(T_w - T_\infty)$.
Θ	: $= (qc^3\nu^2/g\beta\lambda^3)^{1/4}$.
λ	: thermal conductivity.
ν	: kinematic viscosity.
σ	: Stefan-Boltzman constant.
$\Phi x'x'(f)$	: power spectra density distribution, $= Px'x'(f) / \int_0^\infty Px'x'(f) df.$

Suffixes

m, max	: maximum of time mean value in X constant plane.
—	: time mean value.
w	: heated surface.
∞	: ambient fluid.

3. Experimental apparatus and measuring method

The experimental apparatus was arranged symmetrically about the heated plate as shown in Fig.1. The outer walls of the convection room were made of plywood boards of thickness 9 mm, and the side walls of the heated plate were made of acrylic resin of thickness 4 mm, through which the heated plate could be seen from the measuring rooms.

The heated plate consisted of a thin stainless steel foil (0.12 mm thick SUS 304), which was folded into two at its center corresponding to a leading edge, and two sheets of thin polyester film (0.05 mm thick), which were put between the folded parts of the stainless foil for the purpose of electrical insulation. The folded stainless foil and the inserted polyester films were stuck together by adhesive. This mul-

1. heated plate, 2. convection room, 3. measuring rooms, 4. He-Ne laser, 5. photo-multiplier, 6. thermocouple probe to measure temperature in the boundary layer, 7. thermocouple probes to measure ambient fluid temperature.

Fig.1 Experimental apparatus

tilayer test plate, 980 mm wide with 5000 mm effective height and total thickness less than 0.7 mm, was heated uniformly by an electric current. The heated plate could be moved within a length of 120 mm perpendicularly to its surface by sliding steel blocks, from which it was suspended vertically, along steel guides installed near the ceiling of the convection room. Between the polyester films and at the center of the width of the heated plate, thermocouples (C.C. of 0.1 mm dia.) were inserted at 50 mm intervals vertically and were used for measuring surface temperature on the heated plate by a digital voltmeter with 0.001mV resolution.

The temperature field in the boundary layer was measured by a fine thermocouple (C.A. of 25 μ m dia. or C.C. of 30 μ m dia.) which was stretched between the tips of a two-tined folk holder, which was made of piano-wire of 0.5 mm dia. and could be slightly moved perpendicularly to the heated plate by using a micrometer caliper. The distance between the two tips was about 40 mm and the hot junction was placed at its center. The thermal e.m.f. of this boundary layer thermocouple was amplified and recorded on a recorder through a lowpass filter.

The hot junctions of all thermocouples were made by butt resistance welding and calibrated by a standard thermometer with 0.1 $^{\circ}$ C resolution. The velocity field in the boundary layer was measured by an LDV (KANOMAX, Model 1900) which was used in dual beam forward scatter mode. The laser was a 15 mW He-Ne laser. The distance between two beams was 50 mm and the focal length of the converging lens was 593 mm. Hence the scattering volume was approximately 0.5 mm in diameter and 4 ~ 5 mm long. Tobacco smoke was used as scattering particles. Once tobacco smoke filled the convection room, velocity measurement was made possible for about 7 hours. A tracker type signal processor was used together with a frequency shift system.

The center of the measuring volume was fixed at about 3 mm directly under the hot junction of the boundary layer thermocouple. The distance, Y, between the measuring point and the heated surface was changed by horizontally moving (within 120 mm) the heated plate itself. The distance Y was measured by sighting a mark on the heated plate through a small cathetometer in the measuring room. Measurements of velocity and temperature in the turbulent boundary layer were started about 5 minutes after the heated plate, which had been moved slowly for changing Y, became stationary.

The output signal from the frequency tracker, in the same way as the amplified thermal e.m.f. of the boundary layer thermocouple, was recorded on the data recorder. Digital data were acquired from the reproduced signal by an analog-digital converter (12 bit) and analyzed by a mini-computer (Melcom 70/25 system). The sampling interval was 10 msec. and the number of the data points was about 8000 (or 4096 only for spectrum analysis). Therefore, this sampling period was about 80 seconds. There was an insignificant difference between mean values obtained by some digital data

which were acquired for some periods of 80 seconds from the reproduced signal for about 3 minutes. The differences of rms value between the amplitude analysis (number of data was about 8000) and Fourier analysis (number of data was 4096) were less than about 2 %.

The convective heat flux qc was determined by the following equations:

$$qc = q - qr, \quad qr = \epsilon \sigma (T_w^4 - T_v^4) \quad (1)$$

where T_v was the temperature on the inner surface of the convection room at the same height as T_w was measured. The emissivity of the heated surface, ϵ , was 0.16.[#] The properties other than volume expansion were evaluated at the following reference temperature:

$$T_r = (3 T_w + T_{\infty}) / 4 \quad (2)$$

Measurements of velocity and temperature in the boundary layer were performed in quasi-steady state of free convection, which began at about 1.5 hours after the start of heating, and during the night to avoid severe variation of atmospheric temperature in the day time.

4. Experimental results and discussions

4-1. Local heat transfer coefficient

Examples of measurement of the heated surface temperature, the ambient fluid temperature and the convective heat flux at the heated surface are shown in Fig.2. When q was 127 W/m², a transition-turbulent region⁽¹⁾ could be recognized in the temperature distribution on the heated surface.

In Fig.3 local Nusselt number distributions, which were estimated from the measured temperature distributions for various q , were plotted against $Gr_x \cdot Pr$. In the laminar region ($Gr_x \cdot Pr < 3 \times 10^{11}$), which is not shown in this figure, the present local Nusselt number distribution agreed relatively well with the following similarity solution in the case of a uniform-heat-flux

[#] Measurement of emissivity on the heated surface by using a radiation thermometer gave values of the emissivity ϵ from 0.14 to 0.17. Finally the value of emissivity on the heated stainless steel surface was decided by the following trial and error method. In the first place, qc was estimated by Eq.(1), using a properly assumed emissivity and the measured values T_w , T_v and q . The local Nusselt number which was determined by this calculated value of qc was compared with Eq.(3). This trial and error calculation to find appropriate value of emissivity was continued until the obtained local Nusselt number for higher q agreed with Eq.(3). Consequently, the resultant value of ϵ was 0.16, which was an intermediate value in the values measured by a radiation thermometer. Experimental and theoretical results by Fujii et al.⁽⁸⁾ indicated that the present trial and error method was reasonable. Furthermore, in the present experiment, qr was not larger than 30 % of q . Hence 5 % error in qr caused about 2 % error in qc , which was relatively small.

Fig.2 Ambient fluid temperature, heated surface temperature and convective heat flux on the heated surface.

Fig.3 Local Nusselt number distribution.

surface without thermal radiation.

$$Nux = 0.520 (Grx*Pr)^{0.2} \quad (3)$$

In the turbulent region ($8 \times 10^{12} < Grx*Pr < 2 \times 10^{14}$) the present experimental results were correlated well by the following equation which was obtained by the least square method:

$$Nux = 0.175 (Grx*Pr)^{0.256} \quad (4)$$

In order to compare the present results with the previous experimental results obtained by using a uniform temperature vertical plate, the following transformation equation was used:

$$Grx^* = Nux Grx \quad (5)$$

Eq.(4) was transformed into Eq.(6) by Eq.(5).

$$Nux = 0.0961 (Grx Pr)^{0.344} \quad (6)$$

$$2.5 \times 10^{10} < Grx Pr < 2.7 \times 10^{11}$$

On the other hand, the previous experimental results by Cheesewright⁽⁴⁾ gave the following correlation equation:

$$Nux = 0.0245 (Grx Pr)^{2/5} \quad (7)$$

$$2.3 \times 10^{10} < Grx Pr < 1.3 \times 10^{11}$$

And Hishida et al.⁽⁷⁾ gave the following correlation equation:

$$Nux = 0.120 (Grx Pr)^{1/3} \quad (8)$$

$$10^{10} < Grx Pr$$

Present result, Eq.(6), gave intermediate values of the local Nusselt number between the previous two, Eqs.(6) and (7). In the following comparisons, Eq.(5) was used throughout.

4-2. Temperature field in the turbulent boundary layer

The measured temperature profile in the laminar boundary layer agreed well with the numerical solution⁽¹¹⁾ of free convection along a vertical uniform-heat-flux plate without thermal radiation. This agreement means that the present measurements of temperature and distance Y from the heated surface were sufficiently accurate. In Fig.4, the present mean temperature profiles in the turbulent boundary layer are compared with experimental results by Smith and theoretical results by Fujii et al. It seems that the dimensionless mean temperature profiles in the turbulent boundary layer are correlated approximately by ζ , i.e., the abscissa in Fig.4 which was proposed by Fujii et al.⁽¹²⁾ (When the dimensionless mean temperature profiles for $5.2 \times 10^{10} < Grx < 1.5 \times 10^{11}$ were plotted against ζ , the differences among dimensionless profiles were less than about 3.5 % of the temperature difference between the heated surface and the ambient fluid.) All measured mean temperatures are lower than the theoretical temperature in the main part of the boundary layer.

Profiles of dimensionless temperature deviation in the turbulent boundary layer are compared in Fig.5. Present value of ζ , at which the maximum temperature deviation was found ($\zeta \approx 0.6$, $Y \approx 4$ mm) was slightly less than the value ($\zeta \approx 0.8$) obtained by Smith. Present maximum temperature deviations were about 20 % lower than the maximum deviation by Smith. Profiles of dimensionless temperature deviation, $(t'^2)^{1/2} / (Tw - T\infty)$, not shown in Fig.5, which were obtained by Hishida et al. using a tungsten probe with 5 μ m in diameter, agreed approximately with the present results.

In Figs.6 and 7, the skewness factor

Fig.4 Dimensionless mean temperature profiles in the turbulent boundary layer.

Fig. 5 Profiles of dimensionless temperature deviation.

and the flatness factor of probability density distribution of temperature are plotted against ζ . These profiles are quite similar to the results (not shown in the figure) obtained by Smith, and there is little difference in the scatter of these data between the present results and Smith's results. Hence it seems that the sampling time of the present experiment (about 80 sec.), shorter than that of Smith's experiment (about 5 minutes), did not pose a serious problem.

According to Figs. 6 and 7, the probability density of temperature changes gradually from Gaussian distribution very near the plate to a more skewed and peaked one in proportion to the distance from the plate. At $\zeta \approx 0.2 \sim 0.3$ ($Y \approx 1.4 \sim 2.1$ mm), the skewness and flatness factors have their maximum values. More extensive mixing by a turbulence takes place in this region, and a convective transport to this region from the outer cooler regions occurs intermittently. At the location where maximum deviation of temperature fluctuation was found (indicated by the symbol $(\overline{t'^2})^{1/2}_{\max}$ in the figure), the probability distribution is much

Fig. 6 Skewness factor profiles of temperature

Fig. 7 Flatness factor profiles of temperature

wider, more symmetric and uniformly dispersed. Further out beyond the region where $\zeta \approx 1$, it has a longer foot toward the higher temperature in contrast with that in the inner region. In this region, where a lower mean temperature was found, the convective transport from the inner hotter region occurs intermittently.

4-3. Velocity field in the turbulent boundary layer.

Measured velocity profiles in the laminar region are compared with a finite difference solution of free convection around the uniform-heat-flux surface in Fig. 8. Profiles of the measured streamwise velocity U agree well with the numerical solution. At first sight it seems that the measured velocity in the normal direction to the plate, V , is higher than the numerical solution and the difference between the experimental and theoretical solutions is relatively large. But the measured values of velocity V were about 1 cm/sec at most. (These values are nearly equal to the value of U at $YX^{-1/5} \approx 5$.) Hence the difference of the velocity V between experiment and theory is very small and as small as the difference of the velocity U . Considering that the present system of velocity measurement had a guaranteed accuracy of about 1 cm/sec at most and the numerical solution was not totally accurate (the case of uniform-heat-flux and constant properties), the measured velocities, U and V , which agree well with the numerical solution within the limit of the guaranteed accuracy, are very appropriate.

Mean streamwise velocities in the turbulent boundary layer are compared in Fig. 9. Results measured by Smith were generally similar to Cheesewright's measurements⁴⁾ (not shown in this figure) and were considered to be too low as Hoogendoorn et al.³⁾ pointed out. In the region of the boundary layer beyond the location of the maximum mean streamwise velocity, all measured velocity profiles were lower than the theoretical values.

Profiles of dimensionless streamwise velocity deviation, $(u'^2)^{1/2}/U_m$, are compared in Fig. 10. The profile obtained by Fujii et al.⁹⁾ corresponds to a dimensionless turbulent kinematic energy, $\sqrt{E}/U_m$, which was calculated theoretically. Smith and Fujii et al. mentioned as follows: Exact-

Fig. 8 Velocity profiles across laminar free convection boundary layer

Fig.9 Profiles of dimensionless mean stream-wise velocity across the turbulent free convection boundary layer.

ly speaking $(\overline{u'^2})^{1/2} / \overline{U}_m$ is not equal to $\sqrt{E}/\overline{U}_m$, but assuming that $(\overline{v'^2})^{1/2} \approx (\overline{w'^2})^{1/2} \approx 0.5 (\overline{u'^2})^{1/2}$, $(\overline{u'^2})^{1/2} / \overline{U}_m$ can be approximated by $\sqrt{E} / \overline{U}_m$. ## Previous measurements using a hot wire anemometer indicated that the location of the maximum mean velocity $\overline{U}_m$ agreed approximately with the location where the maximum velocity deviation $(\overline{u'^2})^{1/2}_{\max}$ was found. But the present measurement indicates that the location of the maximum velocity deviation $(\overline{u'^2})^{1/2}_{\max}$ is situated at a position of the boundary layer beyond the location of $\overline{U}_m$. Generally, it seems that the theoretically estimated profile of $\sqrt{E}/\overline{U}_m$ agrees practically with the present experimental results of $(\overline{u'^2})^{1/2} / \overline{U}_m$.

In investigation of an isothermal plane wall jet⁽¹³⁾ ($U_0 S / \nu = 2.0 \times 10^4$, U_0 is a blow-off velocity at nozzle and S is a nozzle height.), whose mean velocity profile is considered to be similar to that of the turbulent free convection boundary layer, experimental results indicate that the relative relationship between the location of $\overline{U}_m$ and $\overline{u'^2}_{\max}$ is approximately similar to that of the free convection boundary layer. (Within the limits of the available data, $Y(\overline{u'^2} = \overline{u'^2}_{\max}) / Y(\overline{U} = \overline{U}_{\max}) = 4 \sim 6$, and this spreading of the values in the right hand side is larger for the free convection than for the wall jet.) Similarly in the lateral profiles of Reynolds shear stress, which will be described later, there is a resemblance between the wall jet and the present free convection boundary layer. It seems that features in the lateral profile

Fig.10 Profiles of dimensionless velocity deviation

Fig.11 Skewness factor profiles of stream-wise velocity.

Fig.12 Flatness factor profiles of stream-wise velocity.

of these turbulence quantities are roughly common to the flows which have an analogous lateral profile of the mean streamwise velocity.

In Figs.11 and 12, the skewness and the flatness factor of probability density distribution of streamwise velocity are plotted against ζ . Smith mentioned that probability distributions are nearly symmetrical because $|Sv| < 0.1$. But the present experimental results indicate that probability distributions of streamwise velocity are not necessarily symmetrical and have long feet towards higher velocities in the region of the lower mean velocities and towards lower velocities in the region of the higher mean velocities. Present results of the flatness factors are relatively similar to Smith's results. These two figures indicate that

As shown in Fig.13, $\overline{v'^2}$ is nearly equal to $\overline{u'^2} / 2$ for $\zeta > 8$, but $\overline{v'^2}$ is lower than $\overline{u'^2} / 2$ for $\zeta < 8$, although it may happen by chance that $\overline{w'^2} - \overline{u'^2} / 2$ is nearly equal to $\overline{u'^2} / 2 - \overline{v'^2}$. This problem can not be solved precisely without the available data of $\overline{w'^2}$. However, considering that $\overline{w'^2}$ has not yet been measured, it is unavoidable that the profile of $\sqrt{E} / \overline{U}_m$ must be compared with that of $(\overline{u'^2})^{1/2} / \overline{U}_m$. $\overline{v'^2}$ is smaller than $\overline{u'^2}$ and their profiles are roughly similar. (The location where their maximum values are found agreed with each other.) Hence it is not likely that one arrives at incorrect conclusions by present comparison.

Fig.13 Comparison of velocity deviation between velocities in X and Y directions.

probability distributions of streamwise velocity are uniformly dispersed and symmetrical in the region where u'^2 is at a maximum.

Velocity deviations, u'^2 and v'^2 are compared in Fig.13. Profiles of these two velocity deviations are analogous at first sight. But v'^2 is smaller than $0.5u'^2$ for $\zeta < 8$, although Fujii et al. assumed that $v'^2 \approx 0.5u'^2$, on the basis of Smith's data.

Profiles of dimensionless Reynolds shear stress are compared in Fig.14. $u'v'$ was estimated⁽¹⁴⁾ by the difference of the velocity deviations between the velocities in two directions inclined at $\pm 45^\circ$ from the X axis and in parallel with the X-Y plane. Dimensionless Reynolds shear stress is positive in regions inside the approximate U_m location and negative in outer regions. The positions where $-u'v'$ are at minimum approximately agree with the location of u'^2_{max} . As mentioned before, these features of the profile are analogous to that of the wall jet. An accurate relative relation between the locations where U is at a maximum and where $-u'v'$ crosses the zero line could not be obtained. The theoretically obtained profile is more similar to the present experimental result than Smith's experimental result using a hot wire.

4-4. Covariances between temperature and velocities

The profiles of a dimensionless lateral turbulent heat flux are compared in Fig.15. The dimensionless absolute values of the present results are higher than Smith's experimental results and Fujiis' theoretical results except in the region very near the plate and in the outer-most region.

Profiles of covariances $Ru't'$ between u' and t' are compared in Fig.16. The present experiment generally gives lower values of $Ru't'$ than Smith's results and different locations where $Ru't'$ is at a maximum as well. These tendencies of profiles $Ru't'$ are similar to those of profiles $(u'^2)^{1/2}$. These experimental results show that $Prt \approx 1$ for $\zeta > 2$ (except when the profile of Prt has a peak value of 2 at the location ($\zeta \approx 11$) where $u'v'$ is at a maximum). In order to find the value of Prt for smaller ζ than 2, the relative relation between the locations where $\partial U/\partial Y = 0$ and $u'v' = 0$ must be measured exactly. Hence it is difficult to evaluate an accurate value of Prt for ζ

Fig.14 Profiles of dimensionless Reynolds shear stress.

Fig.15 Profiles of dimensionless lateral turbulent heat flux.

Fig.16 Profiles of covariance between streamwise velocity and temperature, $u't' / (u'^2)^{1/2} (t'^2)^{1/2}$

≤ 2 from the present data.

4-5. Power spectra distribution

The power spectra distributions of temperature and streamwise velocity are shown in Fig.17. Several peaks in the power spectra distributions are found, but they are not significant. Solid lines indicate the distributions proportional to f^{-3} and $f^{-5/3}$, respectively. There is a range

where $\Phi u'$ is proportional to $f^{-5/3}$ and this is called an inertial subrange. A range where $\Phi t'$ is proportional to $f^{-5/3}$ is found as well, and such a range is called an inertial convective subrange. Further there is a range where $\Phi t'$ is proportional to f^{-3} and this is considered an inertial conductive subrange.

5. Conclusions

The turbulence characteristics of the free convection turbulent boundary layer along a vertical plate with uniform-heat-generation in air were measured by an LDV and a fine thermocouple. The obtained experimental results lead to the following conclusions.

(1) In the turbulent region, the local Nusselt number is correlated by the following equation.

$$Nux = 0.175 (Grx \cdot Pr)^{0.256} \\ 8 \times 10^{12} < Grx < 2 \times 10^{14}$$

(2) The present temperature fields in the free convection turbulent boundary layer were practically equal to those in the previous experiments on a uniform temperature vertical plate.

(3) Concerning the turbulence quantities directly connected with the velocity fluctuations, several distinct differences between present results and previous experimental results obtained using a hot wire were found. The important differences are enumerated as follows:

3-1. The location where the streamwise velocity deviation is at a maximum (which coincides with the location of v'^2_{max}) is at about $\zeta \approx 10$ and does not correspond to the location where the maximum mean streamwise velocity is found ($\zeta \approx 1.7$).

3-2. Probability density distributions of the streamwise velocity are not necessarily symmetrical in all parts across the boundary layer.

3-3. Reynolds shear stress distributions are positive in the region inside the approximate location of U_m and negative in the outer region.

3-4. Absolute values of the dimensionless lateral turbulent heat flux are larger than Smith's results.

3-5. The profile of the covariance between u' and t' is similar to the profile of $(u'^2)^{1/2}$ and its maximum value is about 0.5.

3-6. The turbulent Prandtl number is nearly equal to 1 in the region outside the location of U_m .

(4) In the case of 3-1 and 3-2, the present experimental results are quite similar to the theoretical results by the mean turbulent energy method and roughly correspond to the experimental results of the isothermal plane wall jet.

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Fig.1 Power spectral density distributions of temperature and streamwise velocity.

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References

- (1) Fujii, T., Dennetsu-kogaku no shinten (in Japanese), Vol.3 (1974), p.1, Yookendo.
- (2) Smith, R.R., Ph.D. Thesis Univ. London (1972).
- (3) Hoogendoorn, C.T. and Euser, H., Proc. 6th Int. Heat Transfer Conf., No-2 (1978), p.193.
- (4) Cheesewright, R., Trans. ASME, Ser. C, Vol.90, No.1 (1968), p.1.
- (5) Vliet, G.C. and Ross, D.C., Trans. ASME, Ser.C, Vol.97, No.4 (1975), p.549.
- (6) Cheesewright, R. and Doan, K.S., Int. J. Heat Mass Transfer, Vol.21, No.7 (1978), p.911.
- (7) Hishida, M., et al., 15th and 16th National Heat Transfer Sympo. Japan (in Japanese), (1978), p.415 and (1979), p.424 respectively.
- (8) Fujii, T., et al., Trans. JSME (in Japanese), Vol.44, No.387 (1978), p.3832.
- (9) Fujii, T. and Fujii, M., Trans. JSME (in Japanese), Vol.43, No.374 (1977), p.3825.
- (10) Plumb, O.A. and Kennedy, L.A., Trans. ASME, Ser.C, Vol.99, No.1 (1977), p.79.
- (11) Miyamoto, M. and Akiyoshi, T., Bull. JSME, Vol.25, No.202 (1982), p.583.
- (12) Fujii, T. et al., Int. J. Heat Mass Transfer, Vol.13, No.5 (1970), p.753.
- (13) Yamada, H., et al., Memoirs Faculty Engng. Yamaguchi Univ. (in Japanese), Vol.30, No.2 (1980), p.183.
- (14) Fujii, S., Text of LDV seminar (in Japanese), (1978), p.80, Nagare no Kashika Kondankai.