

CHARACTERISTICS OF TURBULENT COMBINED-CONVECTION BOUNDARY LAYER ALONG A VERTICAL HEATED PLATE

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ABSTRACT

Fluid flow and heat transfer characteristics in a turbulent combined-convection boundary layer in air along a vertical heated plate have been investigated with a normal hot wire and a cold wire. The measured heat transfer rates and turbulent quantities show that the turbulent transition moves downstream with a slight increase in freestream velocity. Then, the heat transfer rate rapidly decreases to about 40 % of that obtained in the turbulent natural-convection boundary layer, and velocity and temperature fluctuations become smaller in amplitude and change from random to harmonic at a specific frequency. Thus, the characteristics of the turbulent combined-convection boundary layer differ in several respects from those observed in both natural and forced convection. Based on the experimental results, the regimes of boundary layer flows are classified as a function of local Reynolds and Grashof numbers.

INTRODUCTION

In designing electric power plants, it is indispensable to correctly evaluate the heat transfer characteristics of turbulent combined-convection boundary layers (Hattori et al., 1995). Combined-convection phenomena are frequently encountered in nature and engineering applications, and many studies have been reported. However, most of them are concerned with laminar combined-convection flows and there are few investigations on turbulent combined convection. Therefore, the turbulent characteristics of combined convection have yet to be clarified, and the accumulation of experimental data for turbulent quantities is eagerly desired.

The turbulent natural-convection boundary layer aided by

freestream along a vertical heated plate is the one of typical turbulent combined-convection flows. For this boundary layer flow, it has been known that turbulence is suppressed and the heat transfer rate decreased under certain conditions (Hall and Price, 1970).

Kitamura and Inagaki (1987) and Inagaki and Kitamura (1988) conducted experiments with water and air as the working fluid and obtained the quantitative correlation between the heat transfer rate and flow conditions. In their experiment with water (Kitamura and Inagaki, 1987), the changes in the velocity and temperature fields were also investigated by using a hot-film probe and a flow visualization technique. However, the origin of the reduction in heat transfer rate has not been traced clearly because reliable measurements of turbulent quantities near the wall are very difficult for low speed flows with relatively large fluctuations of velocity and temperature. Krishnamurthy and Gebhart (1989) also performed measurements on a combined-convection boundary layer flow of compressed air. They indicated that the turbulent transition of the boundary layer delayed with increasing freestream velocity, but their study was focused on the transition from laminar to turbulence in combined convection.

Recently, Patel et al. (1998) numerically examined the heat transfer characteristics from turbulent natural convection to turbulent forced convection along a vertical plate by using a low Reynolds-number turbulence model. They predicted the reduction in heat transfer rate in the combined-convection region and proposed a map of the various convection flow regimes classified with a criterion for the variation of heat transfer rate. However, the

capability of the turbulence model was not verified because of the conclusive lack of experimental data for turbulent quantities in combined convection.

The purpose of this study is to clarify how the fluid flow and heat transfer characteristics in the turbulent natural-convection boundary layer change with the introduction of freestream velocity and to accumulate credible experimental data for turbulent combined convection. Measurements with a normal hot wire and a cold wire have been mainly conducted in the near-wall region of the combined-convection boundary layer in air. The variations of mean and turbulent quantities in the velocity and thermal fields with increasing freestream velocity are discussed and the regimes of various boundary layer flows are identified on the basis of the turbulent characteristics.

EXPERIMENTAL APPARATUS AND PROCEDURE

Figure 1 shows a schematic drawing of experimental apparatus, which comprises a vertical wind tunnel, heaters and measurement instruments.

The heated surface generating flow was an aluminum plate 4 m high, 0.8 m wide and 0.02 m thick. The surface was finished to a smooth mirror for preventing heat loss by radiation. Twenty electric heaters were attached to the back side of the plate and the surface temperature was kept uniformly by controlling the heating current of each. The maximum output of each heater was 4 kW, and the surface temperature of the plate could be increased up to 500 °C.

The vertical wind tunnel with solid boundary was designed in accordance with the previous reports (Fukatsu, 1934, Lumley, 1964, Rae and Pope, 1984) to produce an ideal flow field. The heated plate was placed vertically in the test section of 1 m × 1 m area and 6.2 m height. The maximum power of a motor-driven blower was 11 kW, and the freestream velocity U_∞ up to about 10 m/s was obtained in the test section. In the settling chamber of 2 × 2 m² area and 1 m length, four damping screens and a honeycomb were installed. With this experimental apparatus, the turbulent boundary layer in both natural and forced convection along a vertical heated plate could be developed.

Instantaneous velocity and temperature were measured with a normal hot wire and a cold wire made of 3.1 μm diameter tungsten. The sensitive lengths of hot and cold wires were 2 mm and 4 mm, respectively, and the cold wire was located 2.5 mm upstream of the hot wire. Temperature compensation of the hot wire was carried out by the technique of Hishida and Nagano (1978). The measurement error caused by the spatial difference between wires was minimized by delaying temperature signals of the cold wire by using Taylor's hypothesis. The amplified voltage outputs of these wires were processed with a personal computer after analog to digital conversion.

The thermal and flow conditions in the test section and the accuracy of measurement were verified in the preliminary experiments. The uniformity of surface temperature was within 0.5 °C, and the spatial non-uniformity ratio and the relative fluctuation ratio of freestream velocity were below 1.6 % and below 0.8 %, respectively. It was confirmed that

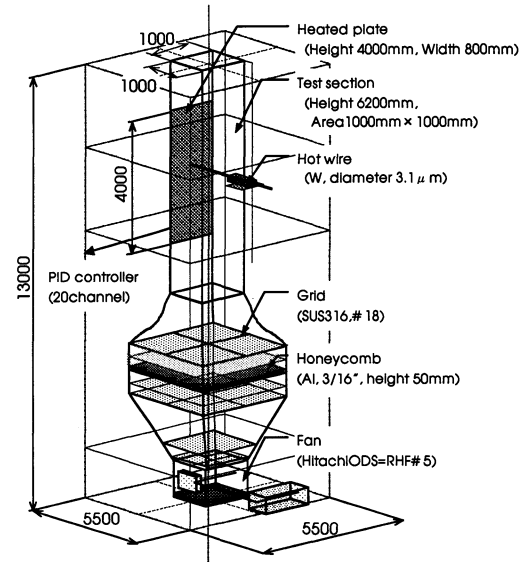


Fig. 1 Schematic drawing of experimental apparatus

turbulent quantities measured near the wall in the natural-convection boundary layer agreed well with the data taken by Tsuji and Nagano (1988a).

Experiments were carried out under the conditions of uniform surface temperature T_w in the range of 40~100 °C. The ambient fluid temperature T_∞ was somewhat different for each experiment within 23~29 °C. The vertical distance x from the leading edge of plate to measuring locations was changed from 0.265 to 3.765 m. The ranges of local Reynolds number $Re_x (= U_\infty x / \nu, \nu$: kinematic viscosity) and local Grashof number $Gr_x (= g \beta (T_w - T_\infty) x^3 / \nu^2, g$: gravitational acceleration, β : volumetric expansion coefficient) were $0 \sim 1.9 \times 10^6$ and $1.3 \times 10^8 \sim 3.5 \times 10^{11}$, respectively. Physical properties were evaluated at the film temperature $T_f = (T_w + T_\infty)/2$ except for $\beta = 1/T_\infty$.

RESULTS AND DISCUSSION

Local Heat Transfer Rate

Heat transfer characteristics of the turbulent natural-convection boundary layer with the introduction of freestream velocity were investigated. The heat transfer rates were estimated from temperature gradients near the wall. For various Grashof numbers, local Nusselt numbers $Nux (= hx/\lambda, h$: heat transfer coefficient, λ : thermal conductivity) are shown in Fig. 2. The value of Nux is normalized with that of turbulent pure natural convection $(Nux)_n$ and Gr_x/Re_x^3 is taken as the coordinate. For constant Gr_x , the decrease in Gr_x/Re_x^3 implies the increase in freestream velocity. On the other hand, if Gr_x/Re_x^3 and the thermal condition are constant, the change in Gr_x corresponds to that in x .

A drastic reduction in Nux with increasing freestream velocity is observed, i.e., $Nux/(Nux)_n$ decreases to about 0.4 at a value of Gr_x/Re_x^3 for a given Gr_x . When attention is paid to $Gr_x/Re_x^3 \approx 10^{-3}$, $Nux/(Nux)_n$ decreases with

decreasing Grx and takes the smallest value at $Grx = 1.05 \sim 1.10 \times 10^{11}$. Therefore, it is conjectured that Nux still remains at a high value in the region downstream of the location where the Nux reduction occurs with increasing freestream velocity.

Such a decrease in Nux in the combined-convection boundary layer is also observed in the experiment with air of Inagaki and Kitamura (1988). However, the minimum value of $Nux/(Nux)_n$ remains at about 0.75 and the occurrence of Nux reduction is not so abrupt as that in the present experiment. The discrepancy between the both results may be attributed to the difference in experimental setup and conditions. In their experiment, a test section of small area was used and relatively large disturbances were involved in the freestream, which gave the transition Reynolds number of a remarkably small value for pure forced convection. We made an effort to control freestream disturbances, and thus it is considered that the essential characteristics of the turbulent combined-convection boundary layer appeared more clearly.

Mean Velocity and Mean Temperature Profiles

The changes in the streamwise mean velocity and mean temperature profiles in the boundary layer for $Grx = 3.30 \sim 3.58 \times 10^{11}$ and $Grx/Rex^3 = \infty \sim 3.75 \times 10^{-5}$ (corresponding the freestream velocity of $0 \sim 1.1$ m/s) are shown in Figs. 3 and 4, respectively. The mean velocity U , the mean temperature T and the distance from the wall y are normalized as the similarity variables used for the laminar natural-convection boundary layer. Since Grx and x are almost constant, the abscissa $\eta = (y/x)Grx^{1/4}$ is directly proportional to the distance from the wall. As seen from these figures, the mean velocity and temperature profiles markedly change with the introduction of freestream velocity. With increasing freestream velocity, the thicknesses of velocity and thermal boundary layers decrease, and the maximum mean velocity increases and its location approaches the wall. At $Grx/Rex^3 = 1.15 \times 10^{-4}$, the dimensionless value of the maximum mean velocity which is 0.41 at $Grx/Rex^3 = 1.65 \times 10^{-4}$ reaches 0.58 with a slight increase in freestream velocity, and then the sudden decrease in local heat transfer rate occurs as shown in Fig. 2. Thus, the change in Nux is closely correlated with those in the mean velocity and mean temperature.

For $Grx/Rex^3 = 3.75 \times 10^{-5}$, the laminar combined-convection boundary layer was calculated numerically and the profiles of velocity and temperature are plotted by solid lines in Figs. 3 and 4, respectively. The measurements conform well to the calculated results for the laminar boundary layer. Judging from the behavior of turbulent quantities will be mentioned later, it is concluded that the combined-convection boundary layer changes from turbulence to laminar with a slight increase in freestream velocity and the location of transition to the turbulent boundary layer shifts farther downstream.

Krishnamurthy and Gebhart (1989) reported that the transition to turbulence in the combined-convection boundary layer was fairly delayed in comparison with that in

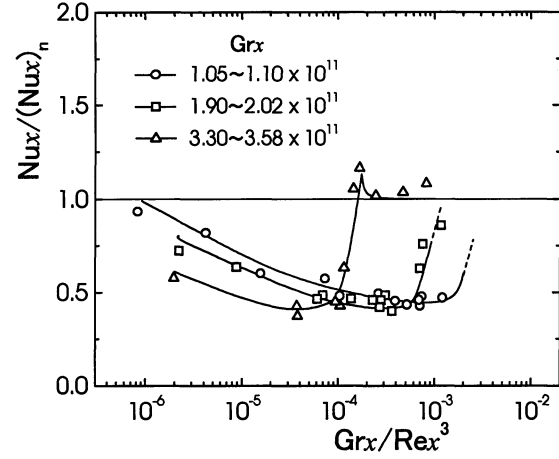


Fig. 2 Local heat transfer rate

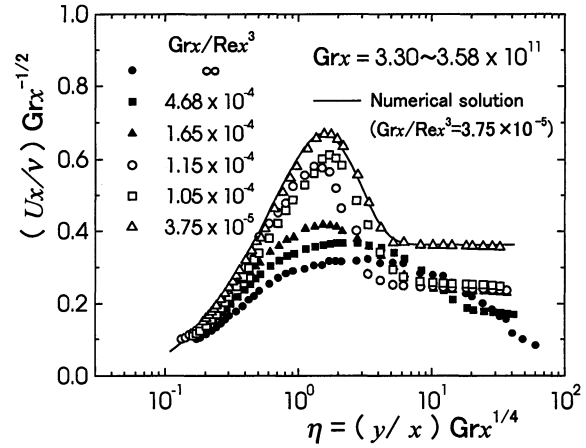


Fig. 3 Mean velocity profile

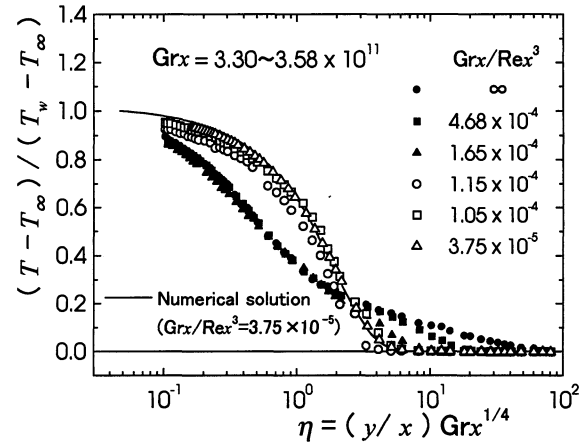


Fig. 4 Mean temperature profile

pure natural convection. Therefore, such a laminarization of the combined-convection boundary layer may be regarded as a phenomenon caused by the delay of transition.

Intensities of Velocity and Temperature Fluctuations and Turbulent Heat Flux

Figure 5 shows the intensity profiles of streamwise velocity fluctuation u normalized by the maximum mean velocity U_m in the transition from turbulence to laminar. In the turbulent natural-convection boundary layer, the maximum intensity of velocity fluctuation occurs at the location $\eta \simeq 25$ beyond the maximum mean velocity location $\eta \simeq 3$. This intensity profile is peculiar to the turbulent natural-convection boundary layer (Tsuiji and Nagano, 1988a). With the addition of freestream velocity ($Grx/Rex^3 = 4.68 \times 10^{-4}$), the intensity of velocity fluctuation begins to decrease in the whole boundary layer region, although the profile is similar to that in the natural-convection boundary layer.

In the range of $Grx/Rex^3 = 1.65 \times 10^{-4} \sim 1.05 \times 10^{-4}$, the intensity profile varies remarkably in accordance with the changes of local heat transfer rate and mean velocity profile as mentioned previously. At $Grx/Rex^3 = 1.65 \times 10^{-4}$, the fluctuation intensity larger than that in pure natural convection appears at the maximum mean velocity location ($\eta \simeq 1.5$). Moreover, at $Grx/Rex^3 = 1.15 \times 10^{-4}$ and 1.05×10^{-4} , the intensity profile of velocity fluctuation decreases and takes two peaks with an infinitesimal value near the maximum mean velocity location. In the initial phase of the transition in combined convection, it is confirmed by the linear instability analysis of Carey and Gebhart (1983) and the experiment of Krishnamurthy and Gebhart (1989) that the intensity of velocity fluctuation takes an infinitesimal value at the maximum mean velocity location. Therefore, the appearance of the fluctuation intensity profile having two peaks certainly characterizes the transition of the combined-convection boundary layer.

With still more increase in freestream velocity ($Grx/Rex^3 = 3.75 \times 10^{-5}$), the intensity of velocity fluctuation becomes extremely small with the laminarization of the boundary layer. As the freestream velocity becomes sufficiently large ($Grx/Rex^3 < 10^{-6}$), the boundary layer changes again to turbulence and turbulent characteristics of forced convection appear.

In general, the turbulent energy is mainly produced through the mean shear motion. However, in the combined-convection boundary layer, the intensity of velocity fluctuation decreases in spite of the mean velocity gradient larger than that in turbulent pure natural convection as shown in Fig. 3. This fact indicates that the conception for usual turbulence is no longer applicable to this boundary layer. Since the near-wall turbulent characteristics of natural convection significantly differ from those of forced convection (Tsuiji and Nagano, 1988b), it is conjectured that the laminarization and peculiar intensity profile of velocity fluctuation in combined convection will result from the essential difference between natural and forced convection.

The changes in the intensity of temperature fluctuation t with the transition from turbulence to laminar are shown in Fig. 6, being normalized by the temperature difference between the surface temperature T_w and the ambient temperature T_∞ . The intensity of temperature fluctuation

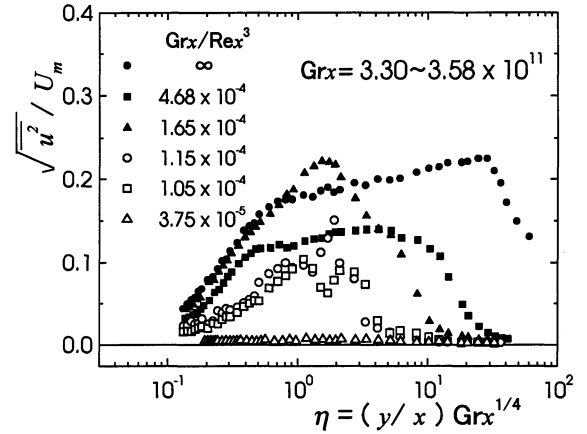


Fig. 5 Intensity of velocity fluctuation

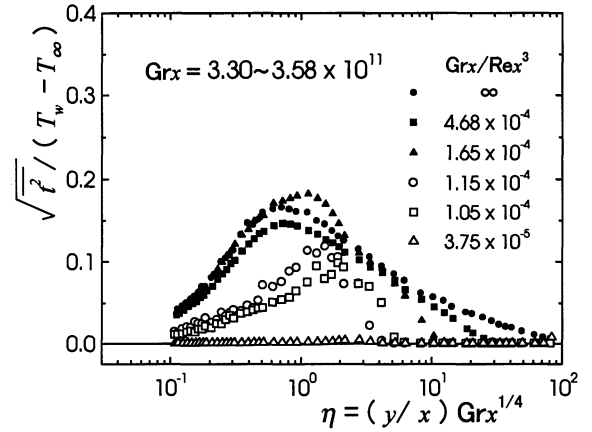


Fig. 6 Intensity of temperature fluctuation

rapidly varies with increase in freestream velocity, keeping step with the change in the velocity fluctuation intensity. The increasing and decreasing tendencies of the maximum intensity of temperature fluctuation have a close resemblance to those of velocity fluctuation. At $Grx/Rex^3 = 4.68 \times 10^{-4}$, the intensity profile of temperature fluctuation makes no great difference from that in pure natural convection. However, with increasing Grx/Rex^3 , the temperature fluctuation intensity decreases and the location of the maximum intensity gradually approaches the maximum mean velocity location. At $Grx/Rex^3 = 3.75 \times 10^{-5}$, the intensity of temperature fluctuation becomes extremely small as well as that of velocity fluctuation.

Figure 7 shows the streamwise turbulent heat flux \overline{ut} normalized by the maximum mean velocity and the temperature difference. The turbulent heat flux in the natural-convection boundary layer has a positive peak at the maximum mean velocity location and takes small negative values near the wall. With the addition of freestream velocity ($Grx/Rex^3 = 4.68 \times 10^{-4}$), \overline{ut} decreases at the maximum mean velocity location and increases in the negative value near the wall. At $Grx/Rex^3 = 1.65 \times 10^{-4}$, the value of \overline{ut} increases again at the maximum mean velocity location, whereas the negative value of \overline{ut} decreases near

the wall. Then, the value of Nux becomes larger than that in turbulent pure natural convection as seen in Fig. 2. With still more increase in freestream velocity ($Grx/Rex^3 = 1.05 \times 10^{-4}$), the profile of turbulent heat flux takes a zero crossing at the maximum mean velocity location from negative values near the wall to positive values. At $Grx/Rex^3 = 3.75 \times 10^{-5}$, the $\overline{u}t$ value also becomes almost zero in the whole boundary layer region.

As mentioned above, turbulent quantities observed in the combined-convection boundary layer suddenly change with a slight increase in freestream velocity. It seems to be very difficult to correctly predict such a behavior of turbulent combined convection with existing turbulence models. Although the accumulation of experimental data for turbulent combined convection is before everything, some improvement of turbulence models will be also required.

Waveforms of Velocity and Temperature Fluctuations

Waveforms of velocity fluctuation u and temperature fluctuation t measured at the near-wall location, where the mean velocity takes about a half the maximum mean velocity, are displayed in Figs. 8 and 9, respectively. In the case of turbulent pure natural convection, long-period waves indicating large-scale fluid motions are dominant in both the velocity and thermal fields. Though the waveforms at $Grx/Rex^3 = 4.68 \times 10^{-4}$ are still similar to those of pure natural convection, large-amplitude and high-frequency waveforms appear at $Grx/Rex^3 = 1.65 \times 10^{-4}$, which corresponds to the temporal increases in the intensities of velocity and temperature fluctuations near the wall as shown in Figs. 5 and 6. With further increase in freestream velocity, the waveforms become smaller in amplitude and vary from random to harmonic with a specific frequency, and almost disappear at $Grx/Rex^3 = 3.75 \times 10^{-5}$.

Regimes of Boundary Layer Flows

The classification of boundary layer flows is very important with regard to engineering applications. Patel et al. (1998) proposed a map of the various convection flow regimes by utilizing the numerical results obtained with a low Reynolds-number $k-\epsilon$ turbulence model. Following their map, we have made a map based on the experiment. The boundary layer flows were identified in the following manner: when waveforms are random and the profiles of fluctuation intensities are similar to those in pure natural or pure forced convection, the flow regime is regarded as turbulence; in case harmonic waveforms with a specific frequency appear, the flow is regarded as transition; and the flow is regarded as laminar when the intensities of velocity and temperature fluctuations become almost zero and the profiles of mean velocity and mean temperature coincide with the theoretical ones obtained for the laminar combined-convection boundary layer.

The regimes of boundary layer flows in the coordinates Rex and Grx are shown in Fig. 10. The transition regime corresponds to the region placed between thick and thin dotted curves. For the laminar region, the flow regime can be identified as natural, combined and forced convection

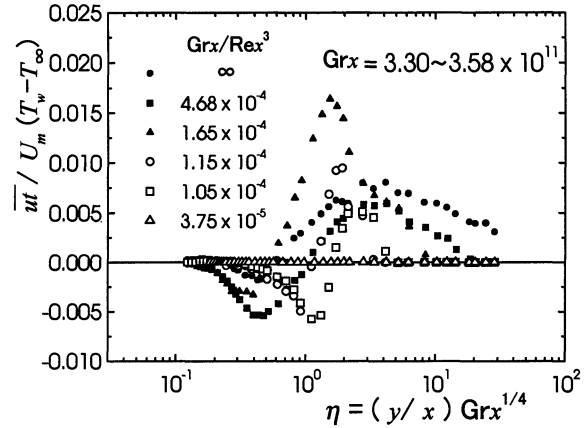


Fig. 7 Turbulent heat flux

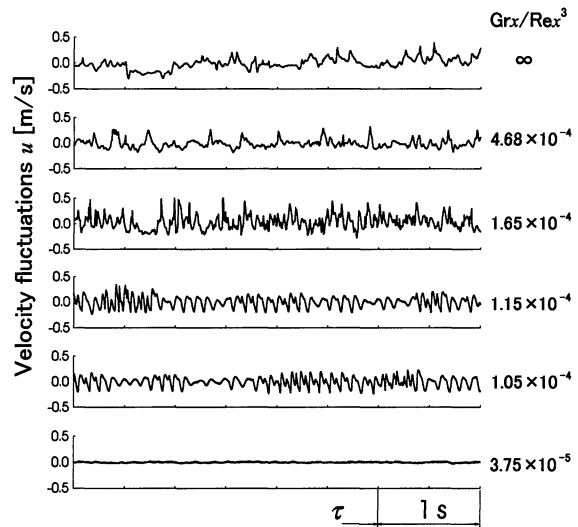


Fig. 8 Waveforms of velocity fluctuation

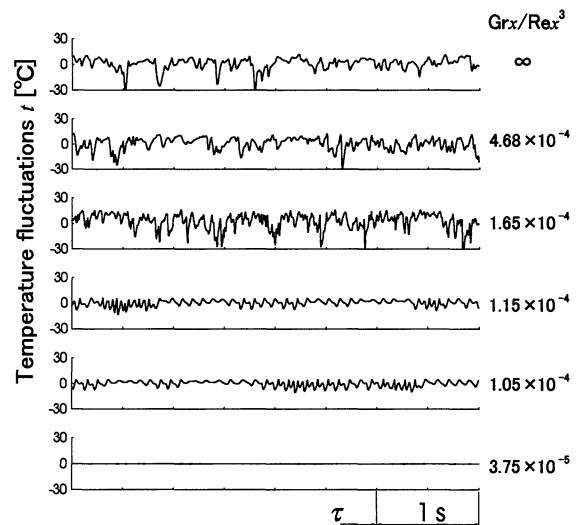


Fig. 9 Waveforms of temperature fluctuation

with a criterion that Nux deviates more than 5 % from the calculated values for laminar pure natural and forced convection. This identification is shown with two chain lines (plotted as Richardson number $Rix = Grx/Rex^2 = \text{const.}$) in Fig. 10, which agrees well with the result of Patel et al. (1998).

In the turbulent natural-convection boundary layer, the transition occurs at about $Grx = 3 \times 10^9$ and the turbulent boundary layer develops in the range $Grx > 10^{10}$. Nevertheless, with the addition of freestream velocity, the region of laminar combined convection extends to the large Grx region and the transition is remarkably delayed: the boundary layer for $Rex \simeq 2 \times 10^5$ and $Grx \simeq 3 \times 10^{11}$ is still laminar although the Grx value is 100 times as large as the critical Grashof number in pure natural convection. On the map presented by Patel et al. (1998), the region $Grx > 5 \times 10^9$ for moderate Rex is divided into turbulent combined convection and turbulent natural convection. In practice, however, the laminar combined-convection regime appears in the region regarded as turbulent combined convection as shown in Fig. 10.

CONCLUSIONS

The fluid flow and heat transfer characteristics in the turbulent combined-convection boundary layer in air along a vertical heated plate were experimentally investigated with a normal hot wire and a cold wire paying close attention to freestream conditions. The results of the present study may be summarized as follows.

1. A drastic reduction in Nux is observed in the combined convection with a slight increase in freestream velocity and the value of Nux decreases to about 40 % of that in the turbulent natural convection. This behavior of Nux is due to the boundary layer transition from turbulence to laminar, and the transition location is displaced in the region farther downstream of that observed in pure natural convection. As the freestream velocity becomes sufficiently large, the boundary layer changes again to turbulence having characteristics of forced convection

2. With a laminarization of the boundary layer, velocity and temperature fluctuations become smaller in amplitude and change from random to harmonic at a specific frequency, and then the intensity profile having two peaks appears.

3. The regimes of boundary layer flows are classified with the experimental results. With increasing freestream velocity, the region of laminar combined convection extends to the large Grx region far from the critical Grashof number in pure natural convection.

REFERENCES

- Carey, V. P., and Gebhart, B., 1983, "The Stability and Disturbance Amplification Characteristics of Vertical Mixed Convection Flow," *J. Fluid Mech.*, Vol. 127, pp. 185-201.
- Fukatsu, R., 1934, *Wind-Tunnel Experimental Method*, Kyoritsusya, Tokyo, in Japanese.
- Hall, W. B., and Price, P. H., 1970, "Mixed Forced and Free Convection From a Vertical Heated Plate to Air," *Proc. 4th Int. Heat Transfer Conf.*, Paris, Vol. 4, NC 3.3.

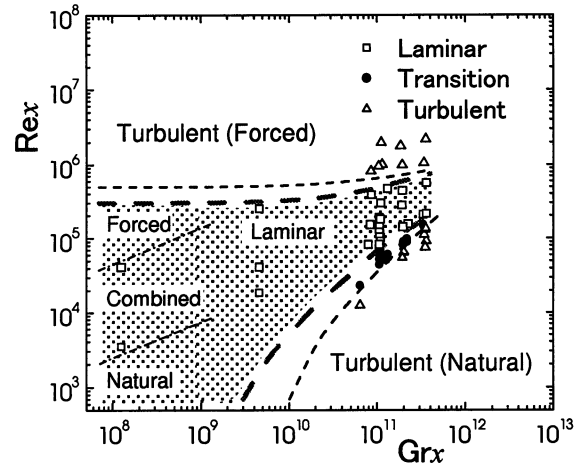


Fig. 10 Regimes of boundary layer flows

Hattori, Y., Kashiwagi, E., Yamakawa, H., and Wataru M., 1995, "Experiments of Natural Convection to Evaluate Heat Transfer in the Spent Fuel Dry Storage Facilities," *Proc. 3rd Int. Conf. on Nuclear Engineering*, Kyoto, pp. 1927-1932.

Hishida, M., and Nagano, Y., 1978, "Simultaneous Measurements of Velocity and Temperature in Nonisothermal Flows," *ASME J. Heat Transfer*, Vol. 100, pp. 340-345.

Inagaki, T., and Kitamura, K., 1988, "Turbulent Heat Transfer of Combined Forced and Natural Convection Along a Vertical Flat Plate (Effect of Prandtl Number)," *JSME B*, Vol. 54, pp. 2515-2522, in Japanese.

Kitamura, K., and Inagaki, T., 1987, "Turbulent Heat and Momentum Transfer of Combined Forced and Natural Convection Along a Vertical Flat Plate - Aiding Flow," *Int. J. Heat Mass Transfer*, Vol. 30, pp. 23-41.

Krishnamurthy, R., and Gebhart, B., 1989, "An Experimental Study of Transition to Turbulence in Vertical Mixed Convection Flows," *ASME J. Heat Transfer*, Vol. 111, pp. 121-130.

Lumley, J. L., 1964, "Passage of a Turbulent Stream Through Honeycomb of Large Length-to-Diameter Ratio," *ASME J. Basic Engineering*, pp. 218-220.

Patel, K. Armaly, B. F., and Chen, T. S., "Transition From Turbulent Natural to Turbulent Forced Convection," *ASME J. Heat Transfer*, Vol. 120, pp. 1086-1088.

Rae, W. H., and Pope, A., 1984, *A Low-Speed Wind Tunnel Testing*, 2nd ed., John Wiley & Sons, Inc. NY.

Tsuji, T., and Nagano, Y., 1988a, "Characteristics of a Turbulent Natural Convection Boundary Layer Along a Vertical Flat Plate," *Int. J. Heat Mass Transfer*, Vol. 31, pp. 1723-1734.

Tsuji, T., and Nagano, Y., 1988b, "Turbulence Measurements in a Natural Convection Boundary Layer Along a Vertical Flat Plate," *Int. J. Heat Mass Transfer*, Vol. 31, pp. 2101-2111.