EFFECTS OF FREESTREAM TURBULENCE ON COMBINED-CONVECTION BOUNDARY LAYER ALONG A VERTICAL HEATED PLATE

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ABSTRACT

The effects of freestream turbulence on the turbulent combined-convection boundary layer, which is created by imposing an aiding freestream to a turbulent natural-convection boundary layer along a vertical plate have been experimentally investigated. Using an active turbulence grid, the high level turbulence involved in the freestream was generated. The measured heat transfer rates and turbulent quantities show the turbulent heat transfer characteristics markedly changes with an increase in the freestream turbulence. When the freestream turbulence level is extremely low, the rapid decreases in heat transfer rate due to the transition location to turbulence moving downstream with a weak freestream occur. As the freestream turbulence level arises, the laminar region of combined convection is drastically shortened. Simultaneously, the dependence of freestream velocity on the heat transfer rate appreciably diminishes, and the heat transfer rate of combined convection increases with the freestream turbulence. In addition, it is found that turbulent characteristics in the boundary layer strongly depend on the lengthscale of freestream turbulence.

INTRODUCTION

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 determined that the suppression of turbulence and the reduction in the heat transfer rate arise under certain conditions (Kitamura and Inagaki, 1987; Inagaki, 1996; Patel et al., 1998). The mechanism for the reduction in the heat transfer rate, however, has not been fully comprehended, because of a lack of credible data for near-wall turbulent quantities directly controlling the turbulent heat transfer. Recently, we experimentally investigated the details of heat and fluid characteristics in the boundary layer, including the wall region (Hattori et al., 1999; 2000; 2001). Through the turbulent measurements with hot- and cold-wires and a particle image velocimetry, it was revealed that the delay of turbulence transition occurs with a weak freestream, and simultaneously, the local heat transfer rate of combined convection suddenly decreases. Abu-Mulaweh et al. (2000) also obtained a similar conclusion with the turbulent measurement by using a laser Doppler velocimeter and a cold-wire anemometer.

As is analogized from the turbulence transition of forced convection (e.g. Blair, 1983; Schultz and Volino, 2003), it is suggested that the heat transfer characteristics of combined-convection strongly depend on the freestream turbulence. Nevertheless, previous experiments have not always taken sufficient care to the effects of freestream turbulence, and thus no significant information relating to the turbulent characteristics of combined convection beneath freestream turbulence has been obtained.

On the other hand, the structural characteristics in the turbulent forced-convection boundary layer with the freestream turbulence have been examined extensively. For the boundary layer on a flat plate, Blair (1983) conducted experiments to determine the impact of freestream turbulence on the turbulent heat transfer characteristics. In these experiments, the effects on skin friction and on heat transfer rate were a function of the freestream turbulence intensity, lengthscale and the boundary layer momentum thickness Reynolds number. Castro (1984) also described the empirical correlation between skin friction and a freestream turbulence parameter containing a dependence on both intensity and length scale. The special attention is paid to the Reynolds number effects, and he suggested that the relative importance of intensity and lengthscale changes at low Reynolds numbers. Hancock and Bradshaw (1989) performed the turbulent measurement in the presence of grid-generated freestream turbulence with a wide range of lengthscales. With the conditionally averaged measurements, turbulence structures of boundary layer were thoroughly discussed, and it was shown that the change in structure is directly related to the lengthscale corresponding to the boundary layer thickness. Considering these experimental results, it becomes clear that the lengthscale of freestream turbulence considerably affects the turbulent characteristics of boundary layer. Since the boundary layer thickness of natural convection is thicker than that of forced convection, this implies that the effects of freestream turbulence becomes more notable for the high freestream turbulence.

Thus, aiming to clarify the effects of freestream turbulence on the turbulent heat transfer of combined convection, the turbulence statistics in the boundary layer were obtained for a freestream turbulence with a wide range of Taylor microscale Reynolds number Re_λ. The change in heat transfer rate of combined convection with increasing freestream turbulence level are examined, and the dependence of freestream turbulence on turbulent characteristics was dicussed.

EXPERIMENTAL APPARATUS AND PROCEDURE

The experiments were conducted in the same vertical windtunnel described in detail by Hattori et al. (2000). The only change to the faility for the present study was the addition of an active turbulence grid (Makita et al., 1987; Mydlarsk and Warhaft, 1996) to generate the high turbulence levels involved in the freestream required for this study. Figure 1 shows the active turbulence grid, which was installed at the front of the working section. The distance of the plate leading edge from the grid was 980mm. The mesh spacing M, between the grid bars is 110 mm, providing a tunnel cross-section of $10M \times 10M$. Each of the 18 grid bar with triangular wings independently rotated and flapped in a random way with a stepping motor. The rotation speed of the grid bars was set to 2 r.p.s.. The randomness and rotation rate of the grid bars were controlled with a PC to vary the turbulence intensities and lengthscale. The instantaneous velocity and temperature were measured with normal hot- and cold-wires made of 3.1mm diameter tungsten. For the amplified voltage outputs of these wires, the analog to digital conversion was performed at a sampling frequency of 2kHz, and then the statistics were calculated with about 16 sec data for each measuring point.

For constant local Grashof number, $\mathrm{Gr}x_h$=1.5×10^{11}, the measurements were made at two freestream turbulence levels (MFST and HFST). The isothermal wall temperature T_w was 83.0 C, and the ambient fluid temperature T_e was somewhat different for each experiment, in the range of 31.8 - 34.3 C. The measuring location was fixed at the vertical distance x_h=3.265 m from the leading edge of the heated plate. The flow parameters obtained at the measuring location for 6 representative case are shown in table 1. The Taylor-microscale λ was estimated by the spectra of velocity fluctuation assuming

Table 1: Flow parameters at measuring location x_h=3.265m.

	$U_e[m/s]$	$\mathrm{Re}x_h$	u'_e/U_e	$\lambda[mm]$	Re_λ
MFST	0.28	4.9×10^4	0.027	0.36	0.2
MFST	0.82	1.4×10^5	0.021	1.27	1.3
MFST	7.86	1.4×10^6	0.037	6.59	116
HFST	0.25	4.2×10^4	0.172	1.76	4.4
HFST	0.79	1.4×10^5	0.116	5.97	33
HFST	7.03	1.2×10^6	0.202	12.4	1090

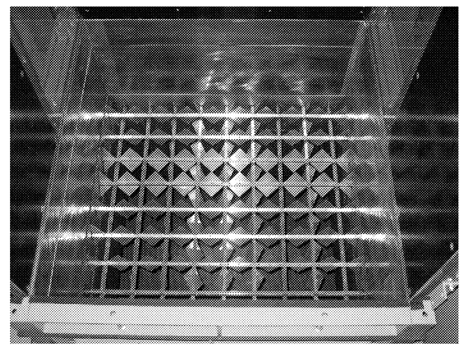

Figure 1: Photo of active turbulence grid of wind tunnel.

the local isotropy. The freestream velocity U_e was varied from 0 to 7.86 m/s giving a variation in $\mathrm{Re}x_h$ from 0 to 1×10^6. The turbulence intensities of medium (MFST) and high (HFST) freestream turbulence with the active grid were 2.7-3.7% and 11.6-20.2%, respectively. With the turbulence intensity, the value of λ also increases, and the Re_λ of HFST exceed 1000 for $\mathrm{Re}x_h = 1.2 \times 10^6$.

RESULTS AND DISCUSSION

Transition from natural to combined convection

The changes in heat transfer rate of combined convection with increasing freestream velocity were investigated. The heat transfer rates were estimated from temperature gradients near the wall. For MSFT and HFST, Nusselt number $\mathrm{Nu}x_h$ ($=hx_h/\lambda$, h:heat transfer coefficient, λ: thermal conductivity) is shown in figure 2. The results obtained for extreme low freestream turbulence (LFST) without the active turbulence grid also plotted in this figure. The values of $\mathrm{Nu}x_h$ are normalized with those of the turbulent pure natural convection $(\mathrm{Nu}x_h)_n$ and $\mathrm{Gr}x_h/\mathrm{Re}x_h$ is taken as the coordinate, because this parameter is suitable for evaluating the beginning point of reduction in heat transfer rate for LFST (Hattori et al., 2001). The dependence of $\mathrm{Nu}x_h$ on freestream velocity markedly changes with the increase in freestream turbulence. When the freestream turbulence level is low (LFST), a drastic reduction in $\mathrm{Nu}x_h$ is observed at $\mathrm{Gr}x_h/\mathrm{Re}x_h$=3×10^6, and then $\mathrm{Nu}x_h/(\mathrm{Nu}x_h)_n$ decreases to about 0.4 at $\mathrm{Gr}x_h/\mathrm{Re}x_h$=2×10^6. On the other hand, the occurrence of $\mathrm{Nu}x_h$ reduction for MFST and HFST is not so abrupt. The $\mathrm{Nu}x_h/(\mathrm{Nu}x_h)_n$ of MFST gradually decrease with the increase in freestream velocity ($\mathrm{Gr}x_h/\mathrm{Re}x_h < 2\times10^6$), but the value of $\mathrm{Nu}x_h/(\mathrm{Nu}x_h)_n$ still remains at about 0.8 even at $\mathrm{G}x_h/\mathrm{Re}x_h = 1 \times 10^6$. Such a behavior of $\mathrm{Nu}x_h$ agrees well with that obtained by Kita-

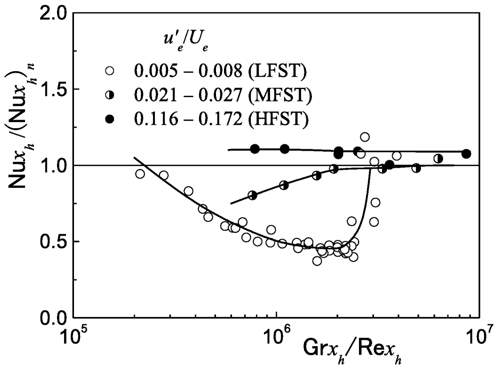

Figure 2: Local heat transfer rate with Grx_h/Rex_h.

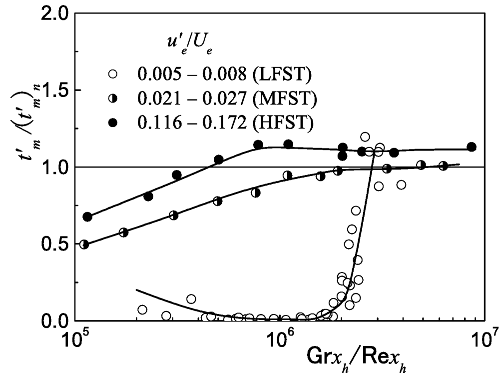

Figure 3: Maximum intensity of temperarture fluctuation with Grx_h/Rex_h.

mura and Inagaki (1987). In their experiment, a test section with a small area was used and relatively large disturbances were involved in the freestream. With more increase in a freestream turbulence (HFST), the effects of freestream velocity on the heat transfer rate appreciably diminish and the Nux_h of combined convection remains almost constant, regardless of Grx_h/Rex_h.

Figure 2 shows the change in the maximum intensity of temperature fluctuation t'_m as a function of Grx_h/Rex_h. The maximum temperature fluctuation is normalized by that of turbulent pure natural convection $(t'_m)_n$. The behavior of t'_m against Grx/Rex has a resemblance to that of Nux_h. For MFST and HFST, the values of t'_m remain almost constant in the range of $Grx_h/Rex_h > 2 \times 10^6$, while the intensity of temperature fluctuation for LFST becomes extremely small in the range of $Grx_h/Rex_h < 3 \times 10^6$, reflecting that the boundary layer changes from turbulence to laminar. Then, t'_m gently decline with a further increase in freestream velocity, but the significant temperature fluctuation in the combined-convection boundary layer was preserved even at $Grx_h/Rex_h = 1 \times 10^5$.

In regard to the effects of freestream turbulence level, it is found that Nux_h and t'_m for HFST are considerably higher than those for MFST. In addition, the value of Grx_h/Rex_h, indicating the beginning of reduction in Nux_h and t'_m, also change with the increase in freestream turbulence, i.e., the reduction occurs in the range of $Grx_h/Rex_h < 2 \times 10^6$ for MFST, and in the range of $Grx_h/Rex_h < 8 \times 10^5$ for HFST. Thus, it is suggested that the turbulence heat transfer of combined convection becomes more active as the freestream turbulence level raise.

Basic turbulent statistics

Considering the condition that the reduction in the heat transfer rate arises with the increase in freestream velocity, we examined the turbulent statistics of combined convection at $Grx_h/Rex_h = 3 \times 10^6$, 1×10^6 for MFST and HFST.

The streamwise velocity profiles for mean and fluctuation intensity in the boundary layer are shown in figures 4, 5, respectively. The mean velocity U and the distance from the wall y are normalized as the similarity variables used for the laminar natural-convection boundary layer, and the intensity of velocity fluctuation u' is normalized by the maximum mean velocity U_m (Tsuji and Nagano, 1989). At $Grx_h/Rex_h = 3 \times 10^6$, the profiles of U remarkably differ from those for laminar combined-convection boundary layer, unlike that, for

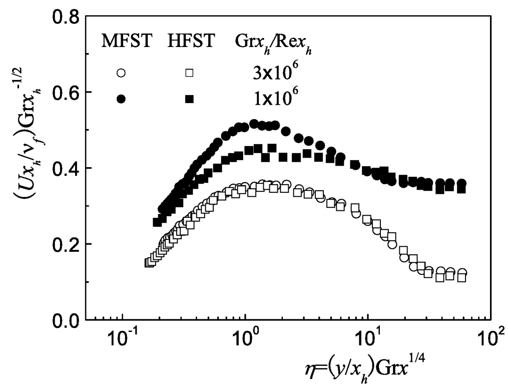

Figure 4: Mean velocity profile.

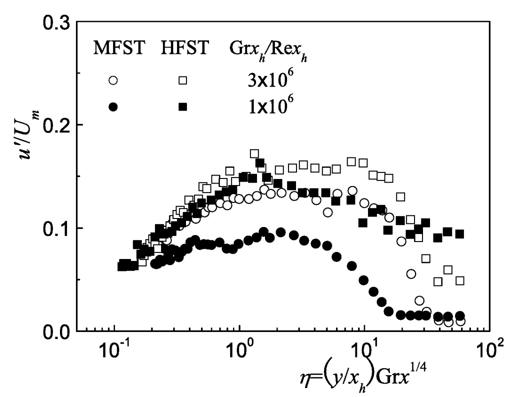

Figure 5: Intensity of velocity fluctuation.

LFST (Hattori et al., 2000). The boundary layer thickness for MFST, HFST is quite thicker than that of laminar flow. Moreover the maximum mean velocity U_m remains low, while the value of U_m for LFST increases with transition to laminar (Hattoril et al.,2000). In accordance with such mean velocity profiles, the velocity fluctuation for MFST, HFST maintains over the entire boundary layer region, although the rapid decay in fluctuation occurs for LFST (Hattori et al., 2000).

The temperature profiles for mean and fluctuation intensity are shown in figures 6, 7, being normalized by the temper-

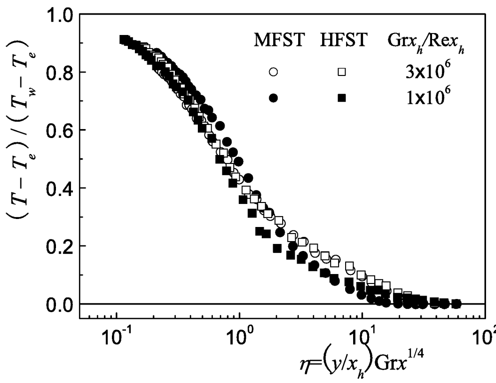

Figure 6: Mean temperature profile.

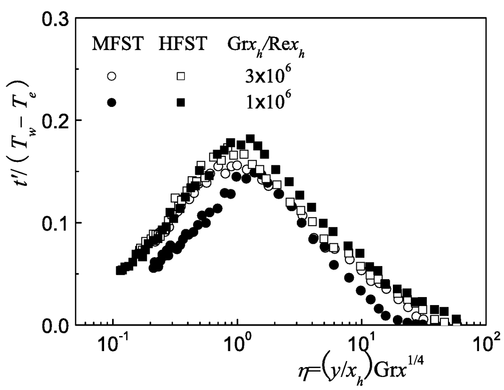

Figure 7: Intensity of temperature fluctuation.

ature difference between the wall temperature T_w and the ambient temperature T_e. The effects of freestream turbulence on temperature field closely resemble those of velocity field, i.e., the boundary layer thickness of temperature fields for MFST, HFST is also thicker than that of lamiar flow, and the intensities of temperature fluctuation is still large even at $\mathrm{Gr}x_h/\mathrm{Re}x_h = 1 \times 10^6$

From these results it is conjectured that the two kinds of heat transfer reduction mechanism of combined convection may exist. When the freestream turbulence is quite small, the heat transfer rate suddenly decreases with the transition location to turbulence moving downstream. In contrast to this, the transition of the boundary layer from turbulence to laminar with an freestream velocity is virtually eliminated by adding freestream turbulence, and the reduction in heat transfer rate with freestream turbulence is caused by the suppression of turbulence.

Here, concentrating on the effects of freestream turbulence level, the comparison of these profiles between MFST and HFST suggests the turbulent statistics of combined convection for MFST and HFST are similar at $\mathrm{Gr}x_h/\mathrm{Re}x_h = 3 \times 10^6$. The mean velocity and temperature profiles are independent of freestream turbulence level, and the profiles of mean velocity and temperature for HFST agree well with those for MFST. The intensities of velocity and temperature fluctuations for HFST are also similar to those for MFST, although there exist some quantitative differences. On the other hand, with the increase in freestream velocity ($\mathrm{Gr}x_h/\mathrm{Re}x_h = 1 \times 10^6$), the

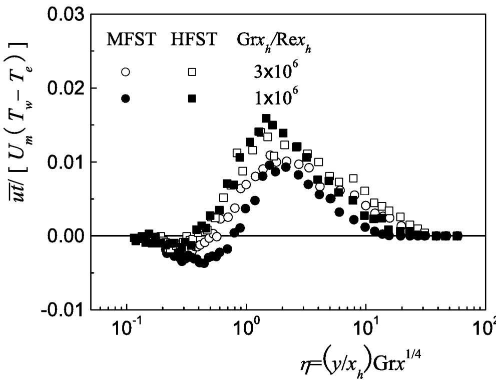

Figure 8: Turbulent heat flux.

noticeable discrepancy between both results appears. This implies that the heat and fluid flow characteristics of turbulent combined- convection boundary layer are closely connected with the freestream turbulence level.

Structural characteristics

Figure 8 shows the streamwise turbulent heat flux $\overline{ut}$ normalized by the maximum mean velocity and the temperature difference at $\mathrm{Gr}x_h/\mathrm{Re}x_h = 3 \times 10^6$, 1×10^6 for MFST and HFST. Independently of freestream turbulence level, the profiles obtained at $\mathrm{Gr}x_h/\mathrm{Re}x_h = 3 \times 10^6$ agree well with that of turbulent combined convection for LFST (Hattori et al., 2000). The effects of freestream turbulence level becomes clear at $\mathrm{Gr}x_h/\mathrm{Re}x_h = 1 \times 10^6$. When the freestream turbulence level is high (HFST), the profile of $\overline{ut}$ does not appreciably change with $\mathrm{Gr}x_h/\mathrm{Re}x_h$. On the other hand, the turbulent heat flux for MFST noticeably changes with the increase in freestream velocity. In particular, $\overline{ut}$ near the wall ($\eta < 2$), which is quite sensitive to the freestream velocity (Hattori et al, 2000) increases in the negative value.

The behavior of higher order correlations for MFST and HFST was examined to understand the effects of freestream turbulence level on the turbulence structure of combined convection. The skewness factors $S(u)$, $S(t)$ and the flatness factors $F(u)$, $F(t)$, which are third- and fourth-order moments of velocity and temperature fluctuations, are presented in figures 9, 10, respectively. The effects of freestream turbulence level clearly appear in the outer layer of velocity fields at $\mathrm{Gr}x_h/\mathrm{Re}x_h = 1 \times 10^6$, whereas there are agreements among the profiles at $\mathrm{Gr}x_h/\mathrm{Re}x_h = 3 \times 10^6$, in spite of significant difference of freestream turbulence. Here, we refer to the region from the wall to the maximum velocity location as the inner layer and the region between maximum velocity location and the edge of the boundary layer as the outer layer. For MFST, $S(u)$ shift towards positive with the increase in freestream velocity, and simultaneously $F(u)$ at $\mathrm{Gr}x_h/\mathrm{Re}x_h = 1 \times 10^6$ becomes substantially higher than that at $\mathrm{Gr}x_h/\mathrm{Re}x_h = 3 \times 10^6$. These profiles of $S(u)$, $F(u)$ are attributed to the intermittent phenomena with high-speed fluid motions. On the contrary, $S(u)$ and $F(u)$ obtained at $\mathrm{Gr}x_h/\mathrm{Re}x_h = 3 \times 10^6$ becomes similar to those for the Gaussian probability distribution ($S(u) = 0$ and $F(u) = 3$). Then, at the edge of the boundary layer, flatness factors, $F(u)$ becomes much smaller for HFST. Kalter and Fernholz (2001) also reported that such a change in $F(u)$ with freestream turbulence indicates the less convolved outer

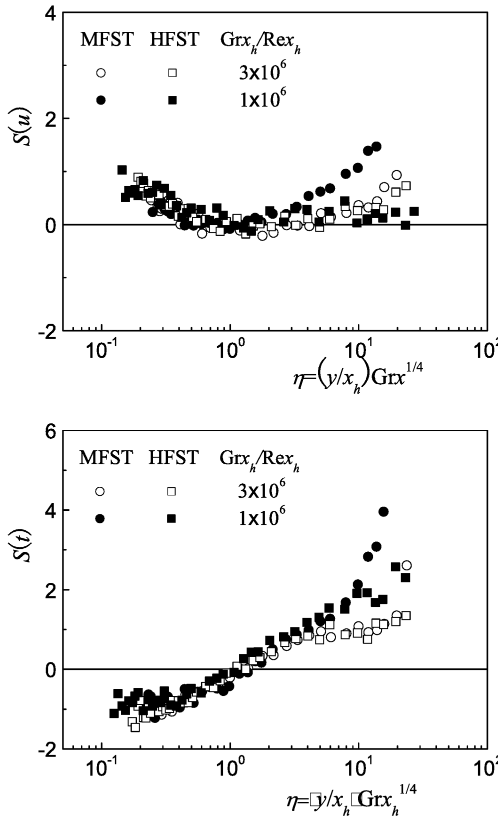

Figure 9: Skewness factors of velocity and temperature fluctuation.

edge of boundary layer, and thus, these results indicate the freestream turbulence directly relates to the fluid motion in the outer layer.

Figure 11 depicts the power spectra of velocity fluctuation, which are observed in the inner layer (η=1; η = $(y/x_h)\text{Gr}x^{1/4}$), and in the outer layer (η=10), and also shown in the figure is the power spectra of freestream turbulence. At $\text{Gr}x_h/\text{Re}x_h = 3\times10^6$ for MFST and HFST, the fluctuations in the wavenumber range of $10-10^2 m^{-1}$ become evident in the both layers. These profiles of power spectra agree well with those for LFST (Hattori et al., 2001). With the increases in freestream velocity, the peaks of power spectra in the both layers have almost the same value which agrees with that of freestream turbulence, which is similar to the result obtained for forced convection boundary layer with high freestream turbulence (Thole and Bogard, 1996). Then, for HFST, the boundary layer flows is controlled by the largescale fluctuation corresponding to the boundary layer thickness (k=1-10m^{-1}) even in the inner layer. Since the large-scale structures in the outer layer play an important role in turbulent transport of natural- and combined-convection boundary layer (Kitamura et al., 1985; Tsuji et al., 1992; Hattori et al., 2001), these results indicate that the turbulence heat transfer of combined convection depend on the turbulence lengthscale involved in the freestream.

CONCLUDING REMARKS

The turbulent characteristics in the combined-convection

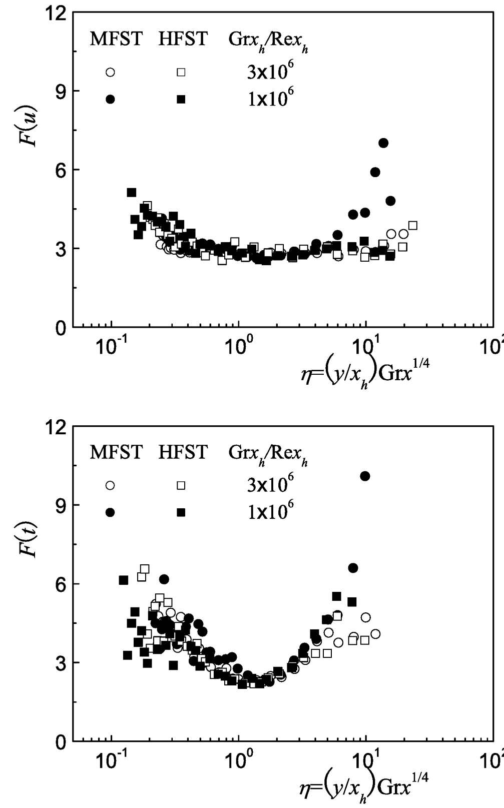

Figure 10: Flatness factors of velocity and temperature fluctuation.

boundary layer with an aiding freestream were investigated, especially paying attention to the effects of freestream turbulence level. The turbulence statistics in the boundary layer were obtained for a freestream turbulence with a wide range of Taylor microscale Reynolds number, and the change in turbulent characteristics with the increase in freestream turbulence level are discussed. The results of the present study may be summarized as follows:

1. The occurrence of heat transfer reduction is not so abrupt with freestream turbulence, although when the freestream turbulence level is low, a drastic reduction in heat transfer rate occurs.

2. The turbulence heat transfer of combined convection becomes more active as the freestream turbulence level raise.

3. For high freestream turbulence level, the boundary layer flows is controlled by the largescale fluctuation corresponding to the boundary layer thickness (k=1-10m^{-1}) even in the inner layer.

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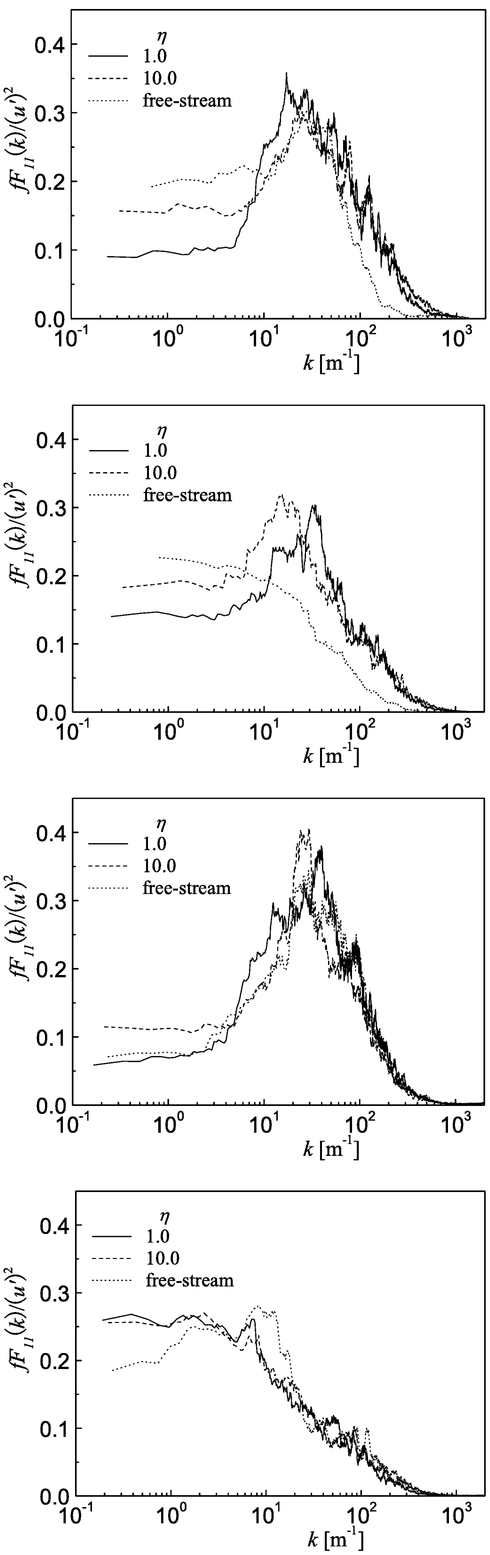

Figure 11: Spectra of velocity fluctuation.

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