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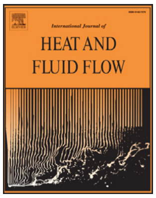

Higher-order and length-scale statistics of velocity and temperature fluctuations in turbulent boundary layer along a heated vertical flat plate

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ABSTRACT

Time-developing direct numerical simulation (DNS) was performed to clarify the higher-order turbulent behaviors in the thermally-driven boundary layers both in air and water along a heated vertical flat plate. The predicted statistics of the heat transfer rates and the higher-order turbulent behaviors such as skewness factors, flatness factors and spatial correlation coefficients of the velocity and temperature fluctuations in the natural-convection boundary layer correspond well with those obtained from experiments for space-developing flows. The numerical results reveal that the turbulent structures of the buoyancy-driven boundary layers are mainly controlled by the fluid motions in the outer region of the boundary layer, and these large-scale structures are strongly connected with the generation of turbulence in the thermally-driven boundary layers, in accordance with the actual observations for space-developing flows. Moreover, to specify the turbulence structures of the boundary layers, the cross-correlation coefficients and the characteristic length scales are examined for the velocity and thermal fields. Consequently, it is found that with a slight increase in freestream velocity, the cross-correlation coefficient for the Reynolds shear stress and turbulent heat flux increases for opposing flow and decreases for aiding flow, and the integral scales for the velocity and temperature fields become larger for opposing flow and smaller for aiding flow compared with those for the pure natural-convection boundary layer.

1. Introduction

Combined-convection flows caused by the interaction of natural- and forced-convection flows are frequently encountered in nature and many transport phenomena originated with thermal engineering. The analysis of the thermally-driven boundary layer with various freestreams (i.e., combined-convection boundary layers) is of great importance not only to clarify these transport mechanisms but also to elucidate the turbulence structures of the buoyancy-driven boundary layers. In most cases, freestreams are often superimposed on the pure natural-convection boundary layer and the turbulence characteristics vary with the magnitude and direction of freestream and working fluids.

Therefore, the turbulent fundamental and structural characteristics in the buoyancy- and thermally-driven boundary layers have received more attentions as a continuing research topic for the thermal and fluid mechanics community for long time because the phenomenon is employed in many engineering applications. However, there are very limited investigations dealing with the characteristics of the thermally-driven boundary layers with various freestreams (combined-convection boundary layers) along a heated vertical flat plate, compared with those for combined convection in the vertical passages such as pipes and channels performed with the aim of engineering applications (for instances, An et al., 1999; He et al., 2002; Jackson et al., 1989, 1999; Joye 1996, 2003; Kasagi and Nishimura, 1997; Kim et al., 2008; Petukhov and Sporygin, 1968; Petukhov et al., 1982; Wang et al., 2004; Watts and Chou, 1982). The fundamental turbulent characteristics of the combined-convection boundary layers with aiding and opposing flows along a heated vertical flat plate have been clarified to some extent through the experimental researches (Abu-Mulaweh et al., 2000; Hall and Price, 1970; Hattori et al., 2000, 2001; Inagaki and Kitamura, 1988a,b; Kitamura and Inagaki, 1987; Krishnamurthy and Gebhart, 1989). Most of these studies reported a sudden reduction in heat transfer rates in the combined-convection bound-

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Nomenclature

c_p	specific heat at constant pressure, kJ/(kg.K)
$F(u')$, $F(v')$, $F(w')$, $F(t')$	flatness factors of u', v', w' and t'
g	gravitational acceleration, m/s^2
Gr_δ	Grashof number based on integral thickness δ, $\frac{g\beta\Delta T_w\delta^3}{\nu^2}$
h	heat transfer coefficient, W/(m^2.K)
k	thermal conductivity, W/(m.K)
Nu_δ	Nusselt number based on integral thickness δ, $h\delta/k$
p	pressure, Pa
Pr	Prandtl number, $\mu c_p/k$
Re_δ	Reynolds number based on integral thickness δ, $U_\infty\ \delta/\nu$
$R_{t'}$	spatial correlation in the thermal field
$R_{u'}$	spatial correlation in the streamwise velocity field
$R_{u't'}$	cross-correlation coefficient between u' and t', $u't'/(\sqrt{u'^2}\sqrt{t'^2})$
$R_{u'v'}$	cross-correlation coefficient between u' and v', $u'v'/(\sqrt{u'^2}\sqrt{v'^2})$
$S(u')$, $S(v')$, $S(w')$, $S(t')$	skewness factors of u', v', w' and t'
T	mean temperature, °C
t	instantaneous temperature, °C
t'	temperature fluctuation, °C
U	mean streamwise velocity, m/s
u	instantaneous streamwise velocity, m/s
u'	streamwise velocity fluctuation, m/s
u_i	instantaneous velocity in x_i direction, m/s
U_0	characteristics velocity, ν/δ_0, m/s
v	instantaneous wall-normal velocity, m/s
v'	wall-normal velocity fluctuation, m/s
w	instantaneous spanwise velocity, m/s
w'	spanwise velocity fluctuation, m/s
x	vertical distance from leading edge of flat plate, m
x_i	coordinate in tensor notation, m
y	distance from wall, m
z	spanwise distance, m

Greek symbols

α	thermal diffusivity, m^2/s
β	coefficients of volume expansion, 1/K
ΔT_w	temperature difference between wall and ambient, $T_w - T_\infty$, °C
δ	integral thickness of velocity boundary layer, $\int_0^\infty U/U_{\max}\,dy$, m
δ_0	initial value of integral thickness of velocity boundary layer in the laminar region, m
θ	dimensionless temperature, $(t - T_\infty)/\Delta T_w$
μ	viscosity, Pa.s
ν	kinematic viscosity, m^2/s
ρ	density, kg/m^3
τ	time, s

Superscript

$*$	normalized variables with δ_0 and ν

Subscripts

max	maximum value
min	minimum value
w	wall condition
0	initial condition
∞	ambient condition

ary layer with aiding flow (freestream in the direction opposite to the gravitational force), and it was revealed that such an appearance of heat transfer characteristics was due to the laminarization of the boundary layer with increasing freestream velocity (Hattori et al., 2000, 2001). On the other hand, for opposing flow (freestream in the direction to the gravitational force), heat transfer rates rose with the increasing freestream velocity (Inagaki and Kitamura, 1988a,b). However, some essential features in the fundamental and structural characteristics of the boundary layer are still not sufficiently understood due to the difficulty in obtaining reliable experimental data for all turbulent quantities. Moreover, the experiments on the buoyancy-driven boundary layer are often accompanied by the arrangement of a huge apparatus and the difficulty in obtaining measurements of highly fluctuating velocity and temperature, and thus information obtained from the experiment is very limited and many points remained unclear and less understood for these boundary layer flows.

To make a breakthrough in such circumstances and to collect data unavailable in the experiment, we attempted to conduct a direct numerical simulations for the time-developing natural-convection boundary layer both in air and water (Abedin et al., 2009) and the combined-convection boundary layer with aiding and opposing flows both in air and water (Abedin et al., 2010; 2012a,b). As the results of these simulations, it was found that turbulence statistics obtained for time-developing boundary layers agreed well with the measurements obtained from the experiments for practical space-developing flows, when the comparison between the numerical and experimental results was made with the integral thickness of the velocity boundary layer as a characteristic length scale. Therefore, it was confirmed that turbulence characteristics of the thermally-driven boundary layers could be predicted with time-developing direct numerical simulations to some extent. In the past, we have also extensively clarified some fundamental and structural characteristics for the thermally-driven boundary layers (Abedin and Tsuji, 2009; 2010a,b; Abedin et al., 2010; 2012a,b). In some of the researches it was found that with a slight increase in freestream velocity, the transition region moved downstream for aiding flow and upstream for opposing flow in accordance with the experimental fact that the transition delayed for aiding flow and quickened for opposing flow (Abedin et al., 2010). It was also reported that for aiding flow, turbulence characteristics indicated the behaviors proceeding the laminarization of the boundary layer, and for opposing flow, the large scale fluid motions were apparent and became larger than those for the pure natural convection boundary layer with increasing freestream velocity (Abedin and Tsuji, 2009; Abedin et al., 2012b). The numerical results for aiding flow also revealed that the transition began at a thick laminar boundary layer due to the delay of the transition and large-scale vortex-like excitations centering on the spanwise direction were followed, while, for opposing flow, the transition began at a thin laminar boundary layer due to the quickening of the transition and relatively small-scale vortex-like excitations were generated with the progress of transition (Abedin and Tsuji, 2010b). To improve the significance of the numerical results, the association of turbulence statistics between time- and space-developing flows were also investigated, consequently, the numerical results for time-developing flow were converted to

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