International Journal of Heat and Mass Transfer 109 (2017) 428–439

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Wall-resolved large eddy simulation of turbulent mixed-convection heat transfer along a heated vertical flat plate

Ayodeji Ojofeitimi [a,*], Yasuo Hattori [b]

[a] Department of Aerospace Engineering, University of Maryland-College Park, MD 20740, USA
[b] Fluid Science Sector, Central Research Institute of Electric Power Industry, 1646 Abiko, Abiko-shi, Chiba-ken 270-1194, Japan

ARTICLE INFO

Article history:
Received 31 August 2016
Received in revised form 26 December 2016
Accepted 7 February 2017

Keywords:
Turbulent boundary layer
Mixed convection
Turbulent heat transfer
Large eddy simulation
Boundary layer transition

ABSTRACT

The present study aims to assess the predictive capabilities of wall-resolved large eddy simulation (LES) in computing the fluid flow and heat transfer characteristics in a mixed-convection turbulent boundary layer that developed along a large flat plate vertically mounted in air. The maximum Rayleigh number was approximately 3×10^{11}, which resulted in fully developed turbulence conditions. To enhance the accuracy, computational efficiency, and numerical stability, the LES solved the low-Mach number compressible flow governing equations, which included fluctuating density effects and pressure-density decoupling. For the subgrid scale (*SGS*) closure, a locally dynamic Smagorinsky SGS model was implemented into the LES solver to enable the backscatter phenomenon intrinsic to transitioning boundary layer flows. The LES illustrated exceptional agreement with the statistics profiles in the boundary layer obtained with the experiments of previous studies, which showed sensitivity to freestream conditions. In particular, the LES correctly predicted the turbulent heat flux in the streamwise direction near the heated surface. Furthermore, the LES captured the rapid changes in spectra of fluctuating temperature and velocities due to the delay of transition with increasing freestream velocity.

Published by Elsevier Ltd.

1. Introduction

Many fluid transport processes encountered in nature and engineering applications are strongly affected by the presence of buoyancy. The buoyancy effect can be a consequence of temperature gradients within the flowfield. Such flowfield may be driven primarily by the buoyancy force (natural-convection) or it can be a combination of buoyancy and a weakly forced ambient flow induced via some mechanical means (mixed-convection). In these flows, the structural characteristics of the boundary layer are profoundly intricate, and it is a direct consequence of the non-linear effects and mutual coupling of the velocity and thermal flowfields.

Strongly affected buoyant flows are largely unstable and the flow mechanism can easily become turbulent. In mixed-convection boundary layer flows, the turbulent heat transfer characteristics not only depend upon the buoyancy induced temperature fluctuations, but also on the direction of the weakly forced ambient flow. The direction of the forced flow can be the same as the upward motion induced by buoyancy over a vertically heated flat plate (aiding flow) or in the opposite direction (opposite flow).

Due to the complexities intrinsic to mixed-convection turbulent boundary layer flows, there have been limited experimental and numerical studies of such flows over vertical flat surfaces. The turbulent characteristics of mixed-convection turbulent boundary layers in aiding flow have been experimentally studied to elucidate the fundamental structure of the boundary layer [11–14,21,22]. These measurements indicated the decrease in wall heat transfer was attributable to suppression of turbulence in the mixed-convection turbulent boundary layer. Several researchers have similarly attempted to numerically investigate mixed-convection turbulent wall flows over heated vertical flat surfaces [2,20,31]. Direct numerical simulation (DNS) [2,20] and Reynolds Averaged Navier Stokes (RANS) [31] results illustrated that the Nusselt number decreased as the freestream velocity was imposed on the natural-convection turbulent boundary layer. Furthermore, the DNS results revealed the turbulent heat transfer in aiding and opposite flows differs significantly [21]. To date, there is no detailed LES-based computational study of mixed-convection turbulent wall flows over heated vertical flat surfaces. This can be attributed to the fact that the simulation of mixed-convection turbulent boundary layers remains a formidable task. One of the difficulties entailed in computing buoyancy affected wall flows is that the classical analysis developed for momentum-driven turbulent wall flows based upon the decomposition of the near-wall

---

* Corresponding author.
E-mail address: aojofeitimi@outlook.com (A. Ojofeitimi).

http://dx.doi.org/10.1016/j.ijheatmasstransfer.2017.02.020
0017-9310/Published by Elsevier Ltd.

Nomenclature

$\mathbf{I}$	unit tensor
$\mathbf{L}$	Leonard stress tensor
$\mathbf{M}$	rate of strain tensor
$\mathbf{S}$	rate of strain tensor
$\mathbf{u}$	velocity instantaneous, m/s
$\mathbf{x}$	general spatial coordinate, m
C_d	dynamic coefficient
c_p	specific heat at constant pressure, kJ/(kg K)
Gr_x	local Grashof number, $\frac{g\beta(T_w-T_\infty)x^3}{\nu^2}$
Re_x	local Reynolds number, $U_\infty x/\nu$
Ri_x	local Richardson number, Gr_x/Re_x^2
t'	temperature fluctuation, K
u', v'	fluctuating velocity components, m/s
$u't'$	streamwise turbulent heat flux, (m K)/s
$u'v'$	Reynolds Shear Stress, m^2/s^2
y^*	non-dimensional wall unit
g	gravitational acceleration, m/s^2
h	enthalpy, J
p	pressure, Pa
Pr	Prandtl, $\mu c_p/\kappa$
q, $\mathbf{q}$	heat flux, W/m^2
R	universal gas constant, J/(K mol)
T	temperature, K
t	time, s
U	mean streamwise velocity, m/s
W	molecular weight of air, kg/kmol
x, y, z	coordinate components, m

Greek symbols

α	thermal diffusivity, m^2/s
β	volume expansion coefficient, 1/K
Δ	difference operator
δ	momentum boundary layer integral length, m
∞	freestream/ambient condition
κ	thermal conductivity, W/(m K)
μ	viscosity, Pa s
∇	gradient operator
ν	kinematic viscosity, m^2/s
ρ	density, kg/m^3
σ	stress, Pa
τ	shear stress, Pa

Oversymbols

$--$	ensemble-averaged quantity
$\sim$	Favre filtered
$\wedge$	test filter

Subscripts

$B1, B2, B3$	streamwise direction mesh related scales
SGS	sub-grid scale
VSL	viscous sublayer
w	wall

Superscripts

$'$	fluctuating component
$''$	deviatoric component

region into a viscous sublayer and logarithmic layer needs to be carefully adapted. A second difficulty is that such flows often correspond to high Reynolds numbers (i.e. high Grashof and Rayleigh numbers), and it can be computationally expensive and numerically challenging to resolve the turbulent heat transfer near the wall since momentum driven turbulent flow classical inner layer scalings do not strictly apply. These numerical challenges were observed in the LES computations of [3,27] and ergodicity-based DNS of [1,2], all of which employed artificial treatments to reproduce the transition from laminar to turbulence in the boundary layer, have not firmly grasped the turbulence characteristics in the near-wall region.

The utilization of large eddy simulation in computing turbulent boundary layers follows two approaches [32], namely fine- and coarse-grained computations. Fine-grained simulations correspond to wall-resolved simulations, whereby the viscous sublayer is fully resolved to capture the near-wall small scale turbulence physics, and the first off-the wall grid node is within the viscous sublayer. However, the constraint associated with performing fine-grained LES calculations lies in the fact that at high Reynolds numbers, i.e. thin viscous sublayer, the computational requirements becomes prohibitively expensive for engineering-level simulations. Coarse-grained simulations correspond to wall-layer modeled simulations where approximate equations are utilized to estimate the near-wall viscous sublayer region. The approximate equations are used to reconstruct the wall-shear stress and wall-heat flux, and the first off-the wall grid node is usually outside the viscous sublayer.

In the present study, we present wall-resolved large eddy simulation of mixed-convection turbulent boundary layer flows over an isothermal heated vertical flat plate configuration and address the shortcomings of previously mentioned works, i.e. their inability to accurately resolve the laminar to turbulence transition "naturally" and near-wall turbulent flow characteristics. The canonical configuration corresponds to experimental measurements previously performed by Hattori et al. [12–14], which dealt with the rapid change in the transition process and near-wall structures of a natural-convection boundary layer as the freestream velocity is increased.

2. Approach

2.1. Experimental configuration

As described in Refs. [13,14], the experimental configuration corresponds to an isothermal heated flat plate inside a low-speed vertical wind tunnel. The wind tunnel comprises a blower which can force air into the test section up to 10 m/s. Downstream of the blower resides a diffuser with a relatively large cone angle that can slow down the flow enough to induce flow separation. Thus, three safety screens were positioned in the diffuser to smooth out variations in the velocity field. To dampen freestream disturbance or turbulence, four fine mesh damping screens along with a honeycomb were placed in the settling chamber.

The dimensions of the plate were 4 m high and 0.8 m wide to generate two-dimensional turbulent flow, and 0.02 m thick to prevent deformation due to thermal stress. The plate was mounted vertically on the back wall of the vertical wind tunnel. The temperature of the plate was kept uniform at approximately 370 K via electric heaters implemented at the rear of the plate. The ambient temperature for the experiments was approximately 300 K. Temperature and velocity data in the turbulent boundary layer were