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Large eddy simulation of a transitional, thermal Blasius flow at low Reynolds number

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ABSTRACT

Large eddy simulation (LES) of a transitional, thermal Blasius flowfield at a sufficiently low Reynolds number along an isothermal, flat plate is presented herein. Prior experiments observed that boundary layer transition is induced by the presence of streamwise vortex instability caused by the complex interaction between thermal buoyancy and forced convection dynamics. The maximum Grashof and Reynolds numbers employed in the LES were approximately 1.05×10^{11} and 1.18×10^{5}, respectively. To further 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 transitional boundary layer flows. The LES accurately predicted the onset of streamwise vortex instability and the eventual three-dimensional vortex breakdown of the underlying mean flow into a fully developed turbulent boundary layer, when compared to previously measured data. In the developed turbulence region, quadrant analyses indicated $Q2$ and $Q4$ events dominated the contribution to the Reynolds shear stress in the near-wall region, whereas $Q1$ and $Q3$ events contributed considerably to the wall-normal turbulent heat flux. And, as a result of the instability within the conduction layer, the layer erupts and intermittently releases buoyant thermal plumes. These recurring intermittent events inside the conduction layer deflect and deform the flowfield quantities near the wall, resulting in a plurality of peculiar peaks and shear layers inside the boundary layer. Furthermore, these buoyant thermal plumes are the dominant turbulence production mechanism farther away from the wall in the downstream region of the developed turbulent boundary layer flow. Near the wall, however, forced convection turbulent flow effects were observed, in which the shear production term was the primary contributor to the generation of turbulent kinetic energy, and quasi-streamwise and horseshoe-like vortex structures were observed in the developed turbulence region.

1. Introduction

A plethora of fluid transport processes encountered in nature and engineering applications are strongly affected by thermal buoyancy. Thermally buoyant flows can be largely unstable, and the flowfield mechanism can easily become turbulent. Particularly, in Blasius boundary layer flows with appreciable thermal buoyancy, non-linear streamwise vortex instabilities can restructure the underlying mean flow, thereby resulting in a three-dimensional breakdown of the boundary layer.

The characteristics of the streamwise vortex instability of thermal Blasius flows have been experimentally studied to elucidate the structure of the boundary layer [22,33,51]. Imura et al. [22] conducted experiments and discovered three distinct flow regimes within the flowfield. Their measurements indicated an initial region of laminar forced convection where buoyancy effects were insignificant near the leading edge of the flat plate. The second regime was termed the transition region (the onset and breakdown of streamwise vortices). The third regime was called the turbulent free convection region due to the near-constant heat transfer coefficient that was observed subsequent to the transition region. The measurements of [51] illustrated that the local heat transfer coefficient decreased with increasing streamwise distance, as observable in laminar forced convection, near the leading edge of the plate. Farther downstream, the heat transfer coefficient deviated from the laminar forced convection trend with an inflection point and rapidly increased. Subsequently, the heat transfer coefficient remained nearly constant. Wang [51] conjectured an instability

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Nomenclature

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

	Greek symbols
α	thermal diffusivity, m^2/s
β	volume expansion coefficient, 1/K
Δ	difference operator
δ	numerical momentum boundary layer integral length, m
∞	freestream/ambient condition
κ	thermal conductivity, W/(m K)
λ	spanwise wavelength, m
μ	viscosity, Pa s
∇	gradient operator
ν	kinematic viscosity, m^2/s
ω_x	streamwise vorticity, 1/s
ω_y	wall-normal vorticity, 1/s
ρ	density, kg/m^3
σ	stress, Pa
τ	shear stress, Pa
Oversymbols	
$\bar{}$	ensemble-averaged quantity
$\tilde{}$	Favre-filtered
$\hat{}$	test filter
Subscripts	
qu	quadrant contribution
SGS	subgrid scale
VSL	viscous sublayer
w	wall
Superscripts	
$'$	fluctuating component
$''$	deviatoric component

mechanism as the cause of the inflection and abrupt increase that was seen in the local heat transfer coefficient. The measurements of [33] indicated the onset of streamwise vortex instability was the inception of the transition from two-dimensional laminar flow to three-dimensional vortex flow. The measurements illustrated that vortex flow commenced with ordered and stable pairs of laminar streamwise vortices in clockwise and counter-clockwise directions, whereby the vortices grow and an eventual vortex collapse occurs that evolves into fully developed turbulent flow. Furthermore, the measurements of [21] indicated the onset of streamwise vortices was not associated with an immediate increase in the Nusselt number over the heated, flat plate.

Several researchers have similarly attempted to investigate theoretically the vortex instability of thermal Blasius flows over the heated, flat plate configuration [5,16,17,35,53]. In general, the theoretical analyses showed streamwise vortex instability can occur in the presence of significant thermal buoyancy, and the mean flow becomes susceptible to this mode of instability as the temperature difference between the isothermally heated, flat plate and freestream increased. Numerically, Ramachandran et al. [45] performed Reynolds-Averaged Navier-Stokes (RANS) simulations of thermal Blasius flow over an isothermally heated, flat plate. The flowfield was resolved by solving two-dimensional RANS equations, and it was determined that such an approach was inherently inadequate. The inadequacies of assuming a two-dimensional flowfield were attributed to its (two-dimensional RANS equations) inability to capture the transition region, which comprised the onset of streamwise vortices and eventual breakdown of the mean flow into full-scale turbulence. The direct numerical simulations (DNS) of [19] observed the flowfield comprised two-dimensional laminar forced convection and three-dimensional vortex flow regions. Moreover, the authors concluded $Gr_x/Re_x^{1.5}$, a ratio formulated by [22], is the appropriate parameter for characterizing heat transfer in the flowfield.

To emphasize the difficulty with conducting experiments and numerical simulations of these low Reynolds number, transitional boundary layers with thermal instability, a number of studies have been performed for such flows in bottom-heated, rectangular ducts and plane channel geometries. The measurements of [3,29,31] illustrated the onset of vortex flow and instability at higher Grashof numbers and at lower Reynolds numbers. These findings were comparably observed in the numerical simulations of [6,10,20,41], in which vortex rolls were seen in the flowfield at high Grashof and low Reynolds numbers. The combined experimental and numerical simulation efforts of [55] observed that the vortex flow pattern changed from longitudinal to transverse rolls when the Reynolds number was lowered, and the appearance of transverse rolls in lower Reynolds numbers and higher Grashof numbers were ascribed to possibly oscillating thermal plumes in the upstream. Similarly, the combined flow visualization and numerical simulation of [4] illustrated that at low Reynolds numbers, the vortex rolls were longer and stronger, and at higher Reynolds numbers,