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# 主論文の要旨

論文題目 Direct Numerical Simulations on the Development of Boundary Layer with Heat Transfer under the Effects of External and Internal Disturbances (外部および内部乱れの影響を受けた熱輸送を伴う境界層の発達に関する直接数値計算)

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## 論文内容の要旨

A boundary layer is a very thin layer of fluid adjacent to a bounding surface where the effects of viscosity are significant and the velocity increases from zero at the surface and approaches the free-stream velocity at the edge. As one of the canonical wall-bounded shear flows, the boundary layer exists widely in both nature and industry. The detailed flow structure in a pure boundary layer without any disturbance has been investigated over decades. However, there are many situations in practice, particularly in the engineering applications, that the flow is unsteady and contains disturbances (hereafter referred to as the external disturbance) or the surface is unsmooth and it significantly disturbs the flow (hereafter referred to as the internal disturbance). This point is actually very important in a scalar field such as heat transfer across the surface. In heat exchangers, for instance, the flow is usually turbulent to modify the thermal boundary layer and affect heat transfer. Thus, from viewpoints of flow control and improvement in such engineering devices, it is of importance to clarify the effects of external and internal disturbances on a boundary layer with heat transfer. In particular, such disturbances significantly influence in the developing region of a boundary layer rather than in the developed region.

In the present study, a boundary layer with heat transfer under the effects of various disturbances is investigated by means of three-dimensional direct numerical simulation (DNS). Compared with the experimental studies, DNS are quite useful since it can give more information of the boundary layer, especially in the near-wall region. Three types of disturbances which are common in both fundamental and applied applications are employed: a tripping object mounted on the wall, the grid turbulence, and a wake of a square bar. The aims of this study are as follows:

(1) To elucidate the effects of various disturbances on the development of a boundary layer.

(2) To elucidate the effects of various disturbances on the momentum and heat transfer in a boundary layer.

(3) To elucidate the contribution of vortical motions to heat transfer in a boundary layer.

(4) To provide a basis for flow control and heat transfer enhancement in a boundary layer by utilizing various disturbances.

In Chapter 1, the basic theories on boundary layer, including the boundary layer transition and the boundary layer structure, are introduced. Besides, the previous studies on boundary layer with various disturbances are summarized as well.

In Chapter 2, the details of numerical methods used in the present study are provided. In DNS, the governing equations, i.e. the normalized continuity equation, incompressible Navier-Stokes equations, and the scalar transfer equation are numerically solved without any turbulence model. The fractional step method in which the computations for velocity and pressure are decoupled is used to solve these governing equations. A semi-implicit third-order Runge-Kutta scheme is employed for time advancement. So as to increase the numerical stability with less computational cost, only the viscous and diffusion terms along the wall-normal direction are advanced implicitly by using the Crank-Nicolson scheme at each sub-step. The resulting Poisson equation for pressure is solved at each sub-step by an iterative method called Stable Bi-Conjugate Gradient method (Bi-CGStab). In order to prevent the spurious pressure oscillations, the staggered arrangement for velocity, pressure, and temperature is employed; in other words, the pressure and temperature are stored at the center of the mesh volume and the velocities are located at the center of the mesh surface. With regard to the spatial discretization, the convection terms are discretized by using a fully conservative second-order central difference scheme to enhance the conservation of the kinetic energy. The viscous and diffusion terms along the streamwise and wall-normal directions are discretized by the second-order central difference scheme. In order to increase the accuracy, the fourth-order central difference scheme is adopted for the discretization of the viscous and diffusion terms along the spanwise direction.

In Chapter 3, the effects of internal disturbance generated by a tripping object on the development of boundary layer with heat transfer are investigated and discussed. The tripping object contains nine small cubes which are placed alternatively in the spanwise direction and is mounted at the leading edge of the boundary layer. It is found that the boundary layer has been triggered by the tripping object and the flow in this boundary layer is to some extent transitional. Moreover, the effect of the tripping object on the development of the boundary layer is weak, especially in the downstream region. Only small-amplitude fluctuations are generated in the vicinity of the tripping object and the flow in the downstream region has a laminar-like structure. In addition, heat transfer is slightly enhanced by the tripping object, and there is almost no effect on the skin friction. From the visualization of the voritical structures, it is observed that the hairpin-like structure exists in the upstream region. Such structure is the product of the tripping object and straddles the low-speed streaks. In the downstream region, on the other hand, the longitudinal structures are prevalent.

In Chapter 4, the effects of external disturbance generated by a biplane regular grid on the development of boundary layer with heat transfer are investigated and discussed. In this case, the grid turbulence has a turbulence intensity of 50% at the beginning and then decays exponentially to 7% in the downstream region. It has been confirmed that such grid turbulence is nearly homogeneous and isotropic. The results show that the boundary layer is triggered by the biplane regular grid and the boundary layer flow becomes the turbulent state even though the Reynolds number based on the momentum thickness, $Re_\theta$, is low. Besides, skin friction and heat transfer in the boundary layer are more enhanced by the grid turbulence. It also found that strong strain in the viscous sublayer, which is induced by the vortical motion in the buffer layer, contributes to the enhancement of heat transfer.

In Chapter 5, the effects of external disturbance generated by a wake of a square bar on the development of boundary layer with heat transfer are investigated and discussed. Unlike the grid turbulence, such external disturbances are anisotropic and often periodic in the near-wake region. In this case, the axis of the square bar is parallel to the bottom wall and normal to the flow direction. The gap between the square bar and the bottom wall is varied in two cases. It is known that the boundary layers in these two cases have been triggered by the wakes of the square bar and the flows in these boundary layers are to some extent transitional. In the large-gap case, the alternating negative and positive vortices, shed from the bar, perturb the boundary layer by advecting the fluid wallward and outward in turn. In the small-gap case, on the other hand, the negative vortices are large and occupy almost the entire region, which lead to the strong backward sweep motions of fluid near the bottom wall. This induces the reduction of the velocity near the bottom wall hence the skin friction in comparison with the large-gap case. Furthermore, it is observed that the negative (clockwise) vortices generally suppress the thermal boundary layer by engulfing the hot fluid from the outer region into the near-wall region, which makes the temperature gradient large. On the other hand, the positive (counter-clockwise) vortices seem to stretch the thermal boundary layer by ejecting the cold fluid from the near-wall region into the outer region and it makes the temperature gradient small. In the small-gap case, the thermal boundary layer is strongly suppressed by the large negative vortices. This results in the larger temperature gradient and more active heat transfer in comparison with the large-gap case.

Based on the above results for each case, the following conclusions can be made.

(1) The boundary layer affected by the grid turbulence has been developed into turbulent state even though the Reynolds number based on the momentum thickness, $Re_\theta$, is low, while the boundary layer flows are still in transition under the effects of the tripping object and the wake of a square bar.

(2) The effect of the tripping object on skin friction and heat transfer in a boundary layer is relative small. They are most enhanced by the grid turbulence. On the other hand, the effect of the wake of a square bar varies with the gap between the square bar and the bottom wall. Skin friction is reduced but heat transfer is more active in the small-gap case, while they are both reduced in the large-gap case.

(3) In the case with the grid turbulence, strong strain in the viscous sublayer, which is induced by the vortical motion in the buffer layer, contributes to the enhancement of heat transfer. On the other hand, in the case with a wake of a square bar (small-gap case), the active heat transfer is attributed to the large negative vortices shed from upper side of the square bar.

(4) From the viewpoints of heat transfer enhancement and skin friction reduction in a boundary layer, it is preferred to utilize a wake of a square bar with small gap between it and the bottom wall.