Numerical Study of Flow Characteristics due to Interaction Between a Pair of Vortices in a Turbulent Boundary Layer

Jang Sik Yang*

Advanced Environment & Energy Technology Research Institute,
K.K. Incinerator Engineering & Construction Co., Ltd.,
Inno-biz Center 206, Mandeok 3-dong, Buk-gu, Busan 616-829, Korea

This paper represents a numerical study of the flow field due to the interactions between a pair of vortices produced by vortex generators in a rectangular channel flow. In order to analyze longitudinal vortices induced by the vortex generators, the pseudo-compressibility method is introduced into the Reynolds-averaged Navier-Stokes equations of a 3-dimensional unsteady, incompressible viscous flow. A two-layer $k-\varepsilon$ turbulence model is applied to a flat plate 3-dimensional turbulence boundary to predict the flow structure and turbulence characteristics of the vortices. The computational results predict accurately the vortex characteristics related to the flow field, the Reynolds shear stresses and turbulent kinetic energy. Also, in the prediction of skin friction characteristics the computational results are reasonably close to those of the experiment obtained from other researchers.

**Key Words:** Vortex Generator, Longitudinal Vortices, Pseudo-Compressibility, Half-delta Wing

1. Introduction

The vortices, which are produced by vortex generators, have an effect on flow and temperature fields because they have complicated three-dimensional turbulence characteristics. This flow, which has longitudinal velocity components, is an important phenomenon in fluid dynamics and heat transfer and it can disturb boundary layer structure strongly and affect heat transfer characteristics.

Many experimental studies on the heat transfer and the interactions between vortices in a turbulent boundary layer have been carried out. In addition, proper rules for the design and installation of vortex generators have been studied. Eibeck and Eaton (1987) have conducted experiments on longitudinal vortices embedded in a turbulent boundary layer and observed that the longitudinal vortices are found to influence heat transfer enhancement significantly. Pauley and Eaton (1988) studied two types of flow patterns induced by vortex generators with changing angles of attack; the flow between vortices is directed either away from the wall, common-flow-up, or toward the wall, common-flow-down. Numerical researchers have often used the experimental results of Pauley and Eaton to prove the validation of numerical schemes developed by them. The structure and development of streamwise vortex arrays embedded in a turbulent boundary were investigated by Wendt and Hingst (1994). Recently, studies on the performance of vortex generators, which are used as heat exchangers, have been performed widely.

With experimental studies, numerical studies focusing on the interactions between vortices and boundary layers have been carried out using the
vortices generated by vortex generators as models. Using the PNS (Parabolized Navier–Stokes) method, Anderson and Gibb (1992) performed a study on the longitudinal vortices induced by vortex generators. They also examined the fluid flow characteristics with respect to the geometric arrays of different vortex generators set up at the S–duct inlet. Numerical simulations of turbulent flows in a rectangular channel with mounted vortex generators on the bottom wall were carried out by Zhu et al. (1993). The flow field was computed by solving the Reynolds–averaged Navier–Stokes and energy equations, and the turbulence was taken into account by solving standard $k$–$\varepsilon$ model equations with the wall law. Kim and Patel (1994) performed experimental and numerical studies of the interaction between the vortices and the turbulent boundary layer generated in the duct with flat plates and curvatures. Kim et al. (1996) studied heat transfer characteristics and flow structure in turbulent flows through a flat plate three–dimensional turbulent boundary layer containing built–in vortex generators using the PNS, the standard $k$–$\varepsilon$ turbulent model and the eddy diffusivity. They concluded that heat transfer and skin friction showed relatively good results in comparison with experimental data and the heat transfer enhancement in the vicinity of the wall was due to the spanwise attachment of the vortices as they developed in the streamwise direction. Yang and Lee (2000) performed a numerical simulation of the common–flow–down induced by vortex generators. They observed that their results showed good agreement with the experiment of Pauley and Eaton (1988) and the computations of Kim et al. (1996). Lee and Kim (2004a and 2004b) studied the vortex flow characteristics of a sharp–edged delta wing at high angles of attack and concluded that an increase in the free stream velocity resulted in stronger leading edge vortices with an outboard movement and their computations provided qualitatively reasonable predictions of vertical flow characteristics, compared with past wind tunnel measurement.

As mentioned above, a better understanding of the heat transfer and flow field characteristics in a turbulent boundary layer with longitudinal vortices is very important in engineering designs, such as heat exchangers, mixing devices and controllers of separation flow. In the present study, the flow field behind vortex generators is modeled by the information obtained from studies on a delta wing. Three–dimensional Reynolds Navier–Stokes equations and a two–layer $k$–$\varepsilon$ turbulent model are also used to analyze the vortices occurring behind the vortex generators. The numerical results obtained from the present study are compared with those of the experiment of Pauley and Eaton (1998).

2. Numerical Analysis

2.1 Governing equation

Three–dimensional unsteady, incompressible viscous flow can be defined as

Continuity equation

$$\frac{\partial u_i}{\partial x_i} = 0$$

(1)

Momentum equation

$$\frac{\partial p}{\partial t} + \frac{\partial \rho u_i u_j}{\partial x_i} = -\frac{\partial p}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_j}$$

(2)

Incompressible Navier–Stokes equations have the characteristics of an elliptic partial differential equation. However, if a pseudo–compressibility method is applied to solve the incompressible N–S equations, the system of equations given above can be solved efficiently because they can be given to a hyperbolic governing equation. This is similar to the case in which the steady, incompressible N–S equation is used for the compressible flow (Kwak et al., 1986).

Although the coordinate system in the present study is expressed in the cartesian coordinate system, the governing Eqs. (1) and (2) are defined in the generalized coordinate system to apply to complex geometries. The governing Eqs. (1) and (2), which employ the Boussinesq assumption and pseudo–compressibility, are made dimensionless and then transformed into the generalized coordinate system as follows: