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Large eddy simulation of turbulent natural convection between symmetrically heated vertical parallel plates for water

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ABSTRACT

The boundary layer interaction effect of the turbulent natural convection in the gap between symmetrically heated vertical parallel plates was evaluated using a numerical simulation in the present study. A large eddy simulation was conducted, and a Vreman model was used as a dynamic subgrid-scale model. The numerical simulation was validated thorough a comparison with the experimental result for the turbulent natural convection adjacent to a single vertical heated plate. The boundary interaction effect was investigated by varying the gap between the parallel plates. The results showed that the flow for vertical parallel plates had a lower heat transfer rate than a vertical plate flow. The boundary layers and vortex structure were evaluated. The heat transfer was reduced as a result of a reduced velocity gradient in the outer region of the velocity boundary layer. The averaged heat transfer was similar to that of the laminar flow.

1. Introduction

Natural convection flow occurs in the gap between two heated vertical parallel plates in many mechanical engineering settings. For example, such a flow is used to cool computer motherboards, electrical transformers, spent nuclear fuel, and in many other applications. Recently, such flow has been used to generate electricity and provide ventilation in buildings to reduce energy consumption [1–4]. Therefore, it is important to evaluate the heat and fluid flow characteristics of this type of flow to improve and optimize mechanical devices and building structures. The interaction of the two boundary layers has been of great interest because of its complicated flow structure and key role in determining the heat transfer characteristics.

In the past, the laminar natural convection flow associated with heated vertical parallel plates has been precisely studied, with the first experiment conducted by Elenbass [5], where he calculated the average heat transfer rate by introducing the aspect ratio of the vertical parallel plates. Aihara et al. [6–9] numerically simulated parallel plates flows with various aspect ratios and thermophysical fluid properties and obtained a comprehensive average heat transfer rate distribution map. Furthermore, Maruyama [10] numerically simulated the laminar convection in a vertical concentric annular duct and found that the analytical formula for the average heat transfer rate of vertical parallel plates could be available for a vertical concentric annular duct using the characteristic length proposed by Aihara et al. [7]. Additionally, Aihara [11–15] conducted experiments and evaluated the heat transfer rate and temperature boundary layer quantitatively using the Schliren method.

The turbulent natural convection flow associated with heated parallel plates has been investigated for many years, using both numerical calculations and experiments. Miyamoto et al. [16] conducted an experiment on the turbulent natural convection of asymmetrically heated vertical parallel plates for air, evaluating the local heat transfer rate distribution at some ranges of vertical locations, while varying the gap between the vertical parallel plates, with a uniform heat flux condition. Yilmaz et al. [17] carried out similar experiments, obtaining details of the turbulent fields under a uniform temperature condition. Furthermore, they compared experimental and numerical results and confirmed that a low Reynolds number k–ε model had the ability to predict the turbulent flow qualitatively. Alzwayi et al. [18] analyzed an asymmetrically heated vertical parallel plates flow using a realizable k–ε model [19] and they investigated the gap effect of the parallel plates on the turbulent flow. However, two-dimensional calculation may overestimate or underestimate the turbulence because of an incorrect turbulent viscosity calculation. Recently, a three-dimensional calculation of the turbulent natural convection was evaluated using large eddy simulation (LES). Barhagni et al. [20] investigated the turbulent natural convection boundary layer on a vertical cylinder

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Nomenclature

b	gap of vertical parallel plates, m
c	specific heat capacity, J/(kg K)
c_v	constant value, 0.1
c_{bulk}	bulk velocity, m/s
g	gravitational acceleration, m/s^2
q	turbulent subgrid-scale heat flux, m K/s
K	constant value, 1.0×10^{-6}
h	heat transfer coefficient $\frac{-\lambda}{T_w - T_0} \cdot \frac{dT}{dx}\big\|_w$, W/(m^2 K)
L	length of heated plate, m
ξ	characteristic length, m
Nu_y	local Nusselt number, –
$\overline{Nu_\xi}$	averaged Nusselt number, –
Ra_y	local Rayleigh number, –
Ra_ξ^*	modified Rayleigh number, –
u_i	instantaneous velocity, m/s
v_m	max velocity of the vertical direction, m/s
p	modified pressure, m^2/s^2
Pr_t	turbulent Prandtl number, –
Q	Q value, 1/s^2
r	gradient of variables
S_{ij}	strain tensor, 1/s
T	temperature, K
t	time, s
τ	turbulent subgrid-scale tensor, m^2/s^2
W_{ij}	vorticity tensor, 1/s
x_i	coordinate in tensor notation, m
x	horizontal distance from heated plate, m
y	vertical distance from bottom edge of heated plate, m

Greek symbols

$d\alpha$	gradient of thermal diffusivity by temperature, m^2/(s K)
$d\mu$	gradient of viscosity by temperature, Pa s/(K)
$d\nu$	gradient of thermal diffusivity by temperature, m^2/(s K)
α	thermal diffusivity, m^2/s
β	thermal expansion coefficient, 1/K
Δ	mesh size, m
ΔT	temperature difference, K
δ	integral thickness of velocity boundary layer, –
μ	viscosity, Pa s
ν	kinematic viscosity, m^2/s
ψ	limited function, shape coefficient
λ	thermal conductivity, W/m K
ρ	density, kg/m^3

Superscripts

–	filter, time-averaged value

Subscripts

0	ambient temperature condition
m	mesh
n	normal direction
P	grid point
r	reference
W	west
w	wall
E	east
SGS	subgrid scale

using Smagorinsky model [21] and found that Smagorinsky model could predict the developed flow qualitatively. Yan et al. [22] analyzed the turbulent natural convection of the vertical plate using Smagorinsky model and they conducted the FFT analysis of the turbulent natural convection. Because the turbulent natural convection is one of the spatially developing flows, the subgrid-scale models, which can distinguish between the laminar and turbulent flow, are preferred. However, Smagorinsky model cannot distinguish between the laminar and turbulent flow, and hence, other subgrid-scale models are required. In the past, some dynamic subgrid-scale models, which can distinguish between the laminar and turbulent flow, have been developed and the typical dynamic subgrid-scale models among them are the dynamic Smagorinsky model [23] and the Vreman [24] model. Lau et al. [25] calculated the turbulent natural convection for asymmetrically heated vertical parallel plates. They found that the Vreman model could accurately predict the turbulent heat transfer, performing significantly better than the dynamic Smagorinsky model.

Research has also been undertaken on the turbulent flow in the case of symmetrically heated plates. Habib et al. [26] conducted an experimental investigation of the turbulent natural convection for symmetrically heated vertical parallel plates with a gap of 125 mm and measured the turbulent intensity using the laser Doppler velocimetry (LDV) method. Daverat et al. [27] obtained the average heat transfer rate in relation to the modified Rayleigh number by varying the gap between the parallel plates and found that the heat transfer rate increased with increasing modified Rayleigh number. However, these experiments did not evaluate a fully developed turbulent region at a high local Rayleigh number. In order to understand the characteristics of the heat and fluid flow in a developed region, Badr et al. [28] simulated a fully developed region using a low Reynolds k–ε model and developed an empirical formula for the average heat transfer rate that depended on the modified Rayleigh number. However, the boundary layer interaction effect was not investigated because, like the k–ε model, Reynolds-averaged numerical simulation (RANS) cannot simulate an inhomogeneous turbulent flow like a turbulent natural convection correctly.

To clarify the boundary layer interaction effect of the turbulent natural convection between symmetrically heated vertical parallel plates, an LES using the Vreman model as a dynamic subgrid-scale model was conducted in this study. Using the integral thickness of the velocity boundary layer of the vertical plate as a reference value, the gap between the vertical parallel plates was varied. The heat transfer rates were evaluated using the local Rayleigh number and modified Rayleigh number. The boundary layers were compared with each gap, and the turbulent vortex between the vertical parallel plates was visualized to evaluate the instability of the turbulence.

2. Calculation method

The governing equations used in the present study can be written as follows:

$$\frac{\partial \overline{u_k}}{\partial x_k} = 0,$$

$$\frac{\partial \overline{u_i}}{\partial t} + \frac{\partial}{\partial x_i}(\overline{u_j}\ \overline{u_i}) - \frac{\partial}{\partial x_j}\left\{\frac{\mu}{\rho_0}\left(\frac{\partial \overline{u_i}}{\partial x_j} + \frac{\partial \overline{u_i}}{\partial x_i}\right) - \tau_{ij}\right\} = -\frac{\partial \overline{p}}{\partial x_i} + g\beta(\overline{T} - T_0), \tag{1}$$

$$\frac{\partial \overline{T}}{\partial t} + \frac{\partial}{\partial x_j}(\overline{T}\ \overline{u_j}) - \frac{\partial}{\partial x_k}\left(\frac{\lambda}{\rho_0 c_0}\frac{\partial \overline{T}}{\partial x_k} + q_t\right) = 0.$$