International Journal of Heat and Mass Transfer 104 (2017) 456–466

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Influence of radiation effect on turbulent natural convection in cubic cavity at normal temperature atmospheric gas

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ARTICLE INFO

Article history:
Received 16 May 2016
Received in revised form 17 August 2016
Accepted 18 August 2016

Keywords:
Turbulent natural convection
Large eddy simulation
Radiation element method
Vreman model
Full-spectrum model
Gas radiation
Surface radiation
Radiative transfer

ABSTRACT

The turbulence structure, boundary layer, and heat transfer of turbulent natural convection, including radiation effects inside the cubic cavity, were investigated in this study. Large eddy simulation was conducted, and Vreman model was adopted for the dynamic subgrid-scale model. To calculate the radiative heat flux efficiently, a coupled calculation method, using the radiation element method by ray emission model, was constructed. To separate the radiation effects of the gas and surface radiations, four calculation conditions have been analyzed; non-radiation, gas radiation, surface radiation, and combined radiation. Observing the vortices structure using the Q value revealed that the surface radiation effect was more dominant for the flow instability than the gas radiation effect. An evaluation of the boundary layers for both the gas and surface radiation effects showed that the flow circulation inside the cubic cavity was enhanced. The surface radiation was dominant in the generation of the shear stress by the turbulent flow. The total heat transfer, which includes the convective and radiative heat transfers, have been investigated. The surface radiation affected on the radiative heat transfer significantly as compared to the gas radiation. The radiation effects changed the radiative heat transfers, while the convective heat transfers of all the calculation conditions were similar.

1. Introduction

Natural convections do not require external energy, such as the difference in pressure. Therefore, reduced energy consumption can be achieved by frequently utilizing natural convections. To utilize natural convections effectively, much research on the topic have been conducted numerically and experimentally [1–6]. Natural convections, which take place in 1–100 m space, have been applied for ventilation systems of large-scale buildings [7,8]. Furthermore, large-scale natural convections have the ability to operate as electrical generation systems, such as the solar chimney system [9,10].

To evaluate the heat and fluid flow characteristics of the large-scale natural convection quantitatively, not only convective heat transfer, but also radiative heat transfer has to be studied. The radiative heat transfer, ignoring the scattering effects, is categorized into surface radiation and gas radiation. Surface radiation is a phenomenon where the radiation is absorbed or emitted via surfaces. On the other hand, gas radiation is a phenomenon where the radiation emitted from the surface are absorbed by the gas, while gas is emitting the radiation simultaneously. When the spatial scale is small, the surface radiation becomes dominant on the radiative heat transfer and affects the convection, as compared with the gas radiation [11]. However, when the spatial scale becomes larger, the gas radiation effects have to be considered and evaluated because of the increase in the optical thickness.

Large-scale natural convections, including radiative heat transfer, have been investigated in previous researches using numerical simulations by two and three dimensions. Xin et al. [12] conducted a direct numerical simulation (DNS), including surface radiation in a turbulent natural convection of a Rayleigh number (Ra) of 1.5×10^9. They found that the calculation results, including the surface radiation, matched the experimental results, which were obtained by Salat et al. [13], as compared with the calculation results without the radiation effects. Sakurai et al. [14] conducted the DNS of the turbulent Rayleigh–Benard convection and evaluated the influence of the optical thickness on the radiative heat flux distribution. Furthermore, Sakurai et al. [15] analyzed the boundary layer using the turbulence statistics from the DNS result. Calculations using large eddy simulation (LES) have also been conducted. Ibrahim et al. [16] analyzed the turbulent natural convections, including both of the surface and gas radiations, using

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http://dx.doi.org/10.1016/j.ijheatmasstransfer.2016.08.059
0017-9310/

Nomenclature

Alphabet

a	weight function for FSK model
c_v	constant value, 0.1
dA	area of the radiation element, m^2
dV	volume of the radiation element, m^3
E	energy spectrum
F	dimensionless frequency, –
F^E	extinction view factor, –
I	radiative intensity, $W\,m^{-2}\,sr^{-1}\,\lambda m^{-1}$
k	absorption coefficient, m^{-1}
K	constant value, 10^{-6}
L	cavity length, m
$\vec{n}$	Normal direction vector, –
Nu	Nusselt number, –
Pr	Prandtl number, –, $\frac{\nu}{\alpha}$
Pr_t	Turbulent Prandtl number
q_r	radiative heat flux, $W\,m^{-2}$
q_t	dimensionless SGS turbulent heat flux, –
Q	dimensionless Q value, –
Q_X	heat generation of radiation element, W
r	gradient of variables
$\vec{r}$	coordinate vector, –
Ra	Rayleigh number, –, $\frac{g\beta L^3 \Delta T}{\nu\alpha}$
$\vec{s}$	optical path vector, –
s	optical path, m
S	optical path, m
S_{ij}	dimensionless strain tensor, –
t	dimensionless time
T	temperature, K
u_i	dimensionless velocity, –
u', v'	velocity fluctuation, –
W_{ij}	dimensionless vortex tensor, –
x_i	dimensionless distance, –
x, y, z	dimensionless ordinate, –

Greek symbols

α	thermal diffusivity, $m^2\,s^{-1}$
α_{SGS}	dimensionless thermal diffusivity of sub-grid scale, –
β	thermal expansion coefficient, K^{-1}
θ	dimensionless temperature, –
θ'	temperature fluctuation, –
δ_{ij}	function of delta
Δ	dimensionless mesh size, –
ε	emissivity, –
g	cumulative function, –
g	gravitational acceleration, $m\,s^{-2}$
Ω	solid angle, –
Ψ	limited function
ν	kinematic viscosity, $m^2\,s^{-1}$
ν_{SGS}	dimensionless kinematic viscosity of sub-grid scale, –
κ	thermal conductivity, $W\,m^{-1}\,K^{-1}$
σ	Stefan–Boltzmann number, $W\,m^{-2}\,K^{-4}$
τ	transmissivity, –
τ_{ij}	dimensionless SGS turbulent stress, –
ΔT	temperature difference, K

Subscripts

ave	average
b	black
c	cooled wall
$conv$	convection
θ	dimensionless temperature
g	cumulative function
T	emission power from the radiation element
E	east
h	heated wall
i,j,m	direction number
J	emission power from the other radiation element
n	normal direction
P	grid point
λ	wavelength
rad	radiation
SGS	sub-grid scale
$total$	total
v	dimensionless velocity
w	wall
W	west

Superscripts

$-$	LES filter, Time-averaged value

two-dimensional calculations, and found that the surface radiation became a more dominant factor in the flow instability, compared with that of the gas radiation. Capdevila et al. [17,18] analyzed the turbulent natural convections in a differentially heated cavity, which had an aspect ratio of five, including the surface and gas radiations, using a semi-gray gas model, and found that the radiations significantly changed the temperature stratification.

To include the surface radiation into a calculation model, the radiation net flux is calculated using the view factors of the surfaces. The view factors are estimated via geometric analysis using the reference tables [19,20] and the calculation cost of the coupled simulation is very low. To include the gas radiation effects, the radiative transfer equation (RTE) has to be solved. Because the absorption coefficient of the gas has a wavelength dependency, the RTE has to be divided by the wavelengths. Therefore, to treat the gas as a non-gray gas, the calculation cost is huge, and the calculation speed becomes very slow. Therefore, the coupled calculations, including the gas radiation, were limited to two-dimensional calculations or of the laminar flow, and a practical calculation method is required.

To consider the non-gray gas, an accurate and practical gas model is required to precisely predict the gas radiation, and significantly reduce the calculations cost. One of the simplest and most famous non-gray gas models is the weighted sum of gray gas (WSGG) model [21]. The WSGG concept is based on replacing the RTE divided by the wavelengths, with the RTE divided by the sum numbers of gray gases. Using this model, the calculation cost could be significantly reduced, and the gas radiation could be treated correctly.

Full-spectrum models, a concept similar to that of the WSGG, have been recently developed. The spectral line-based weighted-sum-of-gray-gases (SLW) [22] model, absorption distribution function (ADF) [23] model, and full-spectrum k-distribution (FSK) [24] model are representations of the full-spectrum model. Using full-spectrum models, the RTE divided by the wavelength, can be replaced with the RTE divided by the cumulative function, which is calculated by the distribution of the absorption coefficient over the full range of the wavelength. Compared with the WSGG, the full-spectrum model is more precise, because it is based on the real absorption coefficient distribution. Recently, coupled simulations of natural convections have been conducted using the full-spectrum model. Colomer et al. [25] calculated the laminar natural convection using the SLW model, and discussed the influence of dividing method for the SLW model by the calculation result.