Applied Thermal Engineering 29 (2009) 2243–2250

Contents lists available at ScienceDirect

Applied Thermal Engineering

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

Investigating the effect of computational grid sizes on the predicted characteristics of thermal radiation for a fire

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ARTICLE INFO

Article history:
Received 8 May 2008
Accepted 12 November 2008
Available online 27 November 2008

Keywords:
CFD
Grid size
Radiative heat flux
Flame height

ABSTRACT

Recently, the phenomenological modeling of fires has been shifted from the engineering application of correlation-based methods to the computational fluid dynamics (CFD) techniques. Therefore, the majority of this paper is to investigate the effects of grid sizes on the predicted radiative characteristics involved in a fire using CFD simulations, with the aim of selecting the appropriate grid size under the consideration of prediction accuracy and computing cost. Based on the present simulations, the predicted flame height increases as the decreasing grid size and would approach to a quasi-steady value if the simulation grids are adopted to be small enough. Similar results are also revealed in the radiative heat flux behaviors. The predicted distributions of radiative heat fluxes have no significant variations as the grid size is reduced to some small value. Several experiments of small pool fires with various diameters (20–38 cm) are conducted to assess the present CFD predictions. Using the appropriate grid size, the predicted results for radiative heat fluxes and flame heights show good agreement with the experimental data for different-size pool fires. This grid size suggested in this paper could assist the CFD simulations of pool fires in obtaining the accurate enough predictions with reasonable computing time.

1. Introduction

Over the past decade, the physical phenomena associated with fires have been intensively investigated since the performance-based fire safety design has been proposed in the fire society. With the dramatic advancement in the computer processing power, modeling of fires has been shifted from the engineering application of correlation-based methods such as zone methods to filtered discrete solution equations by the computational fluid dynamics (CFD) techniques. More sophisticated models are developed in order to represent the physical and chemical processes of fires more realistically. These CFD model developments for fires had been investigated in previous notable works [1–5].

As is well known, the accuracy for simulating the fires highly depends on the resolution of the grid sizes. Using the mixture fraction model, Xin [6] presented the sensitivity of grid distributions for a methane burner with an area of 1 m^2. The results indicated that fire model is sensitive to grid resolution for plume centerline temperature and velocity profiles, especially in the region near the fuel surface. With the similar combustion model, McGrattan et al. [7] predicted the flame height of a propane sand burner with an area of 0.4×0.4 m^2. In their studies, grid sizes of 2.5, 5, 10 and 20 cm were used and only the case with a 2.5 cm grid-cell size does not need the modified factor to predict the flame surface. In addition, it is well recognized that radiation is the dominant mode of heat transfer in the fires [8–12], rendering the radiative heat transfer analysis for a fire becomes a subject of major concern [13–18]. However, the computing cost and prediction accuracy for a fire simulation strongly depend on the choice of numerical treatments for solving the radiative transfer equations (RTEs). It needs more simulation grids to obtain the sufficiently accurate results for these equations, but causing more computing cost. Previous works [13,19–30] had been performed to experimentally and theoretically investigate the thermal radiation from flames. However, the grid independence with various pool fire sizes on flame shape and radiant power from the fires is quite few. Therefore, in order to provide the appropriate computational grids for the CFD simulations of fires, the majority of this paper is to investigate the effects of grid sizes on the fire radiative characteristics, including the flame height and radiative heat fluxes.

The CFD code_FDS [31] is adopted in this paper. Preliminary simulations for the sensitivity studies of different spectral band and solid angle numbers for the RTEs reveal that the gray model (single band) and 500 solid angles are enough to predict the radiative heat fluxes emitted from the burners. Based on the sensitivity simulations for different grid sizes, the predicted flame heights for the 20, 30 and 38 cm pool fires increase with the increasing $D^*/\Delta d$ (i.e. decreasing grid size) and would approach to a converged value as $D^*/\Delta d > 13$. The predicted radiative heat flux distributions also

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1359-4311/$ - see front matter © 2009 Published by Elsevier Ltd.
doi:10.1016/j.applthermaleng.2008.11.010

Nomenclature

C_S	Smagorinsky's constant specific heat (J/kg K)
D	diffusion coefficient (m^2/s)
D^*	characteristic diameter (m), $D^* = \left(\frac{\dot{Q}}{\rho_\infty C_P T_\infty \sqrt{g}}\right)^{\frac{2}{5}}$
G	gravitational acceleration (m^2/s)
H	enthalpy (J/kg)
I	total radiation intensity
I_b	radiation blackbody intensity
$\dot{m}'''$	mass consumption rate per unit volume (kg/m^3 s)
M	molecular weight (kg)
P	pressure (N/m^2)
p_o	background pressure (N/m^2)
Pr	Prandtl number
q''	heat flux (W/m^2)
q''_r	radioactive heat flux (W/m^2)
Q	heat source (W/m^3)
R	ideal gas constant (8.314 J/mol K)
s	unit vector
t	time (s)
T	temperature (K)
u	velocity (m/s)
$\dot{W}'''$	mass generation rate (kg/s m^3)
X	coordinate (m)
Y	mass fraction
Y_F^I	fuel mass fraction in the fuel stream
Y_O^∞	ambient value of fuel mass fraction

Greek symbol

Δd	grid size (m)
κ	absorption coefficient
μ	viscosity (kg/m s)
ν	stoichiometric coefficient
ρ	density (kg/m^3)
τ	shear force (N/m^2)
λ	wavelength (m)
Γ	thermal conductivity (W/mK)

Subscript

F	fuel
i,j,k	tensor index
ℓ	ℓ th species
O	oxygen
P	product
∞	ambient parameter

Superscript

-	averaging parameter

show the similar behaviors and have no significant variations with $D^*/\Delta d > 13$. In addition, the predicted radiative heat fluxes correspond well with those obtained from the experiments as the present simulations adopt $D^*/\Delta d = 13$. Therefore, the grid size of $D^*/\Delta d = 13$ is enough for CFD simulations to resolve the fire characteristics if the sizes of pool fires are within the present investigating ranges.

2. Mathematical models

2.1. Thermal-hydraulic models

Gas in a fire can be considered as compressible flow that satisfies the following compressible equations:

- Continuity equation

$$\frac{\partial\bar{\rho}}{\partial t} + \frac{\partial}{\partial x_i}(\bar{\rho}\bar{u}_i) = 0 \tag{1}$$

- Species equation

$$\left(\frac{\partial(\bar{\rho}\bar{Y}_\ell)}{\partial t} + \frac{\partial(\bar{\rho}\bar{u}_i\bar{Y}_\ell)}{\alpha x_j}\right) = \frac{\partial}{\partial x_j}\left\{\bar{\rho}D_\ell\left(\frac{\partial\bar{Y}_\ell}{\partial x_j}\right)\right\} + \dot{W}'''_\ell \tag{2}$$

- Momentum equation

$$\bar{\rho}\left(\frac{\partial\bar{u}_i}{\partial t} + \bar{u}_j\frac{\partial\bar{u}_i}{\alpha x_j}\right) = -\frac{\partial(\bar{p}-\bar{p}_o)}{\partial x_i} + \frac{\partial}{\partial x_j}\left\{\mu\left(\frac{\partial\bar{u}_i}{\partial x_j} + \frac{\partial\bar{u}_j}{\partial x_i}\right)\right\} + \bar{\rho}g_i - \frac{\partial\tau_{ij}}{\partial x_j} \tag{3}$$

- Energy equation

$$\left(\frac{\partial(\bar{\rho}\bar{h})}{\partial t} + \frac{\partial(\bar{\rho}\bar{u}_j\bar{h})}{\partial x_j}\right) = \frac{\partial\bar{p}_o}{\partial t} + Q + \frac{\partial}{\partial x_j}\left(\Gamma\frac{\partial\bar{T}}{\partial x_j}\right) - \frac{\partial q''_{r,j}}{\partial x_j} + \frac{\partial}{\partial x_j}\sum_\ell\left(\bar{\rho}\bar{h}_\ell D_\ell\frac{\partial\bar{Y}_\ell}{\partial x_j}\right) \tag{4}$$

and $$\bar{h} = \sum_\ell \bar{h}_\ell\bar{Y}_\ell \tag{5}$$

where Q is heat release rate from a fire.

- State equation

$$\bar{p}_o = R\bar{\rho}\bar{T} \tag{6}$$

2.2. Turbulence model

Several turbulence models are available for simulating the fire scenarios, including time-averaging k–ε two-equation model [32,33], large eddy simulation (LES) model [34–36], and direct numerical simulation (DNS) model [37], etc. Present simulation works adopt the LES turbulence model that is originally developed by Smagorinsky [38]. LES is used to model the dissipative processes that occur at length scales smaller than those that are explicitly resolved on the numerical grid. Using the Smagorinsky's model, the turbulent induced Reynolds stresses and heat fluxes can be expressed as follows:

$$\tau_{ij} = \rho(u_iu_j - \bar{u}_i\bar{u}_j) = -2\bar{\rho}(C_S)^2\Delta^2|\bar{S}|\bar{S}_{ij} \tag{7}$$

$$q''_j = \rho(u_jT - \bar{u}_j\bar{T}) = -\frac{\bar{\rho}(C_S)^2}{\Pr}\Delta^2|\bar{S}|\frac{\partial\bar{T}}{\partial x_j} \tag{8}$$

where

$$|\bar{S}| = (2\bar{S}_{ij}\bar{S}_{ij})^{1/2}, \quad \bar{S}_{ij} = \frac{1}{2}\left(\frac{\partial\bar{u}_i}{\partial x_j} + \frac{\partial\bar{u}_j}{\partial x_i}\right) \tag{9}$$

2.3. Combustion models

The mixture fraction combustion model has been described in a review article by Bilger [39]. The mixture fraction combustion model is adopted in the present CFD models. This simplified combustion model assumes that combustion is mixing-controlled and