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Three-dimensional analysis of gas flow and heat transfer in a regenerator with alumina balls

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HIGHLIGHTS

- A three-dimensional unsteady model for regenerator has been developed.
- Interactions between fluid flow and interphase heat transfer has been considered.
- Detailed information about fluid flow and heat transfer within regenerator is presented.
- The geometry of the regenerator has been optimized by the model.

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ABSTRACT

A three-dimensional (3D) unsteady mathematical model for regenerator with alumina balls has been developed based on the assumption of porous media and solved by a commercial computational fluid dynamics (CFD) software, FLUENT. The standard $k-\varepsilon$ turbulence model combined with standard wall functions is used for modeling gas flow. Momentum equation is revised to consider the impact of porous media on fluid flow. Radiation from combustion gas to the storage materials is considered in the model. User-defined functions (UDFs) program has been developed in C language and linked to FLUENT to define user-defined scalar (UDS) transport equation of energy conservation for solid phase, and to calculate interphase heat transfer as well as thermophysical properties of gas and solid phases, which are dependent on temperature. The calculated results were compared with test data, and the maximum relative error is 3.73%. Results of the model calculation showed that after 25 times of alternate changes in heating and cooling cycles, the heat absorption of regenerative balls is equal to heat released to air, implying the operation of regenerator reaches steady state. As the ball diameter decreases, the pressure gradients become steep and fluid velocity decreases. To reduce temperature difference in the horizontal plane, the geometry of the regenerator has been optimized by the model.

1. Introduction

Regenerative combustion system integrates combustion and smoke evacuation. The system has high thermal efficiency [1], high combustion temperature, uniform temperature field, low pollution, and small equipment size [2]. Hence, it is widely used in industrial furnaces [3]. Regenerator, as a key element in regenerative combustion system, consists of a heat-storing matrix, which has a large heat storage capacity, high temperature resistance, low flow resistance. A complete cycle of regenerator operation consists of a heating cycle and a cooling cycle. During the heating cycle, the exhaust gas passes through the regenerator and transfers heat to the matrix. After a certain period, the hot gas flow stops and the cooling cycle begins. During the cooling cycle, cold air passes through the regenerator in the direction opposite to that of the hot gas, and heat is transferred from the matrix to the air. Heat transfer is not only active within each phase, but also between phases.

Many papers have been recently published to understand the performance of regenerative process. Yu et al. [4] provided revised coefficients in Ergun's equation through experiments, and established one-dimensional transient mathematical model to describe heat transfer in fluid and solid phases in regenerator. The intraparticle conduction and the radiation effects were neglected in the model. Zarrinehkafsh et al. [5] developed a mathematical model for

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Nomenclature

A_{sg}	heat exchange area between gas and solid phases per unit volume, $m^2\ m^{-3}$
C	surface characteristic coefficient of holes of grate bricks
C_2	resistance factor, m^{-1}
c	specific heat at constant pressure, J $kg^{-1}\ K^{-1}$
$C_{1\varepsilon}, C_{2\varepsilon}, C_{3\varepsilon}, C_\mu$	constants in standard $k-\varepsilon$ model
D	diameter of a alumina ball, m
d	radius of generative particle, m
d_e	equivalent diameter of holes of grate bricks
G_b	production of turbulent kinetic energy by buoyancy, J $m^{-3}\ s^{-1}$
G_k	production of turbulent kinetic energy by velocity gradient, J $m^{-3}\ s^{-1}$
g_j	component of the gravitational vector in the jth direction, m s^{-2}
h_c	heat transfer coefficient by convection, w $m^{-2}\ K^{-1}$
h_r	heat transfer coefficient by radiation, w $m^{-2}\ K^{-1}$
h_{sg}	total heat transfer coefficient between gas and solid phases, w $m^{-2}\ K^{-1}$
k	turbulent kinetic energy or conductivity, $m^2\ s^{-2}$, w $m^{-1}\ K^{-1}$
Pr	Prandtl number,
Pr_t	turbulent Prandtl number
p	pressure, Pa
q	heat flux, w m^{-2}
Re	Reynolds number
S_i	source term for the ith momentum equation
T	temperature, K
t	time, s
u_i	velocity components, m s^{-1}

Greek symbols

α	permeability, m^2
β	coefficient of thermal expansion
δ_{ij}	kronecker delta
ε	dissipation rate of turbulent kinetic energy per unit mass, $m^2\ s^{-3}$
ε_s	solid emissivity
μ	viscosity of gas, kg $m^{-1}\ s^{-1}$
μ_t	turbulent viscosity, kg $m^{-1}\ s^{-1}$
ρ	density, kg m^{-3}
σ_k	turbulent Prandtl number for k in standard $k-\varepsilon$ model
σ_ε	turbulent Prandtl number for ε in standard $k-\varepsilon$ model
Φ	porosity

Subscripts

g	gas phase
s	solid phase

a fixed bed regenerator. Convective and conductive heat transfers inside the regenerative material were considered. Uniform velocity profile in the fluid phase was assumed. Park et al. [6] established one-dimensional two-phase fluid dynamics model to describe unsteady thermal flow of regenerator with spherical particles, and confirmed that the Reynolds number of the inlet of exhaust gases should be introduced as a regenerator design parameter. Zhong et al. [7] proposed a 3D unsteady mathematical model for heat conduction in heat-storing matrix in hot blast stoves. However, the effect of gas flow on heat transfer was ignored in the model. Rafidi [8] developed a two-dimensional model for honeycomb heat regenerator based on one honeycomb cell, and the results of the model provided a simple design tool for honeycomb regenerator.

Most of the mathematical models used to describe the working process of regenerator either assumed that the distributions of fluid velocity and temperature in the plane perpendicular to fluid flow direction were uniform or ignored interactions between fluid flow and interphase heat transfer inside the regenerator. However, in the practical application, temperature profile is usually non-uniform in the plane vertical to the flow direction, which may result in the earlier damage of heat storage materials in high temperature area. As a result, the performance of the regenerator deteriorates and the operating costs increase. The uneven temperature field usually results from uneven velocity field. Hence, to establish a 3D model for regenerator is necessary. Heat transfer and fluid flow within the regenerator should be solved simultaneously in the model. The objective of this work is to establish an 3D unsteady mathematical model to describe heat transfer and fluid flow within a regenerator with alumina balls based on continuity, momentum, and energy equations using the commercial software FLUENT. Interphase heat transfer was considered by UDFs developed in C language. Detailed information on the distributions of velocity and temperature in the regenerator was given in the paper. Effects of ball diameter and regenerator geometry on the performance of the regenerator were investigated in the study.

2. Establishment of the model

2.1. Physical model and assumptions

The regenerator shown in Fig. 1 consists of a heating storage matrix composed of alumina balls 17 mm in diameter and grate bricks which are used to support the balls and can also store a little amount of heat. The dimensions of the regenerator are shown in Table 1. Fig. 2 shows the computational grid created using Gambit, containing 64982 nodes with hexahedral cells in all zones. Gas flow in the domain containing alumina balls is three-dimensional. However, gas can only flow through the axial direction in the

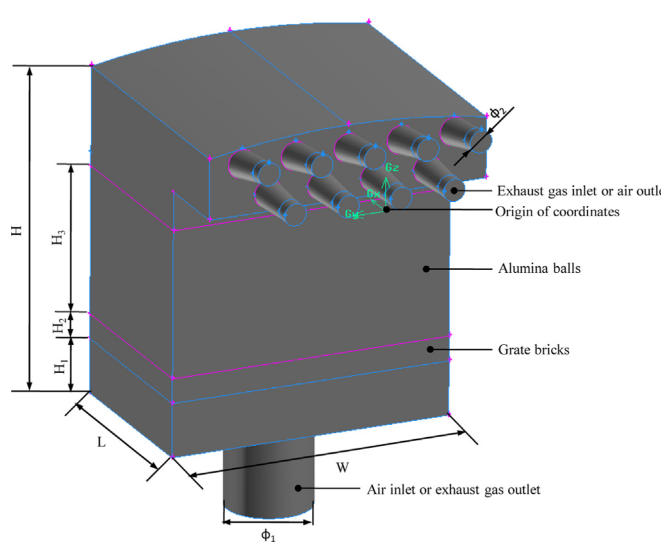

Fig. 1. Schematic of the regenerator.