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Research Paper

Heat transfer performances of honeycomb regenerators with square or hexagon cell opening

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HIGHLIGHTS

- The radiation heat transfer is considered in the improved model.
- Heat transfer performances of regenerators with different openings are compared.
- Energy recovery ratios of regenerators with different side lengths are evaluated.
- Energy recovery ratios of square opening regenerators are higher than hexagon ones.

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ABSTRACT

Honeycomb regenerators with varied cell openings are applied to regenerative combustion systems. A three-dimensional unsteady numerical model, which calculate the gas flow and gas-solid heat transfer in regenerators with square or hexagon cell openings is developed by computational fluid dynamics package, FLUENT. The radiative transfer equation is employed to calculate radiative heat transfer in gas and is added in gas energy conservation equation as a source term. Convection coupled with radiation is used in gas-solid boundary condition. Moreover, temperature-dependent thermal properties of gas and solid are considered in the model. By comparing simulation results with experimental data from the literature, the numerical model is verified. The effects of different cell opening shapes on gas-solid interface heat flux, gas temperature profile and energy recovery ratio are compared. The simulation results show that there is a higher outlet air temperature and energy recovery ratio in square opening cells than hexagon opening cells. Furthermore, the influences of cell opening side length and switching time on air preheating effect and pressure loss are investigated in regenerators with the two different openings.

1. Introduction

Regenerative combustion technology are widely applied in burners of industrial furnaces, and a remarkable energy saving effect is achieved [1,2]. The energy transfer from high temperature flue gas to combustion air is achieved by the alternate flow of flue gas and air in regenerators with solid heat storage and release at the same time. As the core part of regenerative combustion burner, packed bed [3] and honeycomb regenerator are the most frequently used. Sadrameli [4] developed a mathematical model of regenerators filled with alumina spherical packing and solved the equations using finite difference methods. Park et al. [5] investigated the heat transfer process in regenerator with spherical particles with one-dimensional numerical model. Gas-solid temperature, pressure loss and velocity over operation time and ball size were analyzed. Lin [6] and Liu [7] established the two-dimensional and three-dimensional unsteady numerical models respectively and the transient profiles of flow gas and packed bed in the regenerators were examined. The Ergun's equation was employed to calculate pressure loss in ball packed regenerator by Panwar et al. [8]. In addition, the coefficients values of Ergun's equation under simulation were verified with experimental results. The averaged velocity in packing which was modeled as a porous medium was obtained by Darcy's law [9] in the work of Dallaire et al.

However, there is commonly a higher pressure loss [10] and lower effectiveness [11] in packed bed regenerators than in

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Nomenclature

A	cross-sectional area
c	special heat capacity
D_c	directional weights
d	hydraulic diameter
e	side length of regenerator cell
h	specific enthalpy
I	radiation intensity
L	opening perimeter of the cell
l	skeleton wall thickness
$\mathbf{n}$	unit vector normal to wall
p	pressure
Q	mass flow rate
q	heat flux
$\mathbf{r}$	position vector
R	opening ratio
S	source term
$\mathbf{s}$	unit direction vector
s	path length
$\mathbf{s}'$	scattering direction vector
T	temperature
t	time
u	velocity
V	volume of the control volume

Greek symbols

α	convective heat transfer coefficient
ε	emissivity
η	energy recovery ratio
κ	absorption coefficient
λ	thermal conductivity
μ	dynamic viscosity
ρ	density
σ	Stefan-Boltzmann constant
σ_s	scattering coefficient
$\boldsymbol{\tau}$	stress tensor
Φ	phase function
Ω	solid angle

Subscripts

a	air
b	blackbody
c	a regenerator cell
g	flue gas
f	fluid
hex	hexagon cell
i	inlet
o	outlet
r	radiation
s	solid
squ	square cell
tot	the total regenerator
w	boundary wall

honeycomb regenerators. Thermal properties of honeycomb regenerators were experimentally investigated [12,13] by many scholars. Hong et al. [14,15] set up a laboratory-scale test rig to research temperature efficiency over switching time and temperature distributions in air and flue gas shot process over cell densities and lengths. At present, compared with the defect of high cost and long period in experimental tests, the calculations of mathematical model [16] are used in some researches. Liu et al. [17] adopted the analytical model based on two-equation method to investigate the thermal performance in sandwiched metal honeycomb heat exchangers. By analyzing heat transfer characteristics over cell wall length and relative thickness of heat exchanger, the design optimization was obtained. A perturbation solution was applied for establishing the transient heat-transfer model by Ai [18] and the analytical results of the two phase in regenerators was derived. Sphaier et al. [19] used the effective-NTU method to analyze the heat and mass transfer and physical adsorption. This generalized approach was based on analytic calculation of dimensionless parameter. Sanaye et al. [20] combined the effective-NTU method together with genetic algorithm method to optimize the values of design parameters of regenerators.

Many scholars utilize numerical simulation methods [21,22] to account for the transient thermal process in regenerators. Unlike experimental or analytic calculating [23] methods, temperature, velocity, pressure loss and other flow filed parameters profile could be obtained by numerical simulation. Rafidi et al. [24] developed a two-dimensional model to simulate the energy storage, pressure loss and thermal performance over switching time in regenerators composed of two layers that respectively were of alumina and cordierite. The thermal conductivity parallel and perpendicular to flow direction was taken into account in the simulation model. You et al. [25] constructed a three-dimensional numerical model for ceramic honeycomb regenerator to account for the effect of regenerator length, switching time and fluid flowrates on heat transfer and flow resistance performances. In the works of Kang [26] and Cadavid [27], the honeycomb in regenerator was considered as a porous region. The volumetric energy equation for the two-phase zone including fluid energy and solid energy was numerically calculated to derive temperature results.

In general, the investigation on thermal performance of honeycomb regenerators were all in allusion to one single shape of cell cross-section, such as square [28] or hexagon [29] openings. Hence, it is necessary to research on operating characteristics of regenerators over different cell openings for the industrial application.

Heat transfer performances of regenerators with different cell opening shapes, namely square and hexagon, are investigated using different side lengths and switching time in order to get the optimized design parameters and operation methods. An improved model is proposed here, where the radiation heat transfer inside the flue gas, and between gas and solid are considered by coupling the radiative transfer equation with the energy equation, while the previous models always neglected the radiative heat transfer. Moreover, temperature-dependent thermal properties of flue gas, combustion air and matrix are considered in the model. Heat fluxes at the phase interface and air preheated temperature are discussed in this work. Effects of different cell opening shapes, side length and switching time on energy recovery ratio and pressure loss are investigated.

2. Physical model and thermal physical properties

The honeycomb regenerator cross-section is shown in Fig. 1, and it is composed of eight fan shaped parts externally and one circle part inside. The outer diameter, inner diameter and length of the whole regenerator are 500 mm, 95 mm and 600 mm respectively. Honeycomb cells with square or hexagon opening geometry