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Influence of pore distribution on the equivalent thermal conductivity of low porosity ceramic closed-cell foams

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ABSTRACT

The microstructures of porous alumina materials with different porosities were established by introducing the departure factor of pore position and acentric factor of pore diameter to describe the distribution of pores in space and in size, respectively. The contribution of radiation and influence of pore distribution on the equivalent thermal conductivity were discussed based on numerical simulations by the finite volume method (FVM) considering both thermal conduction and radiation. When the pore diameter was less than 10 μm, the radiation component was less than 2%, and radiation could be neglected. Radiative heat transfer played a dominant role for materials with high porosity and large pore size at high temperatures. For micro pore materials (< 100 μm), broad pore size and non-uniform pore space distribution decreased the thermal conductivity across the entire temperature range. For materials with macro pores (> 1 mm), broad pore distribution decreased the thermal conductivity at low temperatures and increased it at high temperatures. The basic prediction model of effective thermal conductivity for a two-component material, the Maxwell–Eucken model (ME1) and its modified model were corrected by introducing the pore structure factor. The results from experiments prove that the numerical values were satisfactory.

1. Introduction[1]

Lightweight lining refractory for industrial furnaces has attracted increased attention in recent years. Lightweight refractory is made of lightweight aggregates and matrix with a complex microstructure consisting of a mixture of different solid phases in granular form, interfaces, eventually cracks, and pores. The pore size in lightweight refractory ranges from the microscale for the aggregates to the millimeter scale for the matrix. In order to reduce the thermal conductivity of lightweight refractory, lightweight aggregates have been made with increasingly smaller-sized closed pores [1–3]. The effective thermal conductivity can be measured using different experimental apparatus [4,5] or calculated by empirical formula [6–8] and numerical modeling [9–11]. There are many analytical models that can be used to predict the effective thermal conductivity of porous materials such as basic structure models [6], including series and parallel models, Maxwell–Eucken models, the effective medium theory (EMT) equation, the co-continuous model [6], more complex theoretical models [9–12] and empirical models [13–15].

It has been verified by experiments and analytical models that the effective thermal conductivity of porous material is not only dependent on the properties of the solid component and porosity but also the structure of the materials that are summarized in Table 1. However, it is difficult to include pore size and distribution in the existing equations based on basic models or complex modified models. Thus, many numerical simulations utilizing the Lattice–Boltzmann (LB) model [16–18], fractal units (IFU) model [19–21] and finite element method (FEM) [22] have been carried out to study the correlations between the effective thermal conductivity and porosity, pore size, pore structure and morphology, and pore distribution, which are also listed in Table 1. Moreover, the kinetic theory of phonons [17,18,23] and Stefan–Boltzmann laws [18] were also used to analyze the effects of porosity and pore size on the effective thermal conductivity of porous material. From Table 1, it can be seen that different or even contradictory conclusions about the influence of pore-size and spatial distribution on the effective thermal conductivity were drawn by using different methods in past studies. The key reason for these conclusions is that radiation was not considered in some models, especially for high

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[1] EMT = the effective medium theory, LB = Lattice–Boltzmann, IFU = fractal units, FEM = finite element method, 2D = two-dimensional, 3D = three-dimensional.

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Nomenclature

Symbols

x, y, z	cartesian coordinates [m]
R	Random numbers between-1 and 1 [dimensionless]
d	pore diameter [μm]
c	departure factor of pore position [dimensionless]
b	acentric factor of pore diameter [dimensionless]
k	conductivity [W/(mK)]
S	volumetric heat source [W]
s	direction of radiation intensity [dimensionless]
Ω	hemispherical solid angle [Sr]
I(s)	radiative intensity [W/Sr]
L	length [m]
T	temperature [K]
q	heat flow rate [W/m^2]
D	dimensional [dimensionless]
Q	heat flow [W]
f	volume fraction [dimensionless]
m	exponential parameter of b [dimensionless]
n	exponential parameter of c [dimensionless]
p	exponential parameter of c [dimensionless]
n*	effective index of refraction [dimensionless]

Greek symbols

$\overrightarrow{\Omega}$	direction [dimensionless]
Γ	projected surface area [m^2]
Kn	Knudsen number [dimensionless]
α	absorption coefficient [dimensionless]
β	coefficient [dimensionless]
γ	specific heat ratio of gas [dimensionless]
σ	Stefan–Boltzmann constant [5.672×10^{-8} W m^{-2} K^{-4}]
φ	pore shape factor [dimensionless]
ρ	density [kg/m^3]
e	the Rosseland extinction coefficient [dimensionless]
0	uniform distribution [dimensionless]
x, y, z	coordinate direction [dimensionless]
eff	effective
s	solid
g	gas
w	at the wall
r	radiation

Subscripts

FM	free-molecule regime
Kn	temperature jump regime
h	hot
c	cold
in	incoming
B	blackbody
avg	average
t	total
1	of the fluid phase
2	of the solid phase

Table 1
Research results on the effective thermal conductivity of porous materials.

Heat transfer model	Research method	Dependence of the effective thermal conductivity	Ref.
Conduction	Calculation using basic model equations	Porosity and material structure	[6,18]
Conduction	Modified analytical model	Pore shape	[11]
Conduction	LB modeling	Porosity and irregular structure pores	[16–18]
Radiation	Kinetic theory of phonons, Stefan-Boltzmann laws	Ideal pore size rang 1–3 μm	[18,23]
Radiation	Numerical modeling	Larger nanopore size	[17]
Conduction	Fractal units model based on the existing conductivity calculation model	Porosity, Smaller size and parallel direction of pore arrangement	[19–21]
Conduction	FEM modeling	Pore distribution produce negligible effect	[22]
Conduction	Experiment and calculation by EMPT	High porosity and even pore size distribution	[18,23,24]
Conduction and radiation	experimentally and Lattice-Boltzmann simulation	High porosity and contact area of interface	[25–27]
Conduction and radiation	Experiment and analytical model	High porosity and micro-scale pore size, pore shape and orientation and temperature	[28–35]

porosity materials at high temperatures.

Radiation plays an important role in the total heat transfer at high temperature especially for higher porosity materials. Wang et al. [24] calculated the effective thermal conductivities of open-cell foam materials using the lattice Boltzmann method assuming the radiation contribution k_{rd} to the thermal conductivity was only relevant for the temperature, solid density, and volume fractions. They found the radiation heat transfer was a non-negligible factor for thermal transport in low-conductivity open-cell foam materials for high-porosity cases. Furthermore, different methods of calculating the radiative thermal properties of porous materials combining radiation and conduction heat transfer models [25–30] have been reported in the past years. Many research results [27–32] showed that radiative conductivity was a function of the temperature, pore size, and porosity. Based on simulations of coupled conduction-radiation heat transfer through open-cell porous foams, simplified models of the effective thermal conductivity were proposed [30–32].

Despite advances on the topic, however, a perfect solution has not yet been obtained to the recognized problems. First, the contribution of radiation to the effective thermal conductivity is described to be sufficiently simple such that pore structure and distribution are not considered. Second, the effect of pore distribution on the effective thermal conductivity remains controversial, as radiation is ignored or its effects are simplified.

In order to determine the effect of thermal radiation on the equivalent thermal conductivity of lightweight corundum refractory, an energy equation considering conduction and radiation was numerically solved in two-dimensional (2D) and three-dimensional (3D) models in this work. The other objective of this study was to investigate the influence of pore space and size distribution on the equivalent thermal conductivity of a porous corundum refractory with multi-scale pores, ranging from micro pores in the lightweight aggregates to millimeter pores in the matrix. The results were compared with an analytical model and experimental data.