Research Article

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Investigation of effective thermal conductivity of SiC foam ceramics with various pore densities

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Abstract: SiC foam ceramics are extensively used in numerous industrial applications that require high-temperature conditions. They can be used as thermal insulation, structural catalyst supports and energy storage materials. In this article, effective thermal conductivity of SiC foam ceramics at high temperature is studied by steady plane heat source method. This research aims to investigate the variations of effective thermal conductivity with pore density, stacking thickness, heat source temperature, and pore arrangement structure of foam ceramics. By a comparison of effective thermal conductivities of various pore density ceramic sheets, the experimental results show that the effective thermal conductivity of foam ceramics decreases with the increase of the pore density and stacking thickness. The effective thermal conductivity of the foam ceramics increases significantly when the heat source temperature is more than 200°C. For modular SiC foam ceramics, increasing the average pore density and sudden change of the pore density between ceramic sheets are not conducive to the increase of the effective thermal conductivity.

Keywords: effective thermal conductivity, foam ceramic, variable pore structure

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Nomenclature

Λ	thermal conductivity, W (m °C)$^{-1}$
δ	thickness of material, m
δ'	total thickness of material of the two-layer ceramic foam, m
q	heat flux, W m^{-2}
t	material surface temperature, °C
T	surface temperature of double-layer ceramic foam, °C
R	thermal resistance of each layer of ceramic foam, °C W^{-1}

Subscripts

eff	effective
h	hot surface
c	cold surface
lf	lower surface of the first layer of foam ceramics
uf	upper surface of the first layer of foam ceramics
ls	lower surface of the second layer of ceramic foam
us	upper surface of the second layer of ceramic foam
C	contact

1 Introduction

Foam ceramics are widely used in many engineering fields due to their large specific surface area, high heat transfer efficiency, and uniform mixing of fluids. The parameter, effective thermal conductivity, is a major concern in predicting the heat transfer efficiency of systems, such as porous media combustion system [1], heat exchangers [2], and solar collectors [3].

Many researchers have paid attention to heat transfer in SiC foam ceramics from different perspectives. Based on experimental tests [4], analytical analysis [5], and numerical simulations [6,7], researchers mostly focused on effects of temperature, pore parameters, and solid thermal conductivity on effective thermal conductivity of SiC foam ceramics. Nemoto *et al.* [8] investigated thermal conductivity of foam ceramics at low temperature. Results pointed out that the thermal conductivity of SiC foam ceramics increases gradually with the increase in temperature during a temperature rise from 4 to 300 K. Zhou *et al.* [9] investigated the effective thermal conductivity of foam ceramics at 800°C. Experimental results showed that foamed mullite-SiC ceramics have an excellent potential as thermal-insulating materials for cement kiln preheaters. Jiang *et al.* [10] reported the effect of SiC foam ceramic particle size on an effective thermal conductivity of form-stable $NaNO_3$. It was found that form-stable $NaNO_3$ (56.6%) that had a skeleton modified by 10% SiC foam ceramics with particle size of 50 nm possessed an effective thermal conductivity of 2.06 W $(m\,K)^{-1}$ at 25°C, which was 265% higher than that of pure $NaNO_3$. Qiu *et al.* [11] experimentally studied effects of specific surface area and pore size on thermal conductivity from mesoporous to macroporous SiC ceramics. Results showed that the thermal conductivity of both gas and solid phases increased with the pore size.

Pore structure directly affects the heat transfer performance of foam ceramics and plays a leading role in the control of temperature distribution under high temperature heat source [12]. Many researchers have studied the effect of porosity and pore density on the effective thermal conductivity of foam ceramics. Mendes *et al.* [13] experimentally investigated the effect of 10 pores per inch (PPI) foam ceramics porosity on the effective thermal conductivity by the transient surface heat source method. Their results showed that the effective thermal conductivity increased by 22% when porosity increased from 0.57 to 0.74 at 1,500 K. Dietrich *et al.* [14] reported that the effective thermal conductivity increased with the increase of porosity, and effective thermal conductivity of foam ceramics with low PPI number was higher than that with high PPI number. Kang *et al.* [15] added nano-sized SiO_2 to a nano-sized SiC and nano-sized carbon template mixture to reduce porosity, resulting in an extremely low effective thermal conductivity in porous SiC–SiO_2 foam ceramics reaching as low as 0.066 W $(m\,K)^{-1}$. Liu and Zhao [16] numerically investigated the influence of geometric (e.g., pore size, pore type, and porosity) on effective thermal conductivity of porous structures with open and closed pores. They found that using nanoscale pores is an effective strategy to achieve an ultralow effective thermal conductivity for the highly porous structures with open and closed pores.

Most of earlier studies focused on measurements of the effective thermal conductivity with single homogeneous materials, especially at high temperature environment for test conditions. However, modular nonuniform foam ceramic composed of foam ceramic sheets with different pore densities are mostly used in porous media burners. Xie *et al.* [17] revealed that the use of high-porosity ceramic foam in combustion zone and low-porosity ceramic foam in preheating zone can achieve efficient combustion. Song *et al.* [18] conducted an experimental study on the premixed combustion of low calorific gas an axial and radial gradually varied porous media burner. They found that the gradually varied porous media burner can burn ultra-low calorific gas of 1.4 MJ m^{-3}. Al-attab *et al.* [19] designed a two-layer porous medium combustion regenerative device for burning low heating value. Results showed that the maximum heat recovery heat exchanger effectiveness was about 93% with an overall system efficiency of 54%. The arrangement of pore structure affects combustion temperature by affecting heat flow transfer characteristics [20,21]. The effective thermal conductivity of modular nonuniform ceramic foam with different pore densities is probably not a simple superposition relationship. Moreover, there are very few studies on the effect of pore mutation and solid skeleton discontinuity on the effective thermal conductivity of foam ceramics. This research aims to investigate effective thermal conductivity of variable pore densities SiC foam ceramics formed by stacking heterogeneous or homogeneous porous media. Three nonuniform pore structures will be designed by superposition of porous media with different pore densities. Effects of heat source temperature, pore density, thickness of porous media, and pore arrangement structure on the effective thermal conductivity will be investigated using a steady plane heat source method. Results have a great significance to the research of high-temperature heat transfer in porous media with variable porosity. This study provides insight into the understanding of effective thermal conductivity of modular SiC foam ceramics and has reference value for the design of thermal insulation materials and energy storage materials.

2 Experimental system

2.1 Experimental setup and methods

DRS-4A series effective thermal conductivity tester (produced by Xiangtan Instrument Co., Ltd.) was used to test

Figure 1: Picture of high-temperature thermal conductivity tester.

the effective thermal conductivity of porous media in high temperature as shown in Figure 1. The tests are carried out in a heating furnace, which is wrapped with insulation cotton to prevent the heat loss. The effective thermal conductivity of foam ceramics is tested based on the steady plane heat source method. Figure 2 shows the schematic of the test principle. The tester consists of three main parts: a temperature control system, a measurement control system, and a data acquisition system. In the instrument heating furnace, silicon carbide rods are used for the heating. The temperature of the hot plate is controlled by a high-precision temperature controller by adjusting current and voltage. The cold plate is composed of a calorimeter plate and a heat protection plate. Four heat flow meters are installed in the calorimeter plate to detect heat flow through the sample. There is a semiconductor refrigeration plate in heat protection plate, which is used to keep the heat protection plate and the calorimeter plate in the same temperature. The constant temperature water tank provides a stable temperature as a reference temperature of the heat flow meter. The hot and cold surface temperatures of foam ceramics are measured by two K-type thermocouples. Thermocouples, heat flux meter and pressure sensor in the instrument, transmit the measured data to computer in real time.

In this test, it is regarded as a pure heat conduction process. The thermal conductivity of the material is calculated according to Fourier's law as follows:

$$\lambda = \frac{q^{\delta}}{t_h - t_c}, \tag{1}$$

where λ is the thermal conductivity (W (m °C)$^{-1}$), q is the heat flux (W m^{-2}), δ is the thickness of material (m), t_h and t_c represent the temperature values of hot and cold surfaces of the material (°C).

2.2 Tested materials

The tested section is SiC foam ceramic material with dimensions of 250 mm × 250 mm × 20 mm as shown in the Figure 3. The porosity is 0.85. Table 1 shows main performance indicators of SiC foam ceramics. With the material stacking thickness of 20–60 mm, and the pore density of 10–30 PPI, experiments are conducted under heat source temperature of 50–600°C.

2.3 Uncertainty analysis

The uncertainties of the experimental results are estimated based on an error analysis of present measurements. The measuring range of the thermal conductivity tester is 0.001–3 W (m °C)$^{-1}$, and the measurement accuracy is better than 5%. K-type thermocouples are calibrated with an accuracy of 0.1°C, and the heat flow meter has an accuracy of 0.01 W m^{-2}. The accuracy of the instrument to measure the thickness of the material is 0.1 mm.

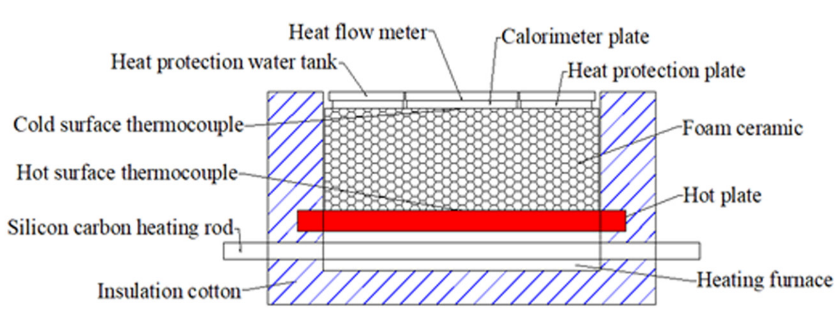

Figure 2: Schematic of the test principle.

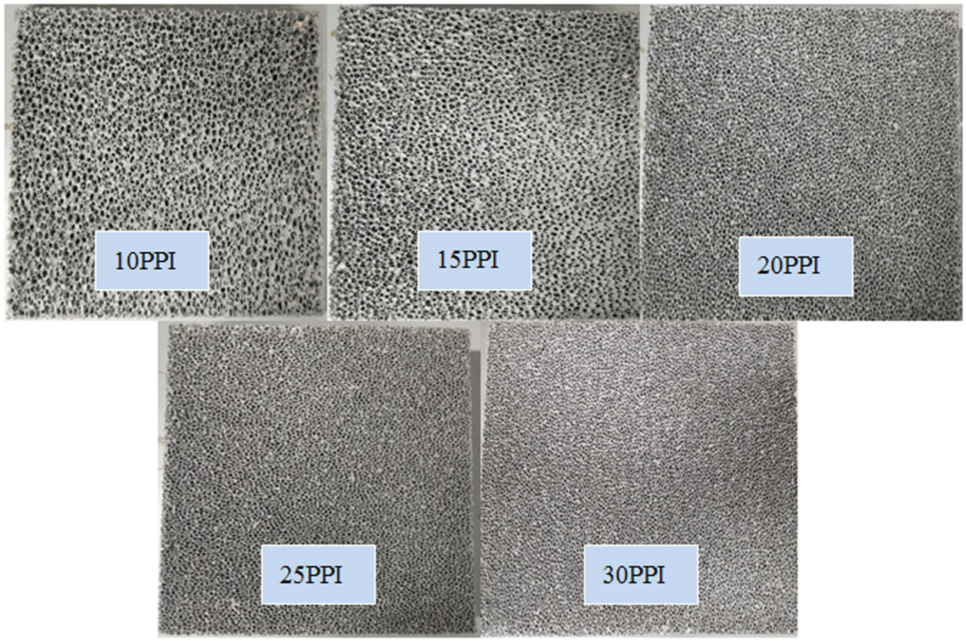

Figure 3: Images of SiC foams.

Table 1: Performance indicators of SiC ceramics foam

Porous medium	SiC foam ceramics
Temperature range (°C)	<1,300
Pore density (PPI)	10–30
Porosity	0.85
Bending strength (MPa/25°C)	0.8
Compressive strength (MPa/25°C)	0.9 MPa/25°C
Thermal shock resistance	6×/1,100°C

3 Results and discussion

3.1 Calibration test of equipment

Neoprene is used to verify the test accuracy of equipment. The thermal conductivity of neoprene at 25°C is 0.23 W (m °C)$^{-1}$. Figure 4 shows relative errors of the thermal conductivity of neoprene with different thicknesses at 25°C. It is found from the figure that the measured thermal conductivity and the relative error increase with the increase of neoprene thickness. This is mainly because the thermal conductivity increases with the increase of neoprene thickness under conditions of constant heat source temperature and heat flux. Increasing the thickness of neoprene makes the thermal insulation conditions more harsh, and errors of its thermal conductivity will be relatively increased. When the thickness is 60 mm, the relative error is still less than 8%, which proves the reliability of the test device.

3.2 Determination of testing pressure

When multiple layers of ceramic foams are superimposed, pressure can directly affect the contact thermal resistance between the ceramic sheets, which cannot be ignored in the measurement of the effective thermal conductivity. The effective thermal conductivity varies with the pressure of two 10 PPI ceramic foam stack at 200°C as shown in Figure 5. It is found that the effective thermal conductivity increases by 2.89% from 0.4009 to 0.4125 W (m °C)$^{-1}$ when the pressure increases from 50 to 100 N. Increasing the pressure makes the contact between the ceramic sheets more compact, which reduces the thermal contact resistance. The

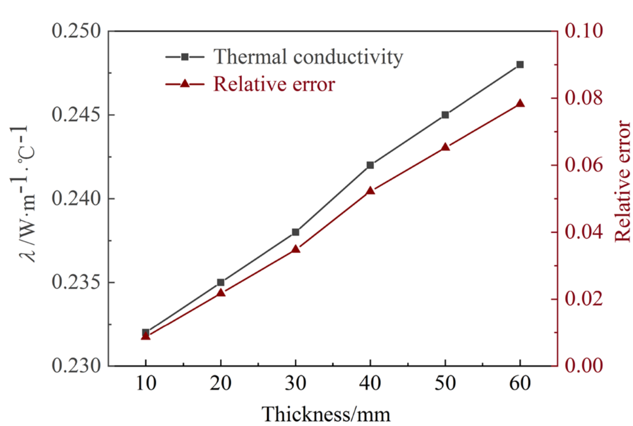

Figure 4: Thermal conductivity and its relative error of neoprene with different thicknesses.

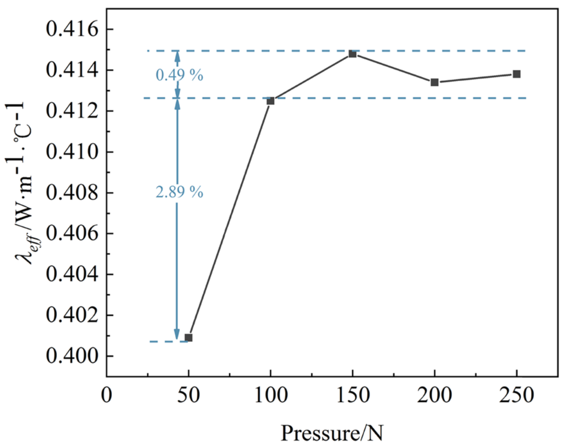

Figure 5: Effective thermal conductivity under different pressures.

effective thermal conductivity increases. However, the deviation of the effective thermal conductivity is within 0.49%, and the deviation tends to be stable when the pressure increases from 100 to 250 N. Ceramic foam is made up of solid skeleton and pore part; hence, the compressive strength of foam ceramics is relatively small at high temperature. To ensure high measurement accuracy of the test, a smaller pressure should be selected for this test. Therefore, 100 N is selected as the pressure for all tests in this study.

3.3 Effect of pore density of foam ceramics

Figure 6 shows the effective thermal conductivity of a single layer ceramic foam under various pore densities, when the heat source temperatures are 100°C and 200°C. At different heat source temperatures, when the pore density increases from 10 to 20 PPI, the effective thermal conductivity decreases slightly in the range of 2.30%. However, the effective thermal conductivity decreases, obviously, when the pore density is higher than 20 PPI. The effective thermal conductivity decreases by 19.86 and 26.54% at 100°C and 200°C, respectively, when the pore density increases from 20 to 30 PPI. This result is mainly because the increase of the pore density of foam ceramics reduces the pore size, which weakens radiation heat transfer capability of foam ceramics. Moreover, the solid skeleton becomes thinner with the increase of the pore density, which leads to the decrease of thermal conductivity. The combined effect results in a reduction of the effective thermal conductivity. Figure 6 also shows that the effective thermal conductivity of foam ceramics with different pore densities slightly increases, when the heat source temperature increases from 100°C to 200°C. With the increase of the heat source temperature, the radiation heat of foam ceramics with the same pore density will increase, leading to an increase in the effective thermal conductivity.

3.4 Effect of thickness of foam ceramic

Figure 7 shows effects of stacking thickness on the effective thermal conductivities of 10 and 15 PPI foam ceramics, when the heat source temperature is 200°C. Effective thermal conductivities of 10 and 15 PPI foam ceramics decrease by 34.66 and 37.47%, respectively, with the increase of stacking thickness from 20 to 60 mm. With the increase of foam ceramic thickness, the increase of thermal contact resistance between ceramic foams is the reason for the reduction of the effective thermal conductivity.

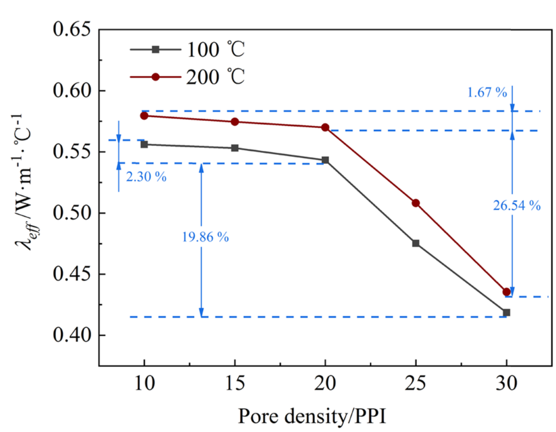

Figure 6: Effect of pore density of foam ceramics on effective thermal conductivity.

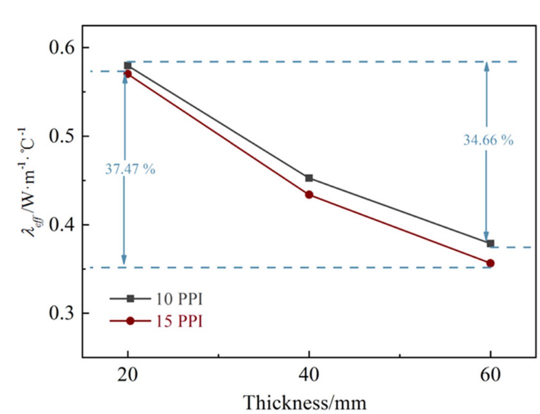

Figure 7: Effect of thickness of foam ceramic on effective thermal conductivity.

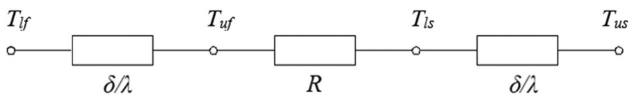

Figure 8: Analysis of thermal resistance during heat transfer.

Figure 8 shows thermal resistance of two foam ceramic stacking during heat transfer. The lower surface temperature of the first layer of foam ceramics is represented by T_{lf}, and the upper surface temperature is represented by T_{uf}. The lower surface temperature of the second layer of ceramic foam is represented by T_{ls}, and the upper surface temperature is represented by T_{us}. R and δ are the thermal resistance and thickness of each layer of ceramic foam, respectively. In the process of series heat transfer with the same heat flux, the sum of the thermal resistance of each link is the total thermal resistance.

Figure 9 shows the temperature changes with thickness when two layers of foam ceramics are superimposed. It is found that the temperature decreases with the increase of thickness. The continuous change of temperature appears fault when the thickness is δ. This is because there is a contact thermal resistance here. According to formula (2), the superposition of multilayer foam ceramics increases the contact thermal resistance, reducing the total effective thermal conductivity.

$$\lambda'_{\mathrm{eff}} = \frac{\delta'}{\frac{\delta}{\lambda_{\mathrm{eff}}} + R_{\mathrm{C}} + \frac{\delta}{\lambda_{\mathrm{eff}}}}, \tag{2}$$

where λ'_{eff} is the total effective thermal conductivity of the two-layer ceramic foam stacking, and λ is the effective thermal conductivity of single layer foam ceramics. δ' and δ are thicknesses of two-layer and single-layer foam ceramics. R_{C} is the contact thermal resistance between the two layers of ceramic foam.

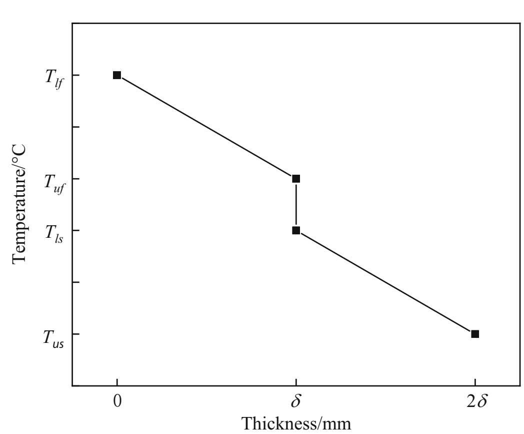

Figure 9: Relationship between temperature and thickness of each layer.

3.5 Effect of heat source temperature

For 10 PPI foam ceramics with different thicknesses, Figure 10 shows the effect of heat source temperature on the effective thermal conductivity. The effective thermal conductivity increases slowly when the heat source temperature is less than 200°C. It increases almost linearly when the temperature is more than 200°C. This is because under low temperature conditions, the heat transfer method of foam ceramics mainly depends on the heat conduction of solid skeleton. The radiant heat transfer under the heat source temperature of more than 200°C accounts for a certain proportion of heat transfer method of foam ceramics, which increases the overall effective thermal conductivity. It is found that the effective thermal conductivity decreases with the increase of stacking thickness of foam ceramic at the same heat source temperature. With the superposition of foam ceramic layers, the thermal contact resistance between layers increases, which leads to a reduction of the effective thermal conductivity.

3.6 Effect of pore structure

Figure 11 shows three pore structures with various pore densities from the hot surface to the cold surface, namely 30-25-20 (module type), 25-20-10 (module type), and 15-15-15 (uniform type). Figure 12 shows the effect of heat source temperature on the effective thermal conductivity of foam ceramics with different pore structures. With the increase of temperature, the radiant heat transfer capacity continues to increase. The effective thermal conductivity of foam ceramics increases with different pore

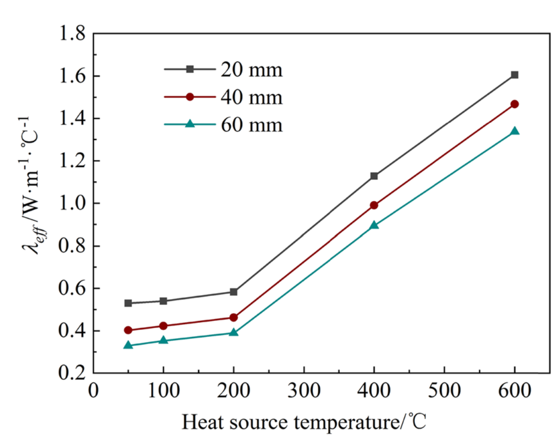

Figure 10: Effect of heat source temperature on effective thermal conductivity.

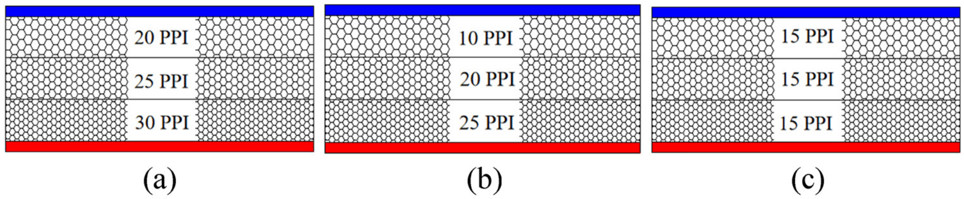

Figure 11: Schematic arrangement of three pore structures (a) 30-25-20 type, (b) 25-20-10 type, and (c) 15-15-15 type.

structures. However, when the heat source temperature is lower than 400°C, the effective thermal conductivity of foam ceramics with different pore structures changes very little. This is because the main heat transfer method is heat conduction at lower temperature, and the radiation heat transfer has little effect on the overall effective thermal conductivity. The difference of effective thermal conductivity of three pore structures become significant when the heat source temperature increases to 400°C. The pore structure with the largest effective thermal conductivity at 600°C is 15-15-15 type, and that with the smallest effective thermal conductivity is 30-25-20 type. The pore density arrangement of the foam ceramic pore structure shows significant influence on this result. Among three structures, 30-25-20 type has the largest average pore density and the smallest average pore diameter, which hinders the radiation heat transfer of pore structure, so the effective thermal conductivity is the smallest. However, the average pore density of 15-15-15 type is the smallest, and the radiation heat transfer is the largest under the same conditions. Therefore, the effective thermal conductivity is the largest. Except the average pore density, sudden changes in the pore density between the foam ceramic sheets also affect the effective thermal conductivity of different pore structures. Compared with the uniform structure (15-15-15 type), there is a sudden change in the pore density between the foam ceramic sheets of modular structure (30-25-20 type and 25-20-10 type). The sudden change in pore density weakens the radiative heat transfer between the foamed ceramic sheets, resulting in a decrease in the effective thermal conductivity. These results indicate that a nonuniform porous medium with a larger average pore density has a smaller effective thermal conductivity. The sudden change of pore density between the foam ceramic sheets is also not conducive to the increase of the effective thermal conductivity. In the field of engineering applications, when SiC foam ceramics are used in thermal insulation materials, a strategy of increasing the average pore density of nonuniform porous media and the sudden change of pore density between ceramic sheets can be adopted. When SiC foam ceramics are used for heat exchangers and solar heat storage, the situation is reversed.

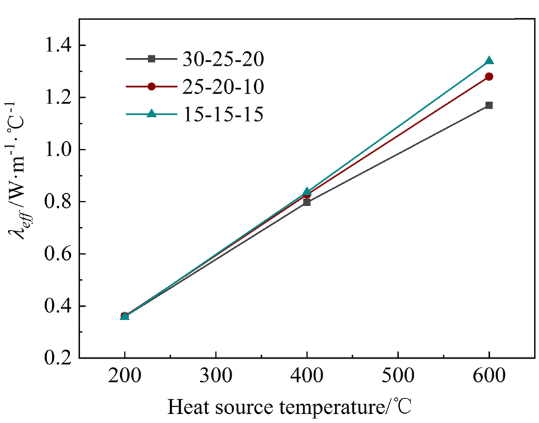

Figure 12: Effect of heat source temperature on effective thermal conductivity.

4 Conclusion

In this study, effects of pore density, stack thickness, and heat source temperature on the effective thermal conductivity of foam ceramics were investigated by a steady plane heat source method. Variations of the effective thermal conductivity of three variable pore structures were compared and analyzed. The main conclusions are shown as follows:

1) The effective thermal conductivity does not change significantly when the pore density of ceramic foam is less than 20 PPI. The effective thermal conductivity decreases by 26.54% when pore density of ceramic foam increases from 20 to 30 PPI. Increasing the stack thickness of foam ceramics is also not conducive to the increase of the effective thermal conductivity.
2) The effective thermal conductivity of foam ceramics with different stacking thickness increases slowly when heat source temperature is less than 200°C, whereas the effective thermal conductivity increases linearly when heat source temperature is more than 200°C.
3) For modular SiC foam ceramics, increasing the average pore density and sudden change of the pore density

between ceramic sheets can reduce the effective thermal conductivity. The difference of the effective thermal conductivity of different variable pore structures increases significantly when the heat source temperature is more than 400°C.

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