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<td><strong>Author(s)</strong></td>
<td>Wang, Baicun; Wang, Liang; Wu, Jiayi; Hong, Yifeng; Yan, Xiaohui; Gong, Hao; Xu, Zhongbin</td>
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Design and characterization of isothermal chambers filled with gradient-porous materials

Baicun WANG*, Liang WANG **, Jiayi WU***, Yifeng HONG****, Xiaohui YAN*, Hao GONG* and Zhongbin XU***
* Department of Thermal Engineering, Tsinghua University, Tsinghua Park, Beijing 100084, China
** School of Mechanical and Aerospace Engineering, Nanyang Technological University, Singapore 639798
E-mail: wangliangtcdri@126.com
*** College of Energy Engineering, Zhejiang University, Hangzhou 310027, China
**** School of Materials Science and Engineering, Georgia Institute of Technology Atlanta, GA 30332, USA

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Abstract
The concept of isothermal chambers filled with GPMs (gradient porous materials) was presented to homogenize the temperature distribution between the center and outer wall of the chambers with disc-shaped cross-section. An analytical heat transfer model was first developed to study the thermal behaviors of the GPMs chamber. Besides, numerical simulation was conducted to obtain the temperature profiles of the chamber with different GPMs. The effects of various gradient parameters on the heat resistance, temperature profiles and filling mass of the chamber were investigated in details. The results indicated that the gradient direction and gradient magnitude have a significant influence on the comprehensive thermal performances of the chamber filled with GPMs. Increasing the porosity gradient of GPMs along radius direction can effectively enhance the heat conduction. Moreover, the optimum gradient magnitude was obtained analytically to further improve the heat conduction of the GPMs chamber.

Key words: Gradient-porous material, Isothermal chamber, Heat transfer, Thermal resistance, Numerical simulation

1. Introduction

In pneumatic systems, the isothermal process is used to change gas state. In such process, the isothermal chamber is widely used to enable approximate isothermal condition (Yang & Shen, 2015). The applications and principles have been introduced in detail in the open literature (Cai, 2008; Kawashima, Ishii, Funaki, & Kagawa, 2004). Kawashima et al. (Kawashima, Kagawa, & Fujita, 2000) first developed the isothermal chamber which can almost reach isothermal condition, due to its larger heat transfer coefficient and area by incorporating porous material (stuffing steel wool). As the charge and discharge process is almost isothermal, instantaneous flow rates into or from the chamber can be obtained by simply measuring the pressure in the chamber (Kawashima et al., 2004). Related quasi-work was contributed by researchers in recent decades. For instance, Angirasa (Angirasa, 2002) proposed a numerical study for forced convection in a channel filled with uniform high-porosity metallic fibrous materials. The results indicated that an improved heat transfer performance can be obtained by making the fiber as thin as possible and maximizing the fiber porosity at the same time. With these designs, the flow rate of fluid can be lowered, leading to a reduced pressure drop and pumping power that is consumed (Dehghan, Jamal-Abad, & Rashidi, 2014; Dehghan, Valipour, & Saedodin, 2015). Yang et al. (Lihong, Yi, & Ping, 2013) considered the stuffer in isothermal chamber as porous fillers for their large porosity. Based on the experimental and simulation results, the discharge processes of chambers with porous materials are nearly isothermal, compared with discharge process of empty chamber.

However, temperature difference still exists between the center and wall of chamber. It is still necessary to enhance the heat conduction and reduce the temperature difference between the center and the wall. Increasing filled wire volume (decreasing the porosity of filled porous materials) can improve the isothermal characteristic. However, this method...
increases the weight as well as the cost. To address these emerging issues, several smart techniques have been proposed, including the constructal design method (Rocha, Lorente, & Bejan, 2002), the iso-geometric shape sensitivity analysis method (Yoon, Ha, & Cho, 2013), the bionic optimization method (Cheng, Li, & Guo, 2003) and adaptive growth method (Lihong & Hangming, 2015). For instance, Rocha et al. (Rocha et al., 2002) developed a hierarchical strategy to optimize the internal structure of a cylinder heat-generating body via inserting high-conductive materials. The geometric detail of the optimized two-material conductive structures was determined based on the minimization of resistance subject to global constraints. The global thermal resistance of different tree-shaped constructs was reported. Based on the minimization of global thermal resistance, a design with either radial inserts or branched inserts was chosen. Yang and Shen (Lihong & Hangming, 2015) also studied the thin copper-wire distribution for heat transfer of an isothermal chamber through topological methods. It was concluded that the conduction in the chamber can be enhanced with topological methods to change the distribution of porous media. Recently, Yang et al. (Sun & Yang, 2013; Yang & Shen, 2015) used the adaptive growth method and the variable density method respectively to optimize the distribution of porous media in order to enhance the heat conduction between the center and the chamber wall.

In the past several decades, the research on gradient-porous materials (GPMs) has grown rapidly (Ahmed, Smith, & Zhang, 2011; Mahamood, Akinlabi, Shukla, & Pityana, 2012; Nemat-Alla, Ata, Bayoumi, & Khair-Eldeen, 2011; Yao, Zhang, & Zhou, 2009). Various GPMs fabrication methods have been created and applied to obtain gradient-porous structures, whose properties can be easily tailored by varying the gradients of porosity or pore size. The applications of such materials include but not limited to thermal isolation and enhancement, separation and tissue engineering scaffolds (Jeong, Jeon, Lee, & Kim, 2015; Lim, Kang, Lee, & Shin, 2014; Niino, Kisara, & Mori, 2005; Wang, Hong, Hou, et al., 2015a; Wang, Hong, Wang, et al., 2015b). Recently, novel designs of GPMs-filled heat exchanger and gradient-porous heat sinks were proposed and numerically investigated in our previous work (Hong & Yao, 2014; Hong, Zhou, & Yao, 2013; Wang, Hong, Hou, et al., 2015a; Wang, Hong, Wang, et al., 2015b). It was found that the thermal and hydraulic performances of these devices were considerably improved compared with those filled with conventional homogeneous-porous materials (HPMs).

However most of the current efforts have focused on the hierarchical strategy of porous media (e.g. fine metal wire) for heat conduction enhancement, only very limited number of reports was found to apply GPMs to improve isothermal characteristics. The development of GPMs and related researchers provide us a new strategy to improve the comprehensive performances of isothermal chambers filled with porous materials. Following this logic flow, the authors proposed a novel design of isothermal chambers filled with GPMs in this work. Based on the porous media filling methods, the heat resistance and thermal performance of the structure filled with GPMs were studied both analytically and numerically. The isothermal performance and mass of chambers filled with various HPMs and GPMs were then compared. Subsequently, the effects of gradient direction and gradient magnitude on heat resistance and temperature profiles were investigated in details. Finally, the optimized gradient magnitude was suggested to enhance heat conduction and lower the filling density simultaneously.

**Nomenclature:**

- $c$: specific heat capacity, J/(kg·K)
- $l$: unit thickness of GPMs, m
- $m_{\text{unit}}$: unit mass, kg
- $r$: radial magnitude, m
- $r_1$: radius of center wall, m
- $r_2$: radius of outer wall, m
- $R$: radial direction
- $R_s$: thermal resistance, K/W
- $T_0$: initial temperature of isothermal chamber, K
- $T_1$: temperature of center wall, K
- $T_2$: temperature of outer wall, K

**Greek symbols**

\[ \alpha : \text{ variation factor of thermal conductivity} \]
\[ \varepsilon : \text{ porosity of porous material} \]
\[ \theta : \text{ angular coordinate} \]
\[ \lambda_s : \text{ thermal conductivity of solid, W/(m·K)} \]
\[ \lambda_f : \text{ thermal conductivity of fluid, W/(m·K)} \]
\[ \lambda_0 : \text{ thermal conductivity of GPMs at center wall, W/(m·K)} \]
\[ \bar{\varepsilon} : \text{ averaged porosity of porous material} \]
\[ \varepsilon_0 : \text{ porosity of GPMs at center wall} \]
\[ \varphi : \text{ heat flow, W} \]
\[ q : \text{ heat flux, W/m}^2 \]

2. Theoretical Analysis

2.1 Model description

The cross-section of the isothermal chamber is a circle shape with the outer radius \( r_2 = 100 \) mm, as shown in Fig.1. To facilitate the analysis, 1/4 of the circle was selected. A small central hole was set for applying heat source on the center wall, with the radius \( r_1 = 10 \) mm. The porosity of the GPMs in the isothermal chamber changes gradually along the radius direction as schematically illustrated in Fig.1, which is thus called the gradient porous materials.

\[
\rho = (1 - \varepsilon)\rho_s + \varepsilon\rho_f
\]
\[
c = (1 - \varepsilon)c_s + \varepsilon c_f
\]
\[
\lambda = (1 - \varepsilon)\lambda_s + \varepsilon \lambda_f
\]
where $\varepsilon$ is the porosity of the porous material, i.e., the volume fraction of the void space in the porous material; $c$ is the specific heat capacity; $\lambda_s$ and $\lambda_f$ are the thermal conductivity of the solid and fluid respectively.

### 2.2 Analytical model

Due to the fact that the research object was a fan, thus here the steady heat conduction equation under polar coordinate was chosen. The 2-D governing equation considering the axial symmetry of the structure is presented as below (Eckert & Drake Jr, 1987):

$$r \frac{\partial T}{\partial r} \frac{\partial T}{\partial r} + \lambda(\frac{\partial T}{\partial r} + r \frac{\partial^2 T}{\partial r^2}) = 0$$

(4)

The distribution of porosity of the porous material along radial direction can be defined as:

$$\varepsilon = \varepsilon_0(1+\beta r)$$

(5)

where $\varepsilon_0$ is the porosity at the center wall of the GPMs. Therefore, from Eq. (5) the thermal conductivity along $r$ can be derived as:

$$\lambda = \lambda_s(1+\alpha r)$$

(6)

$$\lambda_0 = (1-\varepsilon_0)\lambda_s + \varepsilon_0\lambda_f$$

(7)

$$\alpha = \frac{\beta \varepsilon_0 (\lambda_f - \lambda_s)}{\lambda_0}$$

(8)

where $\lambda_0$ is the thermal conductivity of the GPMs at the center wall, $\alpha$ is the variation factor of the thermal conductivity. By substituting Eq. (6) to Eq. (4), the general solution for Eq. (4) can be obtained as following:

$$T = c_1 + c_2 \ln\left(\frac{r}{\alpha r + 1}\right)$$

(9)

The boundary conditions are set as follows:

$$r = r_1, T = T_1$$

(10)

$$r = r_2, T = T_2$$

(11)

where $T_1$, $T_2$ are the temperatures of the center wall and outer wall respectively. Substitute Eqs. (10) and (11) into Eq. (9), the integration constants $c_1$ and $c_2$ are determined:

$$c_1 = \frac{T_1 - T_2}{\ln(\frac{r_1}{\alpha r_1 + 1}) - \ln(\frac{r_2}{\alpha r_2 + 1})}$$

(12)

$$c_2 = \frac{\ln(\frac{r_1}{\alpha r_1 + 1})T_2 - \ln(\frac{r_2}{\alpha r_2 + 1})T_1}{\ln(\frac{r_1}{\alpha r_1 + 1}) - \ln(\frac{r_2}{\alpha r_2 + 1})}$$

(13)

The thermal resistance under steady condition is given as:

$$R_s = \frac{\Delta T}{\varphi}$$

(14)

where $\varphi$ is the heat flow, which is calculated as:

$$\varphi = 2\pi ql$$

(15)
Here the heat flux $q$ is defined as:

$$q = -\lambda \frac{dT}{dr} = -\lambda \frac{c_i}{\alpha r^2 + r}$$

Then the value of thermal resistance $R_s$ can be obtained from Eqs. (14) - (16):

$$R_s = \frac{\ln \frac{r_2}{r_1} (\frac{\alpha r_2 + 1}{\alpha r_1 + 1})}{-2\pi\lambda_0}$$

The filling mass of the GPMs can be expressed as:

$$m_{unit} = (1 - \bar{\epsilon}) \rho s l = (1 - \bar{\epsilon}) \rho t (r_2^2 - r_1^2)$$

where $l$ is the unit thickness of the GPMs, $\bar{\epsilon}$ is the averaged porosity of the GPMs calculated by the following equation:

$$\bar{\epsilon} = \frac{\int_{r_1}^{r_2} 2\pi\epsilon_0 (1 + \beta r) rdr}{\pi (r_2^2 - r_1^2)}$$

3. Numerical simulation

3.1 Numerical simulation method

Based on the model described in Section 2.1, the two-dimensional transient heat conduction equation under polar coordinate can be written as (Eckert & Drake Jr, 1987):

$$\rho c \frac{\partial T}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r} \left(r \lambda \frac{\partial T}{\partial r} \right) + \frac{1}{r} \frac{\partial}{\partial \theta} \left( \frac{\lambda}{r} \frac{\partial T}{\partial \theta} \right)$$

In this work, the numerical simulations were performed using the Computational Fluid Dynamics (CFD) software (Fluent, ANSYS 14.5) (Fluent, 2009). The computational model is shown in Fig. 2. The above governing equations were solved by the finite-volume method based on the transient and axisymmetric conditions. The discretization of the heat conduction equation employs the second-order upwind scheme (Huang, Nakayama, Yang, Yang, & Liu, 2010; Wang, Hong, Hou, et al., 2015a). Relative variations between contiguous iterations were set to be smaller than $10^{-6}$. In running calculations, the time stepping method is selected with a fixed time step size of 1s.

![Computational domain of the CFD model.](Fig. 2)
3.2 Assumptions and boundary conditions

Copper was assumed as the filling material with the thermal conductivity coefficient $\lambda_s = 399\text{W/(m·K)}$. Air was assumed to be filled in the vacant space of porous materials, with constant thermal conductivity coefficient $\lambda_f = 0.0255\text{W/(m·K)}$. The effect of temperature on the thermal conductivity coefficient is considered as negligible. Axis 1 and Axis 2 are set as symmetry, as shown in Fig. 2. The thermal boundary conditions are set as follows: the initial temperature of the computation domain is uniform before the heat transfer process, i.e., $T_0 = 300\text{K}$ when $t = 0$. Then the constant temperature boundary condition is set at the center wall, i.e., $T_{in} = 475.3\text{K}$ when $t > 0$. The temperature of the outer wall after a certain time is monitored during the simulation.

4. Results and discussions

4.1 Effect of direction of porosity-gradient

Based on the theoretical analysis and Eqs. (17) - (19), the thermal resistance and unit mass of one typical HPMs and two types of GPMs with opposite gradient direction are shown in Fig. 3. It indicates that the direction of the porosity gradient significantly influences the thermal resistance and unit mass of the GPMs. The decreasing of porosity gradient in the radial direction ($R$ from center to outer) increases both of the thermal resistance and unit mass compared with the one of HPMs configuration. However, the increasing porosity gradient by $R$ decreases both of the thermal resistance and unit mass. Therefore, the increasing porosity gradient by $R$ is the preferred structure in the design of GPMs isothermal chambers.

In order to further investigate the effects of GPMs on the thermal performances of the chamber, the numerical simulations under transient state were conducted with the same porosity configurations as in the aforementioned cases. Fig. 4 shows the temperature contours of different porous structures, i.e., the HPMs with $\varepsilon = 0.7$, GPMs with $\varepsilon$ increasing from 0.6 to 0.8 along $R$ and GPMs with $\varepsilon$ decreasing from 0.8 to 0.6 along $R$. Obviously, it can be observed that GPMs has considerable influence on the temperature distributions of the chamber during the heat transfer process. After the same processing time, the outer wall temperature of the GPMs case with $\varepsilon$ varies from 0.8 to 0.6 is lower than the HPM case, which indicates that the former one has a higher heat resistance. However, the outer wall temperature of the GPMs case with $\varepsilon$ varies from 0.6 to 0.8 is much higher than that of the HPM case after the same processing time. Therefore, it came to the conclusion that GPMs with increasing porosity along $R$ direction can effectively lower the thermal resistance...
of chambers.

The temperature profiles in the radial direction of different porous structures after certain processing times are shown in Fig. 5. Similarly, for both the HPM and GPMs configurations, the temperatures decrease significantly in the $R$ direction. However, after a certain time, the temperature curve of the GPMs with increasing porosity configuration is much higher than that of the HPM design with $\varepsilon = 0.7$. For instance, after 200s, the outer wall temperature of the GPMs case is 360K, about 20K higher than that of the HPM case. These results are qualitatively consistent with the calculated thermal resistance as illustrated in Fig.3.

$$\text{Fig. 4} \quad \text{Temperature counters of GPMs with different porosity configurations.}$$

$$\text{Fig. 5} \quad \text{Temperature profiles along } R \text{ of various porosity configurations at different processing time.}$$

4.2 Effects of the porosity-gradient magnitude

The variations of minimum thermal resistance ($R_{s-min}$) and unit mass of the GPMs with average porosity ($\varepsilon$) were calculated with MATLAB code based on Eqs. (17) - (19), as shown in Fig. 6. The results show obviously that the unit
mass decreases with the increase of averaged porosity $\bar{\varepsilon}$. However, the minimum thermal resistance increases rather slowly before $\bar{\varepsilon} = 0.8$, and soars up dramatically after that point. The results suggest that the optimum average porosity of the GPMs is around 0.8, at which one can obtain a much lower thermal resistance at a relative smaller unit mass. This result can be a valuable guidance for the GPMs design when the mass and cost of the GPMs is a big consideration.

Figure 6 shows the variation of minimum thermal resistance and unit mass with increasing of average porosity.

Figure 7 shows the influence of $\varepsilon_0$ (porosity at the center wall of the GPMs) on the thermal resistance with different average porosity $\bar{\varepsilon}$. It indicates that with $\bar{\varepsilon}$ is a constant, the increasing of $\varepsilon_0$ can considerably increase the thermal resistance, and the increasing rate is higher when $\varepsilon_0$ becomes larger. The thermal resistance and unit mass of the GPMs configurations with different $\varepsilon_0$ under constant $\varepsilon$ are shown in Fig. 8. By comparing the performances of three GPMs cases with $\varepsilon$ from 0.6 to 0.8 along $R$, 0.5 to 0.9 along $R$ and constant of 0.7, it is found that in the case with $\varepsilon$ from 0.5 to 0.9, both the thermal resistance and unit mass decrease simultaneously. Therefore, a smaller $\varepsilon_0$ is preferred for the design of GPMs structures, which can improve the comprehensive thermal performances of the chamber.
The numerical simulations under transient conditions were conducted to further illustrate the effects of porosity $\varepsilon_0$ on the thermal performance of the GPMs chamber. Fig. 9 shows the temperature contours of different porosity-gradient GPMs: GPMs with $\varepsilon$ from 0.6 to 0.8 along $R$, from 0.5 to 0.9 and from 0.4 to 1.0. It can be seen that at the same processing time, the outer wall temperature increases with the decrease of porosity $\varepsilon_0$ of the GPMs. Fig. 10 shows the temperature profiles in the radial direction of different porosity-gradient GPMs. It can be seen that in every case, the temperature first decreases rapidly in a short length along $R$, and then decrease rather slowly and the curve flattens making the temperature distribution non-uniform in the radial direction. Decreasing the porosity $\varepsilon_0$ of the GPMs can not only increase the outer wall temperature significantly but also make the temperature distribution more uniform. For example, after 200s, the outer wall temperature of GPMs with $\varepsilon$ from 0.4 to 1.0 is 410K, about 50K higher than that of $\varepsilon$ from 0.4 to 1.0 configuration.

Fig. 8  Column bar of thermal resistance and unit mass of GPMs with different porosity configurations.

Fig. 9  Temperature counters of GPMs with different porosity configurations.
Fig. 10 Temperature profiles along R of various porosity configurations at different processing time: (a) 50s, (b) 100s and (c) 200s.

5. Conclusion

In this work, a novel design of isothermal chambers filled with GPMs (gradient porous materials) with a disc-shaped cross-section was proposed. Based on the 1/4 axisymmetric physical model, a theoretical heat transfer model of GPMs chamber was developed. Besides, the numerical simulations based on finite volume method were conducted to obtain the detailed thermal behaviors of the various GPMs filled chambers. The effects of the GPMs gradient direction and gradient magnitude on the thermal resistance, temperature profiles, and unit mass were investigated thoroughly based on the theoretical analysis and numerical simulations. Results indicate that increasing porosity gradient in the radial direction can effectively enhance the thermal performance of the GPMs chamber. Moreover, a smaller porosity $\varepsilon_0$ with respect to a constant average porosity of the GPMs can both improve the heat conductivity and lower the unit mass of the isothermal chamber. The results provide a valuable guidance for the design of GPMs in the potential applications of isothermal chambers.

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