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THERMAL CONDUCTIVITY AND THERMAL CONTACT RESISTANCE OF METAL FOAMS

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ABSTRACT

Unique specifications of metal foams such as relatively low cost, ultra-low density, high surface-area-to-volume ratio, and most importantly, the ability to mix the passing fluid provide them a great potential for a variety of thermal-fluidics applications.

In the present study, a compact analytical model for evaluating the effective thermal conductivity of metal foams is developed. The medium structure is represented as orthogonal cylindrical ligaments that are equally spaced and sized. A unit cell is taken to represent the metal foam. The model accounts for varying cross-sectional ligaments which is consistent with microscopic images.

A numerical analysis is performed to verify the proposed analytical models. The model predictions are in good agreement with existing experimental data and the present numerical results.

A parametric study is then performed to investigate the effects of variation in ligament cross-section geometry, uniformity, and aspect ratio over a wide range of porosities. Moreover, Thermal contact resistance phenomenon is included in the analysis.

NOMENCLATURE

a = Unit cell size, mm

b = Major semi-axis of the outer geometry of ligament cross-section, Fig. 4, mm

b_i = Major semi-axis of the inner geometry of ligament cross-section, Fig. 4, mm

c = Minor semi-axis of the outer geometry of ligament cross-section, Fig. 4, mm

c_i = Minor semi-axis of the inner geometry of ligament cross-section, Fig. 4, mm

k_s = Solid thermal conductivity, $W/m.K$

k_f = Fluid thermal conductivity, $W/m.K$

k_{eff} = Effective thermal conductivity, $W/m.K$

$k_{eff,solid}$ = Effective thermal conductivity for the solid ligament structure, Eq. (28), $W/m.K$

m = Slope of linear variation in ligament cross-section

PPI = Pore density

r = Inner-to-outer void ratio for hollow ligament structures

R = Thermal resistance, K/W

R_{co} = Thermal constriction resistance, K/W

R_{tot} = Total thermal resistance of the unit cell, K/W

R_{MF} = Total thermal resistance of the medium, K/W

TCR = Thermal contact resistance, K/W

Greek symbols

α = Ligament aspect ratio

ε = Porosity of solid ligament metal foams

ε_h	=	Porosity of hollow ligament metal foam
θ	=	Ligament angle, Fig. 2
$\psi\,(\cdot)$	=	Constriction parameter, Eq. (22)
ξ	=	Ratio of ligament radius to the unit cell size
γ	=	Inner-to-outer diameter ratio for hollow ligament structures, $\gamma = b_i/b$

1 INTRODUCTION

Transport phenomena in porous media have been the focus of many industrial and academic investigations [1-4]. The majority of the studies reported in the literature deal with low porosity media such as granular materials and packed beds [1, 2]. Recently, high porosity open-cell media such as open-cell metal foams and fibrous media have received higher attention. Interest in these media stems from their relatively low cost, ultra-low density, high surface area to volume ratio, and most importantly from their ability to mix the passing fluid which provides them great potential for a variety of unique thermal-fluidic applications [3, 4]. Three such technologies are: 1) microelectronics and aerospace requiring high rates and light-weight heat removal solutions, 2) fuel cells that need the capability of simultaneous heat exchanges and chemical reaction, and 3) compact heat exchangers of large capacities at low temperature differentials [4-6]. Also, some of these materials, e.g. Ni based metal foams are suitable for high temperature applications such as solid oxide fuel cells.

The micro structure of metal foams consists of small solid or hollow ligaments forming a network of inter-connected dodecahedral-like cells [5, 7]. The shape and size of these open cells vary throughout the medium which make the structure random and anisotropic.

Two of the parameters that describe such media are: 1) porosity or relative density and 2) pore density (number of pores per unit length) which is typically expressed in the unit of pores per inch (PPI). These structures can be constructed from a wide variety of materials including metals (aluminum, nickel, copper, iron, and steel alloys), polymers, and carbon. More importantly, these micro structures can be tailored to meet a range of requirements.

Predicting transport phenomena in high porosity media plays a key role in optimization of power and thermal management for a variety of industrial applications such as metal foam-based heat exchangers [8, 9]. The high porosity of these materials results in a significant reduction of thermal conductivity of media compared to the solid phase (about 2 orders of magnitude). Evaluating the effective thermal conductivity for metal foams provides a good understanding about the thermal behavior of the medium.

2 LITERATURE REVIEW

Several theoretical approaches have been taken to study the conduction heat transfer in porous media which can be applied to metal foams. These studies can be classified into: 1) asymptotic solutions (bounds), 2) unit cell approach, and 3) random micro structure approach.

2.1 Asymptotic Solutions (Bounds)

Considering different simplified configurations of solid and fluid phases, several asymptotic solutions for porous media have been presented in the literature and are described briefly in this section.

Series and parallel models: Considering fluid and solid phases in series and parallel structures can provide lower and upper bounds for the effective thermal conductivity of a porous medium, respectively. In these models, the heat transfer is assumed to be one dimensional.

Maxwell model: Solving Laplace's equation for non-contacting spherical particles (discontinuous phase) in a medium, Maxwell [10] developed a relationship for effective conductivity of the medium (mixture). For spherical holes in a continuous solid medium, Maxwell model is expressed as:

$$k_{eff,Maxwell} = k_s \frac{k_f(1+2\varepsilon) + 2k_s(1-\varepsilon)}{k_f(1-\varepsilon) + k_s(2+\varepsilon)} \tag{1}$$

where k_s and k_f are the thermal conductivity of the solid ligament (continuous phase) and fluid phase, respectively.

Effective medium theory (EMT) model: The EMT model [11, 12] is similar to Maxwell model and can be derived from the solution of Laplace's equation applied to a single sphere surrounded by a continuous medium. The difference between these models arises from the different assumptions made in order to derive expressions for effective conductivities. The EMT model for a two component medium such as metal foam can be expressed as:

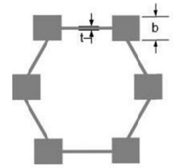
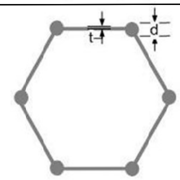
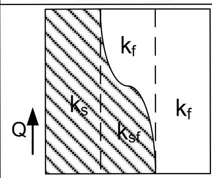
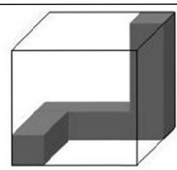
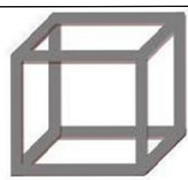
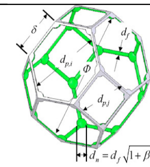
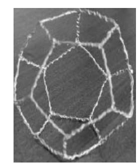
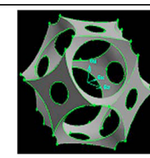
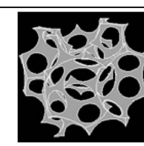
$$\varepsilon\left(\frac{k_f - k_{eff,EMT}}{k_f + 2k_{eff,EMT}}\right) + (1-\varepsilon)\left(\frac{k_s - k_{eff,EMT}}{k_s + 2k_{eff,EMT}}\right) = 0 \tag{2}$$

Maxwell model and EMT model provide upper and lower bounds for the effective thermal conductivity of metal foams, respectively [13]. Also, the thermal conductivity values are closer to the Maxwell model [13].

2.2 Unit Cell Approach

Generally, a unit cell has been taken to represent the metal foam micro structure [3-5, 14-21], and it is assumed that this unit cell can be repeated throughout the medium by virtue of periodicity. The unit cell approach breaks the problem into distinct conduction paths in solid and fluid phases; and calculates the conductivity of the medium as a series/parallel combination of the individual resistances for those paths considering a one-dimensional heat transfer. Applying the energy equation to the suggested unit cell, the effective thermal conductivity can be found analytically or numerically depending on the complexity of the unit cell.

Table 1. Proposed unit cells for metal foams.

Researcher	Unit Cell	Notes
Calmidi and Mahajan [16]		○ Compact 2-D analytical model ○ Unrealistic micro structure (t/b = 0.09) ○ Tuning parameter (t/b) found through fitting experimental data
Bhattacharya et al. [5]		○ More realistic than Calmidi and Mahajan's [16], t/d = 0.19 but more complicated ○ Tuning parameter (t/d) found through fitting experimental data
Hsu et al. [17]		○ Continuously connected and symmetric phases ○ Analogy between mass diffusion and heat conduction to find the effective thermal conductivity in the unit cell
Du Plessis and Fourie [18]		○ Simple model ○ Significant deviations from experimental data
Dul'nev [19]		○ Compact model ○ Unrealistic micro structure ○ Relatively good agreement with experimental data
Boomsma and Poulikakos [20]		○ Terakaidecahedron geometry with cubic nodes in intersection of ligaments ○ Relatively compact analytical model with a tuning parameter (cubic size) found through fitting experimental data ○ Unrealistic micro structure when $\varepsilon < 0.9$
Schmierer and Razani [15]		○ Terakaidecahedron geometry with spherical nodes in intersection of ligaments ○ Realistic micro structure ○ Image and geometrical analyses of the micro structure to find node size, $1 < \beta < 2$ ○ Numerical finite element analysis to calculate the effective thermal conductivity
Ozmat et al. [4]		○ Dodecahedron geometry having 12 pentagon-shaped facets with triangular cross-section ligaments ○ Compact analytical model based on the geometrical features of the unit cell and analogy between electrical and thermal conductivities ○ No lumped materials in intersection of ligament ○ Close agreement with experimental data for low thermal conductivity ratios
Krishnan et al. [21]		○ Body-Centered-Cubic (BCC) structure satisfying minimum surface energies ○ Numerical model to determine the effective thermal conductivity ○ In agreement with experimental data only when porosity is greater than 0.94 because of geometry limitations
Krishnan et al. [21]		○ A15 structure satisfying minimum surface energies ○ Numerical model to determine the effective thermal conductivity ○ In agreement with experimental data for a wide range of porosities

Various unit cell geometries can be found for metal foams in the literature including two and three dimensional structures. The geometry of unit cells, main assumptions, and features of these studies are summarized in Table 1.

2.3 Random Micro Structure Approach

A number of studies done on fibrous media and metal foams considered the medium as a set of equally sized ligaments randomly distributed in the fluid phase [22, 23].
Wang and Pan [23] developed a numerical method based on the Lattice Boltzmann technique to predict the effective thermal conductivity of randomly open-cell porous media. They [23] used a distribution probability for points to be solid nodes and used target probability to construct ligaments between solid nodes.
A critical review of literature reveals:

- DuPlessis and Fourie model [18] highly overestimates the effective thermal conductivity, especially when $\varepsilon < 0.95$.
- Dul'nuv model [19] in spite of its simplicity provides an acceptable estimation of metal foams in higher porosities, $\varepsilon > 0.95$.
- Ozmat model [4] can provide a good estimation of a foam structure when thermal conductivity ratio is so small, e.g. foam-air and foam-vacuum; for higher thermal conductivity ratios, this model underestimates the conductivity, potentially since it does not include heat conduction in the fluid phase.
- Wang and Pan model [23] can predict the thermal conductivity of RVC foam-water structure, but it is not obvious that this model can provide a good estimation for other foam structures. Also, this model is not easy to use, i.e. a geometrical model needs to be developed for each porosity.
- Hsu et al. model [17] provides a good estimation for the effective thermal conductivity when thermal conductivity ratio is close to one, e.g. reticulated vitreous carbon (RVC) foam-water.
- At least one empirically determined tuning parameter is involved in the majority of existing models. These models such as Calmidi and Mahajan model [16] can predict the thermal conductivity for Al foam accurately, but for other foam structures and materials, they overestimate the thermal conductivity.
- Effects of variation of ligaments' cross-section with the porosity, and pore density have not been included in existing models.
- The Thermal contact resistance phenomenon has not been yet investigated in any study. Thermal contact resistance can influence heat transfer especially for high porosity materials.

It can be concluded that existing studies provide useful insights but remain limited to specific ranges of porosity and/or micro structure geometry, and that the need for a general model is still exist.

3 PROPOSED MODEL

The objectives of the present works are:

- Develop and verify comprehensive analytical models for solid and hollow ligaments metal foams that can predict the effective thermal conductivity of different geometries of foam ligament accurately.
- Analyze thermal contact resistance, TCR, at the interface between the foam and solid surfaces.
- Investigate the effects of salient geometrical parameters on the effective thermal conductivity and TCR including ligament cross-section geometry, uniformity, and aspect ratio over a range of porosities to identify the controlling parameters.

In this study, the medium structure is represented as orthogonal cylindrical ligaments that are equally spaced and sized. A unit cell approach is employed to represent the metal foam micro structure. Each cell is made up of three interconnected orthogonal cylindrical ligaments. These cylinders can be solid or hollow. A cubic lumped material is added at intersection of ligaments to imitate the observed micro structures. The present model accounts for varying cross-sectional ligaments which is consistent with electron microscopic images showing larger diameters at intersections of the ligaments [24].

3.1 Geometrical and Thermal Modeling

Morphological investigations reveals that the cross-section of metal foam ligaments is a function of porosity, and changes from circle at $\varepsilon = 0.85$ to inner concave triangle at $\varepsilon = 0.97$ [7, 25].

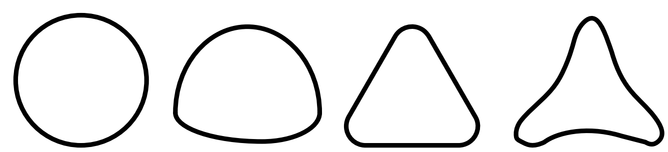


Figure 1. Ligament cross-section at different porosities.

In the present study, a cubic unit cell is considered as a representative of metal foam micro structure. Unit cell geometries for circular cross-section of ligaments are shown in Fig. 2 for solid and hollow ligament structures. The effect of cross-sectional geometry on the analysis is studied through investigating several shapes. An arbitrary symmetric cross-section geometry considered in the present study is shown in Fig. 3. The porosity for the unit cells shown in Fig. 2 can be expressed as:

$$\varepsilon = 1 - A_b\left(\frac{1}{1-\beta_1}\right)\left[\frac{2H+4L}{3}\right] + \left[A_{t1}\left(\frac{\beta_1}{1-\beta_1}\right) + A_{t2}\left(\frac{\beta_2}{1-\beta_2}\right)\right]\left[\frac{2H+4L}{3}\right] - 8\alpha b^3 \quad (3)$$

$$\varepsilon_h = 1 - A_s(2H+4L) - 8\alpha\left(b^3 - b_i{}^3\right) + A_{fi}(b-b_i)(4+2\alpha) \quad (4)$$

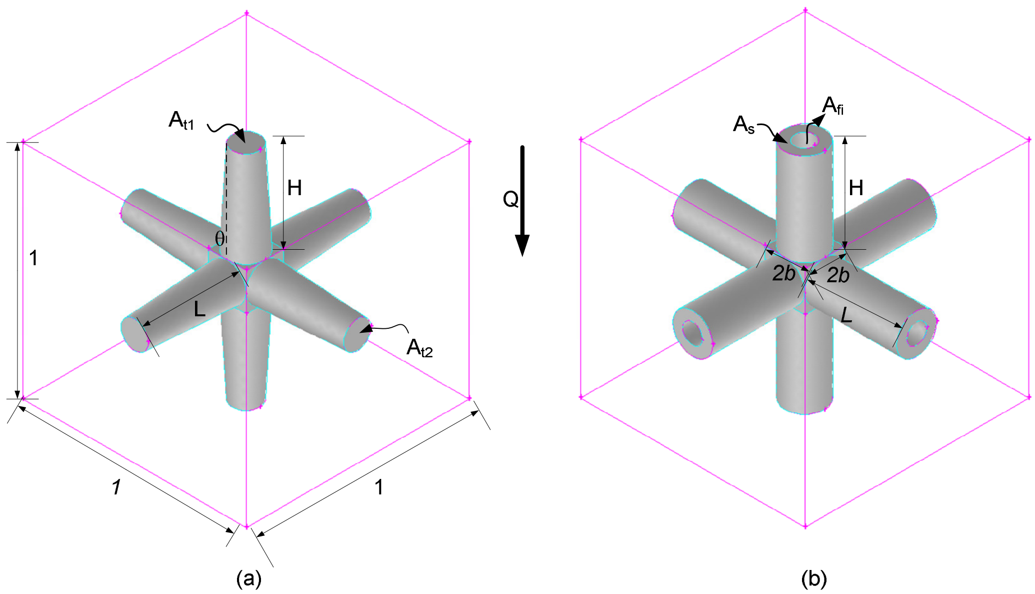


Figure 2. Proposed unit cells: (a) solid ligaments with circular cross-section varying linearly; (b) hollow ligaments with uniform circular cross-section.

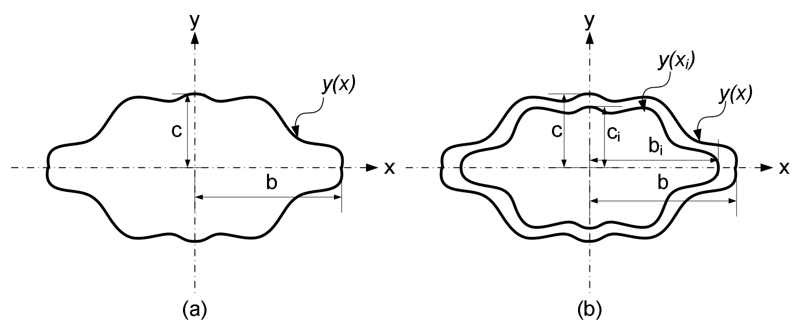


Figure 3. Arbitrary symmetric cross-section geometries: (a) solid ligament; (b) hollow ligament.

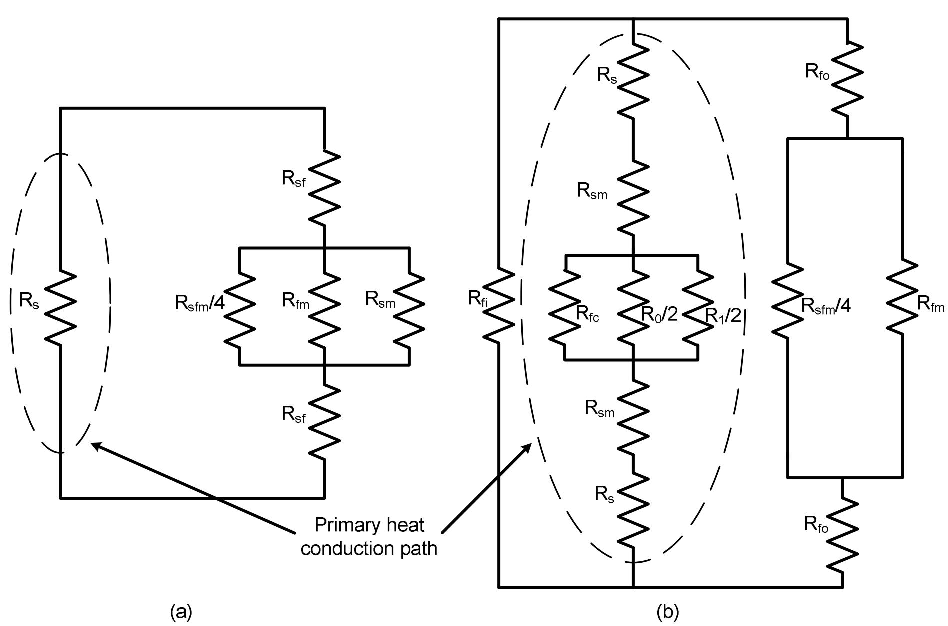


Figure 4. Thermal resistance networks: (a) solid ligament model; (b) hollow ligament model.

where, ε and ε_h are porosities of solid and hollow ligament structures, respectively. β_1 and β_2 are:

$$\begin{cases} \beta_1 = 1 - \left(\frac{H}{b}\right) m \\ \beta_2 = 1 - \left(\frac{L}{b}\right) m \end{cases} \tag{5}$$

where,

$$\begin{cases} H = \frac{1 - 2b\alpha}{2} \\ L = \frac{1 - 2b}{2} \end{cases} \tag{6}$$

where, α is the ligament aspect ratio, $m = \tan\theta$ and θ is the ligament angle shown in Fig. 2. Using geometrical parameters introduced in Figs. 2 and 3, various cross-sectional areas used in Eq. (3) and (4) can be expressed as:

$$A_b = 4\int_0^b y\,dx \tag{7}$$

$$A_{t1} = 4\int_0^{b-mH} y\,dx \tag{8}$$

$$A_{t2} = 4\int_0^{b-mL} y\,dx \tag{9}$$

$$A_s = 4\int_{b_i}^{b} (y - y_i)\,dx \tag{10}$$

$$A_{fi} = 4\int_0^{b_i} y_i\,dx \tag{11}$$

These cross-sectional areas are shown in Fig. 2. Considering one-dimensional heat transfer in the medium, thermal resistance networks are constructed for solid and hollow ligaments metal foams, as depicted in Fig. 4.

The primary paths for heat transfer are through ligaments. These paths include R_s and R_{s1} for the solid and the hollow ligament structures as shown in Fig. 4. The primary thermal resistances can be expressed as:

$$R_s = \frac{1}{k_s A_{t1}} \tag{12}$$

$$R_{s1} = \frac{H}{k_s A_s} \tag{13}$$

$$R_{sm} = \frac{b - b_i}{k_s(4b^2 - A_{fi})} \tag{14}$$

$$R_{fc} = \frac{1 - 2H}{k_f\left[4{b_i}^2 - A_{fi}\right]} \tag{15}$$

$$R_0 = \frac{1}{(b - b_i)}\int_0^{c_i} \frac{dy_i}{k_f x_i + k_s(b - x_i)} \tag{16}$$

$$R_1 = \frac{1}{\alpha(b - b_i)}\int_0^{c_i} \frac{dy_i}{k_f x_i + k_s(b_i - x_i)} \tag{17}$$

Computing all of the thermal resistances shown in Fig. 4, the effective thermal conductivity is evaluated:

$$k_{eff} = \frac{1}{R_{tot}} \tag{18}$$

where, R_{tot} is the total thermal resistance of the unit cell. For low conductivity fluids like air, the total thermal resistance can be simplified by considering only the resistance of primary paths shown in Fig. 4.

$$R_{tot,solid} = R_s \tag{19}$$

$$R_{tot,hollow} = 2R_{s1} + 2R_{sm} + \left(\frac{2}{R_0} + \frac{2}{R_1} + \frac{1}{R_{fc}}\right)^{-1} \tag{20}$$

where, $R_{tot,solid}$ and $R_{tot,hollow}$ are total thermal resistance of solid and hollow ligament structures, respectively.

3.2 Thermal Contact Resistance Model

Thermal contact resistance, TCR, is an important phenomenon at the interface of metal foams and solid surfaces and includes constriction and spreading resistances. Thermal spreading/constriction resistance R_{co} is defined as the difference between the temperature of heat source and the temperature of a heat sink far from it divided by the total heat flow rate through the contact area Q; i.e. $R_{co} = \Delta T/Q$ [26].

A perfect contact is assumed between the foam ligaments and solid surfaces, i.e., the surface out-of-flatness and roughness are neglected as shown in Fig. 5. It should be noted that TCR exists even if the foam is brazed to a solid surface.

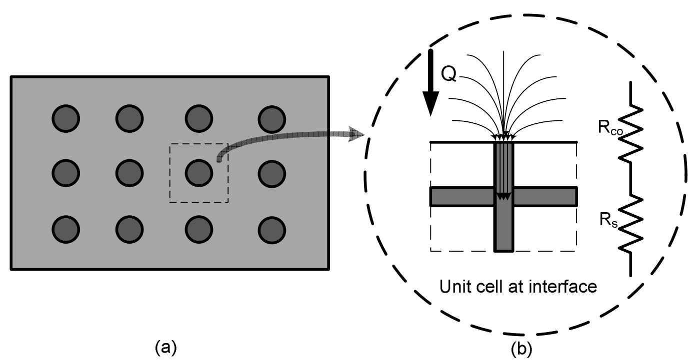


Figure 5. Metal foam in contact with a surface: (a) contact surface; (b) a unit cell at interface.

Sadeghi et al. [27] showed that the effect of heat source geometry on the constriction resistance is negligible, thus, circular cylindrical ligaments are considered in the present study to represent the micro structure of the metal foam.
Cooper et al. [28] showed that all microcontacts must be at the same temperature, provided the conductivity in each body is independent of direction, position and temperature. Roess [29] suggested the following expression for the spreading resistance of close circular, isothermal contact spots:

$$R_{co} = \frac{\psi(\eta)}{4k_s b} \tag{21}$$

where $\eta = 2b/a$ for the present micro structure and $\psi(\cdot)$ is a constriction parameter which accounts for the interference between neighboring contact spots.
A number of correlations for isothermal spreading resistance for the flux tube are available in the literature [28-31]. The correlation proposed by Cooper et al. [28] is used in the present study.

$$\psi(\eta) = (1-\eta)^{1.5} \tag{22}$$

For given values of the porosity and the pore density (PPI), the unit cell size a, the radius b of contact spots can be determined in mm.

$$a = \frac{25.4}{PPI} \tag{23}$$

$$\varepsilon = 1 - \xi^3 \left(\frac{3\pi}{\xi} - 6\pi + 8\right) \tag{24}$$

where $\xi = b/a$. From the above equation b is found.
The constriction resistance will be evaluated using Eq. (21). This resistance is in series with the primary path resistance R_s of unit cells at the interface of the above and bottom contact surfaces.

4 VALIDATION OF THE MODEL

In this section, the present models for solid and hollow ligament structures are compared with existing experimental data over a range of porosities for different foam materials. Also, numerical studies are performed to verify the analytical results. Figure 6 shows a comparison of the solid ligament model with experimental and numerical data for aluminum foam-air at different ligament angles.
To investigate the ligament cross-section variations with porosity, different microscopic images have been taken from ERG Duocel Al foams with different porosities and pore densities. Figure 7 shows one of these microscopic images for ε=0.93 and PPI=10. Our image analysis shows that the slope of the ligament cross-section varies with porosity. To include this effect in the present model, the following relationship is developed through comparison with experimental data.

$$m = \tan\theta = \begin{cases} 0 & , \quad \varepsilon > 0.95 \\ -0.742\varepsilon + 0.721, & \quad \varepsilon \le 0.95 \end{cases} \tag{25}$$

Based on the above relationship, the ligament angle θ varies between 5 to 0 degrees for ε>0.9.

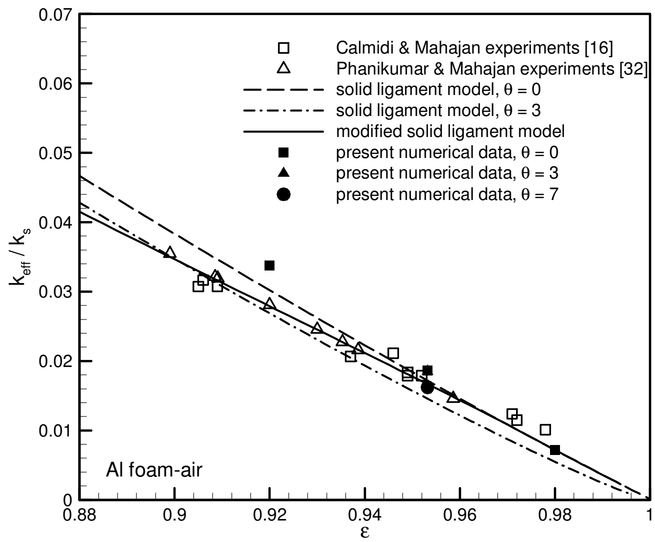


Figure 6. Proposed model in comparison with experimental data [16, 32] and present numerical data for Al foam-air.

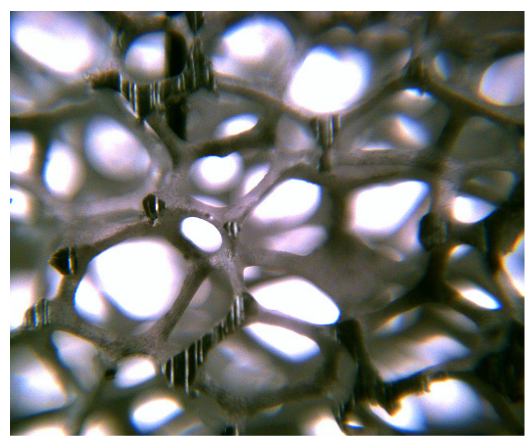


Figure 7. Microscopic image of ERG Duocel Al foam with ε=0.93 and PPI=10.

The modified solid ligament model is compared in Fig. 8 with existing experimental data for a variety of materials and porosities. It can be seen that except for a few points, all data fall within ± 10 % of the model.
The present model for hollow ligament metal foams is compared with Zhao et al. [34] model and experimental data in Fig. 9. Results show that the inner-to-outer diameter ratio γ is a major parameter in the hollow ligament model and is a function of porosity and pore density. It can be seen that Zhao et al. model, Eqs. (7), (10) in [34], underestimates the data, but the present model with an appropriate value of γ provides a good estimation for the thermal conductivity.

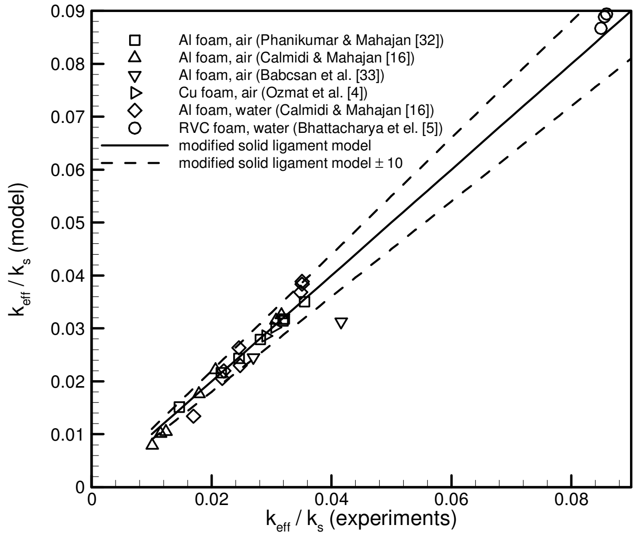


Figure 8. Dimensionless thermal conductivity determined by modified solid ligament model versus dimensionless experimental data.

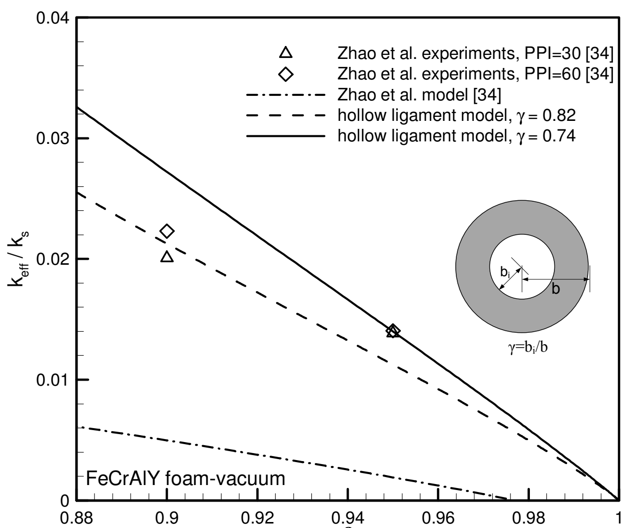


Figure 9. Dimensionless thermal conductivity determined by hollow ligament model in comparison with experimental data [34].

5 PARAMETRIC STUDIES

5.1 Ligament Cross-Section Geometry

Figure 10 shows the effect of ligaments' cross-section geometry on the effective thermal conductivity over a wide range of fluid to solid thermal conductivity ratios, k_f/k_s. As shown, the effect of cross-section geometry is negligible in the modeling. The area exposed to heat transfer in the primary path is approximately equal for different geometries at each porosity; therefore, the shape of ligament has insignificant effect on the effective thermal conductivity.

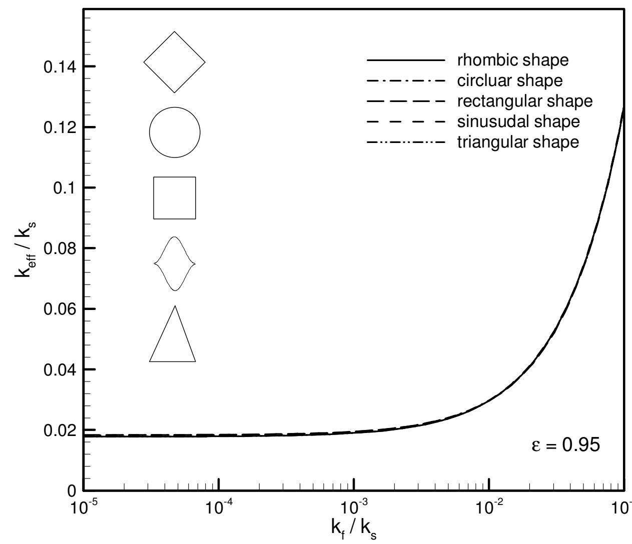


Figure 10. Effect of cross-section geometry on the solid ligament model.

5.2 Ligament Aspect Ratio

The effect of ligament aspect ratio is investigated in Fig. 9 using the solid ligament model with uniform cross-section. As can be seen, this effect is negligible unless for small value of aspect ratio, $\alpha < 0.25$. At lower aspect ratios, unit cell becomes more anisotropic and the lumped material cross-section increases which slightly increases the effective thermal conductivity.

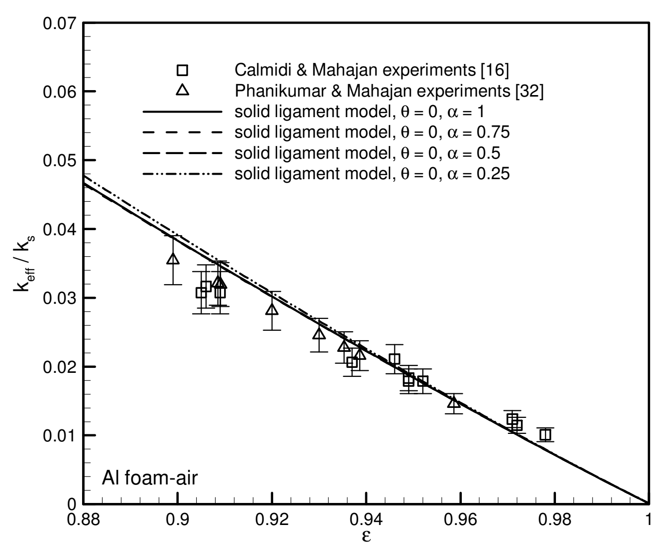


Figure 11. Effect of ligament aspect ratio on the effective thermal conductivity.

As can be seen in Figs. 10 and 11, the effect of cross-section geometry and aspect ratio on the models is insignificant. Therefore, the circular cross-section is used to simplify the models. Using uniform circluar cross-section for ligaments, Eqs. (3), (4) are simplified to:

$$\varepsilon = 1 - b^3\left[\frac{3\pi}{b} - 6\pi + 8\right] \tag{26}$$

$$\varepsilon_h = 1 - b^3\left[\frac{3\pi}{b} - 6\pi + 8\right] + b_i^3\left[\frac{3\pi}{b_i} - 6\pi + 8\right] \tag{27}$$

The effective thermal conductivity for the solid ligament structure is simplified to:

$$k_{eff,solid} = \pi b^2 k_s \tag{28}$$

5.3 Inner-to-outer Void Ratio

Inner-to-outer diameter ratio is an important parameter in the hollow ligament model, see Fig. 9. Inner-to-outer void ratio, r, is used after zhao et al [35] which represents the ratio of the inner and the outer void volumes of ligaments. This ratio for circular ligament can be expressed by:

$$r = \frac{\frac{1}{b^3} - 3\pi\left(\frac{1}{b} - 2\right) - 8}{3\pi\gamma^2\left(\frac{1}{b} - 2\gamma\right) + 8\gamma^3} \tag{29}$$

Figure 12 shows dimensionless thermal conductivity of the hollow ligament structure over a range of porosities for different values of inner-to-outer void ratio, r. An increase in value of r decreases the thermal conductivity. It can be concluded that these structures are not appropriate heat conduction wise with respect to solid ligament foams, because heat must pass through the inner void which increases the total resistance in the primary path.

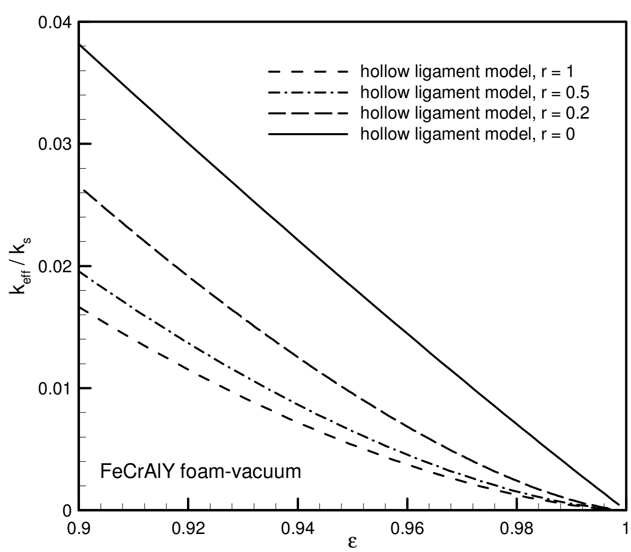


Figure 12. Effect of inner-to-outer void ratio on the effective thermal conductivity.

5.4 Thermal Contact Resistance

Our analysis shows that the PPI and the height, the length in the heat flow direction, of metal foam samples are two controlling parameters of TCR at a given porosity. Effect of porosity and height times pore density ($H_0 \cdot PPI$) are investigated in Fig. 13 for Al foam sample perfectly brazed from the top and the bottom to aluminum sheets. It can be seen that the ratio of TCR to the medium resistance R_{MF} decreases rapidly with an increase in $H_0 \cdot PPI$. Although the thermal contact resistance is smaller for lower porosities, its ratio to the foam resistance is larger. For $H_0 \cdot PPI > 2.4$, the ratio TCR/R_{MF} is less than 5% over a wide range of porosities.

As can be seen, TCR is less than *5%* of the metal foam thermal resistance over a wide range of porosities and pore densities for relatively thick samples, e.g. only 6 mm height is enough to have TCR less than *5%* of the foam resistance when PPI=10. As a result, the thermal contact resistance is negligible for perfectly brazed metal foams. However, since there is no data in the literature, this cannot be verified. An experimental study is well underway at Simon Fraser University to investigate TCR.

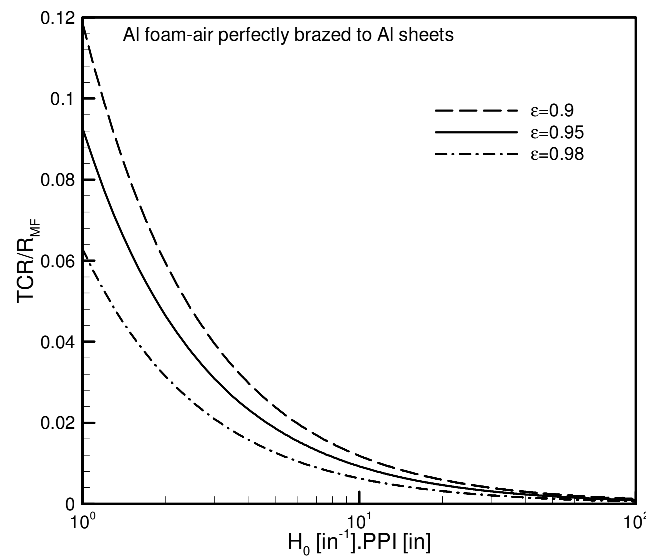


Figure 13. Effect of H_0.PPI on TCR at different pore densities.

6 SUMMARY AND CONCLUSIONS

In this paper, analytical models have been developed for the solid and hollow ligament structures of metal foams. A unit cell approach has been employed to represent the metal foam micro structure which consists of three interconnected orthogonal cylindrical ligaments with a cubic lumped material at their intersection. These cylinders can be solid or hollow. The model accounts for varying cross-sectional ligaments which is consistent with microscopic images showing larger diameters at intersections of the ligaments.

Moreover, a compact model for estimation of thermal contact resistance, TCR, between metal foam and contacting solid surfaces has been developed.

The model predictions are in good agreement with existing experimental data and the present numerical results over a range of porosities for a wide variety of foam materials and structures.

To investigate effects of variations in cross-section, aspect ratio, and inner-to-outer void ratio of ligaments, parametric studies have been performed. Highlights of these studies can be summarized as:

- Ligament cross-section geometry does not influence the effective thermal conductivity for a wide variety of shapes.
- Only small values of ligament aspect ratio have an effect on the effective thermal conductivity.
- An increase in the value of inner-to-outer void ratio decreases the effective thermal conductivity significantly.
- The thermal contact resistance is negligible compared to the medium resistance for perfectly brazed metal foams.

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