Prospective of employing high porosity open-cell metal foams in passive cryogenic radiators for space applications

Tisha Dixit¹ and Indranil Ghosh²

¹ Doctoral Student, Cryogenic Engineering Centre, IIT Kharagpur, India
² Assistant Professor, Cryogenic Engineering Centre, IIT Kharagpur, India

Email: tisha8889@iitkgp.ac.in

Abstract. Passive cryogenic radiators work on the principle of dissipating heat to the outer space purely by radiation. High porosity open-cell metal foams are a relatively new class of extended surfaces. These possess the advantages of high surface area density and low weight, characteristics which the space industry looks for. In case of radiative heat transfer, the porous nature of metal foams permits a deeper penetration of the incident radiation. Consequently, the heat transfer area participating in radiative heat exchange increases thereby enhancing the heat transfer rate. However, effective heat conduction in between the foam struts reduces as a result of the void spaces. These two conflicting phenomenon for radiation heat transfer in metal foams have been studied in this work. Similar to the foam conduction-convection heat transfer analysis, a conduction-radiation heat transfer model has been developed for metal foams in analogy with the conventional solid fin theory. Metal foams have been theoretically represented as simple cubic structures. A comparison of the radiative heat transfer through metal foams and solid fins attached to a surface having constant temperature has been presented. Effect of changes in foam characteristic properties such as porosity and pore density have also been studied.

1. Introduction
Energy transfer to low-temperature space is a commonly employed cooling technique to maintain cryogenic temperatures onboard space vehicles and satellites. The principle is simple – heat loads of the systems onboard are dissipated to the surrounding, which is effectively at a temperature of 4K [1], by radiation heat transfer. Generic term used for such instruments is ‘radiant coolers’ [2]. These radiant coolers may be used to maintain working temperatures for detectors or used as pre-coolers for different cryogenic process plants on board. The cooling capacity obtained from these radiators is in the range of 0.01–1 W with lowest achievable operating temperature of 80K [3]. Although the concept is based on a simple principle, the complexity involved in the supporting instrumentation is tremendous [2].

Open-cell metal foams are primarily porous structures having inter-connected metallic struts and void spaces. Metal foams are principally characterized by three parameters namely, porosity (or relative density), pore size and strut diameter. The porous nature enhances the usable surface area and makes these extremely light-weight while maintaining good structural stability [4, 5]. Literature review discloses that high-porosity metal foams have already found applications in compact heat exchangers [6, 7], heat sinks [8, 9], regenerators [10, 11], solar receivers [12], to name a few. The heat transfer characteristics have been well-investigated by different researchers [13].
Radiation heat transfer is macroscopically a surface phenomenon for most solids and liquids [14]. Between two surfaces, heat transfer by radiation is triggered by fourth order temperature difference and dependent on surface area and material properties. When an incident radiation falls on a metallic opaque surface, a part of it gets reflected depending on surface emissivity and a part is absorbed. Suppose if this metallic surface is of porous nature, the incident radiation will be able to penetrate within the surface. Higher the porosity, more will be the penetration of incident radiation and larger is the probability of radiative heat exchange [15]. Moreover, higher surface area gets exposed to incident radiation in comparison to a non-porous surface.

In the ultra-high vacuum outer space, radiation heat transfer is the only mode of heat transfer available for heating or cooling [16, 17]. Low weight of high porosity open-cell metal foams makes these highly attractive for space applications. Anticipating these to be good candidates as extended surfaces in cryogenic radiators, this work provides a comparison of the conventional solid fin and metal foam fin array in providing radiant cooling. In order to determine the radiant heat transfer through metal foams, their radiative heat transfer coefficient is employed in the conduction-convection foam fin analysis developed by Ghosh [18].

2. Theoretical analysis: metal foam array
Let us consider that a metal foam is attached to a surface of constant temperature and held in vacuum. Therefore the heat loss from the surface shall be by radiation alone. If the energy balance is considered over a differential element of the fin, the resulting equation will involve a fourth degree temperature term [19]. On the other hand, if the radiative heat transfer coefficient is known, the radiative heat transfer through foams can be calculated by employing the conventional fin theory.

Radiation heat transfer through a surface held in vacuum, assuming that the surface does not receive heat input from the surroundings, is given by [16],

\[ Q = \epsilon F_{12} \sigma A_s (T_s^4 - T_\infty^4) \]  \hspace{1cm} (1)

Expressing equation (1) in terms of radiation heat transfer coefficient in the form \( Q = h_r A_s (T_s - T_\infty) \) [14] gives,

\[ h_r = \frac{\epsilon F_{12} \sigma (T_s^4 - T_\infty^4)}{(T_s - T_\infty)} \]  \hspace{1cm} (2)

It may be noted that in case of a solid surface the view factor \( F_{12} \) shall be equal to one. However, the porous nature of metal foams causes internal absorptions and reflections of incident radiation. Consequently, the view factor is less than one. Dixit and Ghosh [20] have developed a theoretical model to determine the view factor based on foam porosity and pore density. In this model it has been assumed that the struts at the periphery alone interact with the surrounding.

Ghosh [18] has modified the conventional solid fin analysis for metal foams. Metal foams have been treated as an array of circular struts having diameter \( d_f \) with protrusions of length \( d_p/2 \) along perpendicular directions at every internal of \( d_p \) (figure 1). The strut diameter \( d_f \) and length \( d_p \) can be calculated the foam porosity and pore density using established correlations [18, 21].

The heat transfer through a single strut of length \( H \) with cross-connections is given by [18],

\[ q_{\text{foam single}} = \sqrt{h_r P k_f A_c (1 + 2 \eta_{1/2}) \theta_b \tanh (m_f H)} \]  \hspace{1cm} (3)

where, \( m_f = m \sqrt{1 + 2 \eta_{1/2}}, m = \frac{h_r P}{k_f A_c} \eta_{1/2} = \frac{\tanh (md_p/2)}{md_p/2} \) and \( \theta_b = T_s - T_\infty \).

The total radiation heat transfer can be calculated by multiplying equation (3) with the total number of struts (of length \( H \)) at the periphery of fin geometry.
3. Comparison of metal foam and solid fin array

Calculation of radiative heat transfer through a single fin is straightforward as the entire surface area is in thermal interaction with the surrounding. On the other hand, when an array of fins is considered, as in figure 2, there exists radiation exchange between neighbouring fins as well [17, 19, 22]. The analysis involves integro-differential system of governing equations requiring numerical solutions [22]. However, few researchers [23, 24] have opted for simplified solutions. While Rea and West [23] have used the concept of U-channel apparent emittance, Shabany [24] have developed simplified view factor correlations to calculate radiative heat transfer coefficient and then employ in the conventional fin theory.

For this study the geometry tested by Rea and West [23] has been taken up as shown in figure 2. The fins have been attached to a base at constant temperature and held in vacuum to promote only radiative heat loss. The dimensions of the finned heat sink are: \( L = 127 \text{ mm} \), \( H = 38.3 \text{ mm} \), \( W = 103.2 \text{ mm} \), \( s = 7.8 \text{ mm} \), \( t = 3.3 \text{ mm} \), \( b = 6.2 \text{ mm} \) and \( n = 10 \). The fins are made of aluminium.
having a surface emittance ($\varepsilon$) of 0.08 and apparent emittance ($\varepsilon_a$) of 0.54. The radiation heat transfer through the solid fin array is given by [23],

$$Q_{\text{rad solid}} = \left\{ (n - 1) \varepsilon_a s + \varepsilon [n t + 2(H + b)] \right\} \sigma (T_s^4 - T_\infty^4)$$

(4)

where the radiative heat transfer through the exposed portion of the base is given by the first term and the second term gives heat transfer through the attached fins.

Now, let the solid fins be replaced by aluminium ($k_f = 220\text{ W/mK}$) metal foams having a porosity of 90% and pore density of 20 PPI. Accordingly, the foam has a strut diameter of $d_f = 0.229\text{ mm}$, pore size of $d_p = 1.029\text{ mm}$ [18, 21] and view factor $F_{12} = 0.7934$ [20]. The foam dimensions and surface emittance are assumed same as of that of solid fin array. The U-channel apparent emittance has also been assumed to be same; however, practically, this will be higher since base shall be exposed to higher radiative interaction due to the porous nature of metal foams.

Each foam fin of dimension $H \times L \times t$ shall consist of $2 \left( \frac{t}{d_p} + \frac{L}{d_p} \right)$ number of fins at the periphery. Accordingly, the radiative heat transfer through the foam fin array, including the exposed portion of the base, can be obtained from the following equation,

$$Q_{\text{rad foam}} = (n - 1) \varepsilon_a s \sigma (T_s^4 - T_\infty^4) + 2 \left( \frac{t}{d_p} + \frac{L}{d_p} \right) n q_{\text{foam single}}$$

(5)

Assuming the temperature of the base at 200K (inherent assumption is that the surface emittance of 0.08 is valid at this temperature as well) and the ambient at liquid nitrogen temperature, mathematical calculations render that the radiation heat transfer through exposed portion of the base is 0.4272 W and that through the solid fins is 0.113 W. On the other hand, the foam fin array is found to provide a radiative heat transfer of 1.153 W in addition to the heat transfer from base. That is, the performance of foam fin array is approximately ten times higher than that of the solid fin array. Furthermore, foam fins provide an added advantage of weighing only 90% in comparison to solid fins.

Effect of change in the foam porosity and pore density on the radiative cooling, keeping all other parameters same as of the earlier analysis, has been depicted in table 1. The strut diameter, strut length and the view factor are calculated accordingly. It can be seen that while the heat transfer rate increases considerably with decrease in porosity, its variation with pore density is marginal. This may be because although with a reduction in porosity (for constant PPI foam) the penetration of radiation through the foam reduces, the participating surface area at the periphery increases. As a result, lower porosity foam provides higher radiation heat transfer rate. Conversely, when the porosity is kept constant, increase in pore density increases the surface area but reduces the heat transfer due to decrease in strut diameter. These two variations tend to compensate each other although a marginal decrease can be seen in the radiative heat transfer rate with increase in pore density.

| Porosity (%) | Pore density (PPI) | Radiation cooling (W) | Net effect |
|--------------|-------------------|-----------------------|------------|
| 80           |                   | 1.324                 |            |
| 85           | 20                | 1.252                 |            |
| 90           |                   | 1.153                 |            |
| 95           |                   | 1.083                 |            |
| 90           | 10                | 1.156                 |            |
|              | 20                | 1.153                 |            |
|              | 30                | 1.150                 |            |

Table 1. Radiation heat transfer through aluminium foam fin array.
4. Conclusions
This study showcases the potential of employing high porosity open-cell metal foams for radiant cryogenic cooling in space applications. A theoretical model has been developed to determine the radiation heat transfer from a finned foam surface using conventional fin theory. In case of the geometry under study, metal foams have been found to provide radiative cooling ten times higher than that of the solid fins. A decrease in porosity as well as the pore density of the metal foam enhances the radiation heat exchange. Further research is necessary so as to practically extract this cooling capacity.

Nomenclature

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\begin{align*}
A_c & \text{ Cross-sectional area of strut (m}^2) = (\pi/4) d_f^2 \\
A_s & \text{ Surface area of foam (m}^2) \\
d_f & \text{ Diameter of strut (m)} \\
d_p & \text{ Pore size (m)} \\
F_{12} & \text{ View factor} \\
h_r & \text{ Radiation heat transfer coefficient (W/m}^2\text{K)} \\
k_f & \text{ Thermal conductivity (W/mK)} \\
n & \text{ Number of fins} \\
P & \text{ Perimeter (m) = } \pi d_f \\
PPI & \text{ Pores per inch} \\
T_s & \text{ Temperature of the base (K)} \\
T_\infty & \text{ Temperature of the surrounding (K)} \\
\varepsilon & \text{ Emissivity} \\
\sigma & \text{ Stephan Boltzmann constant } = 5.67 \times 10^{-8}\text{W/(m}^4\text{K)}
\end{align*}
\]

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