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Research paper

Buoyancy driven convection in open-cell metal foam using the volume averaging theory

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HIGHLIGHTS

- Heat sinks with metal foam are studied in buoyancy driven convection.
- Study is done numerically based on VAT and comparison is made with experiments.
- When only convection is taken into account: differences are smaller than 29%.
- When radiative heat transfer is included: differences are smaller than 9%.
- Sensitivity study shows that convection coefficient is not most important parameter.

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ABSTRACT

Heat sinks with open-cell aluminium foam are studied numerically in buoyancy driven convection with air as surrounding medium. Results from a 2D numerical model are compared to experiments for different foam heights. The numerical model is based on the volume averaging theory. If only convective heat transfer is taken into account in the numerical model, the relative differences between the numerical and experimental results are smaller than 29% for all foam heights studied. However, when the influence of radiation is included in the numerical model, it is shown that the numerical results differ less than 9% with the experimental ones. This clearly shows that it is necessary to properly model radiative heat transfer in numerical models of open-cell aluminium foam in buoyancy driven convection.

Finally, a sensitivity study of ten main parameters of the volume averaged model (closure terms, effective properties) and the experimental setup (substrate temperature, dimensions of the heat sink) is performed. It is shown that the construction details and dimensions of the experimental setup have the largest impact on the heat transfer rate and not the convection coefficient, as is often assumed.

1. Introduction

1.1. Open-cell metal foams: advantages and nomenclature

A key issue in thermal management of low-end electronic components is to ensure that the junction temperature remains below a certain threshold. Typically, this is achieved with heat sinks. Air is preferred as a cooling medium in these applications as it is the most cost-effective solution. Furthermore, air cooling by means of buoyancy driven convection increases the reliability and reduces the operational costs compared to forced convection cooling because no fan is required. A relatively new application for buoyancy driven convection is the cooling of LEDs (Light Emitting Diodes) in automotive and domestic applications [1]. During their operation, LEDs generate heat. As their junction temperature increases, their optical efficiency starts to degrade. Therefore a cooling system is necessary to maintain the junction temperature at a sufficiently low level. Finned heat sinks are most common. There is a continuous search towards new fin designs to cool these electronic components [2–4]. Fins with a higher thermal performance per unit volume can decrease the unit size and weight of the system. Tree-shaped fins [5] and porous media like a packed bed of

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Nomenclature

$\dot{Q}$	electric power supply, W
A	area, m^2
c_p	specific heat capacity, J/kg K
h	heat transfer coefficient, W/m^2 K
k	thermal conductivity, W/m K
P	pressure, N/m^2
Re	Reynolds number, –
T	temperature, K
v	velocity, m/s

Greek symbols

β	inertial coefficient, 1/m
δ	uncertainty in
ε	emissivity, –
ϑ	sensitivity parameter, –
κ	permeability, m^2
μ	dynamic viscosity, Pa s
ρ	density, kg/m^3
σ	Stefan–Boltzmann constant, W/m^2 K^4
ϕ	porosity, –
ω	parameter
Δ	difference, –

Subscripts

conv	convective
d	dispersion
e	effective
env	environment
exp	experimental
f	fluid
fs	interfacial
num	numeric
r	radiative
s	solid
s	substrate

Superscripts

i	intrinsic

Abbreviations

μCT	micro-computed tomography
LED	light emitting diode
PPI	pores per linear inch
PUC	periodic unit cell
TCR	thermal contact resistance

spheres [6] are cited as new application-specific fin structures. Traditional porous media have a volumetric porosity below 70%. The porosity is defined as the ratio of the air volume to the total volume of the porous medium. Open-cell metal foam is a type of porous medium which can have a significantly higher porosity, typically above 90%. In buoyancy driven convection, open-cell metal foams have multiple advantages [7]. The foam has thin struts, creating many tortuous pathways and keeping the boundary layers thin which leads to an increase in the interstitial heat transfer. Due to the high surface-to-volume ratio of metal foams and the deformability in three dimensions, the foam heat sink can be made compact and robust. Moreover, the heat sink is also light, due to the high porosity.

The foams studied in this work are manufactured in-house by an investment casting technique, replicating an organic preform. A detailed description of the production process can be found in De Jaeger [8]. The nomenclature for open-cell aluminium foam (struts, nodes, pores and cells) is illustrated in Fig. 1. Manufacturers often characterize the foam by providing the PPI value (Pores Per linear Inch) and porosity ϕ [8].

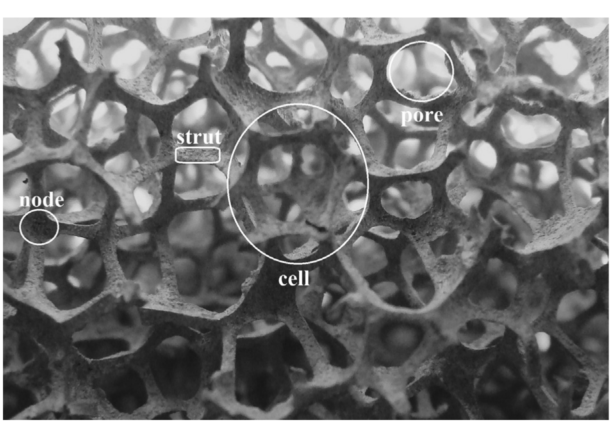

Fig. 1. Illustration of the nomenclature used in open-cell foams.

1.2. Parameters in buoyancy driven convection

Many parameters influence buoyancy driven convection in metal foam. De Schampheleire et al. [9] listed all important parameters for this case: foam material, foam height, geometrical characteristics of the foam, the length-to-width ratio of the heat sink substrate, inclination angle under which the heat sink is positioned, temperature difference between the environment and the substrate, radiative heat transfer contribution, contact resistance between substrate and foam (dependent on the bonding method), construction details of the test rig and the dimensions of the enclosure surrounding the heat sink. Furthermore, these parameters tend to interact with each other, making the analysis of buoyancy driven heat transfer a complex task. Available literature on buoyancy driven convection in open-cell metal foam is limited. Only some of the listed parameters have been studied and reported. In the following, an overview is given of the experimental and numerical work done in buoyancy driven convection.

Experimentally, Bhattacharya and Mahajan [10] studied the influence of pore density and porosity. The authors found that the heat transfer rate increases with a decrease in porosity or increase in metal content. When the porosity is constant, higher pore densities results in a lower heat transfer rate. The influence of the heat sink inclination angle is studied by Qu et al. [11] for copper foam. The inclination angle was varied in steps of 15° from vertical to horizontal orientation. The effect on the Nusselt number was only 6%. Finally, De Schampheleire et al. [9] analysed the influence of different foam heights, pore densities and bonding technologies for a heat sink with a length-to-width ratio of 10. The foam height was varied between 12 and 40 mm, the pore density was 10 and 20 PPI. Two bonding techniques were tested (epoxy and brazing)