EXPERIMENTAL INVESTIGATION OF THE EFFECTS OF FOAM HEIGHT, EMISSIVITY AND ORIENTATION ON BUOYANCY-DRIVEN CONVECTION IN OPEN-CELL ALUMINIUM FOAM

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ABSTRACT

In this paper air-saturated buoyancy-driven convection in open-cell aluminium foam is studied. The effects of foam height, radiative heat transfer and orientation are experimentally investigated. Two aluminium foam heat sinks with the same baseplate dimensions (6” by 4”) are tested. Their respective foam height is 22 mm and 40 mm. The aluminium foam has a porosity of 0.946 and a pore density of 10 pores per linear inch. The heat sinks are tested in a vertical and a horizontal orientation. The effect of radiation is studied by comparing untreated heat sinks with painted versions. During the experiments the power dissipated by the heat sinks is measured as function of the temperature difference between the baseplate of the heat sink and the ambient. The temperature difference is varied from 10 to 70°C.

By increasing the height of the foam, the heat dissipated by the heat sink increases by 49% at a temperature difference of 10°C. However, due to the high hydraulic resistance of the foam, only part of the extra heat exchanging surface area contributes to the convective heat transfer. This is illustrated qualitatively using smoke visualisations.

Painting the heat sinks results in an increase in heat transfer by 10% and 17% on average for the high and low heat sink respectively due to the higher emissivity values. The lower relative improvement of the high heat sink can be explained by the larger temperature drop along the height of the heat sink due to the low thermal conductivity.

Finally, the low painted heat sink dissipated up to 18% more heat in its horizontal orientation compared to the vertical one.

INTRODUCTION

Electronic components are omnipresent in daily life products such as cars, computers, power converters... So it is important to reduce the chance of premature electronics failure and to reduce the electrical energy used by the electronic components.

The main causes of electronics failure are elevated operating temperature, over-voltage, ESD and moisture [1]. The failures caused by elevated operating temperatures could be avoided by cooling the electronic components. Besides the increased lifetime, some components such as LED’s are more efficient at lower temperatures [2].

NOMENCLATURE

A	[m²]	Surface area
D_j	[m]	Junction diameter
h	[-]	Convection coefficient
k	[W/(m.K)]	Thermal conductivity
$\dot{Q}$	[W]	Power of heat
ΔT	[K]	Temperature difference between the heat sink and the surrounding

Abbreviations

ESD	Electro Static Discharge
HS	Heat Sink
LED	Light Emitting Diode
MF	Metal Foam
PPI	Pores Per linear Inch

Special characters

α_a	[m²/m³]	Surface to volume ratio
ϕ	[-]	Volumetric porosity

Nowadays, with the miniaturization of electronic devices and the subsequent rise of heat-fluxes [3, 4], heat sinks are needed to cool down electronic devices.

Passive and active heat sinks can be distinguished. The passive heat sink uses buoyancy-induced convection to dissipate heat. Active heat sinks are equipped with a fan to force air through them and thereby dissipate heat by forced convection.

From an ecological and economical point of view buoyancy-induced heat sinks are favourable over fan driven heat sinks. Buoyancy-induced heat sinks are more reliable, cheaper, maintenance free, and do not use any energy. The only drawback is their lower thermal performance for the same size and weight.

Nowadays, the surface-to-volume ratio of heat sinks is augmented by using fins. These fin shapes can become quite complex, e.g. 3-dimensional surface extensions. One promising material could be high-porous open-cell metal foam.

Open-cell metal foam is a porous media with a very high volumetric porosity (ϕ > 90%). The volumetric porosity is defined as:

$$\phi = \frac{V_{total} - V_{solid}}{V_{total}} \tag{1}$$

Due to a high porosity, the weight of the heat sink will be reduced which is beneficial for mobile applications.

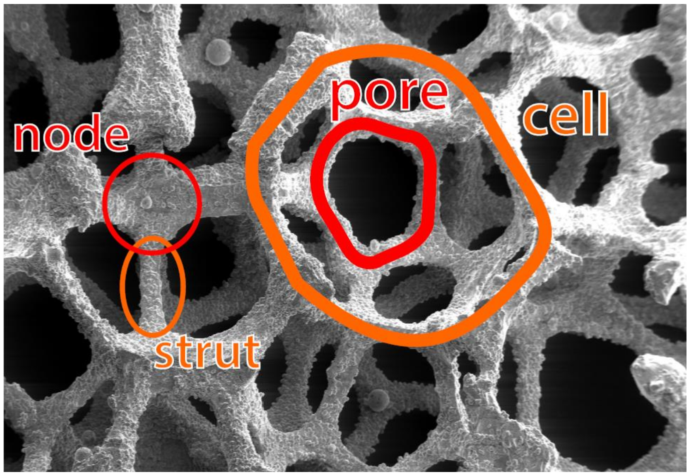

Figure 1 The structure of open cell metal foam.

The structure of metal foam can be found in figure 1. The foam consists of cells which are connected through pores. Each cell is made of several struts which connect in the nodes. Open-cell metal foam is typically characterized by its porosity ϕ and PPI-value.

LITERATURE SURVEY

Aluminium foam used in forced convection is extensively described in literature [5, 6]. But little is known about aluminium foam behaviour in buoyancy-induced convection.

Bhattacharya et al. [7] studied aluminium foam in buoyancy-induced convection in both vertical and horizontal orientation. The authors also compared their metal foam heat sinks with commercially available finned heat sinks. Their metal foam heat sinks outperformed the commercial ones. Qu et al. [8] used 98 sets of experimental data of copper foam heat sinks to construct a correlation for an arbitrary orientation. The authors also studied the effect of the foam height. De Schampheleire et al. [9, 10] studied the effects of the bonding method, foam height, radiative heat transfer and pore density on the heat transfer of metal foam. Based on the experiments of the previously mentioned authors [7-10] conclusions can be made about the influences of porosity, pore size, foam height, radiative heat transfer and orientation on the thermal performance of metal foam heat sinks in buoyancy-induced convection:

- The thermal performance of highly porous metal foam increases with decreasing porosity and fixed pore density. This can be explained by the increased surface area density and the higher thermal conductivity of the foam. A higher thermal conductivity results in a higher fin efficiency.
- The thermal performance decreases with increasing pore density (= decreasing pore size) for a fixed porosity. The effect of the increasing surface area is undone by the increased flow resistance.
- Qu et al. [8] and De Schampheleire et al. [9] concluded that the thermal performance of a heat sink increases with increasing height until an asymptotic value is reached. This asymptotic behaviour is caused by the increasing viscous drag and temperature drop along the foam's height with increasing foam height.
- De Schampheleire et al. [11] concluded that radiative heat transfer has an important effect on the heat transfer of metal foam heat sinks in natural convection. Thus radiation cannot be neglected.
- Both Qu et al. [8] and Bhattacharya et al. [7] found no significant effect of orientation on the thermal performance of metal foam in natural convection.

In this study the effects of radiative heat transfer, orientation and foam height on the thermal performance of metal foam will be investigated. The metal foam heat sinks, tested in open literature, have different dimensions and use different types of foam compared to the ones tested in this study.

EXPERIMENTAL SETUP

Description of Experimental Setup

No standard exists for testing heat sinks in natural convection. So, the experimental setup is based on experimental setups described in literature [7-9, 12, 13]. The setup is designed to have an as low as possible heat loss in order to pursue a one-dimensional heat flux through the heat sink.

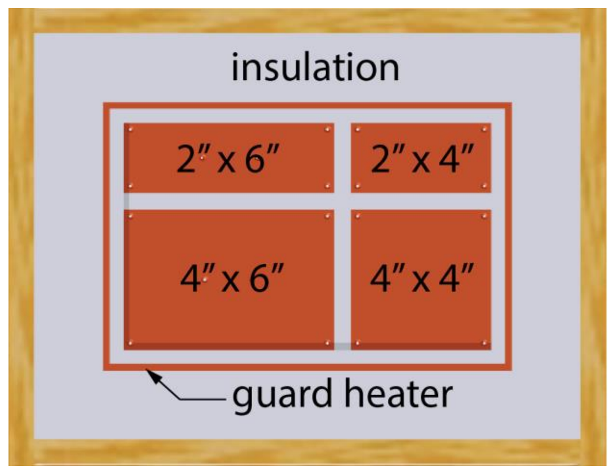

Figure 2 A top view of the experimental setup.

The experimental setup has 4 heaters (2″x4″, 2″x6″, 4″x4″ and 4″x6″) placed in an array (see figure 2) to be able to test different heat sink sizes. The heat sink will be placed on top of one or multiple heaters. In this study only the 4″x6″ heater was used.

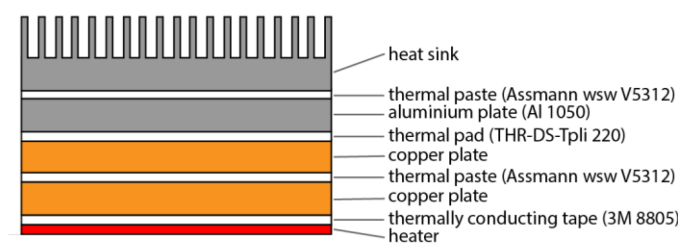

Figure 3 The complete stacking from film heater to heat sink.

Each of the four heaters consists of an electrical film heater (*Omega*® *KH* series) and a stack of metal plates (see figure 3). Two copper plates are used to ensure a uniform temperature

Table 1 Overview of the tested heat sinks

	width [mm]	length [mm]	height [mm]	porosity [-]	PPI	σ [m²/m³]	material
aluminium plate	150.3 ± 0.05	101.4 ± 0.05	-	-	-	-	Al 6060
aluminium foam	150.0 ± 0.05	100.9 ± 0.05	22.2 ± 0.05	0.946	10	400	Al 1050
aluminium foam	149.3 ± 0.05	101.0 ± 0.05	40.0 ± 0.05	0.946	10	400	Al 1050

distribution at the baseplate of the heat sink. This results in a uniform heat flux through the baseplate. An extra aluminium plate is added, to compensate for different baseplate thicknesses. To avoid insulating air gaps between the metal plates, layers of thermal paste (k = 0.8 W/(m.K)) and thermal pads (k = 6 W/(m.K)) are used. The two largest electrical film heaters are each powered by a power supply of *Elektro Automatik®* (PS 8160-04 2U). The two smallest electrical film heaters are each powered by a power supply of *TTi®* (PLH120-P).

Only side guard heaters are used in the experimental setup (see figure 3), while the bottom surface of the main heaters is well insulated. The insulation used in the experimental setup is *Microtherm®* panel (k = 0.0221 W/(m.K)). Between the side guard heater and the main heaters there is 10 mm of insulation. Next to the guard heaters there is 50 mm of insulation and below the heaters there is 100 mm of insulation.

When only a part of the heaters is used, the other heaters are used as guard heaters. The side guard heaters consist of an electrical film heater (Omega® KHLV series) and 2 copper plates. The side guard heaters are powered by a power supply of *TTi®* (PL303QMD-P).

At the top, a 5 mm thick plate of *Pertinax®* (k = 0.2 W/(m.K)) is used to hold the heat sink firmly against the heaters and to form a flush surface with the baseplate of the heat sink.

The temperature of each heater is measured by 3 K-type thermocouples (D_j = 0.5 mm), the temperature of the surrounding is measured by 4 K-type thermocouples (D_j = 0.75 mm) and the temperature of each side guard heater is measured by 2 K-type thermocouples (D_j = 0.5 mm). The thermocouples of the heaters are placed between the two copper plates (see figure 3) into a machined slot. The thermocouples are read out by a precision data acquisition system (*Keithley®* 2700).

Test Samples

Two metal foam heat sinks and a flat aluminium plate are tested (see table 1). All three have the same baseplate dimensions of about 4″x6″. The aluminium foam is glued onto the baseplate with thermal conductive epoxy (*Loctite® ESP110*). *Kontakt Chemie® Graphit 33* is used to increase the emissivity of the test samples during the radiative heat transfer tests.

Data Reduction and Uncertainty Analysis

During the experiments the power dissipated by the heat sink is measured as function of the temperature difference between the baseplate of the heat sink and the ambient. The temperature difference is varied from 10 to 70°C.

The temperature of the side guard heaters is controlled to the average temperature of the heat sink's substrate. Steady-state is reached when the standard deviation of 100 measurements is lower than 0.02. The sampling frequency is 0.17 Hz.

The uncertainty analysis follows the text book of Taylor [14].

All thermocouples are calibrated using a dry block calibrator (*Druck® DBC 150*) and a reference thermometer (*Fluke® 1523*). The average uncertainty of the thermocouples after calibration is ±0.11°C and the maximum uncertainty is ±0.2°C.

The heat dissipated by the heat sink is the power delivered by the electrical heaters minus the total heat loss. This heat loss is estimated by comparing the aluminium plate experiments with correlations from literature [15, 16].

The power dissipated by the electrical heaters is measured internally by the power supplies which feed the electrical heaters. The uncertainty on the power measurement depends on the actual power which is dissipated. The relative uncertainty ranges between 4.7% (5 W) and 1.5% (50 W).

All the dimensions are measured with a calliper with an uncertainty of 0.05 mm.

RESULTS AND DISCUSSION

The Effects of Foam Height

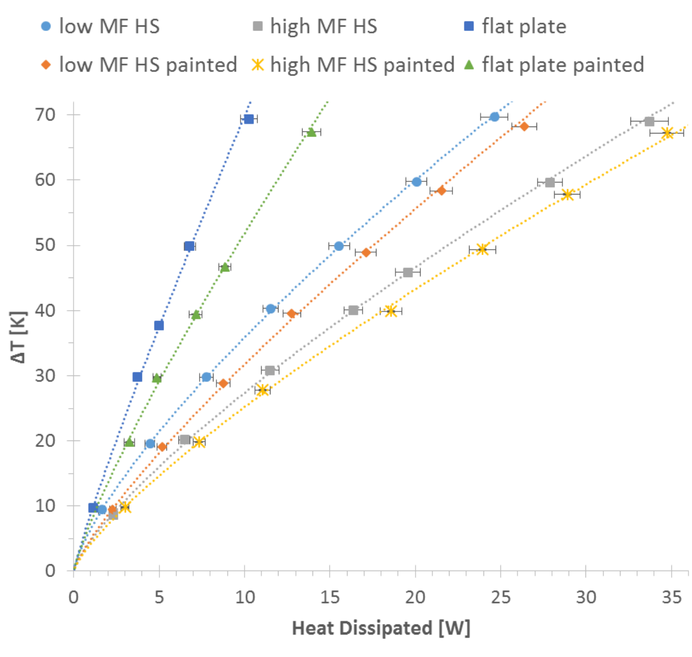

Figure 4 The effect of foam height and emissivity on the heat dissipated by the heat sink in horizontal orientation.

Figure 4 compares the 22 mm foam heat sink with the 40 mm foam heat sink. The high unpainted metal foam heat sink dissipates 49% and 39% more heat compared to the low unpainted heat sink for the lowest and highest temperature difference measured.

Ideally one expects almost a doubling of the dissipated heat if the surface area doubles. But due to the finite thermal conductivity and the relative high hydraulic resistance of the foam material, the increase in dissipated heat is less than double. Due to the finite thermal conductivity, the temperature at the top of the foam is lower for the higher heat sink than for the lower heat sink. Hence, the driving force for heat transfer will be lower. Moreover, the local convection coefficient and the radiative heat transfer increase with increasing temperature difference with the ambient. This suggests that the heat dissipated by a heat sink increases more than linear with the temperature difference between the baseplate and the ambient. But the higher heat flux induces a larger temperature drop over the heat sink. Thus the relative improvement by increasing the height will be less for a higher temperature difference.

Figure 5 The deflection of the flow above the low painted metal foam heat sink in horizontal orientation.

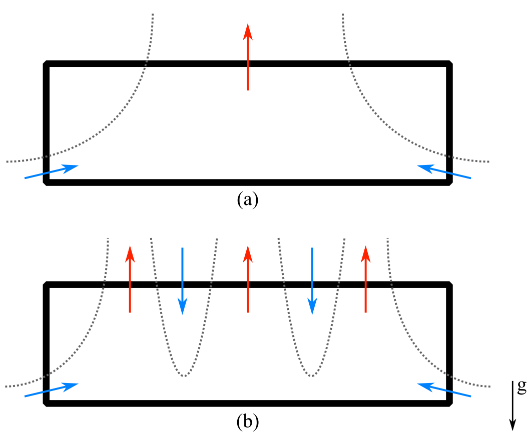

Figure 6 The air flow through a horizontal heat sink in (a) single- and (b) multi-chimney pattern.

Furthermore as a result of the high hydraulic resistance, part of the heat exchanging surface area in the heat sink hardly contributes to the convective heat transfer. This is illustrated by smoke visualization. The smoke is generated by burning incense. Figure 5 shows that the smoke, which entered the metal foam heat sink at the side near the baseplate, exits the metal foam before it reached its centre. The air that exits than deflects to the centre where it rises due to a chimney effect. Because of the deflection to the middle, cold air cannot enter from the top to form a multi-chimney pattern [17] (see figure 6). So part of the heat exchanging surface area hardly contributes to the convective heat transfer.

Similar results are found by Qu et al. [8] and De Schampheleire et al. [9]. Both concluded that the thermal performance of the heat sink increases with increasing height until an asymptotic value is reached due to the increase of hydraulic resistance.

The Effects of Radiative Heat Transfer

To study the effect of emissivity, the metal foam heat sinks are compared with their painted variants. By painting the heat sink black, the emissivity increases. A comparison between the unpainted and painted heat sinks can be found in figure 4. By painting the heat sinks, the heat transfer increased by 10% and 17% on average for the high and low heat sink, respectively. The lower relative improvement of the high heat sink can first of all be explained by its larger temperature drop along the height due to the finite thermal conductivity. This causes a lower wall temperature at the top of the heat sink and thus reduces the driving mechanism for radiation. Secondly there is the lower radiative-surface-to-total-surface-ratio. Only the surface area of the outer layers of pores, which sees the environment, contributes to the radiative heat transfer. Current experimental data confirms the conclusion of De Schampheleire et al. [10], namely the effects of radiative heat transfer cannot be neglected for metal foam in natural convection.

The flat plate has a larger improvement by painting it compared to the metal foam heat sink. This is because the thermal conductivity of the flat plate is very large. Thus the top will have the same temperature as the bottom of the baseplate. Moreover, also the emissivity of the unpainted flat plate is smaller than the emissivity of the unpainted metal foam ($\epsilon \approx 0.2$ vs. $\epsilon \approx 0.5$, respectively).

The Effects of Orientation

The low painted metal foam heat sink is tested in a horizontal and vertical orientation. The results are shown in figure 7. In the vertical orientation, the length of 6″ is parallel with gravity.

At low temperature differences with the ambient, no significant difference exists between the horizontal and vertical orientation. This agrees well with results from open literature [7, 8]. However at higher temperature differences, the horizontal orientation outperforms the vertical one by 18%. This difference can be explained by the different dimensions of the tested heat sinks compared to those tested in open literature. The heat sinks tested by Qu et al. [8] have a square baseplate (100 mm x 100 mm). The dimensions of the heat sinks tested by Bhattacharya et al. [7] are not specified in the paper. The heat sinks tested in our experiments have a rectangular baseplate. In horizontal orientation it is beneficial to have a rectangular shape because there is more surface at the side from where air is drawn into the foam (see figure 5).

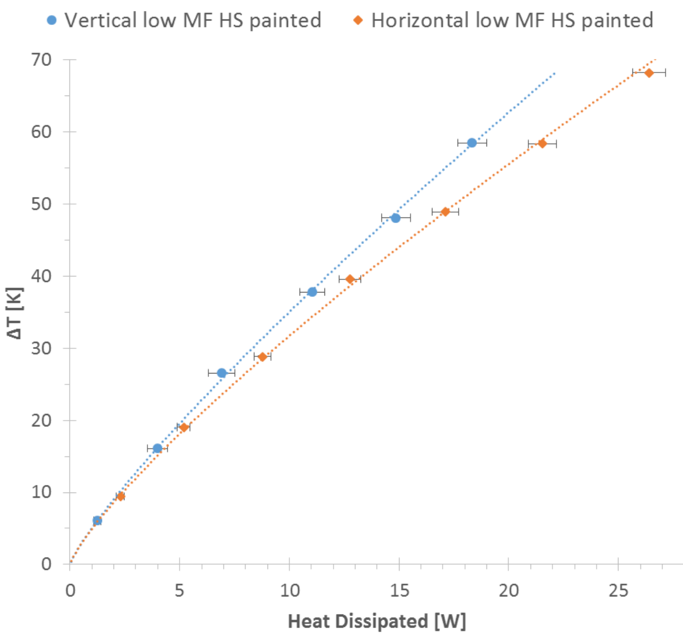

Figure 7 The effect of orientation on the heat dissipated by the heat sink.

CONCLUSION

In this study effects of foam height, radiative heat transfer and orientation on the thermal performance of open-cell aluminium foam in buoyancy-driven convection was studied experimentally.

Two aluminium foam heat sinks with the same baseplate dimensions (6” by 4”) were tested. Their respective foam height is 22 mm and 40 mm. The aluminium foam has a porosity of 0.946 and a pore density of 10 PPI.

During the experiments the power dissipated by the heat sinks was measured as function of the temperature difference between the baseplate of the heat sink and the ambient. The temperature difference was varied from 10 to 70°C. Based on the experimental results several conclusions can be made:

– When increasing the foam height from 22 mm to 40 mm, the heat dissipated by the unpainted heat sink increases by 49% and 39% at a temperature difference of 10°C and 70°C, respectively.
– The increase of the emissivity results in a significant improvement of the thermal performance of a buoyancy-induced heat sink. The magnitude of improvement is related to the thermal conductivity and the dimensions of the heat sink. A higher thermal conductivity results in a higher average wall temperature. A larger outer surface increases the area for radiation to the environment.
– The heat sink dissipates 18% more heat in horizontal orientation than in the vertical one at a temperature difference with the ambient of 70°C. At low temperature differences with the ambient, there is no significant difference between the horizontal and vertical orientation.

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