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THERMAL PERFORMANCE STUDY OF FINNED FOAM HEAT SINKS AND THE EFFECT OF PAINTING AND INCLINATION ANGLE IN NATURAL CONVECTIVE HEAT TRANSFER

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ABSTRACT

In this study, two different types of open-cell aluminium foam samples were experimentally tested: pure metal foam fixed to a substrate (a 'conventional' foam heat sink) and a finned foam heat sinks (where fins are inserted in the foam to increase the effective thermal conductivity). Samples with 5, 8 and 11 fins are tested. The substrate and fins are connected to the foam by epoxy glue (k = 0.55 W/mK). 10 PPI (Pores Per linear Inch) AL1050 foam is used with a porosity of 93%. The dimensions of the substrate are the same for all samples: 102x165 mm². Temperatures of the substrate range from 50 to 90°C. Next to studying the thermal performance in a horizontal orientation, some samples are also tested vertically. Furthermore, the impact of radiative heat transfer is investigated.

The 'conventional' foam heat sink performs best when comparing all foam samples: this is because of the increase in flow resistance in case of finned foam heat sinks. The thermal performance (heat transfer rate) of the 'conventional' foam heat sink is up to 15% higher compared to the worst performing finned heat sink with 11 fins. Effects of the inclination angle are (only) found to be significant for the 'conventional' foam heat sink (up to 15% in heat transfer rate) and painting the foam heat sink results in an increase in thermal performance up to 10.8%.

INTRODUCTION

Low end applications - using e.g. LEDs (Light Emitting Diodes) - require reliable, efficient and compact cooling equipment to ensure their longevity and optimal performance. These claims result in a continuous search to compact **three dimensional shapeable** materials, which are **light** (efficient) and have the ability of dissipating large amounts of energy so it can be operated **without using any fan** (which makes it reliable). Over the past decade, several complex fin shapes have been used to extend the substrate. One class of extended fin design is porous media. A more specific type of porous media, studied here, is open-cell aluminium foams. The nomenclature of open-cell foam is defined in Figure 1. Struts are interconnected in the nodes, forming both cells and pores. The foams studied here have full struts and are (consequently) made through an investment casting technique (basically replicating an organic preform [1]). Typically, manufacturers characterize open-cell foams based on their PPI-value (Pores Per linear Inch) and porosity (ratio of the air volume to the total foam volume). However as the cells are not spherical but orthotropic (due to frothing the preform against gravity [2]), this characterization is not sufficient. Rather two cell diameters (d_1, d_2) and the middle strut cross sectional area (A_0), as indicated in Figure 1, should be used [3]. These values are reported in this work based on micro-computed tomography (µCT) data.

NOMENCLATURE

A	[m²]	area
A_0	[m²]	cross-sectional strut area
d_1	[m]	large cell diameter
d_2	[m]	small cell diameter
h	[W/m²K]	convection coefficient
k	[W/mK]	conductivity
$\dot{Q}$	[W]	heat transfer rate
T	[K]	temperature
Special characters		
η	[-]	fin/foam efficiency
ϕ	[-]	porosity
σ_0	[m²/m³]	specific surface area
Subscripts		
s		substrate
env		environment

For buoyancy-driven flow (i.e. flow driven by a temperature difference), open-cell foam has lots of advantages:

- It has a high surface-to-volume ratio.
- It is shapeable in three dimensions (possible through the used casting technique and available post processing).
- It has a low weight, as the material has a volumetric porosity over 90%.
- It has a high potential to dissipate energy as small struts are creating lots of tortuous pathways, continuously disturbing the boundary layers, keeping them thin.

Natural convective dissipation (especially in comparison with cooling devices in forced convection) is very sensitive to external boundary conditions. The most important ones are listed here [4]:

- Influence of radiation.
- Influence of the inclination angle (angle under which the heat sink is placed).
- Foam material, height and type of foam (d_1, d_2, A_0) used. These parameters are influencing the effective conductivity, heat transfer (surface area) and flow resistance. Placing extra fins in between the foam e.g. will increase both effective solid conductivity and flow resistance [5], which are conflicting for heat transfer.
- Dimensions and temperature of the substrate where the foam is placed on.
- Bonding technique between substrate and foam/fins.
- Box geometry.

Bhattacharya and Mahajan [5] studied the influence of pore density (5, 10, 20 and 40 PPI) and porosity (from 89% to 96%) with substrate temperatures up to 75°C. A decrease in porosity causes an increase in heat transfer rate. Although the flow resistance is higher in this case, the increased effective conductivity compensates the negative effect of the flow resistance. Furthermore, for a higher pore density, a decrease in heat transfer rate is observed, this is due to an increase in the flow resistance. Only the heat sinks height (50 mm) and length (62.5 mm) were reported (not the heat sink width). The authors also investigated *finned* foam heat sinks (as in this work). Samples with 1, 2 and 4 fins were tested. The authors observe an increase of the heat transfer rate by inserting fins. As the length-to-width ratio of the samples of Bhattacharya and Mahajan is unknown (and the absolute length of our heat sink is different), the objective of this research is to investigate the generality of the work of Bhattacharya and Mahajan.

Qu et al. [6] studied influences of inclination angle, pore density (10, 20 and 40 PPI), porosity (90 to 95%) and aspect ratio (foam height) on a square heat sink (100x100mm²). Variation in foam height is found to be the most significant factor: an influence in heat transfer rate of 38% for a foam height variation from 10 to 50 mm. The effect of the inclination angle is found to be non-significant, although, based on the average values, the horizontal orientation always results in a higher performance.

Finally, De Schampheleire et al. [4] studied foam heat sinks with length-to-width ratio of 10, two different pore densities (10 and 20 PPI) and the effect of height and bonding technique (epoxy and brazing). It is found that the brazed samples are superior, and the foam height has (of all studied parameters) the most pronounced effect.

In this work, the objective is to study the effect of incorporating extra fins into a foam heat sink. The dimensions of the substrate are fixed on 102x165 mm² (length-to-width ratio of 1.62). Three finned foam samples are studied, with resp. 5, 8 and 11 fins incorporated in the foam. These samples are compared to a bare plate and a ‘conventional’ foam heat sink (without any fins incorporated in the foam, as studied by [4 - 6]). Furthermore, effects of inclination angle and radiation are studied limited.

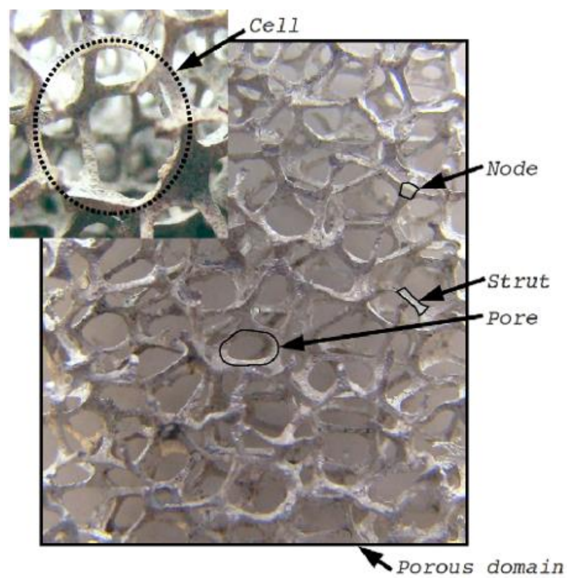


Figure 1 Nomenclature of open-cell (casted) metal foam

DATA GATHERING

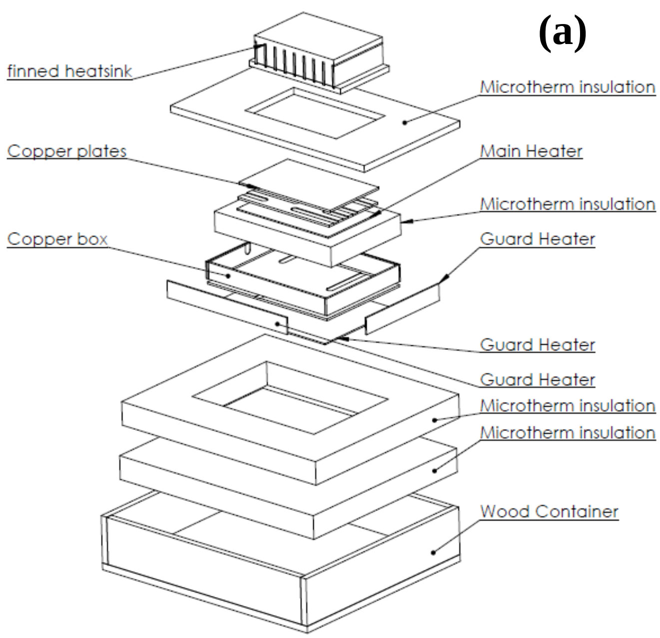
Test rig

Figure 2(a) shows a view of the heater assembly. The aluminium substrate measures 102x165x7 mm³. These dimensions are kept constant for all studied samples. The top surface of this plate equals the height of the surrounding insulation (as indicated in Figure 2(b)). No box is placed around the test rig. One copper plate (102x165x3 mm³) and the main heater are mounted underneath the substrate. The copper plate serves to make the heat flux from the main heater to the substrate uniform. The copper plate is machined to hold 8 thermocouples and cut through a water jet to ensure flatness. To enhance this contact, silicon thermal conductive paste (V5312 from Assmann WSW-Components®) is used.

The main heater is PID controlled with either the substrate temperature or $T_s - T_{env}$ as a set point. The heater is a flexible heater with silicone rubber encapsulation from Watlow Manufacturing Company®. The main heater is able to supply 260 W at a voltage of 120 V. Next to the main heater also five guard heaters are placed (four at each side of the main heater, and one below). The guard heaters are being held on the same temperature as the main heater, ensuring a one dimensional heat flux from the main heater to the substrate.

The power supply for the main heater is a Sorenson DCS 150-8E, while the power supply for the guard heaters are two PL303 QMB from AIM&Thurbly Thandar Instruments®. To measure the power supplied to the main heater, both current and voltage are measured. For the current this is done by measuring the voltage drop over a 10 Ω precision resistor.

As illustrated through Figure 2, the complete assembly is insulated with Promalight 1000R insulation material from Microtherm® with a thermal conductivity of 0.022 W/mK. Underneath the bottom guard heater, 35 mm of insulation is placed.



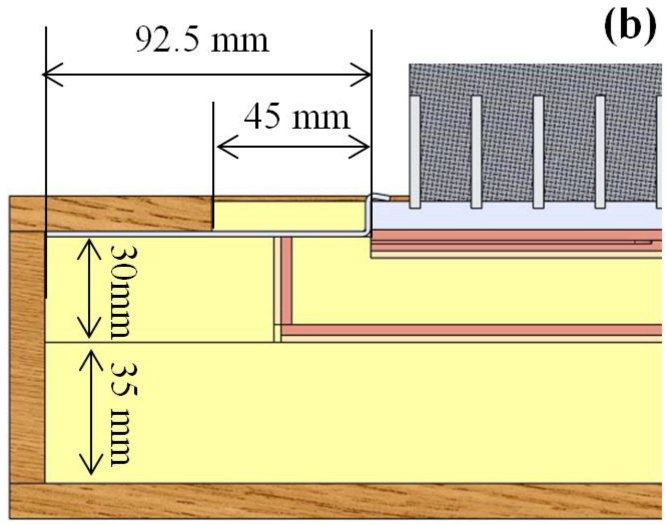


Figure 2 Illustration of the test facility. **(a)** View of the heater assembly. **(b)** Detailed view of attachment of the heat sink

Samples

All samples are made in-house. The foam, fin and substrate material are made out of AL1050, which consists of 99.5% pure aluminium. An illustration of the samples is shown in Figure 3. Fin spacings, the thicknesses of the fin and the foam characteristics $(\phi, d_1, d_2, A_0, \sigma_0)$ are reported in Table 1. As shown by Figure 3(c) and (d), only part of the substrate (102x165x7 mm³) is covered with foam. The foam sample measures only 102x143x40 mm³. As the fin efficiency is expected to be high in natural convection, 10 mm of foam is 'added' on top of the fins (Fig. 3(c) and (d)). The holes in the foam to fit the fins are machined on a CNC machine. Furthermore, the slots in the substrate to put the fins in (Fig. 3(c) and (d)) are also machined with a CNC. The slots in the substrate are 4 mm deep.

The foam is attached to the substrate and/or the incorporated fins by epoxy glue. Also the contact between the fins and the substrate is done by epoxy. The epoxy (k = 0.55 W/mK) is applied to the substrate and the fins, any excess is scraped off and the foam is then pressed on it. The epoxy needs to cure for 1 hour at 150°C. Despite its relatively low thermal conductivity, it has a proper viscosity at room temperature.

Table 1. Characteristics of the foam samples

	Fin spacing [mm]	Thickness fin [mm]	Foam characteristics ϕ [-], d_1 [mm], d_2 [mm], A_0 [10^{-1} mm^2], σ_0 [m^{-1}]
5 fins incorporated with foam	35	3.4	0.933 ± 0.002, 4.22 ± 0.18, 6.23 ± 0.18, 0.998 ± 0.08, 462 ± 35
8 fins incorporated with foam	20	3.4	same foam type
11 fins incorporated with foam	14	3.4	same foam type
'conventional' foam heat sink	N.A.	N.A.	same foam type
flat plate	N.A.	N.A.	N.A.

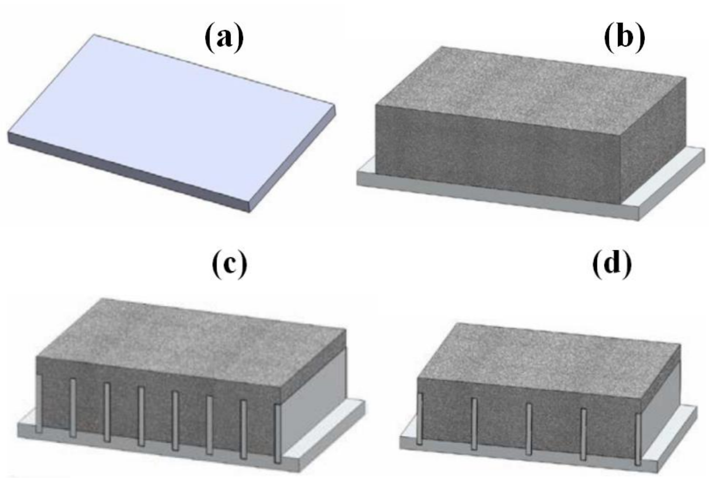


Figure 3 Illustration of some of the studied samples. **(a)** bare plate, **(b)** 'conventional' foam heat sink, **(c)** finned heat sink with 8 fins, **(d)** finned heat sink with 5 fins

Procedure

The temperature of the substrate (T_s) is varied between 50°C and 90°C. The set point target of the substrate temperature is given for each sample in Table 2. The required heat flux to obtain these temperatures is given by $\dot{Q}_{total}$ (Eq. (1)). $\dot{Q}_{total}$ consists of:

- A flux sent (or returned) by the guard heaters ($\pm \dot{Q}_{guard}$).
- A leak flux of the clips ($\dot{Q}_{clips}$, as indicated in Fig. 2 (b), in order to fasten the heat sink when it is placed vertically).
- A leak flux of the insulation ($\dot{Q}_{ins}$).

$$\dot{Q}_{total} = \dot{Q} \pm \dot{Q}_{guard} + \dot{Q}_{clips} + \dot{Q}_{ins} \quad (1)$$

The influence of $\dot{Q}_{guard}$ is calculated and is found to be limited in comparison with the uncertainty in measuring $\dot{Q}_{total}$ and the other leak fluxes. $\dot{Q}_{clips}$ is calculated through a 1D conduction problem and $\dot{Q}_{ins}$ is calculated through finite element analysis in 2D. In this study, only $\dot{Q}$ (based on Eq. (1)) will be reported and used in further calculations.

All measurements are done in steady-state conditions. Steady-state is assumed if the temperature at the main heater does not vary more than 1% over a time span of 5 minutes. The data is gathered by a National Instrument® Data Acquisition System. For every sample, a dataset is obtained by sampling all relevant quantities during 300s at a sampling rate of 1 Hz. The resulting overall thermal resistance is defined as Eq. (2), where the surface of the substrate (A_s) is taken as the heat transferring surface.

$$R_{overall}\left(\frac{\Delta T}{\dot{Q}}\right) = R_{cond,Al} + R_{cond,Cu} + R_{thermal\ paste} + R_{conv}\ \left(\frac{1}{\eta h A_s}\right) \quad (2)$$

The overall thermal resistance includes the thermal conductive resistances of the copper and the aluminium plates (resp. $R_{cond,Cu}$ and $R_{cond,Al}$), thermal paste ($R_{thermal\ paste}$) and the external convective resistance (R_{conv}). After each measurement campaign, the thickness of the thermal paste is measured and it is found to be typically in the order of 1 mm. In the resulting convection coefficient (h in Eq. (2)), both radiative effects and the thermal contact resistance were lumped, as it is difficult to measure contact resistance and radiative heat

Table 2. Temperature set points of the substrate for the different samples.

	T_s [K], vertical	T_s [K], horizontal	T_s [K], painted black Vertical	T_s [K], painted black Horizontal
5 fins incorporated with foam, *epoxy*	*N.A.*	50 – 70 - 90	*N.A.*	*N.A.*
8 fins incorporated with foam, *epoxy*	50 – 70 – 90	50 – 70 – 90	*N.A.*	*N.A.*
11 fins incorporated with foam, *epoxy*	*N.A.*	50 – 70 – 90	*N.A.*	*N.A.*
'conventional' foam heat sink, *epoxy*	50 – 70 – 90	50 – 60 – 70 – 80 – 90	43.64 – 48.63 – 53.53 – 59.27 – 64.41 – 74.44 – 84.15 (fixed ΔT)	50 – 60 – 70 – 80 – 90
flat plate	50 – 60 – 70 – 80 – 90	50 – 60 – 70 – 80 – 90	42.2 – 50.28 – 55.3 – 60.13 – 65.16 – 72.23 – 82.16 (fixed ΔT)	50 – 60 – 70 – 80 – 90

transfer rate with a small uncertainty [4]. As illustrated by De Schampheleire et al. [4], the influence of the thermal contact resistance on the overall thermal resistance is expected to be around 5% for 'conventional' foam heat sinks with length-to-width ratios of 10. This is much lower than the effect in forced convection [7]. In this work either $\dot{Q}$ or ηh (as the foam efficiency is difficult to calculate [8]) will be reported as a function of ΔT. This ΔT is the temperature difference between the average substrate temperature and the ambient air. Some measurements are done for fixed ΔT, whereas others are done for fixed T_s.

Uncertainty analysis

In order to assess the quality of the measurements, a thorough uncertainty analysis was performed. Standard error propagation rules as described by Moffat [9] were used to calculate the overall uncertainty (root-sum-square method). Error on the dimensions of the heat sink varies between 0.5 and 1 mm. Note that all uncertainties in this work are expressed as 95% confidence intervals.

Prior to the measurements, all thermocouples were calibrated using a Druck DBC150 temperature calibrator furnace to eliminate systematic errors. The reference temperature is measured with a FLUKE 1523 PT100 with an accuracy of 0.015°C. The resulting uncertainty on all thermocouples is taken to be 0.1°C conservatively.

For all measurements, the relative uncertainty on ΔT ranges from 3.8% to 5.6%, on $\dot{Q}$ from 2.6% to 8.2% and for ηh from 2.9% to 8.5%. A dimensionless Rayleigh number is not reported as this enters difficulties in selecting a proper characteristic length to compare a foam heat sink in horizontal and vertical orientation.

RESULTS AND DISCUSSIONS

Thermal performance of (finned) foam heat sinks in horizontal orientation

First, the finned foam samples are compared to the 'conventional' foam heat sink and a bare plate for a horizontal orientation. For a range of temperature differences, the heat transfer rate ($\dot{Q}$) send to the substrate is compared in Figure 4. Although the finned foam heat sinks have a higher effective conductivity, they do not transfer more heat due to the higher flow resistance which makes it more difficult for the surrounding air to penetrate into the foam. Of all the finned foam heat sinks, the heat sink with 11 fins performs the worst. The finned heat sink with 5 fins and the heat sink with 8 fins have a same thermal performance (within measurement uncertainty). When comparing the finned foam heat sink with 11 fins to the one with 5 or 8 fins, the thermal performance is between 4% and 12% lower (depending on the imposed ΔT). Along all foam heat sinks, the 'conventional' heat sink has the best performance: up to 15% higher than finned heat sink with 11 fins. The 'conventional' foam heat sink has a no-significant different heat transfer rate in comparison with the 5 and 8 finned heat sink.

These results are very different to the trends observed by Bhattacharya and Mahajan [5]. They observed that increasing the number of fins, increases the heat transfer rate. A priori, one should expect an increase in heat transfer rate by inserting extra fins, as the foam efficiency is typically low (compared to the fin efficiency of finned heat sinks), even in natural convection.

In the current study, however, the length-to-width ratio is small: the distance from the centre of the heat sink to the side is quite large. This makes it difficult for the air to penetrate into the foam: per unit volume of foam material there is less external surface area in contact with air in comparison to samples with a large length-to-width ratio (like the ones tested in [4]). In the former case, inserting extra fins will decrease the heat transfer rate, as it gets even more difficult for the air to penetrate into the foam.

The 'conventional' foam heat sink performs on average 3.5 times better than a bare plate (see Fig. 4). This value is in accordance with the results obtained by Bhattacharya and Mahajan [5].

Similar results are found for the lumped convection coefficient. These are plotted in Figure 5.

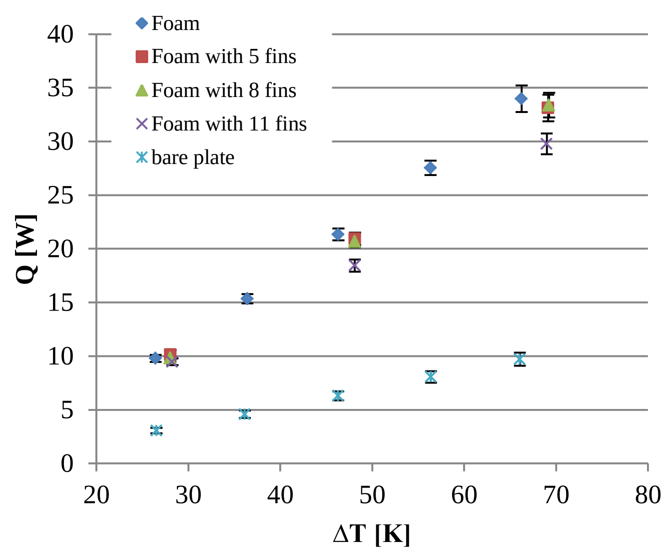


Figure 4 Heat transfer rate ($\dot{Q}$) to the substrate against ΔT for all studied samples, horizontal orientation

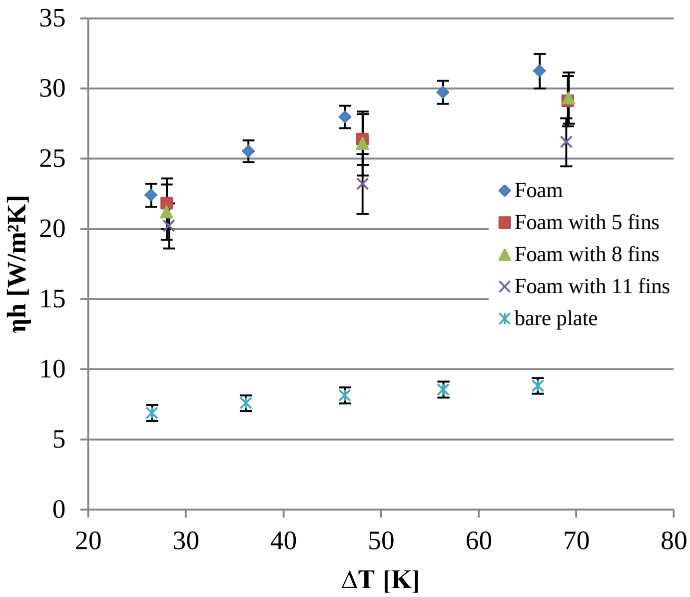


Figure 5 The lumped convection coefficient (ηh) against ΔT for all studied samples, horizontal orientation

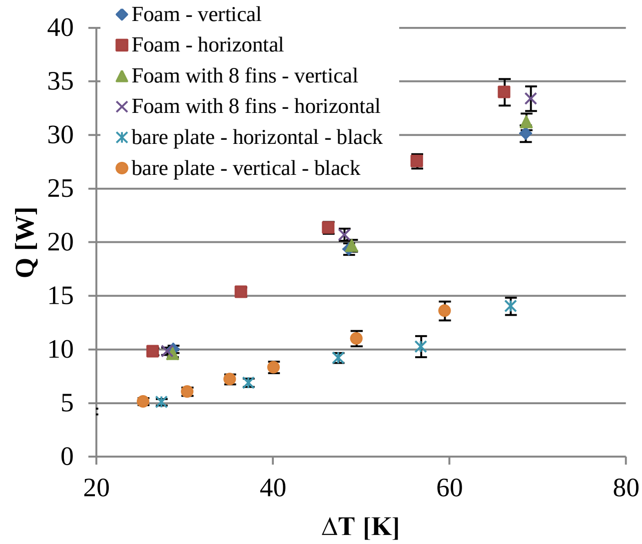


Figure 6 Illustration of the effect of inclination angle (orientation) for the 'conventional' foam heat sink and the 8-finned foam heat sink

Effect of vertical vs. horizontal orientation

A second point of interest in practical applications is the inclination angle (orientation of the heat sink). When the cooling device is mobile and turnable, possible increase or decrease in thermal performance has to be taken into account. To study this, the test rig is placed vertically. The fins are aligned with gravity, so the air gets maximal capability to move through. Experiments are done for the 'conventional' foam heat sink, the finned foam heat sink with 8 fins and the bare plate (painted black).

The effect of the inclination angle is only significant for the bare plate and the 'conventional' foam heat sink, experiencing an effect in heat transfer rate up to resp. 17.1% and 15.2%. For the finned heat sink an in-significant effect is found, up to 6%. The vertical orientation results for the foamed heat sinks in a lower performance, while the bare plate experiences the reverse effect. The effect on the inclination angle is studied for a square foam heat sink by Qu et al. [6].

As the length-to-width ratio in the current study is small (1.62:1), it is more beneficial to operate the heat sinks vertically. In the horizontal position, a single chimney flow pattern will appear. Air is heated from the sides of the foam and is pushed out of the foam due to foam resistance (permeability and inertial coefficient) and decreasing density (increasing temperature of the air). In a vertical position, it seems that more 'active' surface area is in direct contact with the air. The vertical foam height when the heat sink is positioned vertically is a factor 3 larger compared to the vertical foam height when the heat sink is positioned horizontally (102 mm vs. 40 mm, respectively).

Effect of the emissivity (painting)

To study the effect of radiative heat transfer, some of the heat sinks are painted black with a spray (Graphit 33). This results in a higher emissivity (higher than 90%) in the infrared region. This is verified own thermal emissivity measurement equipment (TIR 100-2 from INGLAS).

The influence of increasing the material's emissivity is the highest for the bare plate. The heat transfer rate is increased up to 44.3%. For the 'conventional' foam heat sink, there is a small but significant difference when comparing the horizontal and vertical orientation. For the horizontal orientation, the effect of painting the heat sink is 7.5% while the vertical orientation experiences a higher increase: up to 10.8%.

Painting has the largest effect in heat transfer rate for the bare plate. This is because the initial emissivity of a bare plate (order of magnitude 20%) is typically much lower than the untreated emissivity of metal foam (order of magnitude 50%). So the gain of painting the heat sinks is limited (but significant) for the foam samples.

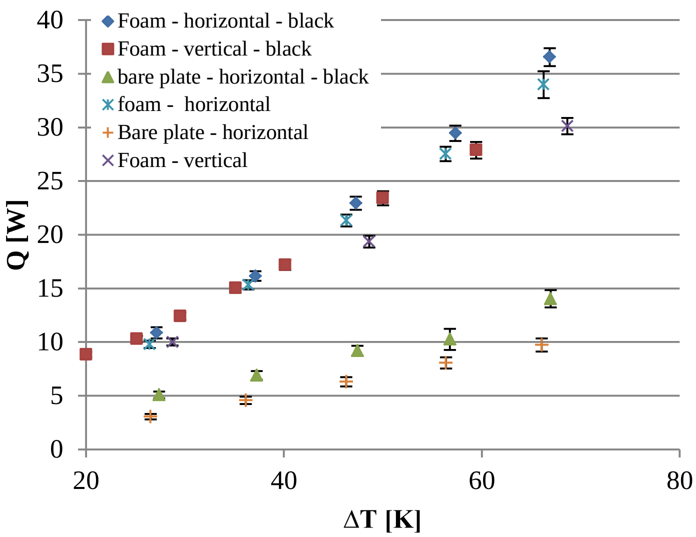


Figure 8 Illustration of the effect of radiative heat transfer by painting the heat sinks

CONCLUSIONS

An experimental study on buoyancy-driven convection in (finned) foam heat sinks (102x165 mm²) is performed. The temperature of the substrate is varied between 50°C and 90°C. In this study the influence of using finned foam heat sinks (with resp. 5, 8 and 11 fins), their orientation (inclination angle) and the emissivity (radiative effect) is reported. The foam heat sinks are also compared to a bare plate.

Following results are obtained:

- The 'conventional' foam heat sink performed the best when all tested foam heat sinks are compared. The heat transfer rate is 15% higher than the worst finned foam heat sink. The more fins that are used, the worse the thermal result.
- Orientation effects are only significant for the 'conventional' foam heat sink (effects up to 15%). Based on the average values, the horizontal foam heat sinks perform better.
- Finally, the effect of an increase emissivity is studied. Effects up to 10.8% are found when painting a vertically orientated conventional foam heat sink.

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