# CONVECTIVE HEAT TRANSFER PERFORMANCE OF STAGGERED HEAT SINK ARRAYS FABRICATED BY SELECTIVE LASER MELTING

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**ABSTRACT**: In this paper, the forced convective heat transfer performances of heat sinks produced by Selective Laser Melting (SLM) were experimentally investigated. In total, three staggered array heat sinks were fabricated by SLM of aluminium alloy AlSi10Mg powders in Future of Manufacturing Lab 1, Singapore Centre for 3D Printing. The heat sinks which are of different fin geometries, namely, circular, rectangular rounded and aerofoil shaped fins (NACA 4424), were tested in a rectangular air flow channel. The flow channel was designed with large wall-to-fin clearance ratios such that pressure differences across the various heat sinks measured under similar flow conditions are negligible. Experiments performed for mass flow rates ranging from 0.00554 kg/s to 0.0387 kg/s showed that the heat transfer performances of the aerofoil and rectangular rounded heat sinks exceeded those of the circular heat sink. The highest enhancement in heat transfer coefficient of 33.9% was recorded with the rectangular round heat sink as compared to the circular heat sink at mass flow rate 0.0387 kg/s whereas the highest enhancement in heat transfer coefficient of 28.7% was achieved with aerofoil at mass flow rate 0.00554 kg/s. It is suggested that the aerodynamically designed aerofoil shapes resulted in minimal hydraulic resistance which allowed larger air flow rate between the fins with insignificant bypass, thereby improving the heat transfer performances of the heat sinks. On the other hand, vortex shedding due

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to the blunt edges of the rounded rectangular heat sink was postulated to have resulted in the enhanced heat transfer.

**KEYWORDS:** Selective laser melting; Heat sink; Convective heat transfer; Aerofoil.

## INTRODUCTION

Advancement in additive manufacturing process has resulted in the development of Selective Laser Melting (SLM), which allows fabrication of solid metal parts from metal powders. Complex and intricate designs can be produced from Computer Aided Design (CAD) drawings which can then be translated to fabrication directly. The components are built by spreading a layer of metallic powder, onto a base plate and then melting the powder using a precise laser to achieve the shape required based on the CAD drawing. The melted powder quickly re-solidifies to form a solid and the process is repeated layer by layer until the component is built. The potential cost reductions, decrease in number of production process and geometric freedom in designs are some of the many factors that contributes to the increase in popularity of this manufacturing technique (Read et al., 2015; Yadroitsev et al., 2015).

Few researchers have studied the potential of using SLM for fabricating heat sinks. Heat sinks are passive devices which make use of extended surfaces to increase heat dissipation from a heat source to the surroundings. Heat is transferred from the base of the heat sink through the fins to the surrounding fluid by conduction and convection. The performance of the heat sink is dependent on parameters such as surface geometry, thermophysical properties of fluid and solid, and fin spacing. Selective Laser Melting shows potential for fabricating heat sinks as it is able to process metals such as aluminium alloys which have high thermal conductivity and produce parts of high densities. Studies were performed by Louvis et al. (2011) and Kempen et al. (2012) on the mechanical properties of aluminium alloys such as AlSi10Mg, Al6061 and AlSi12. Wong et al. (2009) successfully manufactured five air-cooled heat sinks of different geometries using SLM. Neugebauer et al. (2011) produced a miniature water-cooled heat exchanger using SLM and demonstrated that new design approaches can be made to improve efficiency via additive manufacturing. The fine details and close proximity of the parts produced by SLM showcased the process' ability to manufacture high surface-volume ratio heat sinks with intricate and complex designs.

For air-cooled heat transfer devices, pin fin arrays are commonly used. The fins can have cross section areas varying from circular, elliptical, square to rectangular shapes. Due to the flexibility in changing the designs of pin fin heat sinks by simply varying the cross section area of the pins, much research have been carried out to determine the performance of different designs of pin fins. Li and Kim (2008) conducted numerical studies to optimise staggered elliptical pin fin arrays. Sahiti et al. (2006) and Zhou and Catton (2011) conducted numerical studies on a variety of cross-section shapes – circular, square, elliptical, NACA aerofoil, dropform and lancet. In this paper, the authors will investigate the ability of using SLM to produce heat sinks of different geometries and characterise their convective heat transfer performance.

## METHODOLOGY

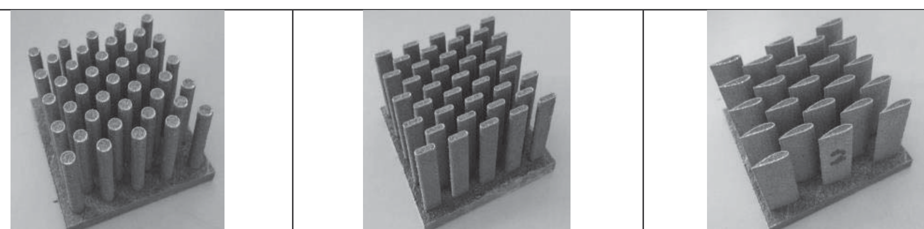
### Surface Preparation

Three heat sinks of staggered arrangements, namely circular, rounded rectangular and aerofoil (NACA-4424) geometries were fabricated using SLM. The machine used is SLM250HL (SLM Solutions GmbH), which is housed in the Future of Manufacturing Laboratory 1 of Singapore

Centre for 3D Printing (SC3DP), Nanyang Technological University. A Gaussian distributed Yb:YAG laser of maximum power of 400 W and laser beam spot size of 80 µm was used for melting the metal powder. AlSi10Mg powders with a distribution size of 20 µm to 63 µm were used.

The base area of the heat sinks was fixed at 50 mm by 50 mm, with a thickness of 5 mm. The fins were fixed at 25 mm height. For the circular arrangement, it consisted of 41 fins, each with diameter of 4 mm and fin pitch of 10 mm. For the rectangular rounded arrangement, the array consists of 41 fins of 2 mm width and 6 mm length each. For the aerofoil arrangement, it consist of 23 NACA-4424 fins, with a maximum thickness at 2.4 mm and chord length of 10 mm. The fabricated heat sinks are shown in Figure 1.

Dimensional accuracy of the printed parts was determined by taking microscopic measurements of the fins. An "OLYMPUS" SZX7 Zoom Stereo Microscope was used in this process. Twenty fins of each heat sink were chosen at random and the dimensions were measured and averaged. The close-up images of the different heat sinks are shown in Figure 2. From the measurements taken, the maximum dimensional error of the fins is 2.5%. For the radius of the circular cross-section (4 mm), length of the rounded rectangular cross-section (6 mm) and chord of the aerofoil cross-section (10 mm), the dimensional errors are 2.4%, 1.1% and 2.4% respectively. The analyses showed that SLM is able to fabricate small and intricate components accurately with only a small dimensional error.



(a) (b) (c)

Figure 1. Fabricated heat sinks of (a) circular, (b) rectangular rounded and (c) aerofoil fins.

(a) (b) (c)

Figure 2. Microscopic view of (a) circular, (b) rectangular rounded and (c) aerofoil fins.

**Heat transfer experimental setup**

The convective heat transfer experiments were conducted by providing air flow over the heat sinks in a vertical channel with a cross-sectional area ($A_{channel}$) of 105.6 mm by 75 mm. The cross-sectional area of the channel is large compared to the heat sink ($A_b$) of 50 mm by 25 mm in the direction of air flow, thus allowing bypass of air flow. This was to simulate the common operating conditions where the heat sinks are not fully ducted. The pressure drop was measured using a pitot tube. The power to the fan was varied to provide air flow at different speed. Air speed ($V_{air}$) is measured by an anemometer at the upstream of the air flow. Thermocouples were included at the inlet and outlet regions of the channel to measure the air stream temperatures, $T_{in}$ and $T_{out}$, respectively. The experimental setup is illustrated in Figure 3.

The heat source for the experiment was provided by four cartridge heaters inserted into a copper block so as to provide uniform heat flux to the surface of the heat sink. The heat sink was attached to the copper block using thermally conductive epoxy, "Omegabond-101", so as to reduce contact resistance. For insulation, 15 mm and 21 mm thick Teflon were used to surround the side and back surfaces, respectively. The heat input to the cartridge heaters were varied using a variable transformer. In order to measure the surface temperature of the heat sinks, two holes were drilled from the side into the base of heat sinks to insert thermocouples. The average of the two temperatures at the heat sink base, $T_w$, was used in calculation. The temperatures of the heat sink, inlet and outlet were recorded using the MW100 Data Acquisition Unit.

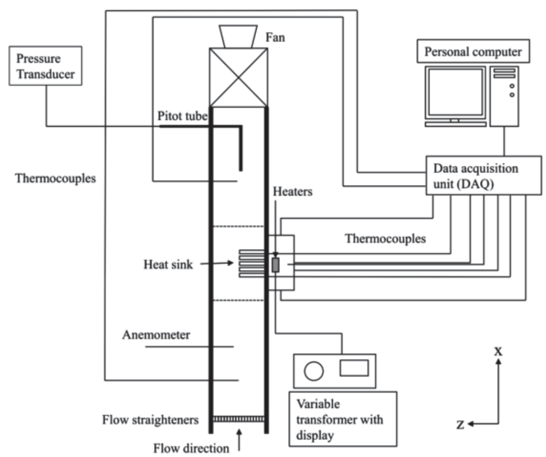



Figure 3. Schematic diagram of setup

**Conduct of experiments and data reduction**

The power to the cartridge heaters can be calculated by the product of current ($I$) and voltage ($V$). The power input was set such that it was equal to 15 W. The average heat loss ($\dot{Q}_{loss}$) due to natural convection was estimated to be about 12%. The total heat input ($\dot{Q}$) to the heat sink is shown in Eq. 1.

$$\dot{Q} = I * V - \dot{Q}_{loss} \quad (1)$$

The air speed was varied from 0.5 m/s to 3.5 m/s at intervals of 0.5 m/s. For each air speed, the temperatures of the heat sink ($T_w$), inlet ($T_{in}$) and outlet ($T_{out}$) were recorded when steady state condition was reached. Steady state condition was determined to be reached when temperature reading fluctuations were within ± 0.1 K for at least 5 minutes. The heat transfer performance of the different heat sinks was determined in terms of the average convective heat transfer coefficient ($h$) as shown in Eq. 2. The surface area was kept constant as the base surface area ($A_b$) of 50 mm by 50 mm as the experiment was designed to determine the effects of cross-section geometries. The mass flow rate of experiment for different velocities is shown in Eq. 3.

$$h = \frac{\dot{Q}}{A_b[T_w - (\frac{T_{out}+T_{in}}{2})]} \quad (2)$$

$$\dot{m} = \rho_{air} V_{air} A_{channel} \quad (3)$$

## RESULTS AND DISCUSSION

Initial tests were carried out to determine the pressure drop across the channel for the different heat sink designs. At the maximum velocity of 3.5 m/s, the average pressure drop across the channel for all heat sinks were constant at approximately 5 Pa. Thus, the air flow for the different heat sinks were hypothesised to be redistributed according to the fluid resistance through the heat sink and bypass regions to attain constant total pressure drop.

The heat transfer coefficient vs mass flow rate for each of the heat sink is plotted in Figure 4. The heat sink with a higher heat transfer coefficient for the same mass flow rate indicates a better heat transfer performance. From the results, the heat sink with rounded rectangular geometry performed the best, followed by the aerofoil geometry and then circular geometry. By using the circular geometry as benchmark, the highest enhancement in heat transfer coefficient of 33.9% was recorded with the rectangular round heat sink as compared to the circular heat sink at mass flow rate 0.0387 kg/s whereas the highest enhancement in heat transfer coefficient of 28.7% was achieved with aerofoil at mass flow rate 0.00554 kg/s.

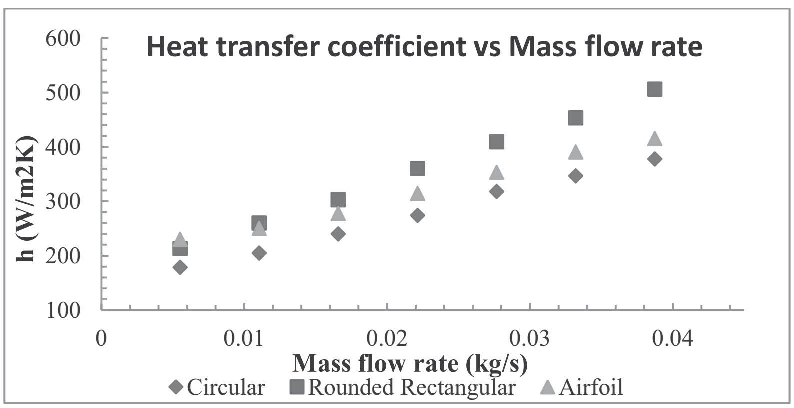



Figure 4. Heat transfer coefficient vs mass flow rate for different heat sinks

The better performance of the rounded rectangular and aerofoil geometries as compared to the circular geometry could be attributed to the effect of bypass. As both the rounded rectangular and airfoil geometries were more streamline in nature, they tend to provide less resistance in air flow and thus allowed a higher air flow rate through the fins. The greater interaction between the cool air and the fins led to better heat transfer performances.

Between the rounded rectangular and aerofoil geometries, the heat transfer performances were comparable at low Reynolds number. However, as the Reynolds number increases, the rounded rectangular geometry outperformed the aerofoil geometry. This could be due to the effect of vortex shedding. Vortex shedding due to the blunt edges could have occurred for the rounded rectangular geometry, but not so for aerofoil geometry due to its superior aerodynamic shape. Thus, the effect of vortex shedding greatly enhanced heat transfer by allow better fluid mixing and surpassed the effect of increased air flow for aerofoil geometry with lower fluid resistance.

## CONCLUSIONS

Three heat sinks of circular, rectangular rounded and aerofoil geometries were fabricated using SLM. The ability to produce parts of high density and complex structures makes SLM suitable for heat transfer application. The highest enhancement in heat transfer coefficient of 33.9% was recorded with the rectangular round heat sink as compared to the circular heat sink at mass flow rate 0.0387 kg/s whereas the highest enhancement in heat transfer coefficient of 28.7% was achieved with aerofoil at mass flow rate 0.00554 kg/s. It is suggested that the aerodynamically designed aerofoil shapes resulted in minimal hydraulic resistance which allowed larger air flow rate between the fins with insignificant bypass, thereby improving the heat transfer performances of the heat sinks. On the other hand, vortex shedding due to the blunt edges of the rounded rectangular heat sink was postulated to have resulted in the enhanced heat transfer.

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