# Passive heat transfer enhancement by 3D printed Pitot tube based heat sink

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**Abstract**

3D printing, also referred to as Additive Manufacturing - AM in case of metal materials, allows to fabricate complex shaped parts and devices in a single step. Extreme flexibility of AM techniques could pave the way to a revolution in conceiving heat transfer devices in the near future. Along this way, we designed and fabricated by AM an innovative heat sink incorporating Pitot tubes for realizing passive heat transfer enhancement. Preliminary tests show that the proposed heat sink allows up to 98% heat transfer augmentation, as compared to conventional heat sinks. We hope this study will help in encouraging the community to explore novel approaches thus moving towards the design of new devices fully exploiting the 3D printing flexibility in the field of thermal engineering.

*Key words:* Heat transfer enhancement, Electronic cooling, Additive manufacturing, Selective laser melting, Pitot tube

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## 1. Introduction

Effective heat transfer enhancement is fundamental in many technological fields such as, for instance, turbine blades cooling [1, 2] and thermal management of electronic devices [3, 4, 5, 6, 7]. 3D printing technologies, also referred to as additive manufacturing (AM) in case of metal materials, have been claimed to be promising techniques for manufacturing heat transfer devices with enhanced performances [8]. Recent works in the literature have shown several interesting and stimulating examples where the peculiarities of AM processes are used to further optimize well-known heat transfer enhancement techniques, such us pin fins [9, 10], vortex generators [11], rough surfaces [12], offset strip fins [9], lattices [9] and porous media [13]. Those works clearly reveal the potential to increase the thermal efficiency of traditional heat transfer techniques by the use of AM. Above all, the extreme flexibility in shape of parts by AM could pave the way to a revolution in the current thinking and designing of heat transfer devices, thanks to unusual morphologies and heat transfer performances.

In this work, we have designed and manufactured by AM a novel heat transfer device based on *Pitot tube* effect. Starting from a conventional plate fin heat sink considered as reference setup [14, 15], we modified it by introducing (i) hollow fins and, on the top of fin array, (ii) a static pressure plug, which is in communication with (iii) several openings at the bottom of hollow fins. The basic idea is exploiting the Pitot tube effect for inducing secondary flows orthogonal to the main flow within fins, thus enhancing heat transfer in the region where the velocity field is less vigorous (i.e. bottom of fins).

The paper is organized as follows: in section 2, the heat sink design, manufacturing and testing procedures are described; in section 3, the experimental results of the Pitot and reference heat sinks are presented and examined; in section 4, conclusions are drawn and perspectives are discussed.

## 2. Materials and methods

Two heat sinks have been manufactured, tested and compared in this work, namely the proposed innovative heat sink and the corresponding reference one. The heat sink with Pitot tubes has been manufactured by the AM process of selective laser melting (SLM), which is also known as direct metal laser sintering (DMLS). This process allows to produce complex-shaped parts by melting metal powders with a laser beam, which is used as power source. An AlSiMg alloy powder supplied by EOS has been adopted in the process, whose properties (e.g. shape, size distribution) are reported elsewhere [16]. Process parameters have been properly chosen, in order to guarantee an extremely low value of bulk porosity (below 0.8%). A detailed description of SLM process and machine parameters used to manufacture the Pitot heat sink are provided in Refs. [12] (section 2.1) and [17] (Tab. 1), respectively.

As depicted in Fig. 1, the Pitot heat sink is made of: (i) a 11x11x5 $mm^3$ parallelepiped; (ii) three 2x10x10 $mm^3$ hollow fins; (iii) a 11x10x6 $mm^3$ static pressure plug. The parallelepiped is the bottom part of heat sink, whereas hollow fins are located on its upper side. Each fin is equally spaced from neighboring ones by 2 $mm$, and fin walls are 0.5 $mm$ thick. Hence, the cavity volume is 1x9x10 $mm^3$ in each fin. Moreover, eight ellipsoidal openings have been placed at the bottom of each fin wall. The latter openings have dimensions 1.6x0.8 $mm^2$, and are arranged along three rows in a staggered configuration. Finally, the walls of the static pressure plug are 1 $mm$ tick laterally, while the remaining ones are 0.5 $mm$ tick. The present heat sink has been manufactured in one step by SLM, whereas bottom and lateral sides of the parallelepiped have been refined by milling, in order to properly insert it into the housing of a heat flux sensor, as detailed in Ref. [18].

A reference heat sink made of copper and manufactured by traditional milling has been also realized and tested for comparison purposes (Fig. 2). This conventional heat sink consists of a parallelepiped with three fins, with the same dimensions as in the Pitot heat sink; however, it differs from the Pitot heat sink as it does not have hollow fins, static pressure plug and openings.

Both Pitot and reference heat sinks are tested in a forced, fully developed and turbulent air flow. The experimental rig is an open loop wind tunnel with hydraulic diameter $D = 187$ $mm$ and average air velocity ($u$) varied from 3 to 15.5 $m/s$. The tunnel length is approximately 25 times the hydraulic diameter dimension, ensuring that air flow achieves fully developed turbulent regime in the ending zone, where the measurement section is located.

A convective heat flux sensor is installed in the measurement section [18]. This sensor is based on the concept of thermal guard, it has a characteristic length of $L = 20$ $mm$ and it is flush mounted on the tunnel wall. As already demonstrated in earlier works, this sensor can accurately measure the local convective heat flux ($Q_c$) transferred from heat sink to air. All details on test rig, experimental procedures, and uncertainties estimation methods here adopted have been reported in Refs. [12, 18, 19, 20].

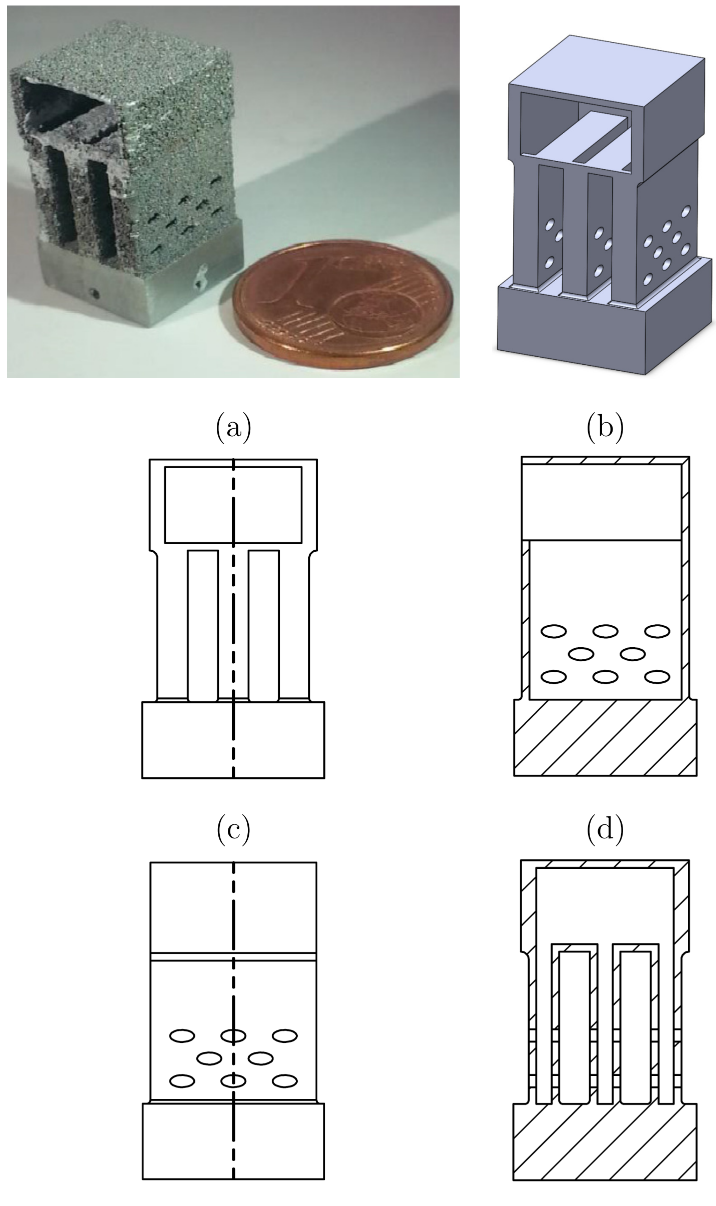



Figure 1: Heat sink with Pitot tubes embedded into the fins. (a) Picture of the prototype. Drawings of the prototype: (b) isometric view; (c, f) front views; (d, e) lateral views. Dashed lines in (c, e) define the cross-sections represented in (d, f).

Figure 2: Reference heat sink.

## 3. Results and discussion

The Pitot heat sink has been first tested in the *open configuration* (Fig. 1). For the sake of comparison, a *closed configuration* has been also tested, where a thin copper foil is glued at the bottom of the static pressure plug, thus preventing the Pitot effect without affecting the overall shape of the heat sink. In fact, in the closed configuration, the foil is intended to stop the secondary flows at the bottom of fins, by inhibiting the fluid communication between static pressure plug and fin openings. Testing the Pitot heat sink in both open and closed configuration is crucial to demonstrate the impact of the sole Pitot effect on heat transfer enhancement. In fact, the heat transfer enhancement due to secondary flows can be quantified by a direct comparison between the two configurations.

The experimental results for the tested heat sinks are reported in Fig. 3, where the measured convective thermal transmittance ($Tr$) of heat sinks as a function of the Reynolds number ($Re_L = uL/\nu$) are showed. Here,

$\nu = 1.6 \times 10^{-5}\ m^2/s$ is the kinematic viscosity of air under testing conditions.

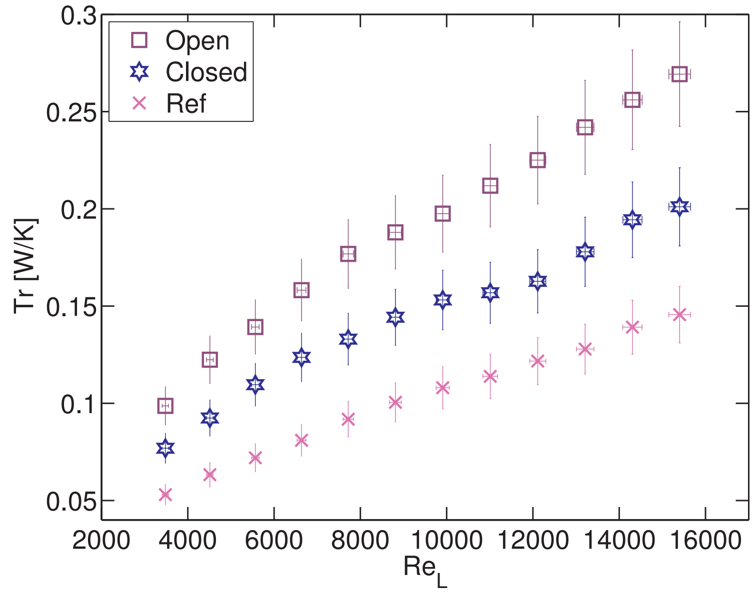
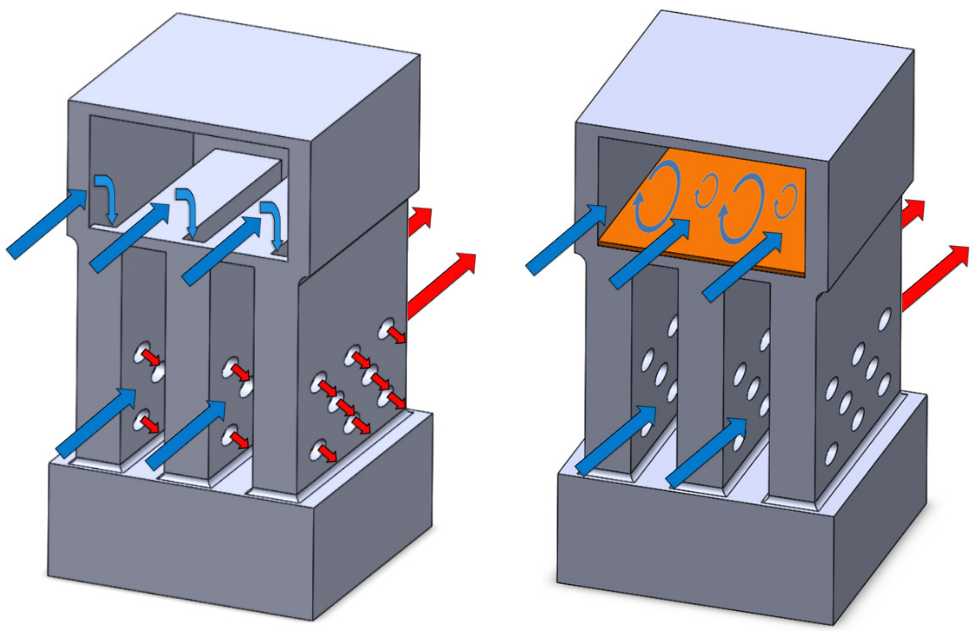



Figure 3: Convective thermal transmittance measured at different Reynolds numbers, for open Pitot (purple squares), closed Pitot (blue stars), and reference (pink crosses) heat sinks. Uncertainties are estimated according to the procedure proposed in Ref. [18].

It is worthwhile to note that the thermal transmittance of the Pitot heat sink with open configuration is higher than the closed one, which is in turn higher than the transmittance of the reference heat sink. The superior performance of the open Pitot configuration as compared to the closed one demonstrates the heat transfer improvement by the secondary flows due to Pitot effect.

As expected, the pressure increase in the plug induces a secondary air flow circulation along the fin cavities, which exits from the openings at the bottom of fin array (Fig. 4a). Hence, the resulting convective heat transfer enhancement stems from two phenomena. First, the secondary air flow along the fin cavities cools down the inner fin walls, therefore an additional heat transfer area is involved in the heat transfer process. Second, air flows out of the openings orthogonally to the primary air flow and fin walls, thus interfering with the boundary layer and consequently enhancing the local heat transfer coefficient on the external fin walls.



(a) (b)

Figure 4: Schematics of the air flow patterns in the Pitot heat sink with (a) open and (b) closed configurations.

The Pitot heat sink with closed configuration shows thermal transmittances lower than the open one, because the fluid separation between static pressure plug and fins cavities prevents the creation of secondary air flows. Hence, the kinetic energy of air entering the tap is dissipated by eddies (Fig.

4b). From our preliminary results, the open Pitot configuration exhibits maximum and average $Tr$ enhancements up to 38% and 32%, respectively, as compared to the closed ones.

Finally, we stress that the reference heat sink has the lowest thermal transmittance among the tested configurations. This happens because the conventional heat sink benefits neither of the additional heat transfer area provided by the static pressure plug (still present in the closed Pitot configuration), nor of the secondary flows induced by the Pitot tubes. Additionally, the innovative heat sink can also benefit of the artificial roughness readily available in parts manufactured by AM, as extensively reported in Ref. [12].

In conclusion, the proposed heat sink based on the Pitot tube effect shows a maximum (average) enhancement in convective thermal transmittance of 95% (88%), as compared to the reference case. Finally, we emphasize that the proposed solution is a *passive* heat transfer augmentation technique, which does not need any additional energy source to work.

## 4. Conclusions

In this study, an unconventional heat sink is proposed, which implements an innovative *passive technique* for heat transfer augmentation. The proposed device has been designed and manufactured in a single step by exploiting the capabilities and flexibility of selective laser melting in fabricating complex shaped components. Given a main flow field, the proposed *Pitot heat sink* induces secondary flows passing through the fin cavities and exiting orthogonally to the main flow. As a result, this solution significantly improves the convective heat transfer by concurrently (i) increasing heat transfer area and

(ii) enhancing local heat transfer coefficient on fin walls, especially in regions where the flow field is less vigorous (fin bottom). The reported experiments show up to 95% increase in thermal performances of Pitot heat sink as compared to standard one. The Pitot tube effect is estimated to have an impact of nearly 40%; two major effects are instead responsible for the remaining 50% enhancement of the AM solution with respect to the conventional heat sink, namely (i) the increase in heat transfer area due to the static pressure plug and (ii) the artificial roughness by AM [12].

The preliminary results reported in this work are intended to shed light on the new frontiers that additive manufacturing are opening in heat transfer engineering. We hope that the extreme geometrical flexibility offered by additive manufacturing may lead to new ways in conceiving and designing next-generation heat transfer devices.

## Competing interests

The authors declare that they have no competing interests.


## Acknowledgments

PA, EC, LV and MF would like to acknowledge the THERMALSKIN project for the revolutionary surface coatings by carbon nanotubes for high heat transfer efficiency (FIRB 2010, grant number RBFR10VZUG) and the NANO-BRIDGE project for the heat and mass transport in NANO-structures by molecular dynamics, systematic model reduction, and non-equilibrium thermodynamics (PRIN 2012, grant number 2012LHPSJC).

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