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The utilization of selective laser melting technology on heat transfer devices for thermal energy conversion applications: A review

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ABSTRACT

This paper reviews advanced heat transfer devices utilizing advanced manufacturing technologies, including well-established thermal management applications. Several factors have recently contributed to developing novel heat transfer devices. One of the potential technologies revolutionizing the field of energy conversion is additive manufacturing (AM), colloquially known as three-dimensional (3D) printing. This technology permits engineers to develop a product with a high level of freeform features both internally and externally within a complex 3D geometry. Among different AM approaches, selective laser melting (SLM) is a well-used technique for developing products with a lower cost-to-complexity ratio and quicker time production compared to other manufacturing processes. The integration of SLM technology into heat exchangers (HXs) and heat sinks (HSs) has a strong potential, especially to fabricate customized and complex freeform shapes. The aim of this research is to review the advancement in design complexities of different industrial heat transfer devices incorporating metal SLM fabrication. The review is not meant to put a ceiling on the AM process, but to enable engineers to have an overview of the capabilities of SLM technology in the field of thermal management applications. This review presents the opportunities and challenges related to the application of SLM technology in connection to novel HXs and HSs, as well as heat pipes (HPs). The latter are passive heat transfer devices utilized in many thermal control applications, especially related to electronics cooling and energy applications.

1. Introduction

During the last decades, increasing heat transfer in many industrial applications has been a major concern, therefore researchers have been engaged to develop new energy saving and conversion strategies for different applications. The utilization of a heat exchanger (HX)/heat sink (HS), as a heat transfer device, is important for a variety of thermal control systems, energy storage systems and energy conversions applications include refrigeration cycles, heat recovery, automotive industry and electronic equipment, as well as renewable energy applications, including fuel cells, thermal energy storage and geothermal [1–5]. In addition, heat pipes (HPs), as passive heat transfer devices that operates by utilizing the latent heat of an internal working fluid, are also progressively used in industry [6–8]. A unique feature of HPs is that the evaporator and condenser sections can be separated by a large distance, and thereby experiencing a minimal temperature difference while transferring large amounts of heat. Hence, energy (heat) can be transported with very low thermal losses. Their simplicity as well as widely varying sizes, shapes and materials allow them to be used in different HX/HS applications [9–11].

Despite the impressive progress that has been made during the past decades on development of HXs/HSs, there are still serious technical challenges in thermal management of compact devices, mainly due to the growing power density, owing in part to increased performance requirements. For example, the maximum chip heat flux of high-performance electronic devices will increase up to 190 W/cm^2 [12] as illustrated in Fig. 1. This provides the requirement for the development of high performance HXs/HSs. For this aim, advances in the manufacturing methods that can precisely fabricate fully functional compact and efficient heat transfer devices is important in engineering applications. They should result in the use of less space and material, and allows for higher thermal loads and power densities. In light of this scenario, a significant effort has been carried out towards additive manufacturing (AM) approaches [13–24].

AM, formerly coined as rapid prototyping and rapid tooling, is also referred to as three-dimensional (3D) printing. Unlike conventional manufacturing processes, AM can directly produce complex 3D parts, with near net shape. It is a process whereby a 3D solid object is fabricated directly from the digital CAD file. AM products are built using successive layers of material that are stacked and bonded, in which

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Nomenclature

d_p	Powder particle diameter (m)
f	Friction factor
h	Heat transfer coefficient (W/m^2 K)
k	Thermal conductivity (W/ m K)
K	Permeability (m^2)
Nu	Nusselt number
r_p	Powder radius (m)
r_c	Capillary radius (m)
Re	Reynolds number
u	Velocity (m/s)

Greek symbols

ε	Porosity (dimension less)
ρ	Density ($kg\,m^{-3}$)
μ	Dynamic viscosity (Pa s)
σ	Surface tension ($N\,m^{-1}$)
θ	contact angle (°)

Subscripts

eff	Effective
l	Liquid
s	Solid

Abbreviations

AM	Additive manufacturing
CAD	Computer-aided design
HP	Heat pipe
HS	Heat sink
HX	Heat exchanger
LHP	Loop heat pipe
SLM	Selective laser melting
PHP	Pulsating heat pipe

each layer holds the shape of a slice of the digital model. AM techniques can be grouped based on the energy source (laser/electron beam), feedstock form (powder/wire) and feeding system (powder bed/blown powder) [25,26]. Each method has its own advantages and drawbacks depending on cost, materials, etc. Details on these manufacturing methods can be found in many reviews [27–32]. The most promising type of AM for fine industrial purposes is the approach using a laser beam as a source of energy and a powder bed system. This technology, selective laser melting (SLM) is the focus of the current review. Through SLM, a part is built by selectively melting material supplied in the form of a fine powder within a powder bed. This approach provides a method for fabricating a single complex geometry that could offer a range of advantages compared to conventional manufacturing techniques, including reducing the total number of parts, higher production rate, unique design and less geometrical constraints [33,34]. These features make SLM technology an important tool in terms of industrial applications [35,36], particularly in highly customized, freeform parts for the thermal management sectors [37–44].

The application of SLM technology within the thermal management field is facilitated by the ease of converting modern heat transfer devices into CAD designs. One ability of SLM is optimizing heat transfer through HX/HS systems to increase surface area of the same length size in comparison of traditional manufactured systems. For an example, traditional HSs employ surface area extensions such as pins and fins for increasing the surface area [45]. This effect can be drastically enhanced by employing an SLM approach [37,38]. In addition, geometrical features on the part could be manufactured to enhance flow mixing, resulting in a further enhancement in heat removal [46]. Another advantage of SLM technology are integrated composite structures or multi-material fabrication [47] to optimize parts of a product, including high thermal conductivity, ease of integration with the heat dissipation component, etc. Therefore, the potential of utilizing SLM in the production of functional heat transfer components such as HXs, HSs and HPs has recently received increased attention.

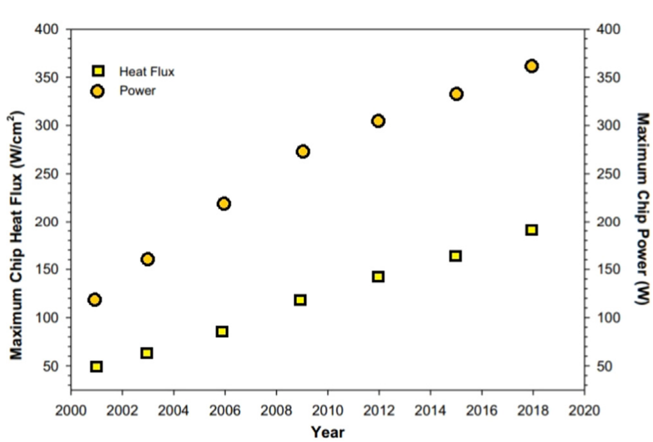


Fig. 1. Power trend high power electronic applications [12].

The study of the fluid flow through porous media structures has also become a popular research subjects in many engineering fields [48–50] and partially also in HXs/HSs and HP research in the thermal management field [51–54]. The fabrication of porous structures has been extensively explored by traditional methods including liquid state processing, solid state processing, electro-deposition and vapor deposition [55]. However, only limited control over the internal structure can be achieved by conventional processes to achieve stable production. Although the shape and size of the pores can be adjusted by changing the parameters of these manufacturing processes, only a randomly organized porous structure can be achieved [56]. Porous structures have been developed recently due to the advancements in AM. SLM technology can fabricate porous structures with predefined net-shape fabrication as well as a range of material choices and shorter process cycle. Hence, enabling the fabrication of highly complex porous structures [57–59]. Furthermore, AM offers the promise of freeform HPs, optimizing heat transfer in given operational conditions. Unique is that the wall and wick are built up together, thereby minimizing thermal resistance. Further integration could even lead to a HP in combination with an external HS to have ideal external thermal contact as well.

All-in-all, SLM is an emerging fabrication technique that shows great advantages and potential compared to conventional methods [28,60]. The challenges of SLM manufacturing include a variety of parameters (powder characteristics and procedure) as well as process parameters (laser power, laser speed and layer thickness) [25,26,34,61]. Also, the design of SLM-fabricated parts is significantly different compared to parts that are fabricated conventionally. Despite the advantages of SLM technology, there has been only limited work in its implementation for HXs/HSs fabrication and associated porous media structures. Several reviews of AM printing techniques are available addressing utilizing of this advance manufacturing in different applications [15,16,19–21]. However, there is no compilation of literature or state-of-the-art review in the enhanced metallic surface technology and porous structures for heat transfer improvement as well HP technology and HXs/HSs utilizing laser AM.

For this aim, we reviewed recent advances in thermal management applications to show the capability of utilizing AM to develop reliable and efficient heat transfer systems, both single-phase and two-phase heat transfer devices. The organization of this paper is as follows. Firstly, SLM technology is briefly described, then, non-traditional single-phase metallic/polymeric HXs/HSs geometries utilizing laser welding are reviewed. Existing porous media fabricated utilizing SLM technology applicable to two-phase devices are introduced as well as reviewing HP fabrication. Finally, applications of such heat thermal management devices are summarized along with future challenges for industrial applications as well as highlighting areas of further research required in design, manufacturing and application.

2. SLM technology

AM is one of the techniques for constructing prototypes, and even parts, with near net shape accuracy and a quick design-to-produce time [25,28]. In this scenario, modern industries are interested in the implementation of several AM technologies depending mainly on the mechanism of processing, materials and energy sources. Laser AM is the most common one. Key metal AM methods, which are categorized by material feed stock include (i) powder bed systems, (ii) powder feed systems and (iii) wire feed systems. In the first one, the energy source transfers energy to the surface of the powder bed, thereby selectively melting the powder. In the powder feed system, the powder is carried through a nozzle to the surface where a laser is used to melt it locally. The last approach, the feed stock method, consists of a wire, which is fused by the energy source. Compared with the powder feed and wire feed systems, generally, the powder bed system permits manufacture of small components and high resolution features.

Within the powder bed systems, when a laser is used for the powder bed fusion the process is referred to the form of laser-based AM [62]. Basically, all AM techniques use a similar principle wherein the part is fabricated by layer-by-layer growth. SLM is an AM technology that uses powder as the initial material and a scanning laser to sequentially melt layers of powdered metal or polymers. Powder Bed Fusion-Laser (PBF-L) and Direct Metal Laser Sintering (DMLS) are other commercial names used for the description of a laser-based powder bed AM process. Among the AM technologies, the most suitable for HX applications is SLM, therefore, this technology is the focus of the current review. The significant advantage of SLM technology includes high flexibility and enabling the fabrication of high-resolution features, highly complex and net-shaped solid parts as well as porous media structures that cannot be manufactured in another way. Such structures enable structural optimization while reducing the associated manufacturing time and material costs by minimizing the component volume.

Fig. 2 shows a schematic diagram of a typical SLM process mechanism. It consists of the build platform system, powder delivery system, and laser and scanner systems. The typical steps for fabricating a complex freeform geometry from transforming a digital CAD file to a real product include [26,27,63]:

- Creating a CAD file to represent the physical part and its translation to an AM machine-readable file format (typically the STL format).
- Slicing the STL file into multiple layers at a prescribed thickness and orientation, and transferring the manufacturing instructions to the machine. Laser scanning begins with predefined tracks after the powder is deposited across the build plate.
- After finishing scanning one layer, the build platform is lowered the depth of a layer and a new layer of powder is deposited on top of the previous layer. This process continues until the last layer is fabricated.
- After unloading the build plate from the machine, loose powder and typically any support structure are removed, and the part is cleaned. Commonly also a heat treatment is performed to reduce internal stresses and improve the material properties.

SLM manufacturing may look simple in theory; however, it is a complex multi-physical processes due to transfer and absorption of laser radiation, heat transfer and powder consolidation [64–68]. To successfully fabricate parts utilizing SLM, different process parameters are involved. Laser-related parameters include laser power, beam diameter and scanning speed. Scanning-related parameters include layer thickness, hatch spacing and beam offset [69,70]. One of the essential operations is laser beam scanning across the surface of a thin powder layer that is deposited on top of a previously consolidated layer. The prediction of the laser energy density to set the ideal process is important [34,71] and depends on the laser power, scanning speed, hatch spacing and the thickness of the deposited powder layer [72]. Identifying the supplied power and exposure time of the laser during each layer are also important factors, achieving an acceptable density of the fabricated part in a reasonable amount of time [73–77]. For example, larger laser spot sizes, smaller hatch distances and longer exposure times mean that a specific point on the powder bed is subjected to the laser energy for a longer period. This increases the density and local wall thickness of the part, with the drawback of considerably longer build times and a larger feature size. Conversely, too much induced laser power also may include vapor bubbles inside the consolidated melt pool. Typically, in SLM the focus is on attaining full density. If the subject however is the fabrication of a porous structure, the process parameters can also control the degree of melting at the laser contact spot and melt pool size, thereby controlling the strut diameter of the porous structures, porosity and strength [25,32]. A detailed discussion for fabrication of porous structure is presented in Section 4.1.

Another important issue in SLM technology is the material choice. Metal, ceramic or polymer powder, or combinations thereof [78–80] are used for various applications. In terms of materials processed, SLM has been used in many studies to produce complex customized parts from metallic materials [81] as well as their alloys including aluminum [82–86], stainless steels [87–91], nickel [92–95] and titanium [96–99], among others, as well as various polymers [100,101]. Special attention is required to explore different areas of applications and to have enough information on materials [27,36] alongside the desired mechanical properties [61,102], which is, however, out of the scope of the current study. The development of new materials will represent innovations in the fabrication process alongside different processing conditions. Readers are asked to refer to [36,86,98] for a more comprehensive explanation on the SLM process.

3. Utilizing SLM technology for single-phase HXs/HSs

The increasing amount of power dissipated through of heat transfer devices imply an increase in thermal management challenges. It is, therefore, important that research into heat transfer enhancement continues [103–106]. Generally, for single-phase HXs/HSs enhanced heat transfer rates are accompanied with an increase in pressure drop, by applying for example fins, leading to higher pumping power

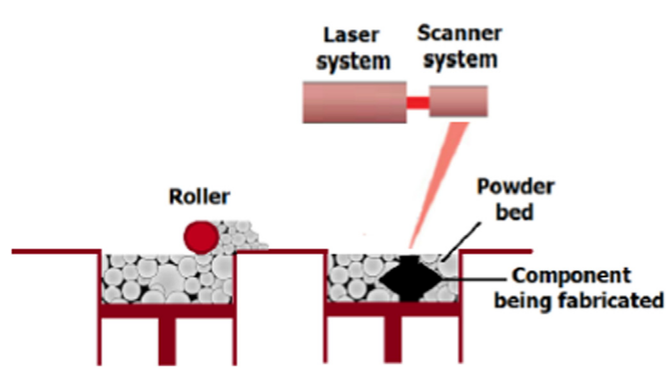


Fig. 2. Process of making a 3D object utilizing SLM technology.

requirements. Researchers have been trying to develop design and manufacturing techniques to enhance the heat transfer rate at a minimum possible pressure drop. Additionally, numerous methods have recently emerged for enhancing convective heat transfer, e.g. porous structures (lattice structures). In this scenario, the combination of efficient thermal conduction along the porous structure and low flow resistance through the pore channels results in highly efficient HXs [52,107–109].

There are extensive reviews on the research and development of traditional manufacturing of HXs [110,111]. However, conventional technologies are limited in their abilities to fabricate complex and compact HX designs. Development of HXs/HSs has been recently the subject of many studies as these technologies were designed decades ago. However, there are much more fabrication methods available, nowadays, such as AM, to manufacture a device with higher efficiencies and/or lower costs. Given the advantages of utilizing SLM technology, advanced complex HXs/HSs have been recently explored permitting components built in forms and shapes that are impossible to fabricate with conventional machining processes [112,113]. For example, Cárdenas et al. [114] designed and mathematically investigated an air-to-air HX based on a hexagonal mesh for the cross-sectional area. The designed HX is highly impractical to manufacture by traditional methods, but can be manufactured through AM relatively easy. They showed a dramatical improvement of thermal performance at smaller scales, however, they did not fabricate and test such an HX. Despite the advantage of using SLM techniques to fabricate complex structures, only limited work has been carried out in the HX/HS applications to enhance the geometric design. Several researchers have attempted to incorporate SLM in the fabrication of HXs/HSs to control the temperature of a medium by enhancing the heat transfer process.

In this section, the developed HXs/HSs by utilizing SLM as well as different techniques to enhance the heat transfer rate in single-phase HX devices are reviewed. Among the commonly studied heat transfer enhancement, several techniques utilizing SLM processes has been analyzed such as vortex generators, pin fins, offset strip fins and porous media and rough surfaces. Those works showed the potential of increasing the thermal performance of conventional heat transfer techniques with the use of SLM. The remainder of this chapter focuses on latest developments through utilizing AM categorized into plate-fin HXs (PFHs) and other HXs as well as a comparison analysis of conventional and additively manufactured single-phase heat transfer devices.

3.1. Plate-fin heat exchangers (PFHXs)

Among different technologies, pin fins have replaced traditional continuous fin arrays such as plate or wavy fins due to the higher volumetric heat transfer rates attainable [115]. Adding fins on a heat transfer surface acts as enhancement of the surface area and the heat transfer coefficient and, thus, reduces the thermal resistance as well as obtaining a low hydraulic diameter. However, thermal performance enhancement is offset by a larger pressure drop through the fin array [116]. Therefore, the number of fin layers, the size of fins, the height of fins and the type of fins must be carefully designed for optimum performance [117]. Among others, Wong et al. [37] fabricated and tested air-cooling of HSs using stainless steel 316 L and aluminum 6061 utilizing SLM technology with fins of circular, elliptical and V-shaped geometries. They performed experiments to determine forced convection heat transfer performances and concluded a higher heat transfer performance of aluminum 6061 as compared to stainless steel 316 L (more than double at higher flow rates). They [38] further showed the capability of SLM to fabricate HSs with different fin geometries (rectangular, rectangular-rounded and lattice type) using aluminum 6061. They demonstrated that increasing the heat transfer surface area by a lattice structure does not necessarily improve heat transfer rates. This structure can only dissipate 54% of the heat that rectangular-rounded fin structure can transfer, while it has a 28% larger heat transfer surface area. They also found that the rectangular and rectangular-rounded fin HS offered the highest heat transfer rate per unit pressure drop. Their research did not take into account optimization of the designed geometries.

Wong et al. [44] and Ho et al. [118] tested the forced convective heat transfer performance of air flow channel HSs produced by SLM. They compared pin fins of circular, rectangular-rounded and aerofoil geometries fabricated from aluminum alloy AlSi10Mg powder. They showed that the heat transfer performances of the aerofoil and rectangular-rounded HSs exceeded those of the circular HS. They also demonstrated that SLM can be employed to design and fabricate HSs of customized geometries for HS applications.

As another approach to enhance heat transfer, Dede et al. [119] studied optimization of an air-cooled HS considering heat conduction plus side-surface convection. A prototype structure was fabricated from AlSi12 utilizing SLM technology. They experimentally evaluated the heat transfer and fluid flow performance of the optimized HS. The results were compared with conventionally fabricated benchmark plate and pin fin HS geometries. They showed a higher coefficient of performance of the optimized HS design fabricated by SLM relative to the benchmark HS designs.

Kirsch and Thole [120] investigated microchannel pin fin arrays that were manufactured using laser-based AM and compared them to traditionally manufactured pin fin arrays from the literature. They showed that the high surface roughness more strongly affected the friction factor augmentation relative to the smooth pin fin arrays. They demonstrated the pressure drop obtained from their samples compared to four pin fin arrays from the literature was extremely high with only a marginal benefit in heat transfer. They also [121] studied the heat transfer and pressure losses in wavy micro channels for gas turbine engines manufactured through AM. The wavy shapes and small sizes of these channels are examples of the design freedom that AM offers. They showed improvement of heat transfer for longer wavelength channels while they indicated high pressure drop without improvement of heat transfer for short wavelength channels.

Considering another approach to enhance thermal performance of HSs, Fasano et al. [43] designed an SLM-fabricated HS heat transfer device based on Pitot tube effect for realizing passive heat transfer enhancement. They modified a conventional plate-fin HS by proposing a surface with hollow perforated pin fins. Their motivation was to induce secondary flows orthogonal to the main flow within the fins of the Pitot tube, thus enhancing heat transfer in the region where the velocity field is less vigorous. They showed 98% heat transfer enhancement of the proposed HS as compared to conventional HSs.

One of the commonly studied heat transfer enhancement designs in many engineering applications is the vortex generator to disturb boundary layer flows. Vortex generators can be categorized as a type of fin because they are generally mounted on the primary heat transfer surface like other types of fin. Such technology can increase the heat transfer coefficient by creating longitudinally spiraling vortices which promote mixing between the wall and core regions of the flow. Aris et al. [46] experimentally studied the heat transfer enhancement and flow pressure losses due to the presence of active vortex generators on a heated rectangular channel surface. The vortex generators were made from shape memory alloys and manufactured in a SLM process. They showed a maximum heat transfer improvements of up to 90% and up to 80% by the single and double wings, respectively, along the downstream direction. They also demonstrated an increase of the corresponding flow pressure losses across the test section by 7% and 63% compared to their de-activated positions, for the single and double vortex generator, respectively.

As presented in above discussion, the typical solution for compactness and thermal resistance reduction is using fins. However, such extended heat transfer surfaces provide additional viscous resistance. In addition, more material and thus potentially heavier HXs and higher manufacturing costs can be the consequence. Therefore, with advances in manufacturing technology, the focus of heat transfer enhancement could be on the potential of eliminating the use of conventional fin concepts (see Table 1). In the following section, other heat transfer improvements developed by AM are addressed.

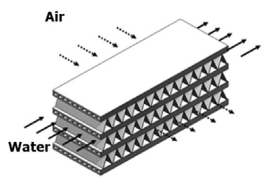
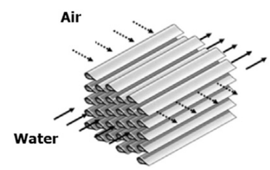
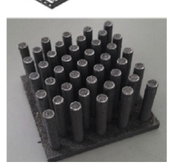
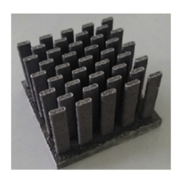
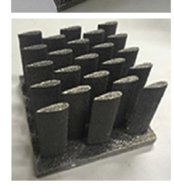
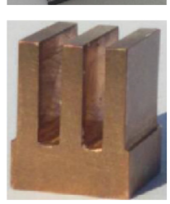
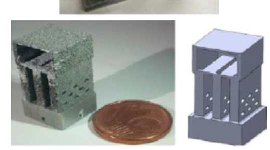
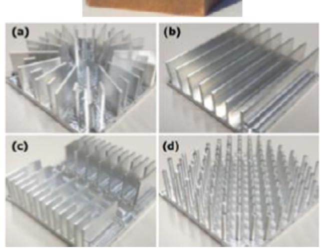
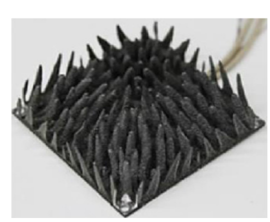
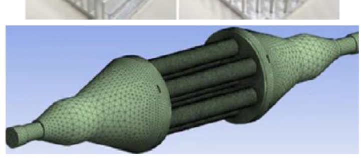
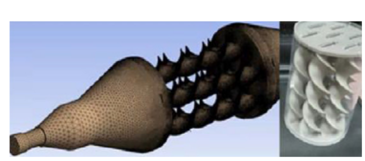
3.2. Other HXs and heat transfer enhancement approaches

The most presented heat transfer devices in this section include micro channels and cross-flow HXs or any combination of these as well as surface modification approaches to enhance heat transfer. One of the methods to achieve compact and high performance heat transfer devices is through the use of micro- scale channels [122]. Advantages of such devices include a high interfacial area of heat transfer surface area. Regarding utilizing SLM techniques in the fabrication of complex HXs made of different materials, micro HXs have found applications in electronics cooling and aerospace systems [1] in which light-weight and small-volume HXs are required. In light of this scenario, Bacellar et al. [123] presented a proof-of-concept design and fabricated small finless tubes and a novel shape that can outperform a microchannel HX as well as providing a shape optimization analysis. They experimentally and numerically showed 50% reduction in size, material, and pressure drop compared to the baseline microchannel HX. Tsopanos et al. [124] fabricated micro cross-flow HXs from Stainless Steel 316 L powder utilizing SLM. They provided a series of experiments using water as fluid, successfully made a prototype and tested it, obtaining an overall heat transfer coefficient of 2.22 kW/m^2 K.

Guo et al. [125] developed an arborescent distributor for a multichannel HX reactor, which enhanced its performance. The proposed multifunctional HX includes 16 sub-channels reunited at a single port, which are the inlet for the case of a distributor and the outlet for the case of a collector. They fabricated two different channel diameter sizes of HX-reactors using laser-based AM of Cobalt-Chrome and polymer powder. A metal-made HX used for experimental investigations and the other one to visualize the internal flow. They showed success in the fabricated HX utilizing laser AM and its performance was superior. They showed high overall heat exchange coefficients around 2–5 kW/m^2 K. They also showed the compact feature of developed HX as they demonstrated lower surface-to-volume ratio by 121 m^2/m^3 compared to baseline designed HXs.

Neugebauer et al. [39] produced a miniature water-cooled HX and radiators using SLM and demonstrated that AM enables new design approaches to improve HX effectiveness. They concluded that AM proved to give superior properties to the component compared to conventional manufacturing methods.

Table 1
Comparison of additively manufactured HXs in comparison of its baseline.

Heat transfer	pressure drop	Baseline	Investigated	References
+39%	-18%			finless tube micro channel [123]
+21%	-			rounded rectangular HS [118]
+35%	-			Airfoil HS [118]
+32%	-			Pitot tube HX [43]
(a)+11.2%, (b)+11.5%, (c)+12.8%, (d)-19.1%	(a)+1.6%, (b)-66%, (c)-15%, (d)-28%			Variable pin fin HS [133]
+40%	-			twisted tube HX [127]

Swirl HXs is another promising techniques to enhance the heat transfer rate by reducing the boundary layer thickness due to generation of a secondary flow in the form of vortices within an existing axial flow [126]. In this category, Bernardin et al. [127] designed and fabricated a fully functional compact twisted tube stainless steel shell and tube HX utilizing laser AM. They numerically showed that the overall heat transfer coefficient can be improved by 40% over a traditional round tube HX; however, they have not experimentally investigated the fabricated HX.

Another heat transfer enhancement is using rough surfaces approaches. Ventola et al. [128] used a laser-based AM technology to fabricate HSs of different artificial surface roughness to enhance the forced convection heat transfer performance for electronics cooling purposes. They showed a maximum heat transfer improvement of 73% as compared to a smooth surface. Stimpson et al. [129] fabricated and tested ten different samples made with the laser AM all having multiple rectangular channels to evaluate roughness effects on flow and heat transfer through the fabricated HX channels. They showed significant augmentation of these parameters compared to smooth channels, particularly with the friction factor for minichannels with small hydraulic diameters. However, augmentation of Nusselt number did not increase proportionally with the augmentation of the friction factor.

Polymeric materials have several favorable properties for HX systems, including low manufacturing cost and weight, antifouling and anticorrosion [100,130]. Readers are referred to [131] for a comprehensive explanation of HXs fabricated by polymer and polymer composite AM. Among others, Cevallos [24] fabricated several polymer HXs utilizing laser-based AM technology from polycarbonate and a polycarbonate-carbon fiber composite. The test HX utilized a webbed tube design, consisting of a planar array of tubes linked by a web of polymer. They applied the designed prototype for gas-liquid HXs. Arie et al. [132] developed a manifold-microchannel design allowing for more compact gas-liquid HXs fabricated by AM. They showed the possibility of increasing heat transfer by 60% compared to a wavy-fin HX. Arie et al. [101] fabricated and tested an air-water polymer HX made of thin polymer sheets using SLM manufacturing. The prime surface polymer HX consists of water channels through which hot water flows. These channels are cooled by air that flows through the gap between the water channels. They experimentally showed the overall heat transfer coefficient of 35–120 W/m^2K for an air-water fluid combination for an air-side flow rate of 3–24 L/s and a water-side flow rate of 12.5 mL/s.

Table 2 shows a list of SLM technologies that have been used for HX/HS applications. The heat transfer device, used material and its particle size, type of the machine and the classification, as well as the main results are summarized. As evidenced, most of the researchers have attempted to join SLM in the fabrication of HSs also using aluminum alloys. SLM manufacturing shows potential for fabricating heat transfer devices using aluminum alloys: AlSi10Mg [83,84], Al6061 [85] and AlSi12 [82]. This might be due to the fact that aluminum alloys have a number of properties that make them eminently suitable for commercial SLM applications. The high strength-to-weight ratio of aluminum enables optimization for structural applications. In addition, the high thermal diffusivity of aluminum alloys combined with the capability of SLM technology for fabricating complex part geometries enable the fabrication of high-efficiency thermal devices, including HSs and HXs [52]. Apart from SLM manufacturing, there are also other AM approaches to fabricate HXs. Selected methods of producing extended surfaces to increase heat transfer to fabricate compact HXs by using AM principles are presented in Table 3.

From the studies available in the literature on utilizing SLM technology in heat transfer devices, it is clear that the research efforts has been focused on developing innovative designs of HXs/HSs with the end goal of improving thermal performance. However, further development is needed to explore the capabilities of novel design structures in HXs to increase compactness and thermal efficiency. It is also observed that most of the cases are applicable to electronic applications.

Table 2
List of current publication on SLM technology in HXs/HSs.

Heat transfer device	Material	Particle size (μm)	Machine type	Classification	Outcome/Results	Ref.
HSs- vortex generators	Nitinol (Ti-50at% Ni)	75	MCP-Realizer 100-SLM	Fabrication, Experiment	Heat transfer improvements of up to 90% and 80% by the single and double wings, respectively, along with increasing the flow pressure losses across the test section of 7% and 63% of the losses at their de-activated positions.	[46]
HSs-pin fin	316L stainless steel/ Aluminium 6061	10-45	MCP Realizer I-SLM	Fabrication-Experiment	Aluminium 6061 was declared as a viable material to be used with the SLM method and heat transferring of more than 2 times of Aluminum HS in comparison of stainless steel	[37]
HSs-pin fin	Aluminium 6061	10–53	MCP Realizer II-SLM	Fabrication-Experiment	Higher heat transfer rate of porous HS in comparison of other ones and succeed in the manufacturing and declaring a need of optimization process.	[38]
HSs- rough surfaces	Aluminium 6061	5-45	EOSINT M270-DMLS	Fabrication-Experiment	a peak of convective heat transfer enhancement of 73%.	[128]
HSs- Pitot tubes	AlSiMg alloy		EOSINT M270-DMLS	Fabrication-Experiment	98% heat transfer improvement in comparison of conventional copper HSs.	[43]
HSs-Pin fins	AlSi10Mg alloy	20–63	SLM 250 HL (SLM Solutions GmbH)	Fabrication-Experiment	Higher thermal performances of the aerofoil and rectangular rounded HSs in comparison of circular one and design and fabrication of customized HSs utilizing applied approach.	[44]
HSs-pin fins	AlSi10Mg alloy	20–63	SLM 250 HL (SLM Solutions GmbH	Fabrication-Experiment	Improving thermal performance of airfoil HSs by decreasing flow resistance vortices formation.	[118]
HSs-pin fins	AlSi12			Optimization, Fabrication, Experiment	Higher coefficient of performance optimized HS relative to the benchmark ones.	[119]
HXs-Micro	316L stainless steel	20-50	MCP-Realizer 100-SLM	Fabrication, Experiment	Production feasibility of micro HXs utilizing SLM.	[124]
HXs-Micro	Cobalt-Chrome			Fabrication, Experiment	Introducing the successful integration of HX-reactor and its performance.	[125]
Micro-fin surface	AlSi10Mg alloy	20–63	SLM 250 HL (SLM Solutions GmbH)	Fabrication, Experiment	An enhancement of heat transfer coefficient of 1.27 W/cm^2 K (70%) as compared to a plain Al-6061 surface.	[218]

Table 3
Other AM approaches in HX fabrications, apart from SLM approach.

Fabrication process	Material	Heat transfer device	References
Fused deposition modeling	Polycarbonate	Webbed tube HX with 2 mm-thick wall and 5-mm inner diameter	Cevallos [24]
Cold spray technology	Aluminum	Pyramidal pin fin arrays HXs	Cormier et al. [113]
	stainless steel	Wire mesh wafers compact HXs	Assaad et al. [257]
Selective laser sintering	Steel alloy	Metal foam filled tubular HX	Hutter [246]
Electron beam melting	Titanium alloy and Aluminum 6061	Hexagonal cellular structures for HX applications	Kumar et al. [258]

Accordingly, in the authors' opinion exploring and investigating the use of a complex geometry with the aim of obtaining designs that simultaneously maximize the thermal performance and minimize the cost are suggested for a wide range of application, such as thermal energy storage, energy recovery, automotive, aerospace, etc.

3.3. Comparative analysis of single-phase heat transfer enhancement technologies

Recent technological advances in the field of AM, particularly SLM, have increased the potential for fabrication of compact HXs/HSs with such technologies. Challenges arise when attempting to evaluate the advantages of AM for specific applications, particularly because little is known regarding the effects of surface roughness of fabricated parts. This section attempt to presents pressure drop and heat transfer results of flow through HXs/Hs in the literature to better understand of utilizing this approach for future developments. Table 1 summarizes different types of single-phase HXs, indicating the improving operational temperature and pressure range of additively manufactured devices compared to conventional ones. As discussed above, extended heat transfer surfaces, apart from enhancing heat transfer, provides additional viscous resistance. Not necessarily though, as it is evidenced in Table 1, some researchers [123,133] enhanced pressure drop while increasing heat transfer by design optimization and using advantages of AM.

Performance of a HX/HS depends upon the heat transfer between the working fluids flowing through it. The comparison between the two materials stainless steel 316 L and aluminum 6061 as presented in Fig. 3 [37], showed significant higher heat transfer rate of aluminum compared to stainless steel. This highlights the need for further development on the use of higher conductivity materials e.g. copper with SLM. Moreover, diamond fin-shaped HS showed a higher heat transfer coefficient compared to other fins due to a higher surface area. The experimental results of [118] presented in Fig. 4, showed higher heat transfer coefficients of airfoil design HS compared to a pin fin HS. They also concluded that by increasing of angle of attack, the heat transfer coefficient increases. The effect is less significant from 0° to 5°, but an increase of heat transfer is more significant by increasing the angle of attach to 10°.

To account for the thermo-hydraulic performance of different heat transfer enhancement technologies in HXs based upon the heat transfer and friction factors, a plot is presented in Fig. 5. In the plot the ratio of the friction factor of the HXs fabricated by SLM is (f) over that of the reference one (f_0) is presented versus the ratio of the related heat transfer enhancement. Literature data for pin fins with different arrays (case A), wavy channel (case B) and rough surface straight channel (case C) fabricated by SLM and pin fins fabricated by conventional manufacturing (D and E) are presented. It is evidenced that, the friction factor augmentation of the pin fin arrays fabricated by SLM is higher than others, with only a slight benefit in heat transfer (Nusselt number). One other observation is that, the pin fins fabricated by SLM showed a significantly higher friction factor augmentation compared to that of wavy and rough straight surface manufactured by SLM. Based on the analysis presented in [134], evaluating the enhanced heat transfer techniques and energy-saving, it is estimated that except for the rough straight surface case (C) fabricated by SLM which is characterized by enhanced heat transfer without energy-saving (heat transfer enhancement is obtained with larger pressure drop penalty); the other cases characterized by heat transfer enhancement per identical pumping power but deteriorated per identical pressured drop. The presented results are important for researchers to design HXs and to understand the effect of the roughness through AM process and future developments.

4. Utilization of SLM in two-phase devices

Advanced designs integrating two-phase systems and phase-change material lead to improved thermal management systems [135–137]. Of the many different types of systems for transferring heat, the HP [6–8,138] is one of the most efficient systems. The HP is an effective passive device for transmitting heat at high rates over long distances with a small temperature drop. The subject of HP research is in

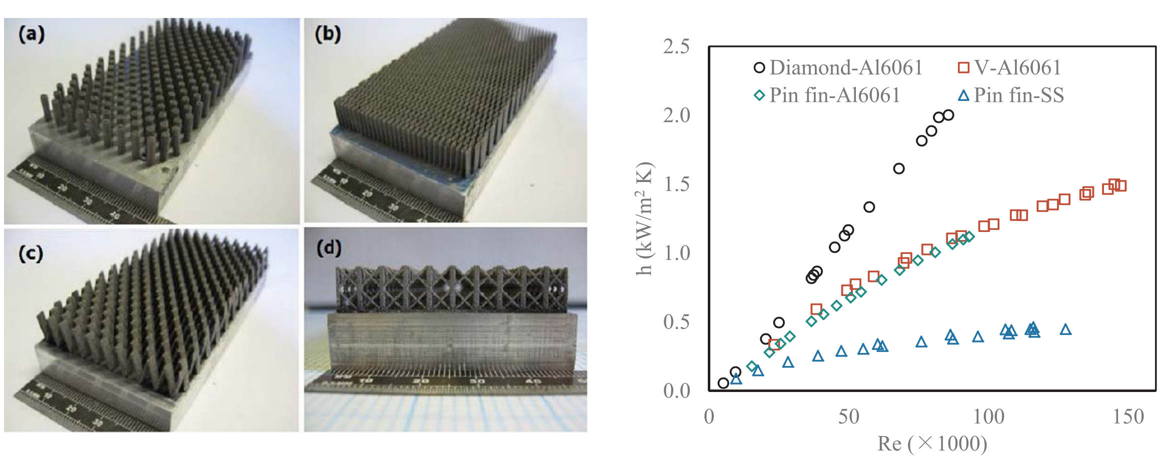


Fig. 3. Additively fabricated HSs (a) Pin fin, (b) Diamond (c) V type and (d) Lattice structure (left) presented in [38] as well as heat transfer performance of investigated geometries (right).

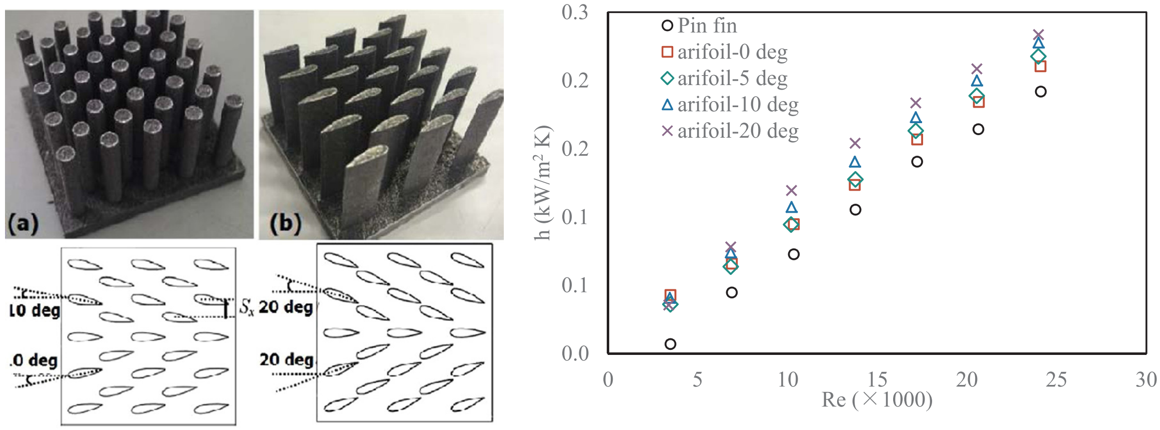


Fig. 4. Photographs of (a) pin fin (b) airfoil HS at different angles geometries presented in [118] as well as heat transfer performance of investigated geometries (right).

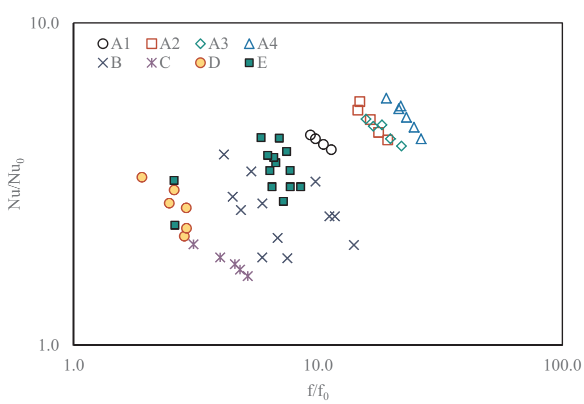


Fig. 5. Comparison of thermo-hydraulic performance of different heat transfer enhancement techniques; A: pin fin with different arrays (SLM) [120], B: wavy microchannels (SLM) [121], C: rough surfaces (SLM) [129], pin fins (conventional) [254] and E: pin fins (conventional) [255].

connection with a large variety of engineering fields: heat transfer, thermodynamics, fluid mechanics and solid mechanics as well as complex physical phenomena and fundamental laws in the thermal-fluids area [6]. Types of HP include, among others, capillary HPs, capillary loop HPs and pulsating HPs [139–142]. They run under the same principles and their geometry can be divided into evaporator and condenser sections in which the working fluid evaporates and condenses, respectively. The working fluid is circulated by capillary forces in a wick structure, gravitational, centrifugal and osmotic forces [6,8]. The integration of HPs into the design of HXs introduces a number of thermal resistances, but do not necessarily mean a larger overall thermal resistance at the systems level [10,11]. In practice, usually, HP-HXs are fabricated in a parallel thermal pathway, thereby distributing heat across the HX more effectively and reducing the overall thermal resistance of the integrated system. The new possibilities of SLM technology combined with two-phase heat transfer devices leads to an explosion of research in the area of passive thermal control management. The aim of this section is not to provide detailed information to cover design variables and operating limits of HPs, as there is already a vast number of reviews available in the literature [10,11,143,144] on this subject. However, the state-of-the-art of developing HPs utilizing SLM technology as well as designing porous media structure are described.

4.1. Designing porous media structures utilizing SLM

Developments in the design of the fluid-thermal transport through a porous media structure are critical to enhance the performance of the heat transfer systems in many technological fields [145,146]. Apart from integrating porous structures into single-phase HXs/HSs to improve convective heat transfer, the utilization includes enhancing evaporation/boiling phenomena as well as the ability to pump fluid by capillarity, e.g. in HPs technology [147–150]. Several types of wick structures have been developed that can be divided into two categories: homogeneous and composite wicks [6–8]. The first ones have the benefit of being relatively simple to design and manufacture, while the second group provides a significant improvement of the wick structure capillarity with the drawback of higher manufacturing costs [143].

Homogeneous wicks are fabricated by one kind of material or machining technique and include, commonly, screen mesh [151,152], sintered powder [153,154] or axially grooved wicks [155,156]. The screen wick consists of a metal or cloth fabric, generating a moderate capillary pressure, low permeability and high effective thermal conductivity [6–8]; however, they have limitations regarding the device geometry and the contact between the fabric layers and the HP wall. Sintered metal wicks are more difficult to fabricate compared to screen wicks, as they are provided by packing and sintering tiny metal particles [157]. Finally, axially grooved wicks are made by placing grooves on the inner surface of the pipe. The performance of axial grooved wicks is quite good (high permeability and effective thermal conductivity) [158], except when the working fluid must ascent against gravity due to low capillary pumping pressure. Drawbacks of grooved wick structures are the difficulty in machining a long pipe [143].

The objective of presenting the design of the sintered powder wick is that sintered powder porous structures are more challenging in terms of fabrication in comparison to the other porous structures. The most fabricated porous structure using SLM is the sinter-style porous media. However, the described characteristics could be applied to other porous structures as well. To select a wick structure for an application, several properties should be considered [159–162]. One is the minimum capillary radius, which should be small if a large capillary pressure difference is required. On the basis of the Young-Laplace equation, a pressure difference of the HP, known as the capillary pressure is commonly expressed as

$$\Delta P_c = \frac{2\sigma\cos\theta}{r_c} \tag{1}$$

where θ is the contact angle, σ is the surface tension coefficient of the liquid and r_c is the capillary radius. The capillary radius is estimated by $r_c = 0.41r_p$, (r_p is radius of powder particles) according to the capillary radius of a packed sphere wick [6]. Another important wick property is the permeability, which has an influence on the fluid transport through the porous media. This parameter is commonly determined by Darcy's law. For an incompressible fluid and for low velocities flows, it is described as

$$\frac{\Delta P}{L} = \frac{\mu_l}{K} u_l \tag{2}$$

where μ_l is the viscosity of the liquid, u_l is the liquid velocity in the interior of a pore and K is the permeability. The permeability should be large to have a small liquid pressure drop, and therefore, higher heat transport capability. However, generally a low permeability has a higher capillary pressure to drive the liquid transport. Several models can be applied for the determination and optimization of this parameter in relation to the porous structure. The most common equations are summarized in Table 4 [163,164]. Effective thermal conductivity is also an important factor for which a large value results in a small temperature drop across the wick. This is a favorable condition in HP design. Most of the available publications on HPs assume that the porous structures are independent of the employed manufacturing technology [165]. However, there is a difference among porous media produced by the different technologies. Several models are proposed in the literature for the prediction of the effective thermal conductivity of fluid-saturated porous structures [6,8], as summarized in Table 5 [166]. Typical assumptions are simple arrangements of the porous media phases in series or in parallel and regular arrangements of the particles (cubic, face-centered cubic or body-centered cubic), neglecting the effects of surface roughness on the particles; applying the analogy with electrical circuits [167,168]. Furthermore, some theoretical models are more detailed and complex presented to predict the effective thermal conductivity of porous structures [169–174]. The presented models to predict thermal conductivities of porous structures may not be appropriate to all types of structures and applied manufacturing technologies [175]. Thus, the contribution of a mathematical model and experimental data on this matter is highly suggested.

In addition, a high thermal conductivity and permeability, and a low minimum capillary radius cannot be combined in most wick structures. Therefore, the designer must always make trade-offs between these competing factors to obtain an ideal wick design [151,153,176–180]. For example, based on the above mentioned discussion and correlations, the capillary pressure depends on the permeability. Both are related to the pore size of the porous structure. A small pore size is favored to increase the capillary pressure; however, decreasing the wick pore size also decreases its permeability. Furthermore, a high thermal conductivity wick has to have a low porosity, resulting in high capillary pressure. This motivates the need of composite wick structures (see Fig. 6) that provide both small pores for generating high capillary pumping pressures and large pores for increasing the permeability of the liquid return path [181–187]. The common types of composite wick structure are two types of screen wick with different pore sizes and similarly axial grooves covered by a small-pore screen wick [6–8]. Also, two different sintered powder porosities can be stacked [188]. Table 6 summarizes some of the studies on composite porous structures [182–184,186,187,189–193]. The majority of research in composite wicks focuses on the heat transfer behavior in HPs; however, no study has successfully fabricated composite porous structures considering controlled particle sizes.

Based on this discussion and the difficulty to fabricate a high-performance porous structure, recent advances in SLM have provided a growing interest in making innovative complex porous media structures with unique engineering characteristics for a wide range of applications [58,194,195]. The principle of fabricating the porous structure using SLM, in respect to what is described in Section 2 includes designing a porous structure in the CAD model by setting the pore shape, size and distribution and controlling the laser parameters in the process. E.g. pore areas can be skipped by the laser and only the powder outside the pore areas can be scanned [196,197]. To produce a porous structure, the structural geometry can be filled with small unit cells. Each unit cell commonly has an octahedral geometry (which need not be the octahedral form) [58,63]. Some of the available forms that have been used in SLM processes to produce porous structures are summarized in Table 7. If the center of the octahedral geometry that fills each unit cell remains at the center of all the unit cells, the resulting geometry is a regular geometry [63]. If it changes from the center point to another point inside the unit cell from cell to cell, the resulting geometry is a randomized geometry. Both regular and randomized porous geometries are shown in Table 7.

In order to obtain the desired porous structure accurately by SLM, several key issues should be considered including optimizing the process [194] and designing unit cells and porous structures that are fit for the SLM process [198]. Previous studies have assessed the manufacturability and mechanical properties of SLM-manufactured porous structures. These studies are typically for stainless steel, titanium and aluminum structures. Several studies have been carried out to evaluate the mechanical strength of porous structure with different materials and unit cells [199–203]. Selected investigations are summarized in Table 7, describing a variety of porous structures based on different types of unit cells. It should be noted that as a general rule the unit cell choice and its design are still missing to characterize a porous structure. Among different parameters, the effect of the build orientation selection and heat treatment [204], cell topologies, strut diameters and cell sizes [205], effect of inclined angles of overhanging structures [194] and the relations between laser operational limits [196] has been recently evaluated. Using SLM technology to produce bio-porous structure has been also reported [197].

In summary, porous media structures are available in a variety of cell shapes and sizes. There are many ongoing types of research on the fabrication of porous media structures by SLM to fabricate structures that are impossible to make otherwise. Although some researchers have reported difficulty in processing porous media structure through SLM technology using metal materials, there are limited studies that report on the manufacturing of the porous media structures for thermal management applications e.g. two-phase devices. The porous media structures proposed and investigated in these studies do not clearly demonstrate the acceptance in HX applications. On the other hand, although SLM can fabricate very complex metal shapes, the fabricating quality can be different as the design and fabricating parameters change. From the review of the published studies, it was found that the processability, optimization and fabricating process of an SLM-produced porous structure were rarely mentioned. Therefore formulating several rules for SLM fabrication of porous structures is necessary, specifically for heat transfer devices including heat and mass transfer. Furthermore, despite the bio-porous wicks structures, the capillary performance in terms of wetting phenomena and capillary effects can be improved [206,207]. The fabrication of such structures is generally difficult, because of complicated and difficult-to-control procedures. In the authors' opinion, future research should focus on porous media utilizing SLM technology with a novel design based on some typical bio-inspired multiscale systems and composite wick structures. This motivates the need of specific properties when designing HPs.

Table 4
Summary of permeability correlations (K is the permeability, ε is the porosity, ϕ is a coefficient).

Medium	Correlation	Refs.
Textile assembly	$K = \frac{d_p^2 \varepsilon^3}{16\varphi(1-\varepsilon)^2}$	
Packed bed balls	$K = \frac{d_p^2 \varepsilon^3}{150(1-\varepsilon)^2} \begin{cases} 50 \times 10^{-6} < d_p < 3 \times 10^{-4} \\ 0.27 < \varepsilon < 0.66 \end{cases}$	
Sphere packing	$K = \frac{d_p^2 \varepsilon^{5.5}}{5.6}$	
Sphere packing	$K = \frac{d_p}{\{18\varepsilon(1-\varepsilon)[1+1.5(1-\varepsilon)^{0.5}] + [180(1-\varepsilon)^2/\varepsilon^3]\}}$	[163]
Sphere, Cube	$K = d_p\{0.709 \ln[\varepsilon^{11/3}/(1-\varepsilon)^2] - 5.09\}$	[164]

Table 5
Summary of effective thermal conductivity correlations (ε is the porosity and k_{eff}, k_l and k_s are the effective thermal conductivity and the thermal conductivity of liquid and solid, respectively).

Model	Correlation	Refs.
Parallel	$k_{eff} = \varepsilon k_l + (1-\varepsilon)k_s$	[166]
Series	$k_{eff} = \frac{k_l k_s}{\varepsilon k_l + (1-\varepsilon)k_l}$	[166]
Lower Maxwell	$k_{eff} = kl\frac{2\varepsilon + (k_s/k_l)(3-2\varepsilon)}{3-\varepsilon+(k_s/k_l)\varepsilon}$	[166]
Upper Maxwell	$k_{eff} = k_l\frac{2(k_s/k_l)2(1-\varepsilon)+(k_s/k_l)(1+2\varepsilon)}{(2+\varepsilon)(k_s/k_l)+1-\varepsilon}$	[166]
Alexander	$k_{eff} = k_l(k_s/k_l)(1-\varepsilon)^{\delta}\begin{cases}\delta = 0.34;\ \text{metalicfelt}\\ \delta = 0.53;\ \text{sintered powder}\\ \delta = 0.34;\ \text{loosingparticles}\end{cases}$	[166]
Effective Medium Theory	$(1-\varepsilon) = \frac{k_s - k_{eff}}{k_s + 2k_{eff}} + \varepsilon\frac{k_l - k_{eff}}{k_l + 2k_{eff}} = 0$	[166]

4.2. Utilizing SLM in HPs

Many industrial processes need to remove thermal energy with high quantities in the order of 10–100 times more than what is capable through single-phase systems (about 1 kW/cm^2). At such high heat fluxes, there is a need for two-phase HXs. Two-phase devices offer a passive heat transferring mechanism over long distances with a low-temperature difference resulting in high thermal performance. One of the most common two-phase devices is the capillary HP (Fig. 7a) [6–8]. A HP includes a sealed container, a wick structure and a small amount of working fluid. Applied heat to the evaporator section is conducted through the wall and wick structure, where the liquid evaporates from the wick. The resulting vapor pressure in the evaporator drives the vapor to the condenser where it condenses. The condensate liquid is then pumped back to the evaporator section; therefore, the HP can continuously transport the latent heat of vaporization from the evaporator to the condenser section. In conventional HP manufacturing methods sintered wicks are fabricated by sintering metal powders together and bonded to the HP internal wall. Although the application of HPs is beneficial to many industries, the actual systems have two major problems: (i) dissipation of high heat fluxes has significant limits connected to the internal wick, the thermal resistance of the contact between the HS in the condenser section and the HP and (ii) the flexibility of the passive two-phase systems. For these reasons, utilizing AM allows for increased flexibility in the realization and integration of freeform HPs. The wick structure can be optimized, overall thermal resistance can be reduced and HPs can comply with size and shape constraints imposed by the embedding system. Moreover, a further degree of miniaturization of the system can be achieved, offering novel applications and improved performances. This creates a range of competitive advantages for manufacturers and users of freeform HP systems.

SLM technology is capable of producing similar porous structures from an array of octahedral geometries formed into a porous media structure (see Section 4.1) as well as the solid parts (the HP wall and end caps) simultaneously. Ameli et al. [63] manufactured and tested aluminum HPs using ammonia as a working fluid with various wicking characteristics. They demonstrated that, with SLM, complicated wick structures of different thicknesses, porosities, permeabilities and pore sizes in different regions of a HP could be controlled. In addition, the entire HP including the end cap, wall, wick and fill tube could be produced in a single process (see Fig. 8).

Another type of two-phase passive device is the loop heat pipe (LHP) powered by capillary pressure in a porous medium in which evaporation of the working fluid takes place. The wick structure is located only in the evaporator (Fig. 7b) [6]. Applied heat to the outer surface of the evaporator section including an internal wick structure, vaporizes the working fluid. The vapor moves to the condenser, where it condenses first as a film on the inner wall of the pipe, and then as a liquid slug flow [143]. A key aspect for achieving the best performance of LHP devices is to make sure that the wick structure operates within their designed thermal-physical specifications [208]. Esarte et al. [209] designed a LHP by utilizing the SLM technique for the fabrication of the primary wick for Light Emitting Diode (LED) lamp applications, aiming to achieve an ideal design according to the specified requirements. They investigated hydraulic-thermal limits, permeability, wettability, capillary pumping and thermal conductivity of the system and showed the different behavior of the LHP under different heat loads.

As a two-phase device operating without a capillary structure, the pulsating heat pipe (PHP) has attracted the attention of many researchers for enhancing heat transfer. PHPs are conventionally made from a long pipe bent into many turns, with the evaporator and condenser sections at opposite ends of these turns (Fig. 7c). Generally, a

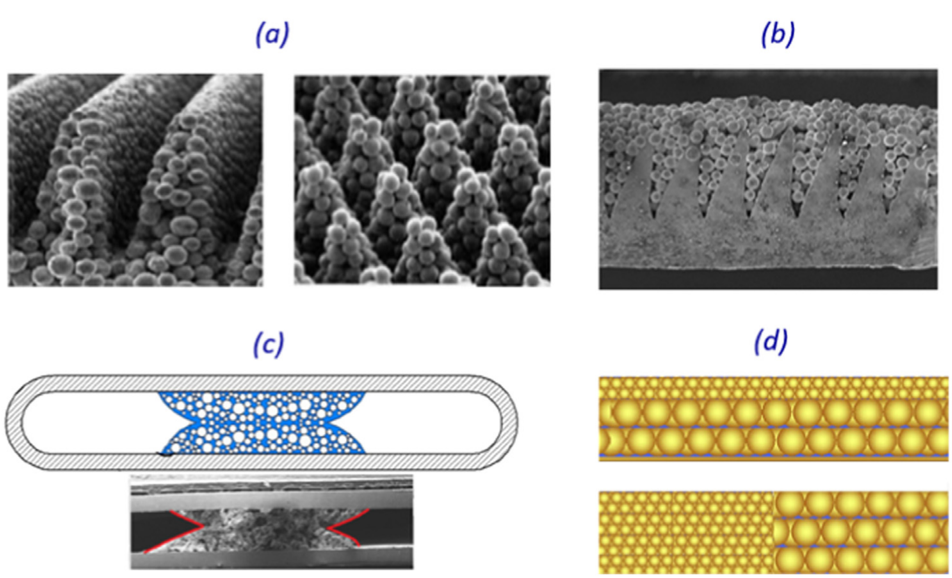
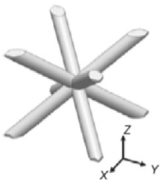
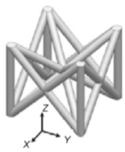
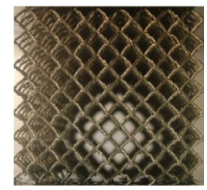
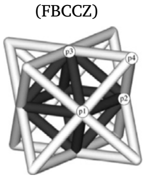
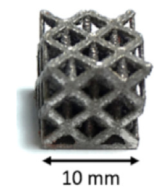
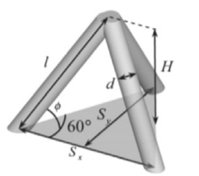
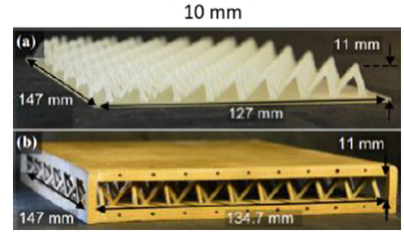
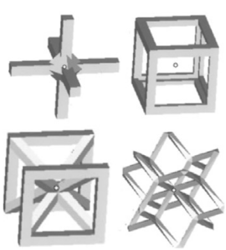
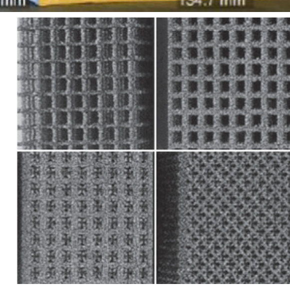
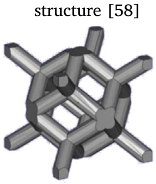
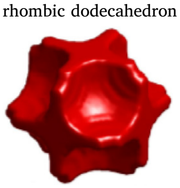
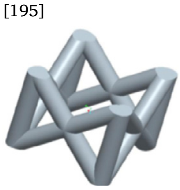
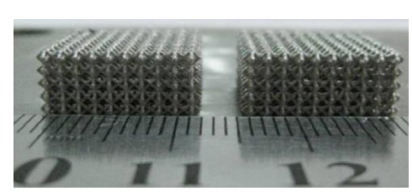


Fig. 6. Improvements in porous media structures: (a) 2D and 3D porous structures [181], [182], (b) micro grooved-sintered powder [183], [184], (d) sintered at the middle of a Flat HP [185] and (e) radially and axially varied pore sizes [187].

Table 6
List of researches on composite porous structure in the HP application.

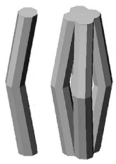
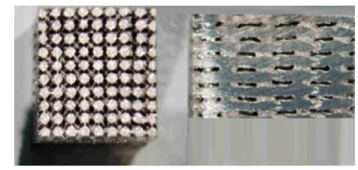
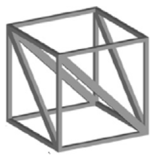
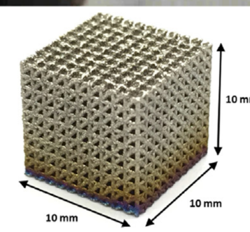
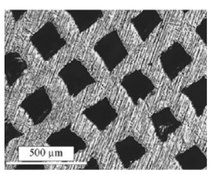
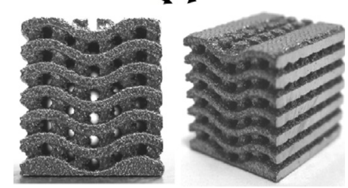
Refs.	Porous material/ working fluid	Device	Method	Porous media	Objective/Results
[189]	Copper/methanol and water	Flat-HP	Analytical, Exp.	Sintered powder in Evap. Section and grooved in Adiabatic and Cond. Sections.	To associates high liquid pumping capacity of sintered metal powder structures with the low liquid pressure drop of grooved structure./ The analytical model showed a good agreement in comparison of experimental data. However, They did not present the improvement of the system in comparison of conventional HP.
[190]	-	HP	Analytical	Grooves and screens	To improve the capillary forces and to extend the evaporation surface./enhancing evaporation heat transfer, 3–6 time higher than grooved wicks.
[186]	Copper mesh, nickel metal powders/ water	HP	Exp.	Screen and sintered	To investigate an enhancement of evaporation heat transfer and the extension of the capillary limit. / Enhancing heat transfer 3 times higher than conventional one.
[187]	Copper mesh and nickel filamentary powder and spherical copper powder	HP	Exp.	Large and small sintered powders pores	To enhance performance in capillary pumping, permeability and evaporative heat transfer/ Enhancing in the effective thermal conductivity as much as 400% as compared to conventional screen one.
[191]	Aluminum and nickel/ ammonia	LHP	Exp.	Large and small powders pores	To improve heat transfer by controlling the particle size./Enhancing evaporation heat transfer six times more than an uniform porous structure.
[182]	Copper / acetone	Surface	Exp.	Grooved and powder pores surface (2D and 3D porous coating)	To examine the effects of porous structure for liquid suction and valley channel for vapor escape/ Enhancing the pool boiling heat transfer.
[183]	Copper/water	HP	Exp.	Micro grooved-sintered powder	To analyze the hydraulic properties of composite Wicks./Enhancing both permeability and capillary performance compared to the sintered wicks and exhibited much larger capillary pressure than the grooved wicks.
[192]	Titanium/water	HP	Exp.-Analytical	Grooved-sintered powder	To analyze and optimize a composite HP./ The maximum enhancement was limited by the pipe inner radius and the wick effective thermal conductivity.
[184]	Copper/water	Flat HP	Exp.-Analytical	Grooved-sintered wick	To enhance miniature HP performance with the advantages of high capillary due to porous sintered powder and high permeability and low flow resistance of grooved channels./ Powder diameter showed a greatest effect on heat transfer limit of the system.
[193]	Copper/ ethanol	LHP	Exp.	Two different porosities	Changing the porosity and the combination of the composite porosity./Decreasing of thermal resistance by 70% when the larger porosity is closer to the heat source wall.

Table 7
List of reported successful recommended cell topology for porous structure unit cells as well as used material and possible application in the heat transfer devices.

Cell topology	Material/application	Manufactured part
 Body-centred cubic (BCC)	316L stainless steel [200] 316L stainless steel [199] Ti6Al4V [201] Aluminium/HP [63]	
 face-centred cubic (FCC) and BCC with vertical axis struts (FBCCZ)	AlSi12Mg [259] 316L stainless steel [199]	
 Octet truss [260]	AlSi10Mg/pool boiling enhancement [219]	
 Tetrahedral structure [261]	(a) Polymer and (b) stainless steel and bronze/ compact HX [262]	
 Cross 1 symmetric structure, G6 and G7 structure, Dode thin structure [58]		
 rhombic dodecahedron structure [263]	Ti–6Al–4V [263,264]	
 [195]	Steel- nickel	
 [194]	316L stainless steel	

(*continued on next page*)

Table 7 (*continued*)

	Titanium [204]	
	Titanium [197]	
	titanium-tantalum alloy [203]	
	stainless steel, nickel alloys and metal–polymer [196]	

conventional PHP consists of tubes arranged in a serpentine way and joined end to end, fabricated using traditional manufacturing methods. Thompson et al. [210] used SLM manufacturing to fabricate a compact flat-plate PHP with innovative design features, including a Ti–6Al–4 V casing and a closed-loop, circular mini-channel consisting of four connected layers. They evaluated the design and manufacturing concerns encountered during the SLM of channel-embedded parts. They showed that the system operates successfully with an effective thermal conductivity of about 110 W/m K at a power input of 50 W. Ibrahim et al. [211] fabricated and tested a multi-layered, Ti-6Al-4V PHP by employing a laser-based AM method. They investigated the effect of the power input, the working fluid (water, acetone, NovecTM 7200 and n-pentane) and operating orientation. They concluded that with the capabilities of AM, many high heat flux thermal management devices, specifically those that use mini- or micro-channels, can be 're-invented' to have embedded channels with typical geometries, arrangements and

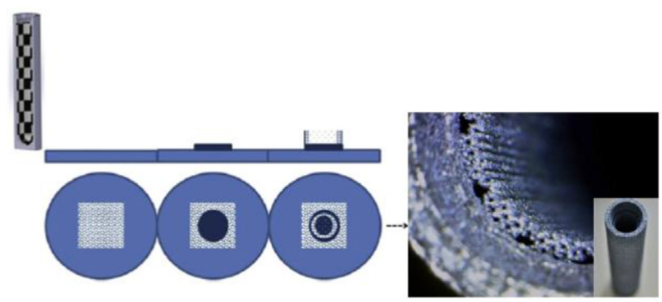


Fig. 8. Fabricated HP by SLM [63].

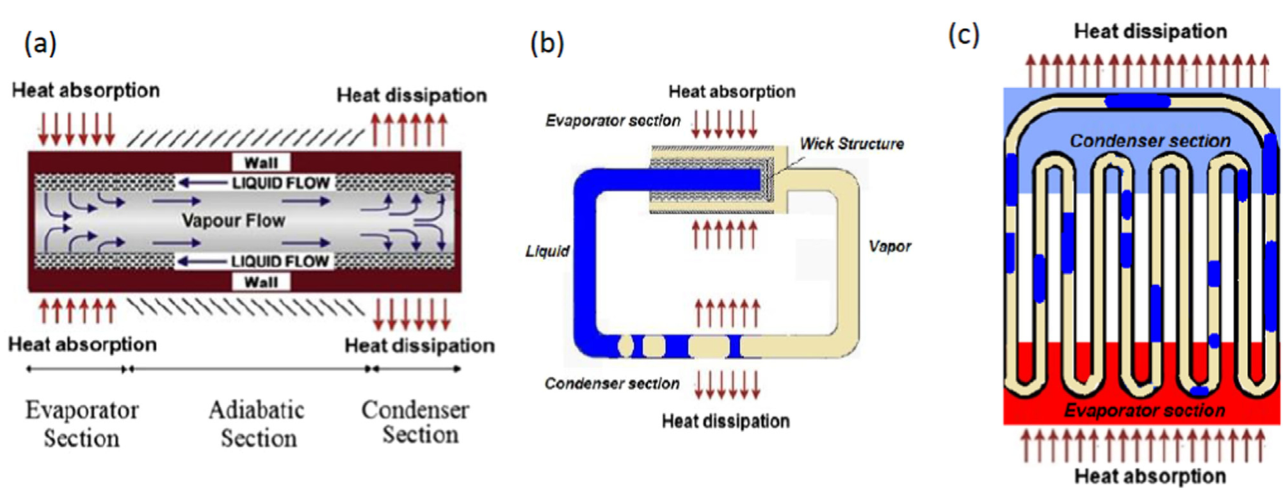


Fig. 7. Schematic view of (a) a HP as well as common wick structures, (b) simplified capillary loop heat pipe (LHP) and (c) pulsating heat pipe (PHP).

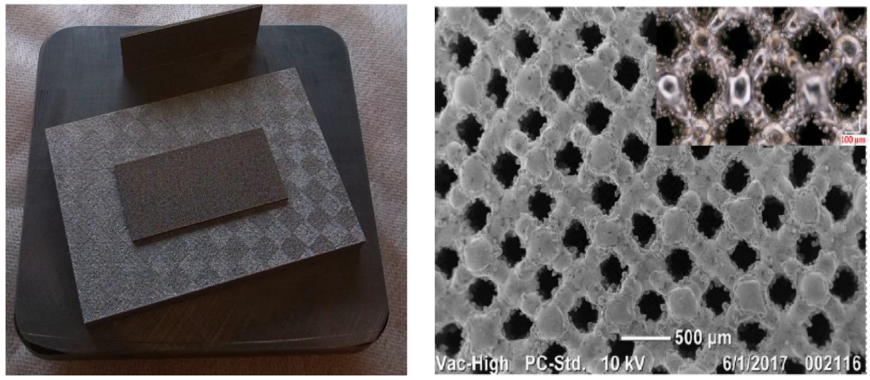


Fig. 9. 3D printed sample (1 × 20 × 40 mm3) (left) and micrograph of the wick structure showing a pore size of 160 µm (right).

Table 8
List of current publication on SLM technology in two-phase devices.

Application	Material	Application	Particle size (µm)	Machine type	Classification	Outcome/Results	Ref.
HP-Sintered Wick	ALSi12	Space	50	MCP Realizer 100	Fabrication	Showing the capability of SLM in making different types of aluminum porous wick structures with the container and end cap built in a single process.	[63]
LHP-Sintered Wick	stainless steel	LED	20–75	SLM (280 HL)	Fabrication, Experiments	Succeed fabrication and performance evaluation.	[209]
PHP	Ti–6Al–4V	Electronic equipment	15–45	System ProX 100	Fabrication, Experiments	Highlighting important design and manufacturing concerns encountered during SLM of channel-embedded parts.	[210]

surface conditions. Recently, Jafari et al. [212] fabricated and tested a stainless steel porous structure for HP applications utilizing SLM (see Fig. 9). They showed that the effective thermal of the wick in the range of 1.8–2.2 W/m K in vacuum condition, ~3 W/m K for ethylene glycol and ~6 W/m K for water as tested fluids, thus observing high sensitivity to the interstitial fluid. They reported possibility of using porous structure for HP systems through SLM. Table 8 summarizes SLM technologies that have been used for HP applications, showing the materials used and its powder particle size, types of machine and the application, as well as the main results.

In the authors' opinion, research carried out on two-phase devices has identified SLM technology as a suitable manufacturing technology. Although few studies have been undertaken to fabricate porous media structures utilizing SLM technology, literature about the thermal-fluid behavior through porous media structures has not been found. More fundamental work and accurate simulation of the multiphase heat and mass transfer and the liquid–vapor interface are needed to understand the physical phenomena of two-phase devices using capillary structures considering SLM technology. Furthermore, accurate fabrication and experimental analysis appear to be important to design a two-phase device for a specific application.

4.3. Other two-phase heat transfer enhancement technologies

Single-phase cooling methods such as natural and forced convection cooling are not capable for high-power-density applications, maintaining an acceptable operational temperature. Thus, HXs exploiting phase transition, play a role of ever-increasing importance in almost any industry. Pool boiling as a phase change cooling method is widely applied, for example, in electronic equipment. There are extensive research attempts to enhance such pool boiling heat transfer coefficient using surface modification techniques and porous structures [213–217]. With advances in manufacturing technology, the possibility of promoting boiling heat transfer with SLM-fabricated surfaces and porous structures has been introduced in the literature. Considering this scenario, Ho et al. [218] attempted to optimize the pool boiling heat transfer performances of SLM-fabricated surfaces with intrinsically designed microstructured features. They fabricated micro-cavities and micro-fins array surface to improve the heat transfer performances using FC-72 as the working fluid (see Fig. 10a). They showed that in comparison to the commercially available plain Al-6061 surface, the AlSi10Mg surfaces fabricated by SLM have significant enhancements in heat transfer coefficients and critical heat flux. A maximum heat transfer coefficient of 1.27 W/cm^2 K and up to 70% improvement in the average heat transfer coefficient as compared to a plain Al-6061 surface were achieved. Very recently, they also [219] studied pool boiling heat transfer of porous structure using FC-72 as a working fluid fabricated by SLM technique (see Fig. 10b). The effect of porous structures thickness was evaluated. They showed a significant enhancement of heat transfer coefficient (around 3 times) and improvement in critical heat flux compared to a plain surface. The research group [220] also experimentally investigated enhanced surfaces with pin fin arrays of different geometries and arrangements fabricated by SLM to determine droplet impact behaviors on their cooling performances (see Fig. 11). They showed that fin density played an important role in the droplet dynamics and improvement of the droplet heat transfer.

4.4. Comparative analysis of two-phase heat transfer enhancement technologies

The results of enhanced two-phase heat transfer utilizing SLM and other surface modification approaches using FC-72 as the working fluid are compared in Fig. 12. The results of investigations into heat transfer rates in pool boiling are usually plotted on a graph of surface heat flux versus temperature difference between heated wall and saturated vapor. Compared to the enhanced surface by porous structure utilizing SLM, Rainey and You [221] obtained similar heat transfer performance, Kim et al. [222] yielded significantly lower heat transfer performance, Sarangi et al. [223] obtained significantly higher heat transfer coefficients up to heat fluxes of 10 W/cm^2. Another additively manufactured enhanced surface structure using micro-fins [218] has a similar trend to that of enhanced surfaces using porous structures up to heat transfer

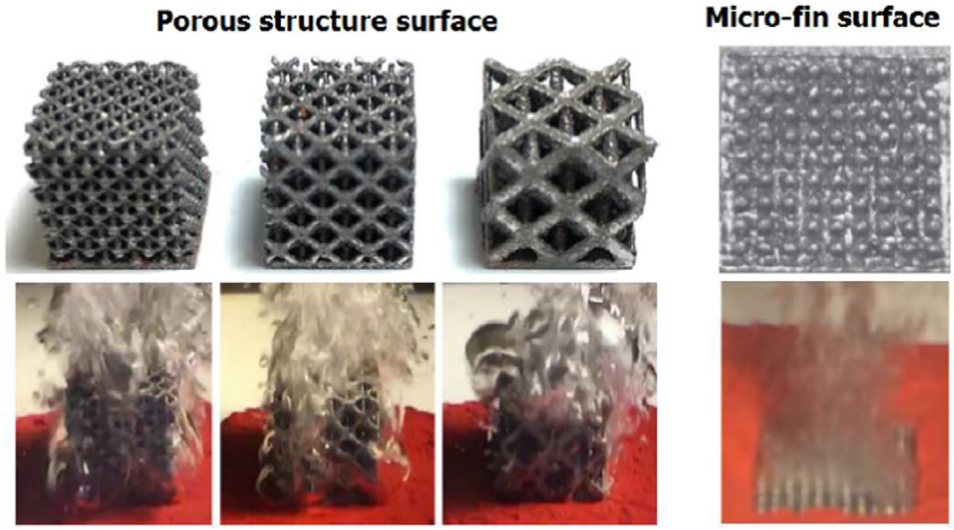


Fig. 10. Fabricated sample to enhance pool boiling as well as an example of boiling pattern utilizing SLM (a) d micro-fin surfaces [218] (b) porous structure [219].

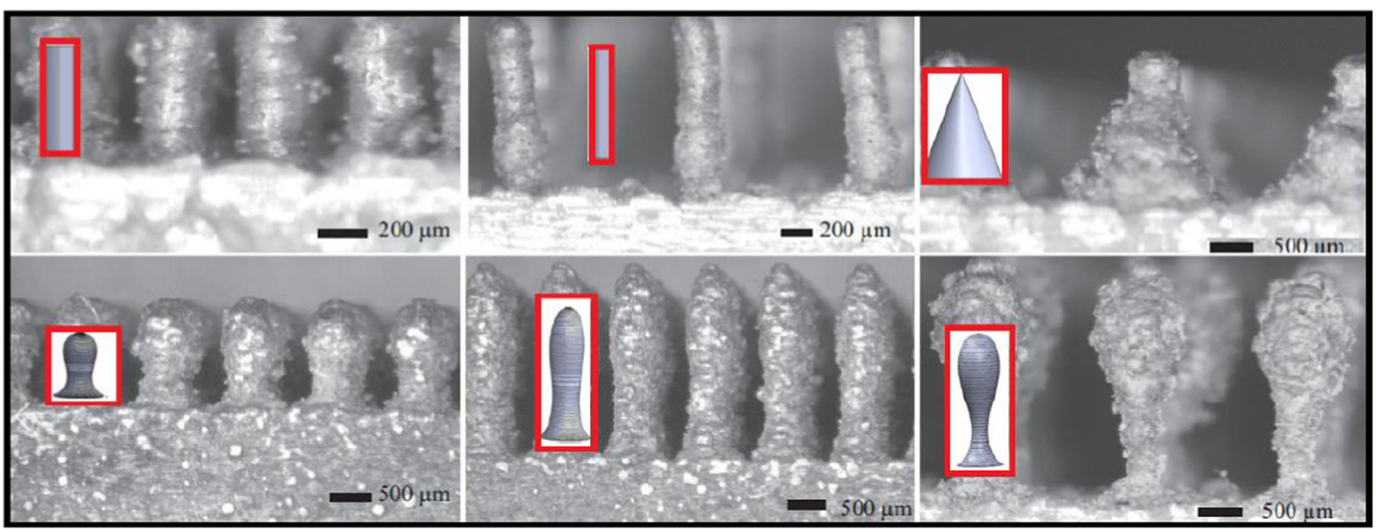


Fig. 11. Microscopic images and related designs of enhanced surface fabricated by SLM [220].

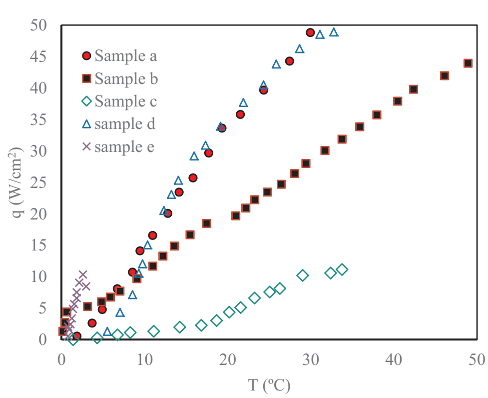


Fig. 12. Comparison of two-phase heat transfer enhancement utilizing SLM and other surface modifications using FC-72 as the working fluid: sample a: a porous structure fabricated by SLM [219]; sample b: a micro-fin substrate fabricated by SLM [218]; sample c: a free particles placed on a plain surface [222]; sample d: a finned surface [221]; sample e: deposited sintered copper particles on a surface [223].

rates of around 10 W/cm^2.

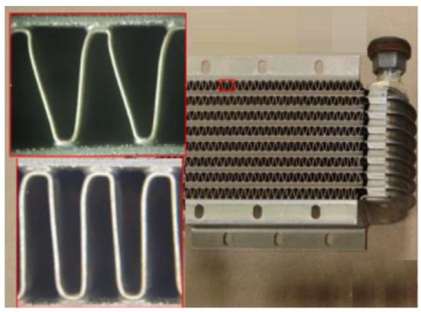
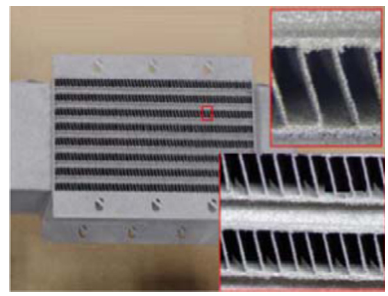
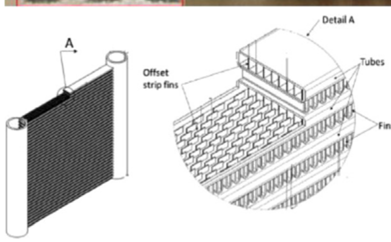
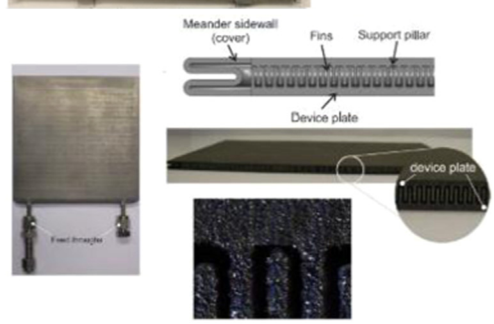
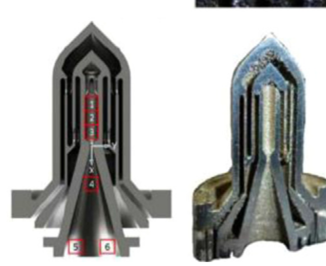
Although surface modification techniques utilizing SLM can enhance the heat transfer coefficients, further investigation and optimization of enhanced surfaces are needed to improve maximum heat transfer capacity as, for example, the maximum chip heat flux of electronic devices will increase up to 190 W/cm^2, [12] as is illustrated in Fig. 1. Therefore, there is a need to develop of enhanced surface approaches, for instance by optimizing the wick structure and material usage to achieve higher heat fluxes. Unfortunately, there is no available data to evaluate and compare the thermal performance of HPs fabricated by SLM.

5. State-of-the-art thermal management utilizing SLM: current and potential applications

Increasing heat transfer performance has been a critical concern in the last decades in many fields. For instance, with the miniaturization of electronic packages, the power density has increased while the amount of heat transfer area on such components has decreased, making the development of effective HXs/HSs a priority. However, there are a number of shortcomings associated with current cooling systems (e.g. low power dissipation potential). The roadmap for HXs/HSs technology for research opportunities is predicting AM to deliver 3D-optimized geometries incorporating enhanced surfaces leading to significant efficiency enhancements. An opportunity exists for AM technology to contribute to the area of thermal management and the exploration of novel designs to improve the energy efficiency and power density. This section highlights important applications of AM in available thermal management applications in the literature and potential applications. Table 9 shows fabricated HXs for differents application by AM.

The technological challenges for thermal management are one of the important issues for high-power modules and packaging systems like power electronic systems. Syed-Khaja et al. [224] used the SLM technique to fabricate a HS concept, which is not feasible to make with conventional production techniques. They experimentally investigated

Table 9
Fabricated HXs for different applications by SLM.

Application	Conventional manufacturing	AM	
aircraft			[248]
aircraft			[249]
aerospace systems			[250]
aerospace systems			[247]
dry cooling of power plants			[243]

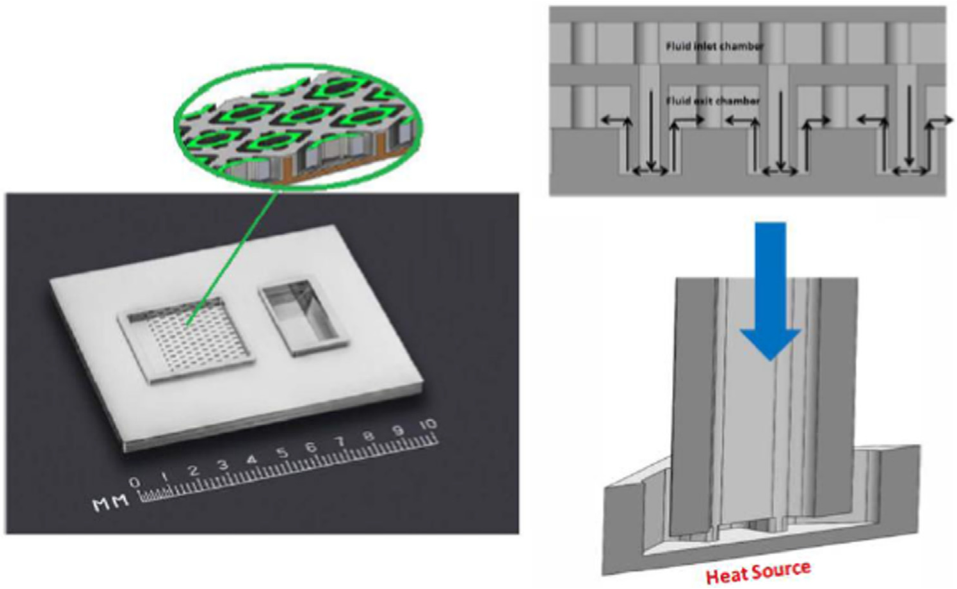


Fig. 13. Images of the HS (left) and schematic view of unite cell (right) presented in [225,256].

the thermal management performance of the system. They showed key-enabling advantages for integrated power electronics over traditional HSs: the reduction in volume (98%), weight (94%) and chip temperatures (33%). Robinson et al. [225] presented the development of a water-cooled microfluidic HX for cooling high heat flux electronics utilizing AM (see Fig. 13). The design is a water-cooled microchannel HS using an array of fins with integrated microjets. They showed an effective thermal conductance of 296 kW/m^2K for a flow rate of 0.5 L/min. They predicted that such system can maintain an average base temperature of under 58 °C with a maximum variation about the mean of ± 3 °C for an imposed heat flux of 1000 W/cm^2.

As an example of electronic cooling equipment, the LED, a solid-state semiconductor device, converts electrical energy into light [226]. With further improvement, LEDs have the great potential to become the new illumination source. However, the real challenge is that the lifetime of LEDs is easily shortened by heat that is generated due to the limited efficiency of the LED itself. Therefore, the thermal design is important and requires an excellent thermal performance to avoid a short lifetime of the system. One of the solutions to improve the thermal control of the system is to integrate the LED system into two-phase devices [227,228]. Incorporating two-phase devices and LEDs through SLM technology can lead to the fabrication of novel systems with maximal thermal performance that are essential for applications like automotive.

Increasing power demands and limited energy resources motivates the discovery of novel and renewable energy sources, as well as energy storage. Thus, there is a need for innovative designs and fabrication processes for improving efficiency and power density for energy storage systems. New energy storage systems fabricated through AM technology could achieve high-storage capacities. As a thermal energy storage system, lithium ion batteries are applicable for portable devices, transportation and stationary applications [229,230]. To satisfy higher energy and power densities, new materials should be developed as well as enhancing battery performance via optimizing the battery electrode structures. AM technology has been considered as a new solution for improving battery performance [231] as well as for fabricating micro batteries [232–234].

As another clean energy device, fuel cells (see Fig. 14) provide great advantages, such as high efficiency, high power density, and low emissions. Among others, Alayavalli and Bourell [235] fabricated electrically conductive, fluid impermeable graphite bipolar plates for a direct methanol fuel cell utilizing AM. They found a significant increase of the electrical conductivity and they showed the capability of AM to produce bipolar plates with complex flow field designs for fuel cell applications. Guo and Leu [236] investigated the electrical conductivity of additively manufactured bipolar plates and compared the performance with bipolar plates made by other manufacturing techniques, e.g. injection molding and compression molding. They [237] also investigated a bio-inspired “leaf” design bipolar plate for the flow field utilizing AM and they showed a 20% improvement in the power density of the fuel cell compared to the conventional designs.

Thermoelectric devices also can convert thermal energy into usable electrical energy from an available heat source or provide temperature control [238]. The conventional thermoelectric modules are acquired as separate components, which are then integrated by mechanical attachment into the engineering system [239]. AM technology is an alternative assembly solution for thermoelectric devices. A few studies are available in the literature providing investigations of processing semiconductor materials using SLM technology. For instance, El-Desouky [240,241] successfully processed a traditional thermoelectric semiconductor material (Bi_2Te_3) through SLM. In this category, Azhari et al. [242] fabricated thick supercapacitor graphene-based electrodes using laser AM. They demonstrated a more porous microstructure compared to electrodes that were mechanically pressed to form powders.

Developed HXs/HSs also can be applied to a variety of high-demand applications including air cooling of power plants. Arie et al. [243] fabricated and tested an additively manufactured air–water HX for dry cooling of power plants. The HX consisted of manifold-microchannels on the air side and rectangular channels on the water side in a cross-flow configuration. They fabricated an integrated HX using SLM technology as a single component using stainless-steel, titanium alloy and aluminum alloy. They showed the performance improvement of 30% and 40% compared to wavy fin and plain plate-fin HXs, respectively. They reported that if the fabrication inaccuracy can be eliminated, a significant performance enhancement could be projected over all of the conventional HXs.

Apart from the application of porous media in HPs, metal foam reactors have the potential to be used in chemical production. The investigation on available commercial metal foams show a limitation on heat and mass transfer characteristics [244]. However, with an alternative manufacturing approach, such as SLM technology, it is possible to build almost any freeform 3D shape. Hutter et al. [245,246] successfully studied the fabrication of metal porous foams by adopting the

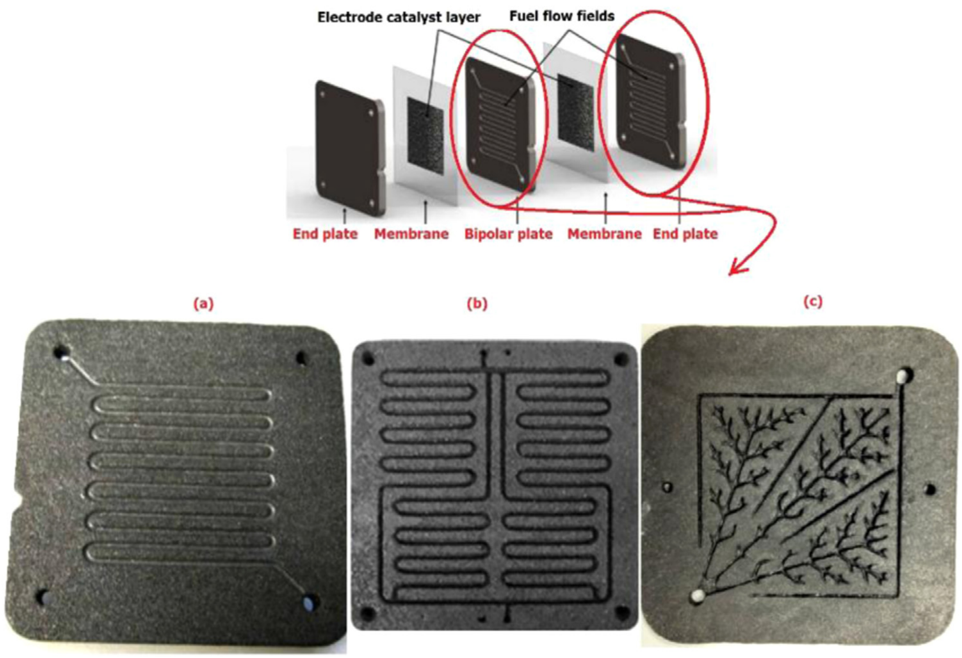


Fig. 14. Additively fabricated bipolar plate for fuel cell applications (a) [235], (b) [236] and (c) [237].

laser AM technique for tubular reactor applications. In comparison to commercially available metal foam inserts, the use of fully sintered metallic porous foams by AM shows convective heat transfer coefficients that are more than two times higher.

Regarding aerospace applications, Resistojet thrusters work on the principle of electrically heating the propellant via a resistance element in spacecraft electro-thermal propulsion systems. Romei et al. [247] designed and manufactured a high-temperature spacecraft resistojet HX manufactured through SLM. They showed feasibility of the production of fine structures with feature sizes below 200 µm in 316 L stainless via SLM. Saltzman et al. [248] fabricated and tested an aircraft oil cooler through AM, similar to a conventional design, but with modifications such as orienting the air and liquid side, extended features and the header walls at an angle. They showed an increase in the heat transfer around 10%, but also observed a higher pressure drop. Hathaway et al. [249] designed and fabricated an aluminum oil cooler fabricated by SLM. They presented the use of AM for a relatively large HX. They observed that the benefit of thermal enhancement was about 18% compared a stock HX, but the pressure drop across the 3D-printed HX is higher than the stock HX. As they reported, this could be because of overall print volume limitations requiring the plate-fins to be oriented at a 45° angle with respect to the tube axes. Placement of the fins created an impinging flow on the fin. Vanapalli et al. [250] fabricated and tested a compact flat-panel gas-gap heat switch operating at cryogenic temperature utilizing SLM. Experiments were performed at various HS temperatures, by varying gas pressure with helium, hydrogen and nitrogen gases. However, they did not present the improvement of the system compared a conventional one.

Observing the key advantages of AM compared to conventional fabrication techniques, this approach is being referred to as the new industrial revolution, however, further improvements is required. For example, AM could enhance the efficiency of thermal energy storage systems by integrating HPs into the structure and thermal control. The manufactured system could have ideal thermal contact as well as an optimized geometry for the desired storage cycle characteristics. This allows the construction of novel storage materials as well as optimized heat transfer surfaces, which is not possible with conventional manufacturing. Another suggestion for future developments regarding renewable energy applications is developing and updating fuel cell stacks utilizing AM. There is a challenge for the thermal management of these systems because of non-uniform heat generation throughout the stack due to a change in mass concentration and temperature gradients. A solution would be to implement a micro HP between bipolar plates. However, a challenge for developing this component is sealing and integration of the HP. The structure of the interior should be well designed to allow good electrical conductivity and thermal conductivity to the wick. For this reason, developing and improving fuel cell systems by integrating HP into fuel cell systems within new materials-based bipolar plates could overcome these challenges and improve fuel cell technology. This integrated system fabricated by AM would increase heat transfer in fuel cell stacks while requiring significantly smaller thermal gradients.

Finally, it should be noted that a major issue with SLM manufacturing is the potential to create real engineering components. To this aim, there is a need to develop a full definition of the performance of the component and ensuring that the cost and environmental performance of the manufacturing process are competitive, or better than, conventional manufacturing processes. To the authors' knowledge, it is not possible to use the experimental data available in the literature to have a clear perspective for defining criteria and guidelines to design HXs/HSs and two-phase devices utilizing SLM manufacturing. The SLM process still needs to be improved in the field of thermal management in terms of production time and costs. Comprehensive investigations should be systematically performed to provide fundamental knowledge and develop integrated thermal management system.

6. Summary and perspective

AM technology takes a key growing position in the modern manufacturing sector, especially in the energy conversion sector, to produce customized freeform shapes that outperform conventional shapes. The working principle of AM technology provides superior flexibility and complex shapes, such as internal cooling channels or porous structures that cannot be achieved by machining. Material must be selectively placed only where needed. These features provide the capability of AM to fabricate optimized HXs that enable working in single-phase or based on phase transition (i.e., evaporation and condensation), such as HP systems. HXs exploiting such enhanced thermal performance play a role of ever-increasing importance in almost any industry, such as electronic sector, energy storage, aerospace applications, etc. This paper addresses a range of current thermal management technologies associated with SLM technology to manufacture solid and porous media structures and their applications. This includes a literature review for single-phase, and two-phase heat transfer devices for enhanced compact HXs utilizing AM. An attempt is to identify and to encourage researchers for future areas of development and investigation of heat transfer devices utilizing AM.

Given the attention on SLM manufacturing to customized production, the key manufacturing process enabling the development of a geometric complexity for a specific application is described. This paper starts with a brief introduction of SLM technology, some common affecting limits and the significance for thermal management systems. Towards the end, the paper focuses more on the utilizing SLM on the HXs, HSs and HPs and their thermal management applications, suggesting possibilities of developed applications in the field of energy conversion and thermal management systems.

Although AM technology recently has undergone significant development, there are very limited studies on the application of laser-assisted AM for thermal management applications, particularly HPs and compact HXs/HSs fabrication. It is still not widely accepted by most industries to fabricate and integrate HXs utilizing AM. This is likely due to fact that there are several known challenges and areas of improvement for AM. The current limitations and needs for future work considering thermal management applications are proposed as follow:

1. There are no specific standards for assessing the properties of additively manufactured heat transfer devices because they depend on many process parameters. Therefore, to obtain accurately fabricated parts, process parameters must be optimized. In addition, there is a lack of reliable thermal conductivity data for 3D-printed HXs/HSs which typically include void fractions. This could be future work for researchers to be considered. Improving the manufacturing technology would benefit industry acceptance.
2. Compact HXs have been receiving a growth in utilization more than that of other types of HXs, likely due to reducing energy consumption and adaptability of components. One of the main challenges is to manufacture very small-scale fin sizes in the order of hundreds of microns thick with high ratio of fin height and thickness. The unique capabilities of AM processes for this aim, greatly enhance the freedom of designers to explore new compact HXs. However, a major difference between a conventionally manufactured and one fabricated by SLM is the surface finish; the fabricated parts utilizing SLM have higher surface roughness. Although highly increased surface roughness would benefit to enhance heat transfer as the flow becomes turbulent, this increases the pressure drop through the system as well. Additional work should be to quantify this surface roughness. Future studies need to determine whether heat transfer benefits from increasing the surface roughness. More studies should be considered to minimize pressure drop.
3. Despite recent development of heat transfer devices through AM, a limitation of additively manufacturing of HXs is to successfully fabricate components from copper, which benefits from improved electrical and thermal properties. Very limited studies reported the manufacturing of copper component utilizing laser AM [251–253]. Practically there is no successfully additively fabricated copper HX or HP. This is because of low laser radiation absorption and high thermal conductivity. Hence more laser output power is required to fabricate appropriate parts. The purpose of future research on material development could be a fundamental investigation of the SLM process of copper.
4. There are very limited studies on the application of laser-assisted AM for HP fabrication as well as fabrication of porous structure through SLM for HPs and HXs/HSs. Available studies do not consider a proper design and numerical analysis of their geometries. This results in a lack of knowledge and fails to predict the overall performance of the system as well as the effects of structural parameters. Thermophysical properties of additively manufactured materials, such as contact angle, wetting, permeability, etc., are also unknown. This requires significant further research and development in terms of design and materials, followed by numerical methods to simulate the thermal performance of the design parts.

Finally, several factors on the development of heat transfer devices are expected to enhance their performance by further improvement of HXs/HSs, depending on an appropriate selection and a careful thermal design. The thermal performance of heat transfer devices can be improved by customizing and utilizing new design options that are not possible with conventional fabrication methods. Previous limitations in HXs fabrication can be overcome through SLM manufacturing to adapt to the next generation of heat fluxes and application requirements. The review carried out in this work shows that SLM technology has great potential in the field of thermal management applications; however, there is a need for adoption and researchers are emerging to take advantage of such technologies. Development of new materials, as well as composites for SLM technology will provide progression beyond the state-of-the-art in design and fabrication of complex HXs/HSs or other complex two-phase devices in a wide range of applications.

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