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# Additive manufacturing of products with functional fluid channels: A review

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ABSTRACT

Products with functional fluid channels can transfer mass or energy and have been widely used in various fields, including aerospace, robotic, and biomedical applications. The manufacturing of these products with complex fluid channels is usually difficult for conventional fabrication methods; thus, a portion of the fluid flow function must be sacrificed to realize the feasible and smooth fabrication. Additive manufacturing not only provides a new way to manufacture the products with complex internal channels but also highlights design revolution for existing products with regular internal channels currently limited by conventional fabrication methods. To date, many publications have been reported on the design and manufacture of products with functional fluid channels, but there is a lack of an overview on this topic. In this paper, the current state of additively manufactured products with fluid channels are reviewed. Different functional fluid channels in heat exchangers, fluid power components, bipolar plates of proton exchange membrane fuel cells, and artificial blood vessels are summarized, and the challenges and further direction of additively manufactured products with functional fluid channels are also discussed.

## 1. Introduction

In industry and society, many products have complex internal structures, which generally show two purposes. One purpose is to achieve structurally lightweight products, which is significance for reducing the costs and energy consumption and improving the endurance of mobile equipment, such as automobiles, aircrafts, and robots. Another is to achieve mass or energy transport by fluid flow (liquid or gas), which is important for the products with functional fluid channels, such as heat exchangers [1–3], fluid power components [4,5], bipolar plates of proton exchange membrane (PEM) fuel cells [6,7], and artificial blood vessels [8,9], as the fluid flow in the internal fluid channels of the products can transfer heat, transmit fluid power, and transport mass, among other functions.

Compared with structural lightweight, fluid flow channels that can transfer mass or energy put forward higher requirements for design methods and manufacturing technology. The design and manufacture of products with internal fluid channels not only need to consider the structural optimization of local fluid channels and the arrangement of all fluid flow channels but also need to take into account the influence of the structure on the target functions, mainly energy transmission and mass transfer. Nevertheless, conventional formative (e.g., forging, mold casting, die casting, plastic injecting) or subtractive manufacturing (e.g., turning, drilling, milling, grinding) have difficulties in manufacturing products with internal fluid channels; thus, it is usually necessary for these methods to sacrifice some functional performance or add extra unnecessary weight to meet manufacturing feasibility. Some products cannot be successfully manufactured when the structure and shape of the internal fluid channels are highly complicated or their sizes are very small.

Additive manufacturing (AM), generally known as 3D printing, is an advanced manufacturing technology that digitally creates 3D objects by successive material addition [10]. AM has demonstrated great advantages in the automation of the production process, a high degree of design freedom, the resulting potential for optimization and material savings, etc. [11–13]. To date, many reviews focusing on the materials, microstructure, or mechanical properties of additively manufactured products exist [14–33]. Nevertheless, a state-of-the-art review of additively manufactured products with internal fluid channels is still absent, even though AM technologies have revolutionized the design and manufacturing of products with functional fluid channels. As such, it is appropriate to conduct a review to summarize the existing research of

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additively manufactured products with internal fluid channels. In this work, several existing additive manufacturing methods of products with fluid channels are introduced; then, the influence of additive manufacturing on the manufacture and design of different functional fluid channels in some representative products, including heat exchangers, fluid power components, bipolar plates of PEM fuel cells, and artificial blood vessels, are highlighted. In addition, the challenges and future directions of additively manufactured products with internal fluid channels are discussed.

## 2. Additive manufacturing of products with functional fluid channels

Since the first stereolithography manufacturing system appeared in the 1980s, AM has been widely used in various fields after years of development, including medicine [34,35], aerospace [36,37], robots [38], and construction [11,39]. To date, there have been many kinds of AM technologies developed for manufacturing various products with internal fluid channels and other internal structures, including vat photopolymerization (VP), material extrusion (ME), powder bed fusion (PBF), direct energy deposition (DED), material jetting (MJ), and sheet lamination (SL). All these AM technologies presently use a layer-based method, where each layer is a thin cross-section of the products derived from the virtual computer-aided design (CAD) data. These AM technologies can be broadly used in various materials categories, including metals, polymers, ceramics, composites, and biological materials.

AM technologies have revolutionized the design and manufacturing of products with functional fluid channels due to their remarkable advantages in some respects. Complex inner fluid channels can be produced using power bed fusion, vat photopolymerization, and material jetting. Simple channels can be made using material extrusion. Advantages of AM technologies for products with internal fluid channels are given as follows:

**(1) Great design freedom for fluid channel arrangement and fluid channel shapes:** AM technologies' flexibility in the manufacturing of highly complex geometries provide the designer great freedom to design both optimized overall fluid channel arrangements (e.g., capillary structure, topology structure, channel array, or even more complex irregular arrangements) and more optimized local fluid channel shapes (e.g., teardrop, rhombic, elliptical, or even more complex irregular shapes); these optimizations are not only beneficial to improve the heat transfer efficiency, heat dissipation efficiency, flow efficiency, or the flow field uniformity of fluid channels but also beneficial for the miniaturization and lightweight of products with internal fluid channels

**(2) Integrated manufacturing of products with fluid channels:** AM technologies can be used to manufacture whole products with internal fluid channels in a one-step process to remove the unnecessary metallurgical or mechanical joints. These joints are usually prone to leakage, especially under the action of internal high-pressure fluid. The integrated manufacturing of products with fluid channels can efficiently avoid the leakage at the joints to significantly improve the safety and service life of products with fluid channels.

**(3) Diversity of available materials for manufacturing products with fluid channels**: Many functional fluids are corrosive to fluid channels, so materials with high corrosion resistance are always expected to be used to manufacture fluid channels. However, materials with high corrosion resistance are often difficult to be processed into the desired flow channels with complex structures. AM is a feasible and rapid way to use these materials to manufacture fluid channels. Thus, AM technologies can use a broad material selection for manufacturing fluid channels with high corrosion resistance. Moreover, fluid channels can be made of multi-material printing, where different materials can be used in different parts of the fluid channels to meet different performance requirements to improve the overall performance of the product. Various sensors can also be printed inside the flow channel to sense the flow rate and fluid pressure in real time, which can provide sensing data for real-time monitoring of fluid characteristics and improve the product intelligence with the fluid channels.

Although AM technologies can bring many advantages to the design and manufacture of products with functional fluid channels, there are still many challenges in multiscale channels: vastly different technology, process, and quality. First, it is difficult to precisely control the forming qualities of the inner surface of the fluid channel, including the surface roughness and contour accuracy, which greatly influence the flow efficiency and heat transfer efficiency of the fluid. Different functional fluid channels often have different specific requirements. For example, it is necessary to reduce the inner surface roughness of the fluid channels in hydraulic components to improve the fluid flow efficiency, while to increase the inner surface roughness of the fluid channels in the heat exchangers improves the heat transfer efficiency. Moreover, high precision nondestructive testing methods of fluid channel quality and testing methods of fluid channel performance also need to be explored future studies. Additionally, although AM technologies bring design freedom to fluid channels, there is still a lack of scientific and effective design criteria for the overall arrangements and local shapes of fluid channels, especially since different design criteria are necessary for products with different functional fluid channels. Therefore, scientists and engineers should understand the tradeoffs between its advantages and limitations when AM is used to produce these products with internal fluid channels.

In the following sections, some representative applications of additive manufacturing in products with internal fluid channels, including heat exchangers, fluid power components, bipolar plates of PEM fuel cells, and artificial blood vessels, are summarized, and the internal fluid channels in these products have different functions (Fig. 1).

## 3. Fluid channels in heat exchangers: heat transfer efficiency

As key components of heat exchangers, the functions of fluid channels are to use fluid flow to transfer heat, so that the desired heating or cooling effect is achieved. Heat exchangers are widely used in refrigeration, air conditioning, power stations, chemical plants, and the petroleum industry, etc. The typical demand of these functional fluid channels in heat exchangers is to achieve high heat transfer efficiency of heat exchangers. Increasing the surface area/volume ratio of fluid channels is the primary way to improve the heat transfer efficiency of heat exchangers. Enhanced heat transfer efficiency can result in significant benefits, including high energy conversion and compact size [40]. Cooling channels in molds used in plastic injection molding and die casting are also discussed here because the design and manufacture of cooling channels are similar to those of fluid channels in heat exchangers, though they do not belong to the same category.

Conventionally, heat exchangers are produced by bending rolled sheets into desirable shapes, and then they are brazed or welded together. The process involves several steps and has a long fabrication time. In plastic injection molds, the drilling method is typically used to produce cooling channels. Both processes restrict the geometry and path of fluid channels, which negatively affect heat transfer efficiency. Laser powder bed fusion (LPBF) is a common AM technology to produce fluid channels with enhanced heat transfer efficiency while VP is also reported. Some additively manufactured products have already been used in industry, such as automobile and power generation, and show great advantages in heat transfer efficiency improvement [41,42].

Some literature has focused on ways to improve heat transfer efficiency of heat exchangers by increasing the surface area/volume ratio using mini- and microchannels without increasing the size and weight [43–46], as shown in Fig. 2(a)-(c). Some researchers have designed and manufactured inclined fins and tapered mini-channels using LPBF technology and a significant increase in heat transfer coefficient was reported [47–49]. Tiwari et al. [43] reported that they used polymers to 3D print a heat transfer manifold with circumferential fins and inter

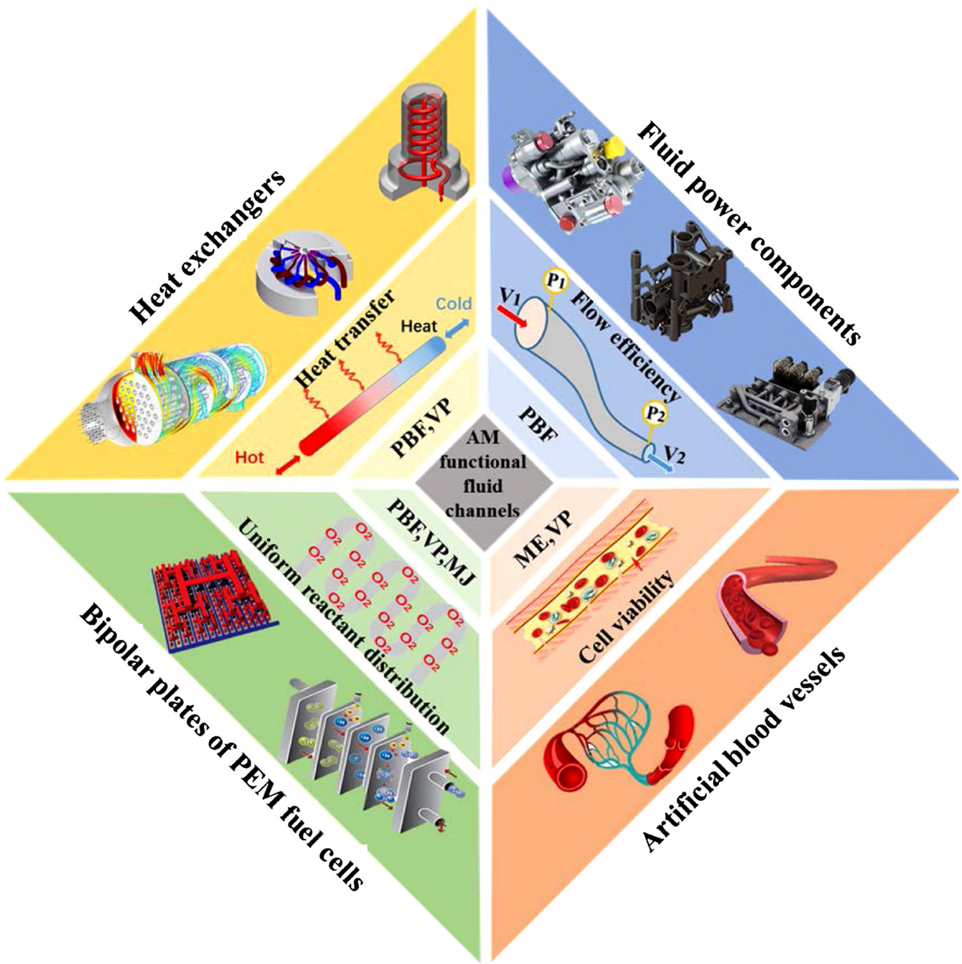


**Fig. 1.** Representative applications of additive manufacturing in products with internal fluid channels.

rifling structures. The heat transfer coefficient was an order of magnitude higher than that of a conventional manufactured manifold. Brooks and Brigden [50] applied lattice structures in the cooling channels which could increase fluid vorticity leading to improved convective heat transfer. Kwon et al. [51] designed various static mixers in water cooling channels. Two types, including twisted tape and chevron, were manufactured using continuous liquid interface production and both could enhance convection heat transfer. Yameen et al. [52] compared the influence of different arrays of pin fins in air channels and/or modified microchannel orientation on heat transfer performance; however, the influence was not significant.

Some literature has focused on the influence of AM channel geometry on the heat transfer performance, as shown in Fig. 2(d)-(f). The Center for Environmental Energy Engineering in the University of Maryland [53] reported hollow droplet shape channels to increase overall heat transfer efficiency by 20 % while the size and weight were reduced. Saifullah et al. [54] designed a new square-shaped section with higher performance for injection molding and compared with the circularly sectioned conformal cooling channels by FEA methods. Various fin structures inside the channels were also found to be useful in increasing thermal conduction. Hearunyakij et al. [55] designed a circular conformal cooling channel with fins to increase cooling efficiency. The results indicated that cooling efficiency increased as the number of fins increased. Moon et al. [56] compared the heat transfer performance of three types of heat sinks with both internal and external fins. Measurements from an AM-fabricated aluminum alloy heat sink showed a four times improvement in power density compared to conventional designs.

With AM technology, conformal cooling channels can be introduced to improve cooling efficiency and increase production, particularly plastic injection molding [57–64], as shown in Fig. 2(g)-(i). Wang et al. [65,66] designed spiral conformal cooling channels based on boundary-distance maps, which could achieve uniform mold cooling. Au and Yu [67] proposed a novel adjustment method to modify the distance between the existing conformal cooling channels and the cavity surface to compensate for increasing coolant temperatures. The results showed that the conformal cooling channels with variable distance had a better cooling efficiency than the convectional conformal cooling channels. Wu and Tovar [68] introduced a coupled thermal-fluid topological optimization algorithm to design conformal cooling channels. The fluid and solid phase materials were optimally distributed over the entire domain in terms of their fluid and thermal-fluid properties include flow resistance, heat conduction, and natural and forced convection after topological optimization. Some results are summarized in Table 1.

## 4. Fluid channels in fluid power components: fluid flow efficiency and lightweighting

The function of fluid channels in fluid power components is to use fluid flow to transmit and control the hydraulic force so that the desired actuation operation is achieved. Fluid power components are widely used in mobile equipment, such as aerospace and robotics. The typical demand of these functional fluid channels in fluid power components is to achieve high power density (or power-to-mass ratio) of fluid power components [69]. To decrease the energy loss in fluid channels or to optimize the fluid flow arrangement to achieve lightweight fluid power

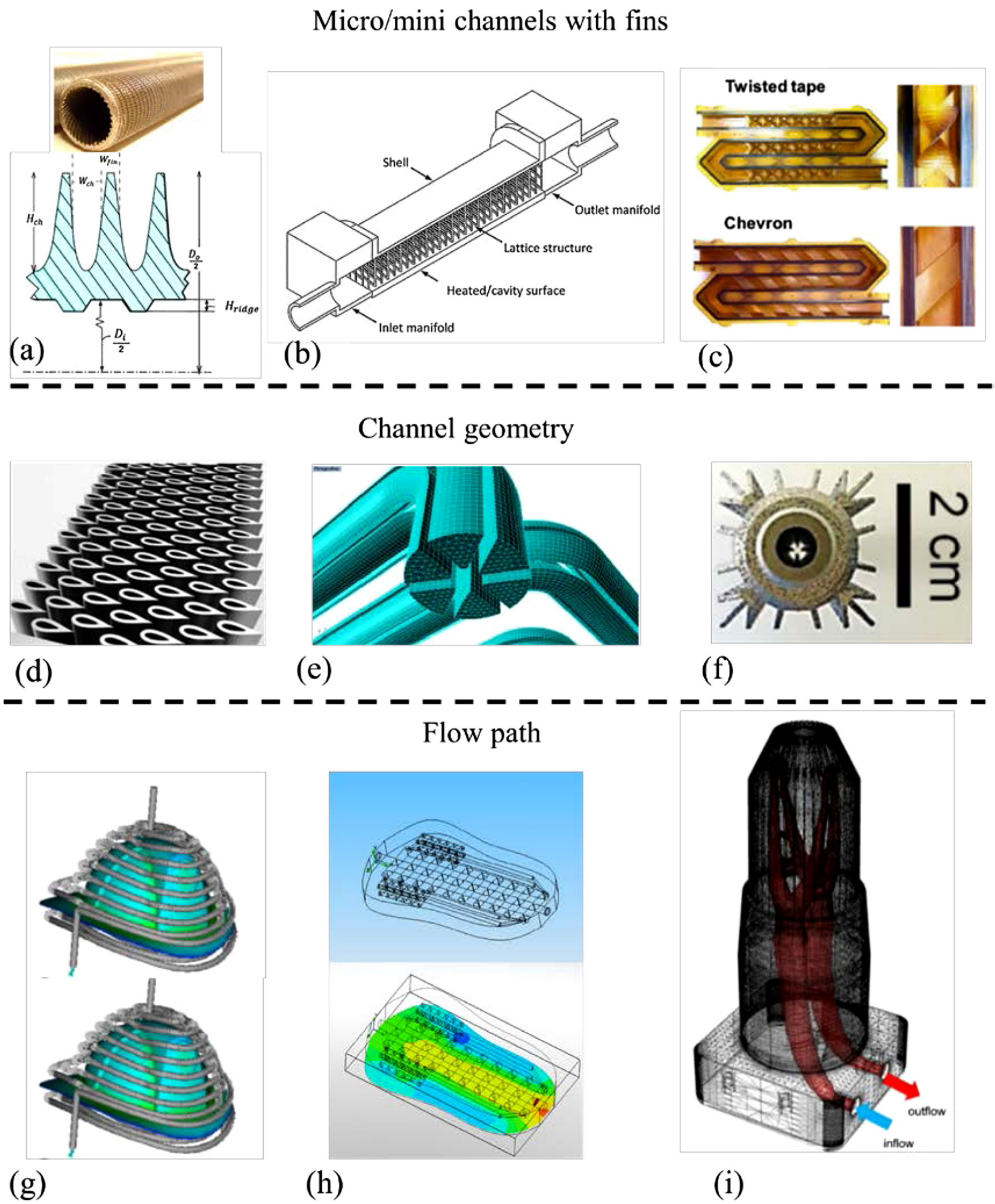


**Fig. 2.** Summary of AM channel design in heat exchangers: (a) manifold with circumferential fins and inter rifling structures [43]; (b) channel filled with lattice structures [50]; (c) polymer channel with mixers [51]; (d) hollow droplet cross-section channel [53]; (e) channel with internal fins [55]; (f) channel with internal and external fins [56] (g) centroidal Voronoi diagram-based and spiral conformal cooling channels [65,66]; (h) variable distance layout conformal cooling channels [67]; (i) thermal-fluid topology layout optimization [68].

components are two main ways to improve the power density of the fluid power components. Additionally, fluid channels in fluid power components are essential parts to transport pressurized fluids; thus, they are required to sustain high pressure to enable high energy conversion efficiency.

Rubber is typically used to produce long flexible pipes used to connect fluid power components that have relative motion, while metal channels are used inside most fluid power components. Since most metal channels in fluid power components are on the millimeter scale, drilling (most common) or casting is often used to produce conventional fluid channels. Drilling is a highly efficient machining technique that produces channels with high accuracy. However, channel geometry and flow path (has to be straight) are significantly restricted leading to a bulk block. Casting is able to produce curved channels; the accuracy can be low, and complex channels remains a great challenge. Selective laser melting (SLM) or LPBF is often used to produce fluid channels in fluid power components due to high accuracy and strength. In addition to the well-known fuel nozzle in leap engines, hydraulic valves, actuators, and manifolds have been produced using SLM by industry and research groups [70–73]. Size and weight were significantly reduced compared to conventional products. Some integrated hydraulic units were also fabricated using AM, which became an essential part in robots and aircrafts to increase dynamic response and loading capacity and to reduce energy consumption. However, few

**Table 1**
Summary of AM heat exchangers with new channel design.

| Method | Materials | AM technology | Contributions | Heat transfer efficiency |
|---|---|---|---|---|
| Micro/mini channels with fins | Stainless-steel; titanium alloy; aluminum alloy [47,48,49] | Powder Bed Fusion | Tapered channels with fins | Heat transfer coefficient increases by 15 − 50 % |
| | Polymer [43] | Not introduced | Design circumferential fins and inter rifling structures | 10x increase |
| | Steel [50] | Only simulation | Lattice structures in the cooling channels | 26.34 % increase |
| | Photopolymers [51] | Continuous liquid interface production | Designed various static mixers in water cooling channels | Reduced thermal resistance in half |
| | Stainless steel [52] | Powder Bed Fusion | compared different arrays of pin fins in air channels and/or modified microchannel orientation | No significant difference among the three types |
| Channel geometry | Titanium [53] | Powder Bed Fusion | Hollow droplet shape channels. The size and weight of the heat exchanger was reduced. | Heat transfer efficiency increased by 20 %. |
| | Structural steel [54] | Only simulation | Compare square sectioned channels with circular channels. | 20 % reduction in cooling time. |
| | Mold steel P20 [55] | Only simulation | Circular conformal cooling channel with internal fins | 8.3 %–21.3 % reduction in cooling time. |
| | AlSi10Mg [56] | Powder Bed Fusion | Compared channels with both internal and external fins | Power density increases by four times |
| Flow path | Mold steel P20 [65,66] | Simulation and optimal algorithms. | Designed spiral conformal cooling channels based on boundary-distance maps | 11.3 % reduction in cooling time than VD-based channel. |
| | Stainless steel [67] | Only simulation | Conformal cooling channels with variable distance | More uniform cooling performance. |
| | Prealloyed tool steel [68] | Powder Bed Fusion | Introduced a coupled thermal-fluid topological optimization algorithm to design conformal cooling channels | / |

details have been released.

Fluid topology, which uses a variable porosity approach to manipulate flow geometries by adding or removing material, has been proposed as an efficient method to optimize and design internal channels with minimal pressure loss. Researchers [74–76] presented exciting results in AM channels using fluid topological optimization based on some typical geometries: a serpentine channel, a U-bend, a straight duct, and a rectangular box. Some results are shown in Fig. 3, which outweigh those results using traditional designs [77–79]. However, such methods were performed based on a given space (design domain).

A hydraulic manifold is a hydraulic circuit with many complex fluid channels that combines hydraulic components in a compact unit. Therefore, design and manufacture of a hydraulic manifold using AM not only shows the channel characterization in fluid power components but also exploits the high design freedom of AM. Renishaw plc. [72] took some examples to illustrate the capability of AM design. The severity of the corner angles, which significantly contributes to flow separation and stagnation, was reduced for optimized flow. Auxiliary holes were eliminated to reduce potential leakage. A cross drilled block manifold was reduced to a pipe network leading to large size and weight reductions. Schmelzle et al. [80] redesigned the structure of a hydraulic manifold, and SLM was used to manufacture it. In the study, stress relief, postprocessing, and nondestructive inspection were also performed and discussed to ensure robust performance. A design approach for part consolidation using metal AM was presented, and noncircular passages were also proposed to improve fabrication quality of fluid channels without internal supports. Fluid dynamics was mentioned but not discussed in depth. Alshare et al. [81] conducted similar work but focused on the pressure loss. They analyzed the fluid dynamics paths based on the extracted piping from the original hydraulic manifold. The model was evaluated through CFD fluid flow and fluid–structure interaction (FSI) to achieve the lowest pressure loss and adequate structural durability. SLM was used to manufacture the optimized manifold. A design flowchart was also presented by taking both fabrication boundaries and fluid dynamics optimization into account. A research group in Zhejiang University also presented work on a hydraulic manifold, which connected to eight valves and one sensor. They also focused on fluid flow by considering gradually curved turns, large turn radii, and lower turn numbers. In addition, friction factor in a SLM fabricated channel was measured and discussed because the influence of the fabrication quality of the channels on fluid flow remains unknown. Some results are summarized in Fig. 4 and Table 2.

## 5. Bipolar plates of PEM fuel cells: uniform reactant distribution

Bipolar plates are vital components of PEM fuel cells, which consist of fluid channels. The function of these fluid channels is to offer fuel and oxidant to reactive sites and remove reaction products, so that the produced current can be collected. The typical demand of these functional fluid channels in bipolar plates is to achieve high energy conversion efficiency of PEM fuel cells. An optimal route for an array of fluid flow channels in bipolar plates can enable uniform chemical reactant distribution to achieve uniform temperature distribution and even current density distribution, so that the energy conversion efficiency of the PEM fuel cell can be improved. However, it is difficult or even impossible for conventional fabrication methods to manufacture bipolar plates with complex fluid channels and conventional fabrication methods are expensive and time consuming. In addition, the available materials are also limited.

PEM fuel cells are promising candidates as zero-emission power sources for transport, portable and stationary cogeneration applications due to their high-power density, high efficiency, low-temperature operation, quick start up capability, and system robustness [82–84]. As shown in Fig. 5, bipolar plates are vital components of PEM fuel cells, that offer fuel and oxidant to reactive sites, remove reaction products, collect produced current, and provide mechanical support for cells in

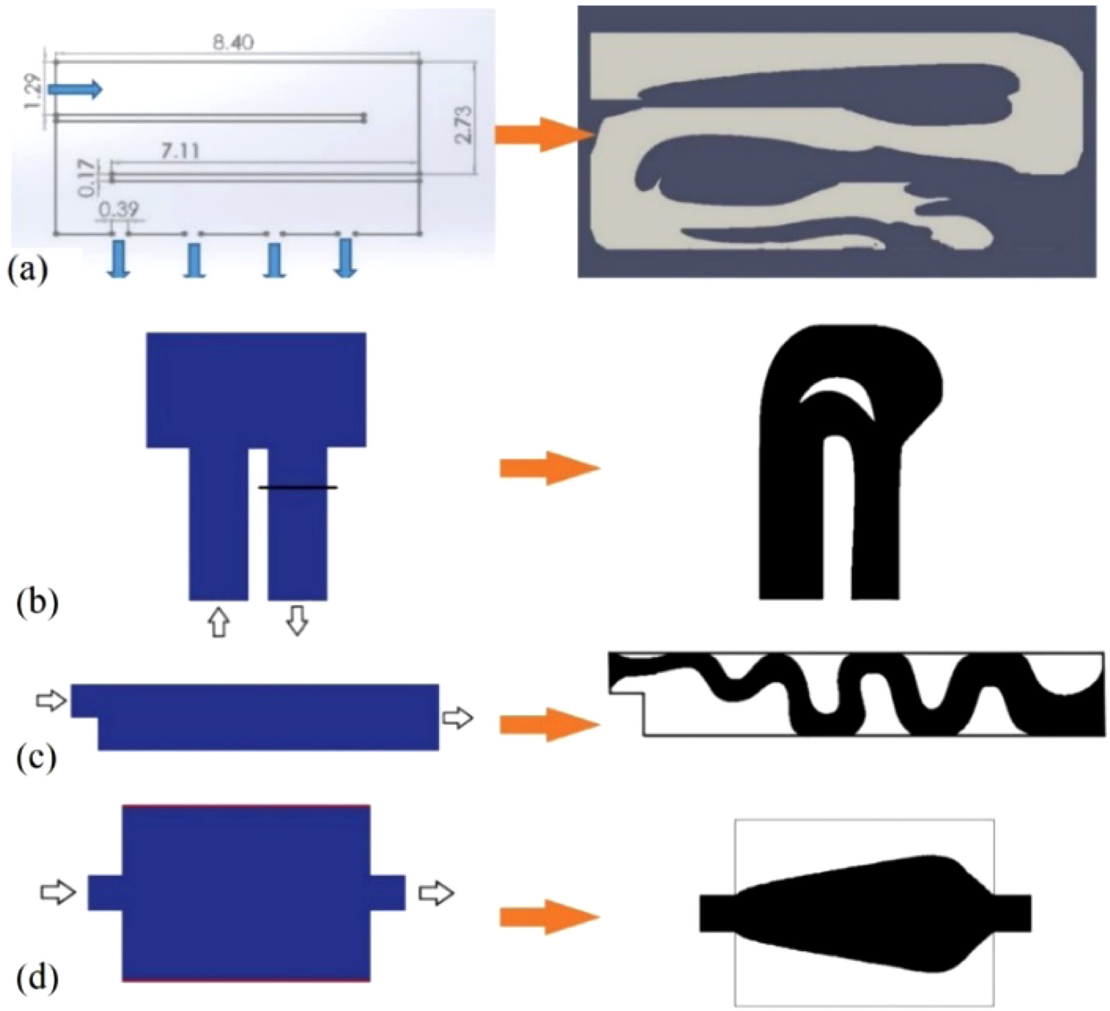


**Fig. 3.** Examples of fluid topology optimization. (a) A serpentine channel reduces pressure loss by 50 % [76]; (b) a U-bend channel reduces pressure loss by 40 % (with box aspect ratio 2:1 and inlet velocity 6 m/s) [75]; (c) a straight duct channel [75]; (d) a rectangular box channel reduces pressure loss by 26 % [75].

the stack. In practice, PEM fuel cell stack design often boils down to bipolar plates design, which, in turn, is basically the design of flow channels formed on the bipolar plates. Requirements for carrying out optimal bipolar plate functions are often met by the appropriate design of the flow channels [85]. The optimization of the gas flow fields of bipolar plates is an important factor for cost reduction and performance improvement of PEM fuel cells. The optimum route for an array of gas flow channels in bipolar plates can make the chemical reactant distribution uniform. When the reactant is evenly distributed over the surface areas of a cell membrane, temperature distribution becomes uniform and current density distribution, thereby limiting the mechanical stress on the membrane electrode assembly and increasing the longevity of the fuel cell [86].

Most graphite-based bipolar plates are manufactured by CNC machining. The manufacturing process of CNC machining is slow because the material brittleness increases the fabrication difficulty [87]. Conventional fabrication methods, such as engraving, stamping and compression molding, are used to manufacture metal-based bipolar plates. Over the last decade, many researchers have focused on improving flow field design to uniformly distribute the reactants and decrease the pressure-drop in bipolar plates [88–94]. However, it is difficult or even impossible for conventional fabrication methods to manufacture bipolar plates with complex fluid channels and the available materials are often limited. Additionally, conventional fabrication methods can be expensive and time consuming. AM is highly capable of manufacturing complex structures of bipolar plates for improving fuel cell performance. To date, several companies have tried to use AM to commercially produce fuel cells [95,96]. Meanwhile, some academic research has been published. Trogadas et al. [97] applied LPBF to manufacture a lung-inspired fractal geometry of bipolar plate flow channels to solve the uneven reactant distribution issue in fuel cells. Five step-by-step branching generations (shown in Fig. 6) were used to design a bipolar plate resulting in more uniform reactant distribution and minimum entropy production. This novel structure cannot be manufactured by conventional fabrication. The experimental results showed that additively manufactured lung-inspired flow field-based fuel cells with four generations outperform the conventional serpentine flow field designs. Uniform reactant distribution and minimal pressure drop were maintained, demonstrating the robustness of this proposed method. Cai et al. [98] put forward a PEM fuel cell with a porous bottom rib 3D cathode flow field. The result shows that this type of structure has a better performance than a conventional, parallel straight cathode flow field as the porous bottom ribs of 3D flow fields are helpful for even reactant distribution.

To ensure maximum closeness to the desired geometry, it is necessary to eliminate any possible gap between the channel rib and acrylic glass and the effect of bipolar plate tightening in experiments. Therefore, Piri designed a novel bipolar plate with enclosed channels via a transparent layer 3-D printed on top of the channels shown in Fig. 6(c) [99]. The numerical simulation results show that the cathode bipolar plate was modified by decreasing the gap between the baffles in the middle section of the transition region, which increases the flow

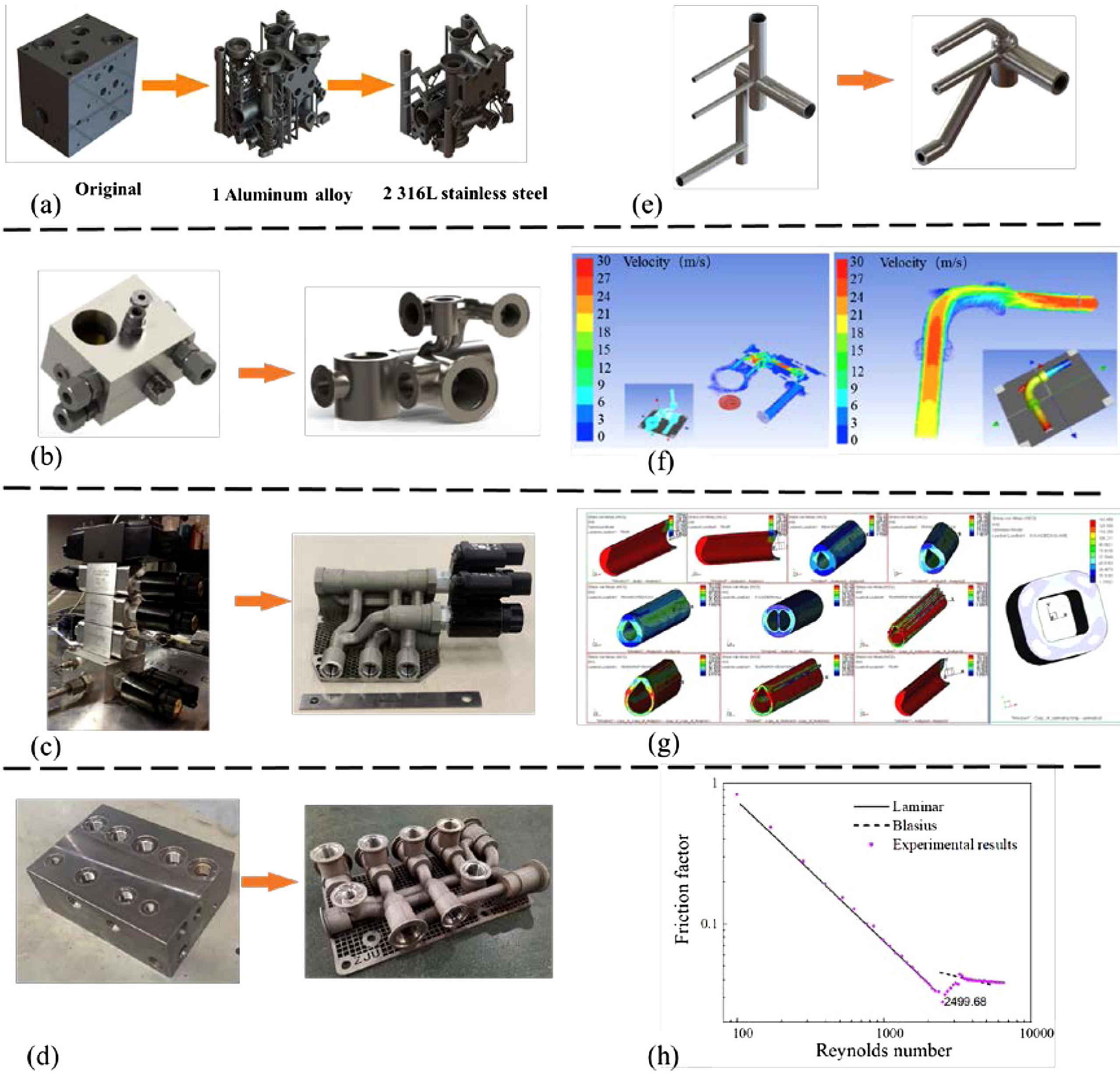


**Fig. 4.** Summary of hydraulic manifolds: comparisons between original and AM manifolds ((a) Renishaw [72], (b) Alshare et al. [81], (c) Schmelzle et al. [80], and (d) ZJU research group); illustrations of the contribution ((e) Renishaw presents a new AM design for optimized flow [72]; (f) Alshare et al. present pressure distribution in two planes in the new AM design [81]; (g) Schmelzle et al. present noncircular channel design and stress analysis [80]; (h) ZJU research group presents the results of friction factors between a SLM-fabricated channel and classical theory).

resistance in the middle section and leads to enhanced flow to the side channels, thereby achieving a uniform pressure and velocity profile in the modified cathode flow field.

## 6. Artificial blood vessel and vascular networks: strength, cell viability, and structure complexity

The function of blood vessels is to use blood flow to exchange substances with tissue fluid to provide oxygen and nutrients for organs and tissues and to expel wastes. Currently, vascular disease is common around the world. Over 15 million people worldwide die from cardiovascular disease every year [100,101] and the healthcare costs are tremendous [102]. Presently, autologous bypass therapy, which makes a detour around the blockage, has been applied to treat vascular diseases in clinics. However, autologous grafts are not always available due to critical conditions of patients and lack of donors [101]. As a result, artificial blood vessels, an ideal solution to that problem, have been under spotlight and investigated in recent years. Therefore, artificial blood vessels must meet the demands of sufficient mechanical properties and good biocompatibility.

On one hand, it is crucial that the mechanical properties, e.g., Young's modulus and tensile strength [103,104], of the artificial blood vessels are close to those of natural blood vessels. On the other hand, the capability to support tissue viability, including oxygen delivery, nutrient transport, and metabolic waste removal [105,106], should also be considered. Over the past several decades, several approaches, including decellularized tissue [107,108], synthetic-based construct [106,109], and natural biomaterial-based constructs [110,111], have been developed for fabricating artificial blood vessels. However, there are still many challenges, including negatively affected biological activity and biomechanical properties due to rigorous decellularization processes [112], difficulty in fabricating small-diameter vessels (below

**Table 2**
Summary and comparison of AM hydraulic manifolds.

| | Materials | Weight reduction | Volume reduction | Pressure drop reduction | Contribution |
|---|---|---|---|---|---|
| Renishaw | Aluminum alloy; 316 l stainless steel [72] (Original: aluminum alloy) | 52 % for aluminum alloy; 36.3 % for stainless steel | 52 % for aluminum alloy; 79 % for stainless steel | Up to 60 % (without details) | Illustrate benefits of AM in hydraulic manifolds; Change abruptly angled junctions between flow paths to curved ones to avoid flow separation and/or stagnation. |
| Alshare et al. | Stainless steel [81] | 84 % | 23 % | 15 % | Optimization with CFD and fluid-structure interaction simulations. |
| Schmelzle et al. | 17−4 stainless steel [80] | 60 % | 53 % | Not mentioned | Noncircular passages; A generalized design approach; |
| Research group in ZJU | 316 l stainless steel | 92 % | 46 % | 31 % | Friction factor is the same between conventional and AM fluid channels in laminar flow. |

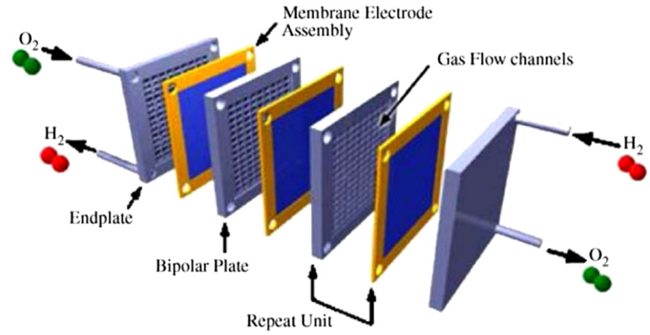


**Fig. 5.** Schematic diagram of PEMFC components [85].

5 mm) using synthetic-based methods [113], and limited mechanical properties of biomaterials [100]. In addition, the manufacturing process is complicated and expensive for the abovementioned approaches.

AM has been used to fabricate artificial blood vessels due to unlimited geometric complexity, material diversity, and high building efficiency. Basically, ME and VP are two common techniques used for this purpose. More specifically, they are extrusion-based printing, inkjet writing, and laser-assist printing.

Extrusion-based printing is mainly studied to embed hollow fiber into a tissue engineering scaffold as a vascular network. A coaxial nozzle with annulus structure is used, where different materials are extruded to form inner and outer phases, as shown in Fig. 7(a) and (b). Based on this method, many studies were carried out focusing on the mechanical properties. Gao et al. [114] produced a high strength cell-laden hydrogel structures with built-in microchannels that showed great potential in nutrients delivery for large scale organs. Dolati et al. [115] enhanced the mechanical strength of vascular conduits by adding carbon nanotubes (CNTs) to sodium alginate, as shown in Fig. 7(c). In addition, some studies were performed to improve the building process and structures. Jung et al. [116] produced blood vessels through a glass capillary and found the inner face could enhance the formation of tubular shapes, which further reduced build time. Attalla et al. [117] designed a scalable tri-axial microfluidic extrusion nozzle, which could fabricate scaffold structures that were multi-cellular and multi-material. Due to the inherent process in extrusion-based printing, it is dificulty to produce vessels with branches.

Inkjet writing fabricates structures directly in the supporting environment, which enables it to fabricate complicated structures, as shown in Fig. 7(d) and (e). As a result, branch structures can be fabricated (Fig. 7(f)) and high cell viability was reported. Tabriz et al. [118] fabricated a branch structure with cell viability (92.9 %) by using $CaCl_2$ and barium ions to enhance primary and long-term stability of the alginate hydrogel and the static stiffness was increased to 20 kPa with 100 mM $CaCl_2$ solution. Huang's group [119,120] fabricated vascular-like structures with 92.4 % cell viability by a compensation-based printing approach, fabricating structures based on different stiffnesses of model parts. In a recent study [121], laponite was used to produce supporting structures and a new strategy "printing-then-solidification" was proposed for fabricating alginate, gelatin, and liquid photosensitive materials (SU-8). A maximum cell viability of 93.6 % was achieved.

In addition, some researchers [122] introduced lasers to assist the fabrication of tissue engineering, as shown in Fig. 7(g)-(i). Extremly high fabricating accuracy can be achieved. Although an energy absorbing layer was introduced, cells still have a high risk of being damaged by the laser energy [123]. All abovementioned methods for fabricating vascular networks are briefly summarized in Table. 3.

## 7. Challenges and future directions

Although AM brings innovation to the manufacture and design of

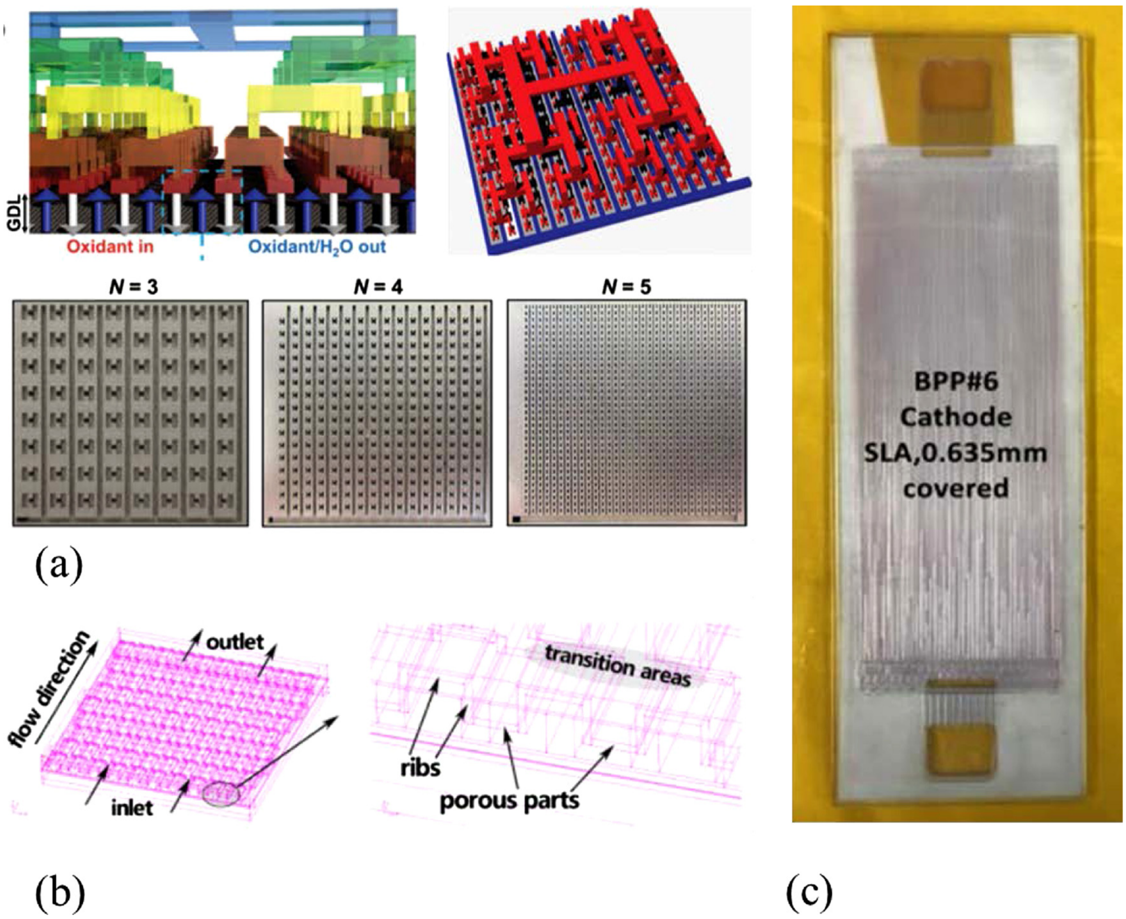


**Fig. 6.** 3D-printed lung-inspired flow fields of bipolar plate [97]; PEMFC with a 3D porous cathode flow field and parallel straight anode channels [98]; SLA bipolar plate with enclosed channels [99].

products with internal fluid channels, there are still challenges that should be resolved in the future. An existing hurdle of additively manufactured products with internal fluid channels is that the forming qualities, including surface roughness, dimensional accuracy, and heterogeneous properties, greatly affect the various functions of products with internal fluid channels, thereby affecting the mass transfer efficiency and increasing the energy loss.

### 7.1. Heat exchangers

For heat transfer efficiency, the mini- and micro- channels can enhance heat transfer performance but often result in poor fluid flow. Those two factors are often need to be considered together [124–127]. To increase heat transfer performance without sacrificing fluid flow efficiency remains a great challenge. In addition, forming quality, including dimensional accuracy (Fig. 8(a)) and surface roughness (Fig. 8(b)), greatly affects heat transfer efficiency. Arie et al. [48] pointed out that a significant performance enhancement could be achieved by improving forming quality. Some literature has indicated that rough surfaces facilitate heat transfer due to increased surface area [128,129]. However, channels with high surface roughness typically decrease mass flow rate. It was pointed out that the reduction in heat transfer was not as large as the reduction in mass flow rate because of the augmentations that occur for rough AM coupons. At a fixed pressure ratio the rough AM surface helps to recover heat transfer lost due to the drop in mass flow from a theoretically smooth channel [124,127].

### 7.2. Fluid power components

To achieve high flow efficiency, channels in fluid power components are often curved, which causes difficulties in removing supports inside the channels postprocessing. Moreover, due to functionalities, channels cannot be built vertically to avoid supports. Therefore, fluid channels are subjected to considerable shape deviation and high surface roughness due to a large overhang region shown in Fig. 9[130,131]. A typical fluid channel built horizontally using SLM is shown in Fig. 8. Curling and dross formation can be found on the top part due to residual stress [132,133]. Noncircular passages (e.g., diamond, teardrop shapes) [80] are an efficient way to improve forming quality. However, stress concentration increases, and results in thicker channel walls leading to more weight. Therefore, the influence of forming quality on the fluid flow in LPBF channels without supports should be investigated. Snyder et al. [130,134] found that the building direction greatly influences the dimensional tolerance and surface roughness which further affects the transitions between flow regimes. The horizontally positioned cylindrical channels have the highest friction factor while the vertical channels have the lowest. Stimpson et al. [124,135] found that the friction factor of the SLM channels built diagonally is higher than that of laminar flow theory at low Reynolds numbers, while in the turbulent region the difference in the SLM channels is large. This work is based on a few types of mini air fluid channels (diameter or equivalent diameter $< 1$ mm). Recently, some researchers found that the laminar flow between a drilled and a LPBF-fabricated channel is almost identical. However, the results are only valid for a fluid channel with 10 mm diameter.

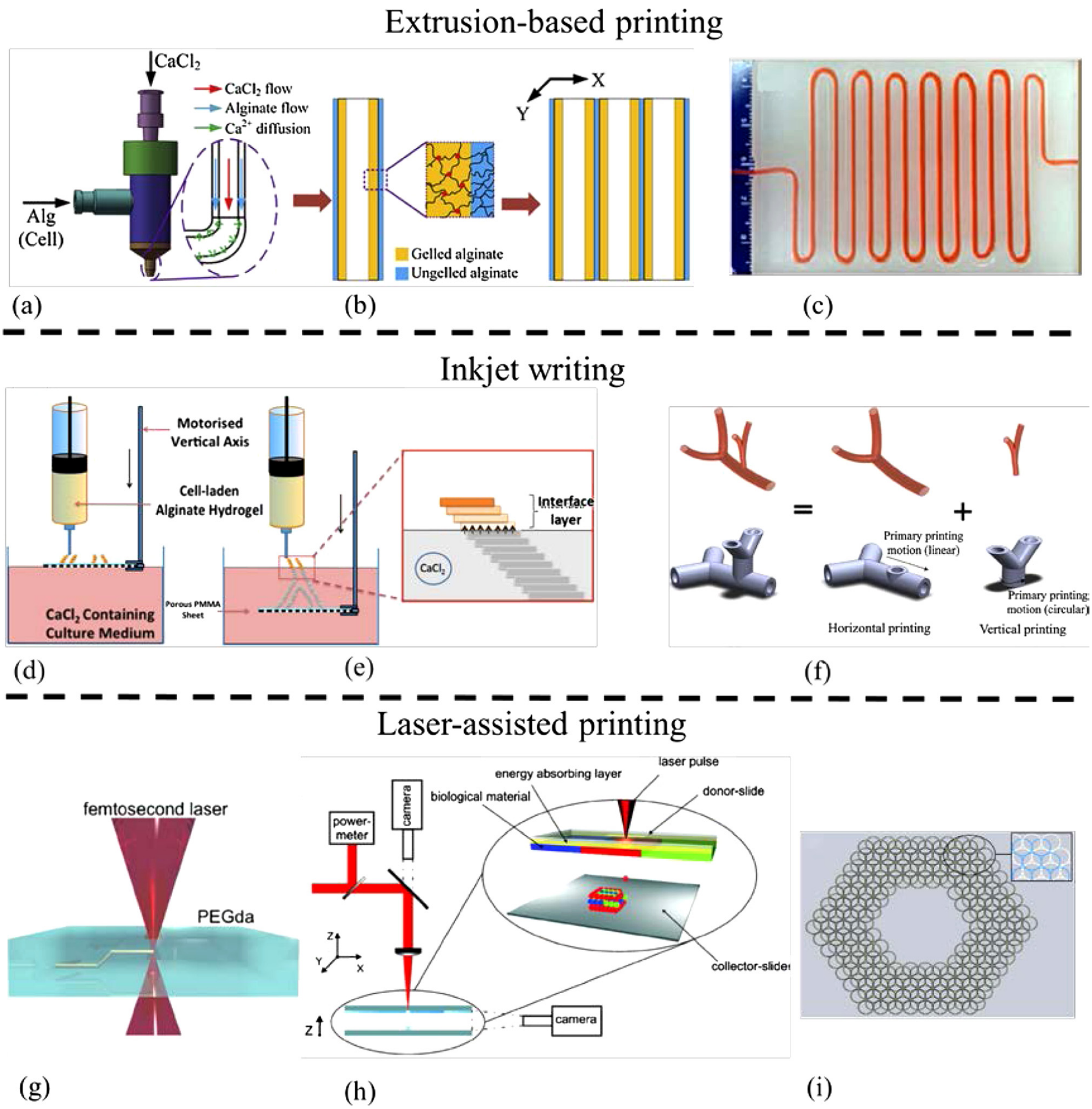


**Fig. 7.** Schematic of existed AM technologies used in vascular net-works and some application examples. (a) and (b) [114], extrusion-based printing. (c), tensile strength was enhanced from 382 kPa to 422 kPa by adding CNTs to sodium alginate [115]. (d) and (e) [118], inkjet writing technology. (f), complex structure (horizontal + vertical) was fabricated with a stiffness of 20 kPa and cell viability of 92.9 % [119]. (g) and (h) [122], laser-assist technology. (i). Scaffold with good cell density and location was fabricated [122].

### *7.3. Bipolar plates*

Gould et.al pointed out that the single-cell stack performs well when compared to a standard one, but a 40-cell fuel cell stack power is 20 % less than expected due to inadequate flatness of several bipolar plates fabricated using PBF. This cell-to-cell mismatch leads to high contact resistance in several cells [136]. Thus, more work is needed to reduce the weight and increase the flatness of bipolar plates made by metal AM before they can be used in larger stacks.

### *7.4. Artificial blood vessels*

Compared to traditional methods, AM technology enables high geometric complexity, material diversity and fabrication efficiency. However, there are some limitations in AM vascular networks. Extrusion-based printing can produce structures with high accuracy but low geometric complex (branch structures are not possible). In addition, cell viability is negatively affected due to the flow shearing while extruded from the nozzle. Inkjet writing enables complex structures with high cell viability while the fabrication accuracy is relatively low (vessel diameter > 3 mm). Moreover, there is a tradeoff between the mechanical properties and cell viability. High alginate concentration increases tensile strength, which reduces cell viability. AM-based blood vessels and vascular networks must improve from materials, machines, and processes to be close to the “optimal” design the natural blood vessels in our body.

Moreover, it is important to consider the local mass and heat transfer functions as well as the overall functions in these additively

**Table 3**
Brief summary of present AM technologies used in vascular net-works.

| Method | Material | Fabricating accuracy | Contributions |
|---|---|---|---|
| Extrusion-based printing | Sodium alginate and $CaCl_2$ [114] | Depend on experimental parameters, e.g., diameters of nozzles, and kinematic accuracy Minimum inner diameter is approximately 15 μm | High sodium alginate concentration and small distance between adjacent hollow fibers promote high strength. |
| | CNTs- sodium alginate and $CaCl_2$ [115] | | Tensile strength was enhanced from 382 kPa to 422 kPa by adding CNTs to sodium alginate. |
| | N-Carboxyethyl chitosan and oxidized dextran [116]. | | Built time could be reduced by printing vessels through a glass capillary. |
| | Collagen, fibrin, sodium alginate and $CaCl_2$ [117] | | Tri-axial extrusion nozzle was designed to produce scaffolds with structures with multi-cellular and multi-material, which leading to high cell viability. |
| Inkjet writing | Sodium alginate, $CaCl_2$ and $BaCl_2$ [118] | Depend on experimental parameters and the minimum inner diameter is approximately 3 mm. | 100 mM $CaCl_2$ solution increased the static stiffness of alginate hydrogel to 20 kPa. In 60 mM $BaCl_2$ solution, the cell viability reached 92.9%. |
| | Sodium alginate and $CaCl_2$ [119,120] | | Overhang structures were fabricated based on a predictive compensation-based approach. 92.4 % printed cell viability was achieved. |
| | Sodium alginate, gelatin and SU-8 [121] | | “Printing-then-solidification” strategy was proposed. 93.6 % printed cell viability was achieved. |
| Laser-assist printing | Ploy(ethylene glycol) diacrylate (PEGda) [122] | Structures with high complexity and high fabrication accuracy. | Two-photon polymerization was used for the fabrication of scaffold. Scaffold with good cell density and location was fabricated. |

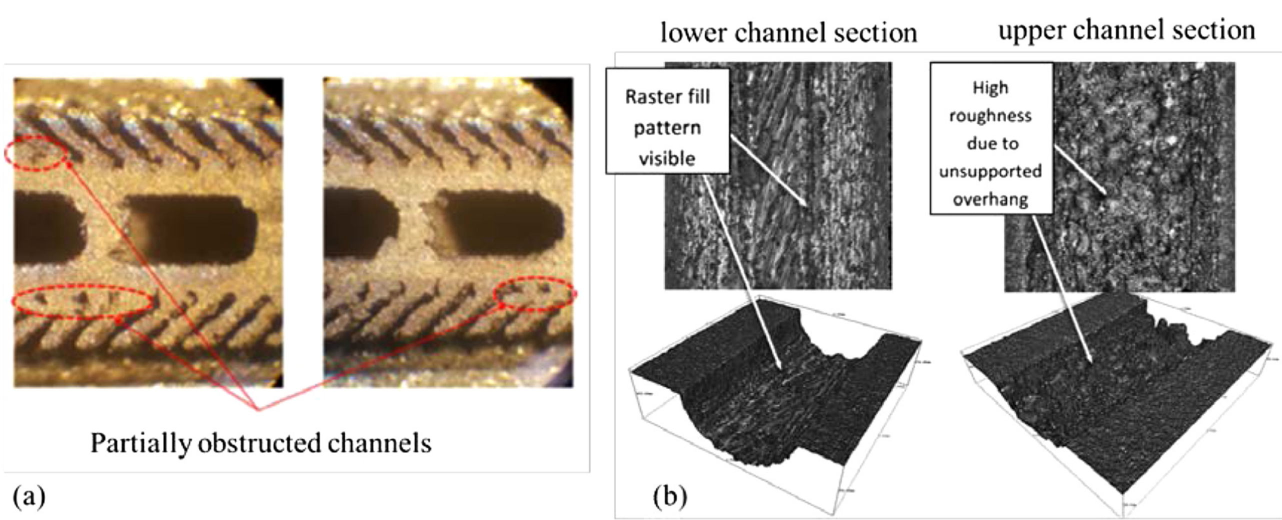


**Fig. 8.** (a) Micrographs of the fins and microchannels of Ti64 prototype [48]; (b)Sample photo and 3D surface scan of 2-mm standard channel profile: lower channel section(left) and upper channel section(right) [69].

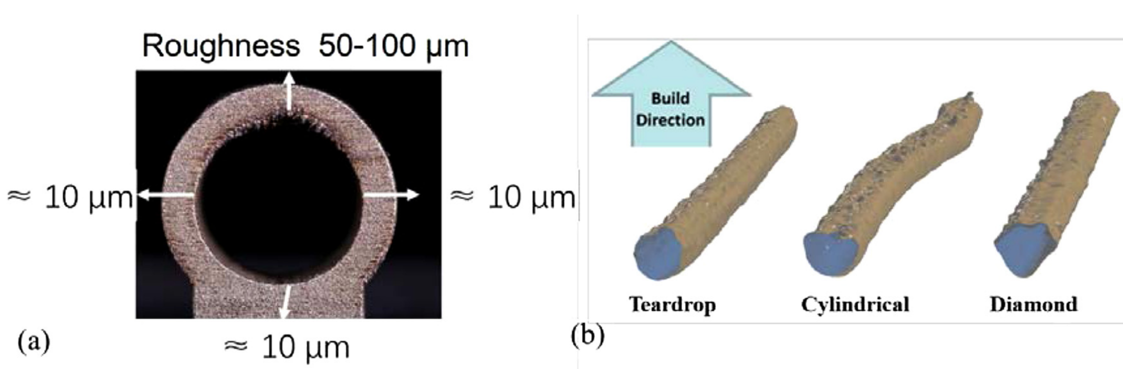


**Fig. 9.** Horizontally fabricated channels using SLM. (a) A photo of an as-built SLM channel shows uneven surface roughness and poor circularity (design diameter = 10 mm). (b) CT scan images of three micro channels [130] show poor cylindricity and high surface roughness.

manufactured products with different fluid channels. Although the AM offers great freedom for the design of these products with internal channels, mature design methods and theory of these products with different functional flow channels is lacking, which highlights a need for effective design methods and theories that can guide the manufacturing of high-performance products. Though fluid topology optimization can be used to improve flow performance for a channel within a given design domain, how to arrange several channels remains a great challenge. In addition, even within a product, the performance requirements and functions of its internal fluid channels are different. The multi-material and multi-process additive manufacturing technology can provide a better way to achieve the multi-functionality of fluid channels in various products [137]. Biomimetic design may give some insights since nature has developed high-performance structures and materials [138,139]. However, at present, relevant research is still in its infancy, and more relevant studies are necessary in the future.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

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