A Review: The Impact Of Geometry And FDM application On Water-Cooled Microchannel Heat Exchanger Performance

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Abstract: Microchannel heat exchangers (MCHXs) are becoming increasingly important for thermal management in various applications due to their high heat transfer efficiency and compact size. However, their performance is highly dependent on the design geometry of the microchannels Traditional manufacturing methods for MCHXs pose limitations in design complexity and material selection. Fused Deposition Modelling (FDM), a prominent additive manufacturing (AM) technique, presents a promising alternative for fabricating MCHXs. This review paper explores the suitability of FDM for face geometry in water-cooled MCHXs, analysing their advantages, limitations, and potential design considerations. Microchannel heat sinks with straight and wavy designs are the two main varieties that have been the focus of extensive research in this field. The current paper provides beneficial information regarding the different designs and methods for heat enhancement and overall thermal performance in straight and wavy microchannel heat sinks.

Keywords: Micro Channel Heat Exchanger, Fused Deposition Modelling, Face Geometry, Pressure drop.

Abbreviations and Nomenclatures:

FMD	Fused Deposition Method
MCHX	Micro channel heat exchanger
MCHS	Micro channel heat sink
PCHX	Printed circuit heat exchanger
FMD	Fused Deposition Method
MMCHE	Manifold Micro channel heat exchanger
CMM	Cubic meters per minute
R_e	Reynolds number

1. Introduction

The increasing demand for efficient thermal management in various industries has propelled the development of MCHXs. These heat exchangers utilize microchannels with high surface area-to-volume ratios to achieve exceptional heat transfer rates with water as the coolant. However, traditional manufacturing methods for MCHXs pose limitations in design complexity and material selection. FDM offers a compelling alternative. This readily available AM technique allows for the creation of customized MCHXs with intricate channel networks, potentially surpassing the capabilities of conventional methods. This paper explores the use of FDM for fabricating both flat and curved face water-cooled MCHXs.

The need for compact packaging of high-power electronics and automotive engine cooling has challenged the capacity of forced air convection as a cooling approach, necessitating a shift toward microscale liquid cooling techniques in order to provide the required heat dissipation. Microchannel heat sinks are of significant technological interest; a variety of channel sizes, cross-sectional shapes, and fluids have been studied under both single- and two-phase flow conditions [1, 2]. Microchannel heat sink geometries have typically been numerically optimized for single-phase flow conditions [3–5]. One drawback of microchannels is the high pressure drop associated with flow through the heat sink, which can be alleviated by the addition of a manifold layer [6]. Such manifold microchannel (MMC) heat sinks reduce pressure drop by decreasing the flow length within the microchannels. Shorter flow lengths also result in a greater portion of the heat sink area experiencing higher heat transfer coefficients associated with developing boundary layers. Manifold designs allow for greater control over surface temperature uniformity and can lead to lower thermal resistances at a fixed pumping power than conventional designs. These fabrication approaches suffer from geometric restrictions; features must be generally rectangular and exist in a single plane. Complex design features such as three-dimensional curves or channels are exceedingly difficult or impossible to fabricate. Heat sinks also require attachment of a secondary lid to seal the channels; in the case of MMC designs, bonding of several layers including the manifold may become necessary. A new additive manufacturing paradigm evolved from the pioneering work of Kodama in the early 1980s, who developed a technique to fabricate 3D structures by selectively curing layers of a photosensitive resin with a UV light source [12]. This technique was quickly commercialized 3 and is now commonly known as stereolithography (SLA). Additional techniques including fused deposition modeling (FDM) and laminated object manufacturing (LOM) were developed and commercialized by the early 1990s [13]. Selective laser sintering (SLS), a process that uses a directed energy source (*e.g.*, laser) to fuse powdered material, was developed by Deckard in 1989 [14]. Laser sintering technology was a crucial step forward that enabled the use of metal powders to produce components. Despite significant refinement of the fabrication processes and introduction of new materials throughout the next two decades, additive manufacturing remained largely confined to prototyping and research applications. In recent years, additively manufactured parts have begun to appear in aerospace applications, where potential weight reduction and geometric flexibility are worth the cost associated with producing and qualifying the parts. Many companies, such as GE Aviation and Airbus, have leveraged additive manufacturing systems to produce parts such as fuel nozzles, brackets, hinges, and tooling [15]. The National Aeronautics and Space Administration (NASA) has invested heavily in additive technologies and has produced different engine components including combustion chambers, turbines, pump housings, and injectors [16, 17]. While these efforts illustrate the value of AM to industry, they also highlight challenges facing widespread commercial usage, including accurate prediction of material properties, part repeatability, process standardization, and effective quality control [18]. A 3D printed heat sink with monolithic structures is built in [30]. Wavy channel structure heat sinks are printed and tested with different design parameters in [31]. A mesh heat sink for a larger surface area is printed in [32].

Table no. 1. A Summary of different designs in Flat face micro-channel.

References	**Design of Flat channel**	**Renumber Range**	**Notable remarks**
Utilizing secondary flow, *Re*-developing flow	Slanted passage	Yasuyoshi Kato et al. [33]	146% increase in overall performance 76.8% drop in thermal resistance 6% decrease in pressure drop
	Sectional oblique fins	Vinoth, et al. [34]	Significant improvement in temperature uniformity More than 100% increase in the local heat transfer coefficient
Double-layer microchannel heat	Double-layer microchannel with truncated top channels	Kulkarni K et al. [29]	Using a three-dimensional model and a simplified conjugate-gradient method for optimization The reduced influence of the upper layer's heating on the bottom layer
Open microchannel heat sinks	Varied the height of fins	Mushtaq I. Hasan [42]	Increasing fin height leads to higher heat transfer and pressure drop The highest heat transfer coefficient was found with a fin height of 0.8 mm
Using fin (extended surface)	Shah, Ramesh K. et al. [35].	15% increases in heat transfer performance	Using fin (extended surface)

		Reducing 3.7 °C in maximum wall temperature& 18% rise in pressure drop	

Table no. 2. A Summary of different designs in wavy face micro-channel.

References	Design of curved channel	Renumber Range	Notable remarks
X.D. Wang et al. [14,18]	Secondary branch	50–700	Nu number enhancements for parallel and wavy arrangements Significant improvement in overall performance by using a modified parallel configuration
X.D. Wang, and W.M. Yan. [18]	Oblique groove finned	250–850	For fins with a width of 125 m, a maximum average Nusselt number of 80 and a pressure drop of 50 kPa at *Re* = 850 are obtained
Kim et al. [12]	Cross-cut flow control	100–400	Maximum 23.81% enhancement in heat transfer performance Maximum 7.04% increase in pressure drop
K. A. Thole [21,23]	Straight and wavy pin-fins	100–1000	Enhancement of the heat transfer coefficient by 0.05 to 2.3 times Increase in pressure drop by 2.6 to 13.6 times The highest enhancement was for wavy pin-fins with opposite spin
Yasuyoshi Kato et al. [33]	Offset zigzag grooves	200- 800	The maximum temperature decreased from 324.02 to 318.01 K Pressure drop reduced from 298.81 kPa to 27.91 kPa
Yuling_Zhai et al. [26]	Staggered configuration-double layer		Significant heat transfer enhancement for the staggered wavy channel with opposite amplitude& The counterflow of straight, staggered channels provided the best overall thermal performance.

From above literature review, conclude that heat dissipation challenges in Automotive and electronics, microchannel heat sinks can be a solution. Here are the key points:

- **Problem:** Traditional cooling methods struggle with high-power electronics and high-speed automobiles due to their compact size.
- **Solution:** Microchannel heat sinks use tiny channels to transfer heat efficiently. Researchers have optimized their design for single-phase flow.
- **Improvement:** Manifold microchannel (MMC) heat sinks address a drawback of regular microchannels - high pressure drop. They achieve this by reducing flow length within the channels. literature review shows that microchannel with curve or wavy face geometry having high heat transfer rate as of low pressure drop compare with flat and other different geometries.

- **Benefits of MMC:**
  - Lower pressure drops
  - More uniform heat transfer
  - Lower thermal resistance
  - Can handle high heat fluxes
- **Traditional Manufacturing limitations:**
  - Limited geometric shapes (mostly rectangular)
  - Difficulty in creating complex 3D features
  - Requires additional steps like bonding layers

The passage then introduces Additive Manufacturing (AM) as a potential solution to these limitations. AM allows for more design freedom and complex features. However, challenges like material property prediction and quality control still need to be addressed for wider adoption in this application.

1.2 Advantages of FDM for MCHXs

- **Design Freedom for Flat and Curved Faces:** Unlike traditional methods, FDM allows for the creation of intricate microchannel networks within both flat and curved faces. This enables optimization of channel size, spacing, and layout for improved heat transfer in flat face designs and facilitates the creation of complex curved flow paths for enhanced efficiency.
- **Material Selection:** FDM offers a variety of printable materials, including polymers with good chemical resistance and some engineering thermoplastics with moderate thermal conductivity. This allows for selection of materials based on application-specific needs, such as corrosion resistance for specific coolants or lightweight designs for aerospace applications.
- **Rapid Prototyping and Low-Volume Production:** FDM allows for rapid prototyping of MCHX designs, enabling faster design iterations and optimization. Additionally, FDM can be suitable for low-volume production runs, offering flexibility compared to traditional methods.

1.3. Limitations of FDM for MCHXs

- **Limited Thermal Conductivity:** Most FDM materials have lower thermal conductivity compared to metals commonly used in traditional MCHXs. This can limit the overall heat transfer efficiency of the exchanger.
- **Surface Roughness:** FDM processes can result in surface roughness within the microchannels. This can increase pressure drop of the water coolant and needs to be balanced with the benefits of increased surface area for heat transfer.
- **Resolution Limitations:** The minimum achievable feature size of FDM can limit the channel size and density to some extent. This may impact the achievable heat transfer surface area compared to other AM techniques.

1.4. Design Considerations for FDM-fabricated MCHXs

- **Channel Design:** Optimizing channel size, aspect ratio (height to width), and spacing is crucial for balancing heat transfer efficiency and pressure drop.
- **Wall Thickness:** FDM wall thickness needs to be considered for structural integrity and maintaining desired channel dimensions while minimizing material usage.
- **Post-processing:** Depending on the application requirements, post-processing techniques like polishing or chemical smoothing might be necessary to improve channel surface finish and reduce pressure drop.

1.5. Flat vs. Curved Face Designs with FDM

- **Flat Face:** FDM offers advantages for creating flat face MCHXs with simple, straight microchannels. However, achieving high heat transfer efficiency might require a larger overall heat exchanger size due to limitations in channel density.
- **Curved Face:** FDM's design freedom allows for the creation of complex curved flow paths within the heat exchanger. This can significantly improve heat transfer efficiency compared to flat face designs, but the design complexity might require additional optimization and potentially increase printing time.

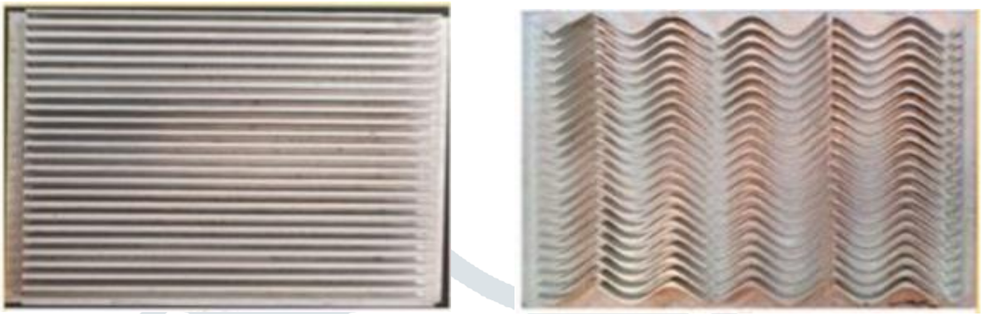


Fig.No.1 Flat and Wavy Faced MCHE

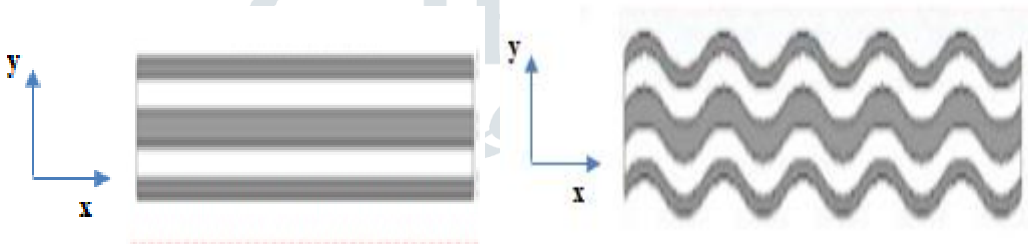


Fig.No.2 Side View of Flat and Wavy Faced MCHE

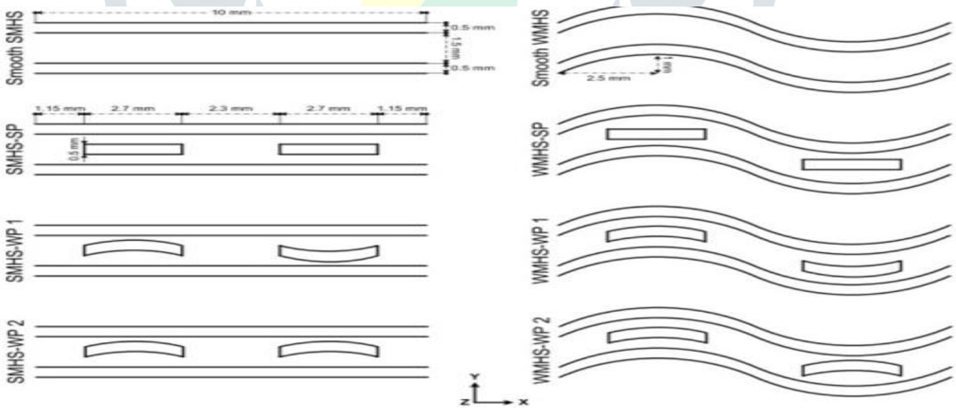


Fig.No.3 Different Geometry in Flat and Wavy Faced Structure Of MCHE

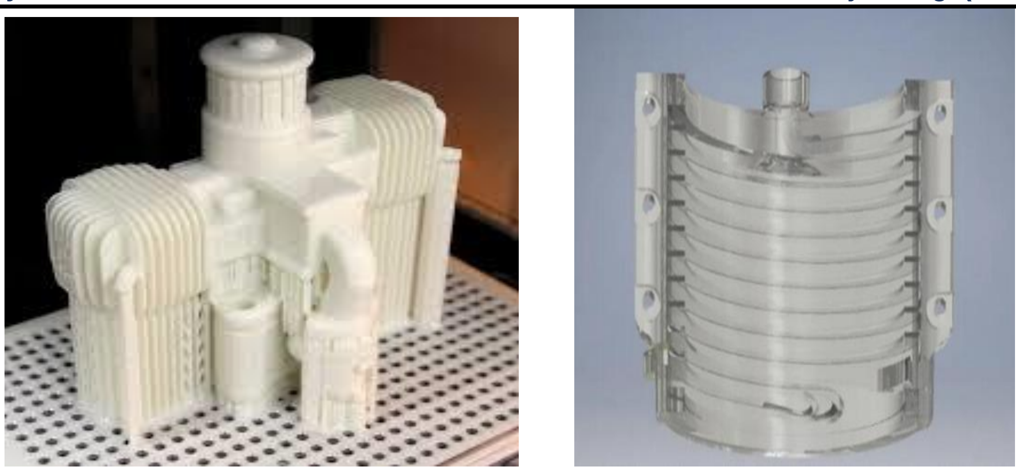


Fig.No.4 3-D Printed (ABS) Water Jacket for Curved Heat Sink

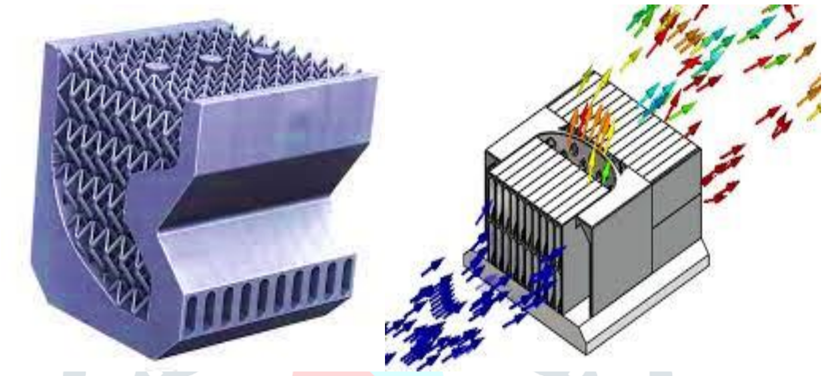
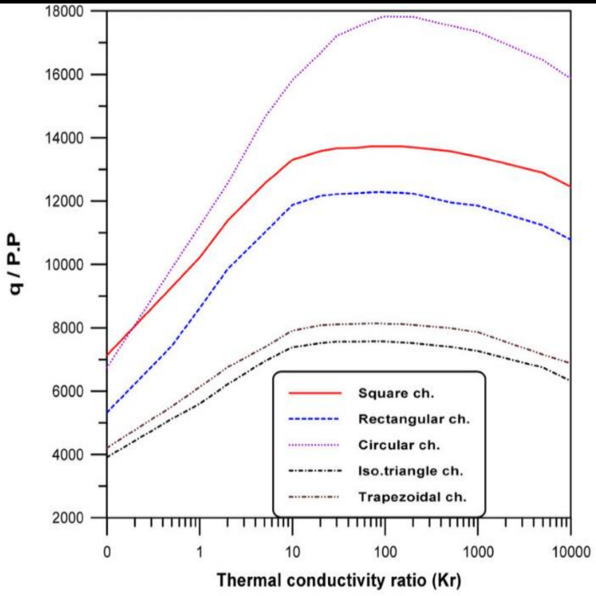


Fig.No.5 3-D Printed Complex Oblique Faced Heat Sink

Fig.No.6 3-D Printed (AL And FDM) Flat And Curved Faced Heat Sink



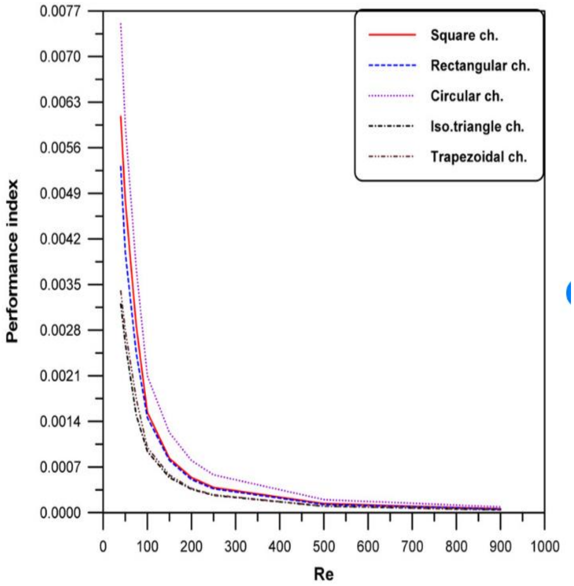


Fig.no.8 Graph of K Vs q/P.P **Fig.no.9 Graph of PI Vs R_e**

The graph no. 8 in the image the ratio of the thermal conductivity of the material to the product of the perimeter (P) and the projected area (P). This ratio is a measure of how efficiently a particular shape conducts heat. According to the graph, Circular channels have the highest thermal conductivity ratio at high q/P. P values, while trapezoidal channels have the lowest thermal conductivity ratio. As the q/P. P value increases, the thermal conductivity ratio of all shapes appears to decrease. (42)

The graph no. 8 in the image is a graph titled "Performance index" that shows the performance of different chip shapes at a certain frequency. The x-axis is labeled "Re" and likely refers to the Reynolds number, a dimensionless number used in fluid mechanics. The y-axis is labeled "Performance index". The graph shows that circular and square channels have the highest performance index at all frequencies, followed by rectangular channels, isosceles triangular channels, and trapezoidal channels. The performance index decreases as the frequency increases for all chip shapes. (44)

2. Result:

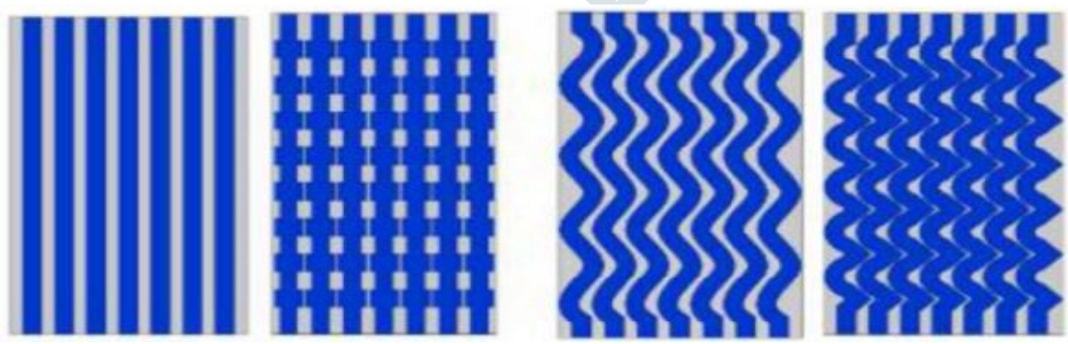


Fig.no. 7 Flat and Wavy Geometry

A 5-channel cold-plate was enough and the temperature could be evidently reduced by increasing the inlet mass flow rate. Additionally, for the bad temperature uniformity in the design 1, design 2 was proposed and compared with the design 1. The maximum temperature and temperature difference decreased 13.3% and 43.3%, respectively. Temperature uniformity was significantly improved [41].

Zekeriya Parlaket al. [43] showed that the Reynolds number range corresponding to the industrial pressure drop limits is between 100 and 400. Nu values obtained in this range for optimum wavy geometry were found at a rate of 10% higher than those of the zigzag channel and 40% higher than those of the straight channels. In addition, when the pressure values of the straight channel did not exceed 10 kPa, the inlet pressure data calculated for zigzag and wavy channel data almost coincided with each other.

Result table no.

Geometry	Description	Pressure Drop
Circular	Smooth, round channel	Lower pressure drops for same flow area compared to other shapes (1)
Rectangular	Flat-sided channel with sharp corners	Slightly Higher pressure drop than circular due to friction at corners (1)
Triangular	Channel with triangular cross-section	Higher pressure drops than circular due to sharp corners (1)
Plate-fin	Stacked fins separating flow channels	Pressure drop depends on fin spacing, thickness, and flow direction. Can be optimized for balance between heat transfer and pressure drop (1)
Impingement	Flow directed perpendicularly onto a flat surface with fins	Offers good heat transfer but can have high pressure drop due to flow redirection (1)
wavy	Smooth, wavy channel	Lowest pressure drops for same flow area compared to other shapes (2)

3.Conclusion

From studied literature review data, it is observed that wavy (curved) micro channel heat exchanger having lowest pressure drop across among flat face and other varying geometry. So wavy faced outperformed for desired pressure drop and effectiveness. Meanwhile, FDM offers a promising approach for fabricating both flat and wavy face water-cooled MCHXs. While limitations like thermal conductivity of printable materials and surface roughness exist, FDM's design flexibility and potential for low-volume production make it a valuable tool for prototyping and potentially niche applications. As FDM technology advances and new materials become available, its role in fabricating high-performance MCHXs is expected to grow.

3.1 Future Research Directions

- Development of FDM filaments with improved thermal conductivity for enhanced heat transfer performance.

- Exploration of multi-material FDM techniques to combine materials with high thermal conductivity for channels and lower cost materials for support structures.

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