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A COMPREHENSIVE REVIEW ON MICROCHANNEL HEAT EXCHANGERS, HEAT SINK, AND POLYMER HEAT EXCHANGERS: CURRENT STATE OF THE ART

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ABSTRACT

Over the past few decades, the world is moving towards miniature products owing to the technological developments in variegated industrial domains such as aerospace, biomedical, electronics, etc. This has led to the exponential growth of efficient micro cooling systems which are light in weight and have effective thermal performance. Microchannel Heat Sinks and Microchannel Heat Exchangers are the widely adopted solutions for such efficient micro cooling systems. This paper comprehensively reviews the recent developments in the field of Microchannel Heat Sinks and Microchannel Heat Exchangers. Initially, the concept of microchannel cooling is discussed. Further, a comprehensive review of materials, fabrication methods, experimental investigation, and numerical analysis is presented.

Keywords: *Microchannel Heat Exchangers, Polymers, Heat Sink, Polymer Heat Exchanger*

1. INTRODUCTION

In recent years, the concept of miniaturization for industrial products is of growing nature. This is due to technological developments in the field of aerospace, medical implants, semiconductor industries, automobile field, electronics devices computer hardware, etc. As the size of the product/system reduces, the heat flux viz. the heat produced per unit area enhances. This is because the product/system has a less available area for the dissipation of heat as compared to the macro systems because of the size factor. Literature suggested that this has been a concern as it may result in the increased generation of the power and heat, and will ultimately cause overheating of these products/systems (Jami *et al.*,2011; Pasupileti and Kandlikar,2009).

The microchannel cooling systems have been applied effectively in variegated domains. The applications include cooling in microchips, airborne electronics (Hamilton and Kennedy,1997), defense electronics (Lee and Mudawar,2009), power devices (Barrau *et al.*,2012), photovoltaics (Gilmore *et al.*, 2018), etc.

A few decades earlier, cooling systems based only on on-air cooling have been used. For systems having higher heat flux, larger and complex air-cooled systems were implemented (A. Sur *et. al.*2016). However, the amount of heat flux has increased exponentially after the semiconductor revolution owing to the size reduction of the system V. (W. Bhatkar, *et. al*. 2021). The conventional air-cooling technique was not effective for such systems (Nitin S Solke *et al* 2021) . Hence, liquid cooling solutions have been developed to improve the heat transfer rate (Mudawar, 2001). Water and refrigerants have been the most commonly used liquids for such systems.

As compared with air cooling systems, the liquid cooling systems have a high convective heat transfer coefficient, resulting in an improved heat transfer rate. Moreover, micro-channels have higher area density in comparison with the macro-scale systems, owing to which the convective heat transfer rate is increased. Ohadi *et al.*, 2018 reviewed the recent developments in High temperature heat exchangers.

Table 1 Classification of Channels

Sr No	**Channel Type**	**Dh according to Kandlikar *et al.*, 2005**	**Dh according to Mehendale *et al.*, 2000**
1	Conventional	Dh < 43 mm	Dh < 43 mm
2	Mini / Compact	200 μm $<$ Dh $\leq$ 3mm	1 mm $<$ Dh $\leq$ 6mm
3	Micro	10 μm $<$ Dh $\leq$ 200 μm	1 μm $<$ Dh $\leq$ 100 μm
4	Meso/ Transitional	100 μm $<$ Dh $\leq$ 1 mm	0.1 μm $<$ Dh $\leq$10 μm
5	Molecular Nano	Dh $\leq$ 0.1 μm	NA

Hydraulic Mean Diameter (D_h), also plays a critical role. For micro cooling systems, the D_h decreases, thereby improving the cooling mechanism. However, for micro-channels, a very high-pressure drop has been observed which has to be considered while designing and analyzing microchannel cooling systems. The channel is referred to as a

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microchannel if the value of D_h is less than 200 µm (Kandlikar *et al.*, 2005). Table 1 describes the classification of the channels based on the value of D_h. There are two popular methods observed in the literature for micro channel cooling viz. microchannel heat sink, and micro channel heat exchangers. These systems have been discussed in the subsequent section.

2. MICROCHANNEL HEAT SINK

The heat sink is a device that transfers heat from the system in which heat is generated to the surroundings through the fins. Maintaining the temperature of the system, which varies due to heat dissipation, is vital for the efficient and effective performance of the product/ system. Introduced initially in the 1980s, it has been evolved and applied widely in the power sector, aerospace, and specifically in the electronics industry, etc.

The heat sink is first introduced by Tuckerman and Pease for extremely high-speed VLSI circuits (Tuckerman and Pease, 1981). The latest microchannel heat sink named hybrid impinging micro-jet microchannel heat sink has been manufactured using metal electrodeposition additive manufacturing process and tested at high heat fluxes greater than or equal to 1000 W/cm^2, for more details studied the article (Kempers *et al.,* 2020). Classifications of Microchannel heat sink on the basis of geometry, fabrication methods, applications and analysis are shown in Fig. 1.

Micro Heat Sink	**Geometry**	Trapezoidal
		Rectangular
		Circular
	Fabrication Methods	Laser cutting
		Etching and sintering
		Micro marching
		Additive manufacturing
	Applications	HVAC Systems
		Electronic industries
		Petrochemical Industries
		Biomedical

Fig. 1 Classifications of Microchannel Heat Sink

A microchannel heat sink (MHS) is widely applied in various domains. Multidimensional research has been carried out on heat sinks. The subsequent sections elaborate the several research aspects such as geometry, fabrication methods, applications, and analysis techniques.

2.1Geometry

Geometry refers to the shapes and sizes of the channels. The heat transfer characteristics of a system have been greatly influenced by the geometry of a microchannel. As stated above, the pressure drop increases due to the size factor in micro-channels. From the literature, it has been observed that the geometric modifications have been the obvious choice to reduce the pressure drop in the channel simultaneously improving the heat transfer rate.

Circular and non-circular-shaped micro-channels such as trapezoidal, rectangular cross-sectional have been used. It has been observed that the non-circular channels have the advantage of the availability of more heat transfer area as compared to the circular sections. Circular cross-sectional geometry is basically used for the flow of fluid in the channel and non-circular geometry provides more heat transfer area (Qasen and Zubair,2018).

It has been observed that a trapezoidal cross-section provides a better heat transfer rate in comparison with a rectangular cross-section (Kumar,2019). Various geometric parameters such as channel width (Deng *et al.,* 2019), aspect ratio, hydraulic diameter (Sahar *et al.*, 2017), channel spacing (Salah *et al.*, 2017), channel height (Soleimanikutanaei *et al.*, 2018) affect the heat transfer rate. Fig. 2 represents the several circular and non-circular microchannels geometrical shapes.

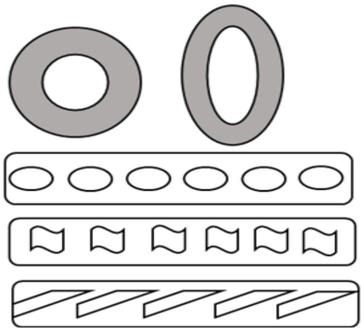

Fig. 2 Circular and Non-circular shapes in Micro-channels

Experiments have been performed on rectangular micro-channels and investigated that the thermal resistance decreases for constant flow rate and pressure drop increases (Sahar et al., 2017). The friction factor decreases with an increase in aspect ratio (AR) (Soleimanikutanaei et al., 2018). Thermal resistance decreases with an increase in AR (H/G) for all the slip coefficients. In addition, AR also affects the thermal resistance of microchannel systems. It is clearly evident from fig. 6 that the value of thermal resistance decreases for the lower values of AR, however, for higher values of AR, the value of thermal resistance increases. For no-slip conditions, the value of thermal resistance increases sharply for higher values of AR (Hajmohammadi et al.,2018).

One of the major drawbacks of micro-channels is high-pressure drop, in spite of that researchers observed the positive effect of geometry on pressure drop. It has been reported in the literature that, the pressure drop could significantly be reduced in microchannel systems with the help of sinusoidal cavities & rectangular ribs (Ghani et al., 2017). Researchers also investigate how dimensionless parameters such as Nusselt no, Reynolds no, etc. behaves with various geometries. It has been reported in the same work that the Nusselt number and friction factor is directly proportional to the relative length and relative width of the rectangular ribs as the thermal boundary layer is interrupted by the increased sized rib, thereby improving the rate of heat transfer (Ghani et al., 2017). After going through much literature, it can be concluded that the bidirectional ribs also play a prominent role in the performance of MCHS. Bidirectional ribs comprise span wise ribs and vertical ribs. The Nusselt number of the microchannel heat sink in the case of vertical ribs is in the range of 1.4 - 2 and in the case of span ribs is in the range of 1.2 – 1.42. Numerical values of Nusselt number show that the heat transfer takes place through pure advection. Reynolds number also affects all the ribbed microchannel systems (Wang et al., 2019). Comparison of triangular and rectangular ribs has been examined keeping Reynolds number less than 350, and it has been observed that the triangular ribs display better performance than rectangular ribs. Another interesting thing that has been examined is regarding the application of semi-circular ribs. The semi-circular rib displays good performance at Reynolds number above 400 (Chai et al., 2016).

2.2 Fabrication Methods

Various methods have been adopted by the industries for the manufacturing of heat sinks. Methods such as extrusion, stamping, die casting, etc. are popular for manufacturing conventional (macro) heat sinks. However, the exact same methods could not be extended for microchannel heat sinks owing to the size effects (A. Sur, et.al 2019),. Hence, the fabrication of MCHS has been taken as a challenging task.

Furthermore, due to the difficulty to manufacture MCHS, the experimental investigations become complicated. Variegated unconventional approaches such as wet & dry etching (Yuan and Tian, 2009), laser machining (Zhou *et al.,* 2014), ultra-sonic micromachining (Cheema *et al.,* 2015), electron beam machining, electro-discharge wire cutting (Dixit and Ghosh, 2015) have been tried. However, literature shows that the above-mentioned methods are very expensive owing to their cost of manufacturing. Hence, continuous research is going on for developing innovative low-cost manufacturing methods. Sintering-based methods such as Lost Carbonate Sintering (LCS) and Direct Metal Laser Sintering (DMLS) have been used for fabricating the microchannel heat sink. The performance of Copper (Cu) micro-channels fabricated with three different methods have been compared. Higher heat transfer coefficients and pressure drops have been observed in a sintered copper microchannel in comparison with conventionally machined microchannels. However, LCS method has resulted in significantly lower pressure drop as compared to the Sintered Cu micro-channels (Diao and Zhao, 2019; Ramesh *et al.,* 2020). The recent trend in fabricating the MCHS shows the applicability of additive manufacturing techniques (Deisenroth *et al.,* 2018). The additively manufactured parts enjoy freedom in terms of the innovative design and geometric constraints & restrictions. Direct-metal-laser-sintering (DMLS) method has been applied for manufacturing two novel designs viz. permeable membrane micro-channel (PMM) heat-sink and manifold micro-channel (MMC) heat-sink. Furthermore, these heat sinks have been tested and characterized at different flow rates (Collins *et al.,* 2019). A multi-metal electrodeposition additive manufacturing process has been adopted for manufacturing micro heat sinks to produce complex flow which is impossible to fabricate with traditional processes. With this design, the highest effective thermal conductivity reported in the literature has been achieved with a moderate level of pressure drop.

2.3 Applications

As stated in section 1.2 microchannel heat sinks have been applied in various industrial sectors. The majority of the applications are in the domain of electronics cooling, space and hydraulic industries.

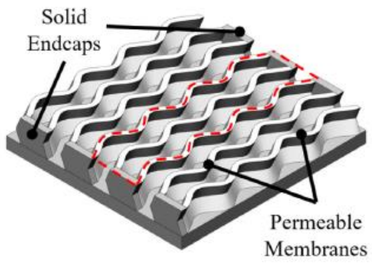

Fig. 3 Permeable membrane Heat Sink for high power electronic device (Collins *et al.,* 2019)

The typical applications from electronics cooling industry include the cooling of computer components such as processors, memory devices (Zhou *et al.,* 2014), IGBTs cooling (Cheema *et al.,* 2015), cooling laser diode arrays (Ramesh *et al.,* 2020). Major applications of the MCHS are found in the field of thermal management electronics. A smart cooling system for achieving the higher heat transfer rate per unit area has been developed (Mukherjee and Mudawar, 2002). Fig. 3 represents permeable membrane heat sink used for ultra-high power electronic devices. A novel cooling embedded technology for the effective cooling of high electron mobility transistors (HEMTs) based on the heat transfer modes such as convection and convection & evaporation has been developed (Gupta *et al.,* 2017). A multi layered MCHS has been developed adopting the natural and forced convection for high power capacity convertor. The 76% and 60% reduction of temperature rise in the MCHS has been observed when compared with the conventional heatsink respectively (Erp *et al.,* 2019).

2.4 Analysis

This section describes various analysis methodologies implemented for MCHS. It includes experimental investigation, analysis in a simulation environment using cutting edge software tools, furthermore discussion on optimization approaches adopted with contemporary computational intelligence methodologies has been added.

In the context of conventional heat sinks, scientists and researchers have preferred experimental-based techniques for investigating the impact of parameters on heat transfer and thermohydraulic properties. However, for MCHS, the experiment-based techniques cannot be effectively applied owing to the size effect (Ramesh *et al.,* 2020).

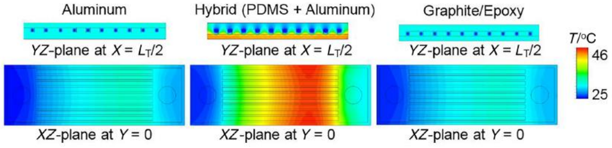

Fig. 4 Temperature Contours for Aluminum, Hybrid & graphite/Epoxy (Ong and Kushaari, 2020)

In view of the above context, computational-based methods have been adopted for numerical investigation of MCHS. Fig. 4 shows the temperature contours for Aluminium, Hybrid (Polydimethylsiloxane + Aluminium) & Graphite/Epoxy heat sinks using computational Fluid Dynamics (CFD). A new stream of research referred to as microfluidics has emerged. Integration of computational methods and microfluidics has brought paradigm shift. Several CFD methodologies have been developed for complex analysis (Ramesh *et al.,* 2020). Two phase flow CFD simulations of microchannels for R-134a refrigerant with Al_2O_3 nanoparticles have been performed. Authors achieved higher heat transfer coefficient with maximum mass flow rate along with the volume concentration (0.03) of Al_2O_3 (Saleem and Jumaah, 2021). Literature shows that the 2D, as well as 3D simulation methodologies, have been applied to analyze the flow and heat transfer mechanism with respect to the microfluidics. It has been reported that 3D simulation techniques show better results as compared to 2D simulation techniques. The investigations for the fluid flow in microchannels have been performed with 2D and 3D simulations techniques by Haghighinia and Movahedirad, 2019. 3D simulation results have been found to be more accurate and in close resemblance with real-world situation. Control-volume finite element method (CVFEM) combining the features of FEM and FVM (Finite Volume method) methods has been applied for the analysis of fluid flow in microchannels (Salah *et al.,* 2017). Along with the classical numerical simulation techniques several evolutionary algorithms have been applied for the optimization of heat transfer rate, pressure drop, entropy generation rate, etc. A genetic algorithm has been applied for minimizing the rate of entropy generation which integrates thermal behavior and pressure drop. The problem has been chosen from the literature. The results obtained with GA have been compared with the classical Newton–Raphson method. GA has exceeded the classical optimization technique, resulting in better performance (Khan *et al.,* 2013). The pumping power and thermal resistance for MCHS has been optimized simultaneously with the prey-predator algorithm.

In addition to that radial basis, neural network has been incorporated to establish the correlation among the parameters. ANOVA method has also been adopted. The results show the suitability of the prey-predator algorithm and the neural networks for optimizing the MCHS performance (Hamadneh *et al.,* 2018).

3. MICROCHANNEL HEAT EXCHANGERS

A Micro-channel heat exchanger (MCHX) is a device that transfers heat from one fluid to the other with or without the mixing of fluids. Heat

Exchangers (HX) can be applied in heating as well as cooling processes. It has been widely applied in a variegated domain such as power industry, food industry, HVAC, Space applications, Auto industry, electronics, and Petrochemical industries (Kong *et al.*, 2016; Song *et al.*, 2017; Kim *et al.*, 2004; Kharati and Akhtari,2018; Andhare *et al.*, 2016). It has been proved that the overall performance of the system largely depends on the effectiveness of the heat exchangers (Dixit and Ghosh, 2015).

Microchannel heat exchangers have been the area of research and widely studied & applied in recent times. The typical characteristics of MCHX that have been studied such as categories (types), fabrication methods, applications, materials have been discussed in the following sections. In the end, comment on recent trends in MCHX has also been added. Low-cost liquid-liquid manifold microchannel heat exchanger have been developed and heat transfer coefficient higher than that of the typical shell & tube and plate-type heat exchangers is achieved by Tiwari *et al.*, 2019. Microchannel heat exchangers (MCHX) have been developed to cater to the growing needs of cooling of miniature systems. Such systems generally contain a diameter, which is less than 1 mm in dimension. Moreover, the β value (area density) exceeds 10,000 m^2/m^3. MCHX has various merits viz. higher heat flux, reduced weight, higher energy efficiency, and compact size. This has powered MCHX to solve a variety of complex thermo-hydraulic problems faced by many researchers/industries (Fan and Luo, 2008).

Fig. 5 represents the schematic of different types of MCHX, which include types, fabrication methods, the material used, various applications employed for MCHX.

Microchannel Heat Exchangers	**Types**	Plate Type
		Cross flow
		Parallel Flow
		Counter Flow
	Applications	HVAC Systems
		Fuel Cells
		Electronic Industry
		Biomedical
	Fabrication Methods	Additive manufacturing
		Micro machining
		Laser marching
		Sintering
	Materials	Metals
		Composite
		Alloys
		Polymers

Fig. 5 Different types of MCHX

3.1 Manufacturing Methods

In general, miniature heat exchangers are fabricated by bonding a stack of micro-machined micro-channel foils/mini channel plates. Table 2 describes the various manufacturing methods adopted according to the materials.

Table 2 Description of Manufacturing methods for MCHX

Material	Manufacturing Methods	Reference
Silicon	Etching	Kang *et al.*, 1998
Glass	Etching	Freitag *et al.*, 2000
SiCN (Silicon carbon Nitride)	Micro-Stereo Lithography	Carman *et al.*, 2002
Nickel	LIGA (Lithography)	Moran *et al.*, 2004
Copper	Micro-Machining (Diamond)/Diffusion Bonding	Kang *et al.*, 1994
Base Metal Alloys	Micro-Machining (Milling)	Halbritter *et al.*, 2004
Copper, stainless steel, aluminium and titanium	Diffusion bonding, electron beam welding and laser welding, multi-tool milling, selective laser melting	Awyer and Shaavan,2004; Bier,1990; Bier *et al.*,1993; Caw *et al.*,2010; Min *et al.*,2008; Tsopanos *et al.*,2005; Jiang *et al.*,2012; Lu *et al.*,2013

Metal and its alloys are fabricated using Micro-Machining (Milling) Diffusion bonding, electron beam welding, and laser welding, multi-tool milling, selective laser melting, sintering, transient liquid phase bonding. Whereas silicon and silicon-based materials are fabricated with Micro stereolithography etc. Etching-based techniques are generally used for manufacturing glass Heat Exchangers.

Recently, additively manufactured heat exchangers are in utmost demand owing to their high mechanical strength and lightweight products.

3.2 Applications

MCHX has been widely incorporated in the field of refrigeration and air conditioning. Roth *et al.*, 2002 presented the MCHX as a power-saving alternative for commercial HVAC systems. This is due to the fact that MCHX requires less amount of refrigerant & moreover has higher efficiency as compared with conventional heat exchangers. However, the commercial applicability of such systems has been limited by their higher manufacturing cost as well as the lack of reliable predictive systems (Roth *et al.*, 2002).

Along with HVAC applications, MCHX have been applied in variegated domains. Several figures below represent the widespread applicability of MCHX specifying application area, salient features of the application, and the representative image of the system/ product. The representative applications are car radiator (Harris *et al.*, 2000), cryosurgical probes, which are used for cancer treatment and Cardiac arrythmia (Ohadi *et al.*, 2013), diffusion bonded and chemically etched printed circuit heat exchangers used in refrigerators (Kim *et al.*, 2010), LNG (Liquified Natural Gas) extraction FPSO (Floating Production Storage & Offloading) (Baek *et al.*, 2010) and integral steam generator (Kromer *et al.*, 2021).

3.3 Recent Approaches

This subsection covers the recent approaches adopted for the development of MCHX. These include experimental investigation, numerical analysis, and simulation, optimization approaches, use of nanofluids etc...

Crossflow and counterflow heat exchangers have been experimentally and numerically analyzed for thermal performance and thermal conductivity. Crossflow heat exchangers with various hydraulic mean diameters but having same active volume have been manufactured. The temperature distribution and thermal power characteristics of these exchangers have been compared with geometrically similar counter flow heat exchangers. Even in micro scale, Counter flow heat exchanger has yielded better rate of heat transfer and temperature distribution (Schubert *et al.*, 2001). The same work has been extended by brandner et. al.,2006 in which the performance of cross flow heat exchangers has been experimentally investigated with two same heat exchangers having different hydraulic mean diameters. Deionized water has been used during experimentation. As a result, the heat exchanger having minimum hydraulic mean diameter gives the better rate of heat transfer.

Dimensional optimization of rectangular geometry including aspect ratio has been carried out for MCHX considering active volume of heat exchanger and constant pressure drop as constraints. Inconel has been considered as a material of construction. Analytical approach has been combined with CFD for determining the optimal aspect ratio. Furthermore, Multi-objective optimization has been carried out for determining the ideal shape of heat exchanger (Foli *et al.*, 2006). As we reduced the dimensions of the channels, heat transfer restricted to the type of fluid used. First of all, the heat transfer rate is being affected by the area density (shows the compactness of the Heat exchanger) and secondly heat transfer rate depends on the thermal properties of the fluid used in the system. Recently, nanofluids have been widely applied to enhance the rate of heat transfer. When nano scale metallic particles are added in the thermal fluids to make the suspended solid solution, it is referred to as nano fluids. This is done to improve the thermal conductivity of the solution and intern the rate of heat transfer (Mohammad *et al.*, 2011). The applicability of nanofluids such as silicon dioxide, titanium dioxide, aluminium oxide and silver with 2%, 5% and 10% volume fraction for square shaped MCHX has been numerically investigated by Mohammed et.al.,2011. The considered performance indicators were effectiveness, pressure drop, rate of heat transfer, coefficient of heat transfer, temperature profile, wall shear stress pumping power and overall performance index. Finite volume method has been applied for analyzing the flow characteristics. Response Surface Methodology has been applied to examine the effects of several geometrical parameters such as row pitch, fin pitch, wall thickness and no. of channels on heat generation pressure drop, Energy efficiency and compactness. Fluent module has been applied for analysis purpose. Furthermore, GA based optimization has been carried out (Glazar *et al.*, 2020)

4. POLYMERS HEAT EXCHANGERS

Polymer Heat Exchanger (PHX) is a recent approach in HX. Traditionally metals have been the obvious choice for HX. This is owing to their suitable mechanical and thermal properties, however, over the period of time, it has been observed that HX manufactured with metals are prone to fouling, corrosion & erosion specifically working in harsh environments. Moreover, weight has been always a concern of metallic HX for aerospace, electronics, and biomedical applications (Chen *et al.*, 2016).

Polymer Heat Exchangers	**Polymer Materials**	Thermosetting polymers
		Thermoplastics
		Composite polymers
	Properties	Physical
		Thermal
		Mechanical
		Chemical
	Applications	HVAC Systems
		Sewage treatment
		Petrochemical Industries
		Biomedical
	Manufacturing	Additive manufacturing
		Micro machining
		Laser marching
		Sintering

Fig. 6 Polymer Heat Exchangers classification

This has led to the continuous development and application of polymers for HX. Over the last decade, significant contributions have been done in the field of PHX. New polymer materials have been developed and applied for manufacturing HX. These polymers offer great advantages over the metals such as high corrosion resistance, high strength to weight ratio, low cost (Cevallos *et al.*, 2012). However, there exist some demerits too, with low thermal conductivity being the prominent one (Glade *et al.*, 2018). Fig. 6 shows the various studies that have been undertaken for the PHX.

This section describes the applicability of polymer materials for heat exchangers. Different polymer materials along with their material properties have been discussed including the applications.

4.1 Polymer Materials for HX

Since the beginning of 21st century, metals are being replaced with polymer materials owing to the unique qualities offered such as high strength to weight ratio, low cost, higher corrosion resistance, etc. The field of heat exchangers is also not an exception. The last couple of decades have seen exponential growth in the field of cutting-edge polymers development, methods for heat transfer improvement, and intern application of polymers for heat exchangers.

The heat exchangers with polymer materials have been first mentioned by Githens *et al.*,1965. Since then, extensive study has been done for the commercial application of polymer heat exchangers. There are polymers that exist in nature such as cotton, wood and rubber. A large number of hybrid synthetic polymers have also been developed. For heat exchanger applications, the mechanical and thermal properties of polymers play a vital role. These properties include density of the material, tensile strength, thermal conductivity, thermal expansion coefficient to name a few. Table 4 describes the thermal properties of generally used polymers for the heat exchangers and whether they are suitable for 3D printing or not.

4.2 Polymer Hollow Fiber Heat Exchangers

Polymer hollow fiber heat exchanger (PHFHE) is novel type of heat exchanger which made entirely on the concept of traditional shell and tube heat exchangers at micro scale level. This type of heat exchanger is firstly proposed by Zarkadas and sirkar,2004. Owing to the very low heat conductivity of polymeric materials, overall heat transfer coefficient is very less as compared to metals, thermal resistance plays an important role for overall heat transfer coefficient calculation. However, to achieve the comparable results, wall thickness should be as low as possible. For this reason, PHFHEs are suitable for low temperature and low-pressure applications.

Table 3 Various existing polymers and their suitability with 3D printing

Polymers	Thermal Conductivity	Melting Point (^{o}C)	Suitable for 3D printing
LCP	0.1-0.5	212-280	Suitable
PFA	0.209	310	Suitable
PC	0.2	288-316	Suitable
PEEK	0.25	340	Suitable
PPS	0.3	280	Suitable
PPSU	0.35	NA	Suitable
PP	0.11	160	Not suitable
PS	0.14	NA	Suitable
PSU	0.22	NA	Suitable
PTFE	0.27	330	Suitable

The major advantage of polymer heat exchangers is not to react with chemicals, anti-fouling, and less weight. Many authors proposed their novel ideas of PHFHEs in the last decade (Zhao *et al.*, 2013). 3 D modeled and numerically analyzed the shell and tube polymer hollow fiber heat exchanger without baffles in CFD fluent. The effect of hollow fibers packing fraction on the overall heat transfer coefficient (U) has also been simulated. The optimum packing fraction is 13-19 %. Thermal performance improvement of PHFHEs through structural optimization. A polypropylene net is placed between the inlet and outlet of the shell side. After the implementation of the net, the authors got 30 % more overall heat transfer coefficient, interested can see the detailed explanation in (Yan *et al.*, 2014). Overall heat transfer coefficient is the important parameter for every heat exchanger. Chen *et al.,* 2016 experimentally investigated polypropylene PHFHE specifically for building heat recovery applications. The effect of various parameters (T_{hi} = hot side inlet temp, T_{ho} = hot side outlet temp, T_{ci} = cold side inlet temp, T_{co} = cold side outlet temp, mt =tube side mass flow rate & ms = shell side mass flow rate) for 3 modules on overall heat transfer coefficient (U), heat exchanger effectiveness (ε), number of transfer units (NTU) & height of transfer units (HTU) have been considered. Authors tried several possibilities to enhance the overall heat transfer coefficient with different polymeric materials and various improvements in the existing design & as evident from the results, module 1 (100 number of fibers) has a higher overall heat transfer coefficient as compared to the other existing PHFHEs.

Raudensky *et al.,* 2017 experimentally analyzed chaotized (random arrangement) flexible PHFHE. Effect of Fiber chaotization on thermal performance has been investigated. Air–water counterflow type of heat exchanger has been manufactured. The authors also tried some design variants to improve the overall heat transfer coefficient. Song *et al.,* 2018 explored the heat transfer processes with and without the change of phase i.e., liquid-liquid, condensation, and condensation/ evaporation. Condensation/ evaporation achieved the better overall heat transfer coefficient. Bartuli *et al.,* 2021 compared the thermal performance of parallel fiber PHFHX with cross-wound structure fibers. Outer diameter & wall thickness of fiber are 1.5 mm and 0.1 mm respectively, It is also shown in the same article that (Polyamide) -72 heat exchanger with 1700 parallel hollow fibers and the length of fibers is 180 mm. Fig. 7 shows that cross-wound (Fibers are placed at an angle of 22.5 degrees to the heat exchanger axis) structured fibers with 2200 fibers and 350 mm length, heat transfer rate has been enhanced from this type of structure owing to increment in turbulence and perfect intermixing of fluid in the shell side. Authors concluded from their findings that cross-wound structure HX is six-time better than parallel structure fiber HX.

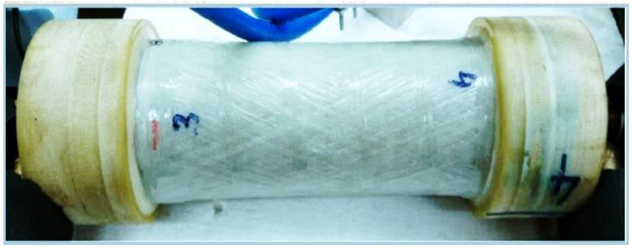

Fig. 7 PVDF Hollow fiber Heat Exchanger (Bartuli *et al.,* 2021)

4.3 Polymer Micro Heat Exchangers

Microchannel Heat Exchangers (MCHX) is applied in variegated domains. MCHX has been so far fabricated using only metals, composites, and metal matrix composites. It is proved from the literature that polymers are effective alternatives to metals. Industrial sectors such as aerospace, automobile, food processing, chemical, petrochemical, and power industries have been shifting to polymers owing to its merits viz. high strength to weight ratio, low cost, and high corrosion resistance. Since the last decade, Heat Exchangers manufactured with polymers are more popular for a variety of industrial applications. Heat exchangers constructed of polymer-based materials could offer an alternative to metallic heat exchangers. However, poor thermal conductivity is the major drawback of polymer composites. Hence, high thermal conductivity polymer composites have been developed. Polymer heat exchangers manufactured with these high-performance polymers are now popular in the industries (Qasem and Zubair, 2018).

Continuous research is going on to adopt polymers/ polymer composites for microchannel heat sinks and heat exchangers. However, some of the researchers have attempted to design and development of microchannel heat sinks using polymers. The research work could be adopted to investigate the applicability of polymers for the microchannel heat exchangers. It will open several new avenues in the field of miniature heat exchangers (Glade *et al.,* 2018). Polymer microchannel heat exchanger and aluminum foil are used to separate the micro-channels and to enhance the thermal performance, heat exchanger is manufactured using stereolithography (Brandner *et al.*, 2007).

Fig. 8 represents the effect of the addition of fillers on the thermal conductivity of polymers. As discussed earlier, the thermal conductivity of common polymers is relatively less as compared to metals. It is in the order of 0.1 - 0.5 W/ m-k, which is due to the intrinsic morphology of polymer chains. Three important methods have been highlighted in the literature to improve the thermal conductivity viz. addition of fillers, metal coating on polymers, and modifying the molecular morphology of the polymers. Fig. 8 shows the improvement in the thermal conductivity of polymers with the addition of carbon-based fillers (Huang *et al.*, 2018). The typical polymers applied for developing the heat exchangers are considered. These polymers include PC (Polycarbonate), PEEK (Polyether Ether ketone), PPS (Polyphenylene Sulphide), PPSU (Polyphenyl Sulfone), PP (Polypropylene), PS (Polystyrene). The orange color in the Fig. 8 represents the thermal conductivity of polymers while blue color indicates the improvement in the thermal conductivity.

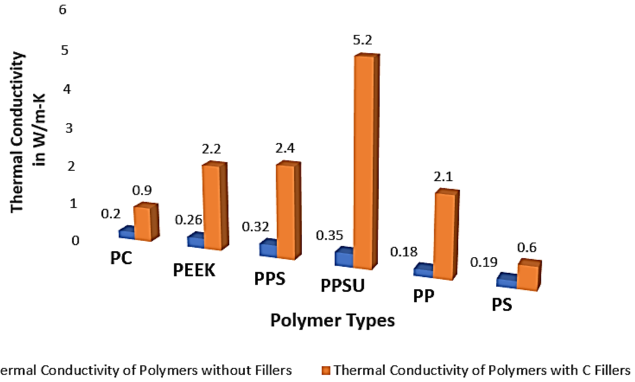

Fig. 8 Effect of carbon fillers on thermal conductivity of polymers

5. EXISTING LACUNAE, CONCLUDING REMARKS & FUTURE DIRECTION

In recent years, the concept of miniaturization for industrial products is on growing nature. With the reduction of the size of the product/system, the enhancement in heat transfer rate and pressure drop is observed. This is mainly due to the lesser availability of heat dissipation area when compared to the macro product/system. and a major reason behind the overheating of micro products/systems. Thus, the microchannel cooling systems have been applied effectively in variegated domains. The applications include cooling in microchips, airborne electronics, defense electronics, power devices, photovoltaics, etc.

From the literature review, it is clear that MCHX has been so far fabricated using only metals, composites, Ceramics, and Metal matrix composites. It is clearly evident from the literature that polymers are the effective alternatives to metals. Industrial sectors such as aerospace, automobile, food processing, chemical, petrochemical, and power industries have been shifting to polymers owing to its merits viz. high strength to weight ratio, low cost, and high corrosion resistance. Over the last decade, Heat Exchangers manufactured with polymers are more popular for a variety of industrial and biomedical applications. Heat exchangers constructed of polymer-based materials could offer an alternative to metallic heat exchangers. However, poor thermal conductivity is the major drawback of polymer composites. Hence, high thermal conductivity polymer composites have been developed. Polymer heat exchangers manufactured with these high-performance polymers are now popular in the industries.

Continuous research is going on to adopt polymers/ polymer composites for microchannel heat sinks and heat exchangers. Some of the researchers have attempted to design and development of microchannel heat sinks using polymers. In the future, the research could be carried out to investigate the applicability of polymers for microchannel heat exchangers. This will be a game-changer industrial solution.

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