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REVIEW

Comparative study of the parameters affecting the performance of microchannels' heat exchangers: Latest advances review

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Abstract

Microchannel heat exchangers are heat exchangers with a tube diameter of less than 1 mm. Conventional cooling approaches such as the forced-air cooling technique fail in high technological compact systems because of the small-sized surfaces of chips and circuits. In comparison, microchannel heat exchangers are being extensively utilized in compact-sized devices where a high heat-transfer medium is required. Moreover, consumers' continued desire for compact products has prompted researchers to study microchannel heat exchangers for their ability to boost the rate of heat transfer that ensures the safety of compact designs. This study presents the evaluation of performance parameters and the manufacturing aspects of microchannel heat exchangers. This study also examines how microchannel heat exchangers are affected by several parameters, including the type of working fluid used, Brownian motion, geometry of the channel, Reynolds number, Nusselt number, Knudsen number, wall resistance of the channel, the effect of gravity, and inlet and outlet arrangement for fluid. Investigating the various geometries for the microchannel indicates that the least pressure drop occurs in square shape cross-section channels while the highest pressure drop occurs in channels with triangular cross-sections. Moreover, it has been observed that, with the addition of nanoparticles to the working fluid, the thermal properties of the exchangers as well as the pressure drop increases while at the same time it reduces the boundary layer thickness. In addition, the Reynolds number affects the performance irrespective of the channel geometry. When the fluid is added with nanoparticles, like, Al_2O_3 and copper oxide (CuO) with different volumetric fractions (φ) of 0%, 0.5%, 1%, 1.5%, and 2%, the performance of the microchannel rises with rising the Reynolds number but conversely when the fluid is used in pure form the performance decreases with the rising value of

Reynolds number. In addition, it has been observed that the overall improvement is obtained at $\varphi = 2\%$ and $Re = 100$ for CuO–water nanofluid. Apart from this, the least heat transfer is recorded at $\varphi = 0.5\%$ and $Re = 1.00$ for both nanofluids. Moreover, this study concludes that the Nusselt number is independent of the Reynolds number in the regime of laminar flow. It is further evident that as the nanoparticle size reduces, the Nusselt number rises when all the remaining conditions are the same. Apart from this, investigating the inlet/outlet arrangement through finite volume method for D-, I-, N-, S-, U-, and V-type arrangements, it is evident that the V-type sink has overall greater performance. In terms of gravity, it is observed that it has no effect on the performance of microchannel heat exchangers. This study further illustrates the effects of the fabrication method on the performance of the microchannel heat exchangers.

KEYWORDS

Brownian motion, channel geometry, effect of gravity, manufacturing aspects, microchannel heat exchangers, nanofluids

1 | INTRODUCTION

For the extraction of heat from hot surfaces, energy conversion, waste heat recovery, and energy conservation heat exchangers play an important role and are considered essential equipment. In heat exchangers, fluid flow is separated by a thin wall. Initially, the heat is exchanged from the hot side fluid to the adjacent wall, from where it is transferred to the cold side fluid. To improve the heat-transfer process of a heat exchanger, improvements can be made in the heat-transfer section of the exchanger. In a direct transfer heat exchanger (recuperator), heat is transiently transferred between fluids through a separating wall.[1] Liang et al. worked on the investigation of the significant parameters to enhance the performance of the ground-type heat exchangers with an aim to enhance the overall efficiency.[2] A membrane-based microchannel refrigeration system powered by three different sources of energy was studied by Chong Zhai and Wei Wu for energy, exergy, environmental and economic analysis. The results show that the microchannel membrane absorption refrigeration system can be used to achieve good performance with carbon neutrality.[3] Two processes occur in the heat exchangers: one is the working fluid flowing in the tubes and the second one is the heat transfer across the cold and hot fluids through the walls. The effectiveness of the heat exchangers might also be enhanced by examining various parameters that affect their performance. Experimental studies have shown that microchannel heat exchangers have distinct features apart from conventional heat exchangers such as a capability to yield small heat-transfer coefficients, having compact size as well as small volume per heat load, with a requirement for less coolant.[4,5]

The growth of mini- and microchannel heat exchangers is materialized out by research of Tuckerman, who discovered that the reduced diameters of the tubes enhance the heat-transfer coefficient.[6,7] In addition, it is uncovered that the Nusselt number remains the same for the constant surface temperature in a fully developed region of $Nu = 3.657$ as presented in Equation (1).

$$Nu = \frac{hD}{k} = 3.657, \tag{1}$$

$$h = (3.657)\frac{k}{D}. \tag{2}$$

Equation (2) indicates that decreasing the channel diameter of the microchannel exchangers enhances the heat-transfer rate. The compactness of modern devices and technological advances have made microchannel heat exchangers an important area for the safe development of advanced nanoscale technology devices.

Crucially, microchannel heat exchangers help accomplish three challenges:

(1) The need to enhance heat transfer.
(2) To increase heat flux dissipation in advanced microelectronic equipment.
(3) Frequent development of microchannels requires high cooling rates.

However, there is a lot of research conducted by different scholars across the globe to explore the performance parameters of the microchannels heat exchangers. But every scholar has focused on one problem or a minute phenomenon (e.g., investigating the effect of the size of the nanoparticle on the nondimensional number, such as the Reynolds number or Nusselt number) is taken under observation for investigation. In the current study an extensive study is conducted to compare and contrast the maximum performance parameters of the microchannel heat exchangers with an aim to present a more robust, systematic, and ordered understanding of these parameters to make this part of the literature easily understandable for the readers. This research is not only limited to the performance of important parameters evaluation to improve the overall efficiency of the microchannel heat exchangers but also focuses on the development of the scalable manufacturing processes that could lead to more efficient channel fabrication. The basic purpose of this research is to compare and contrast the most important parameters to achieve high efficiency for the microchannel heat exchangers considering the available research conducted by different researchers on a specific issue related to the microchannel heat exchangers. The beauty of the current study is that it combines the knowledge of various researchers to give a more understandable picture of the overall improvement of microchannel heat exchangers.

TABLE 1 Classification of heat exchangers.

Type	Channel width	Details
Microscale	1–100 μm	Microstructured exchanger
Mesoscale	100 μm–1 mm	Milli structured
Macroscale	1–6 mm	Compact heat exchanger
Conventional scale	>6 mm	Conventional heat exchanger

1.1 | Classification of heat exchangers into different scales

The heat exchangers classification grounded on the tube diameter is outlined in Table 1.

1.2 | Advantages and disadvantages of the microchannel exchangers

The advantages and disadvantages of microchannel exchangers are outlined in Table 2.

1.3 | Applications of microchannel heat exchangers

This literature review highlights the advances and applications of microchannel heat exchangers. Although microchannel heat exchangers must be further studied before their use for large-scale applications, they have several current uses:

(1) As printed circuit heat exchangers.
(2) In microcooling devices.
(3) For component cooling in gas turbines.
(4) For high-temperature nuclear reactors.
(5) For intensifying operations, such as mixing and chemical reactions.
(6) In the electronics industry and highly technological compact devices.

TABLE 2 Advantages/disadvantages of microchannel heat exchangers.

S. No.	Advantages	Disadvantages
1	Compactness	Pressure drop
2	Effectiveness	Flow maldistribution (reverse flow of fluid due to fouling, size of inlet, or operating conditions)
3	Dynamics	Corrosion, surface fouling
4	Larger surface per unit volume ratio	Cleaning and maintenance are not possible
5	High volumetric heat transfer	Made of costly material
6	No effect of the gravitational field	Can hold a small number of fluids
7	Low resource consumption	Axial conduction

2 | DIFFERENT PARAMETERS AFFECTING THE PERFORMANCE MICROCHANNELS HEAT EXCHANGERS

2.1 | Nanofluids

The usage of nanofluids in microchannel exchangers improves not only the heat-transfer coefficient but also the heat-transfer rate.[8–11] Compared with conventional fluids used for heat-transfer purpose, nanofluids have excellent heat-transfer performance characteristics.[12,13] However, using a nanofluid in the microchannel heat-exchanging device, it will enhance the heat transfer and at the same time cause a corresponding substantial pressure loss. Mohammed et al. experimented with four different nanofluids (titanium dioxide, silicon dioxide, silver, and aluminum oxide) with three distinct volume fractions of nanoparticles (2%, 5%, and 10%) and water as a base liquid.[1] The results indicated that a pressure drop occurred in all cases.[1] Similarly, Rimbault et al. evaluated that as the quantity of the nanoparticles increases in the base liquid, the pressure drop rises further.[14] Pressure drop is the difference in flow pressure at two different points in a duct. The implications of the pressure drop are as follows: the process will require greater energy to maintain the desired flow in the duct, the operation cost of the device increases, and a high-pressure producing unit is necessary to maintain the flow.[15] Notably, Trisaksri and Wongwises experimented on heat sinks composed of microducts and utilized nanofluids for the cooling purposes, it was recorded that there is no additional pressure drop.[16] Alternatively, Chein and Huang experimented on the heat sink with microducts using nanofluids and reported a slight pressure drop due to the usage of the nanofluids during the experiment.[17]

Apart from the dropping pressure in the duct, the use of nanofluids in microchannel heat exchangers improves the rate of heat transfer as well as the overall transfer of heat. Choi et al. showed in their research findings that the thermal conductivity of traditional base fluids nearly doubles if a very small number of nanoparticles are dropped into the base fluids (volume fraction <1%).[18] Other researchers have identified a similar increase in heat transfer corresponding to the increase of nanoparticles up to a certain limit. Xuan and Li reported that the thermal conductivity of the suspended fluid increased by approximately 20% with the addition of a small concentration of nanoparticles.[19] Overall, the researchers found that nanofluids significantly improved transferring of heat. Mapa and Mazhar found that the nanoparticles also cause a reduction in the thickness of the boundary layer.[20]

2.2 | Brownian motion

The nanoparticles follow the Brownian motion (i.e., particles propagate within the liquid by collision) and are regarded as a solid-to-solid transfer of heat from particle to particle, thus increasing the thermal conductivity during the process. The movement of particles as a result of Brownian motion is slower to transfer large amounts of heat through nanofluids. Though, the nanofluid particles form clusters, which enhances the thermal conductivity. In essence, nanofluids improve the heat conduction and overall transfer of heat, but the instant, results in a dropping of pressure in the microchannel heat exchangers.

2.3 | Channel geometry

The variation in channel geometry and size greatly impacts the thermal characteristics of the microchannel heat exchangers. Hasan et al. predicted performance variations with the shape and size of a channel by considering four geometric shapes of the channels, including trapezoidal, triangular, rectangular, and square. It is evident from the result that the geometry of the channel greatly affects the thermal performance of the exchanger. Additionally, the researchers noted that a circular shape geometry had the greatest thermal performance characteristics compared with the other shapes.[22]

Furthermore, a pressure drop was also associated with the tube geometry. The smallest dropping of pressure was experienced in the square shape, which had the lowest thermal performance characteristics. The circular channel demonstrated the second-lowest pressure drop. Conversely, the highest pressure dropping was documented in the triangular shape channel, which had moderate thermal performance characteristics.[22]

Brandner et al. studied a variety of microstructure heat exchangers and compared them to one another. The researchers reported that the thermal performance of the microchannel heat exchanger could be increased by decreasing the hydraulic diameter of the microchannel.[23] Given that, when the number of channels increases or the volume of each channel decreases, there is an increase in the heat transfer, pumping power, and pressure dropping.[22]

2.4 | Reynolds number

The Reynolds number is also an effective dimensionless parameter that influences the performance of microchannel heat exchangers. For instance, Mohammed et al. studied four nanofluids with three distinct nanoparticle volume fractions (2%, 5%, and 10%) and used water as the base medium. They found that the average temperature of the cold liquid decreased as the Reynolds number increased, and was identified as a responsible parameter for the increased heat transfer.[1,24] Manay et al. also studied two different nanofluids (Al_2O_3andCuO) with a water base with four distinct volume fractions, such as ($\varphi_1 = 0\%$ [pure water], $\varphi_2 = 0.5\%$, $\varphi_3 = 1\%$, $\varphi_4 = 1.5\%$, and $\varphi_5 = 2\%$).[25] When the fluid is added with nanoparticles, like, Al_2O_3, and then by CuO with different fractions by volumes, such as $\varphi_2 = 0.5\%$, $\varphi_3 = 1\%$, $\varphi_4 = 1.5\%$, and $\varphi_5 = 2\%$, the performance of the microchannel enhances with the rise of the Reynolds number but conversely, when the fluid is used in pure form, the performance decreased with the rise of Reynolds number. Moreover, for CuO–water nanofluids, it is observed that the overall enhancement is achieved at $\varphi = 2\%$ and $Re = 100$. Apart from that, for both nanofluids, the smallest heat transfer increase is recorded at $\varphi = 0.5\%$ and $Re = 1.000$. No significant increase in friction coefficient was observed with the addition of nanoparticles to pure water. Heat-transfer improvements were obtained for both nanofluids used, but the heat-transfer improvements decreased as the Reynolds number increased. The authors concluded that as heat transfer increases, the Reynolds number increases accordingly.[25] The Nusselt number variation with the Reynolds number is given for all the four-volume fractions against both the nanofluids in Figure 1.

In contrast, Hasan et al. concluded that by using water with constant properties, the Reynolds number affects the performance irrespective of the channel geometry.[22] With a greater Reynolds number, the performance decreases. Similarly, Seyf and Keshavarz Mohammadian observed that reducing the Reynolds number increases the effectiveness and performance of nanofluids with the occurrence of a drop in pressure and degradation in the power of pumping. On the other hand, without nanofluids, as in the case with the use of pure water, the performance declines with the rise in Reynolds number.[21] Interestingly, with the use of silver, the pumping power surges with a corresponding rise in the Reynolds number.[1] Overall, it can be concluded that the Reynolds number affects the performance of microchannel heat exchangers in different ways for nanofluids and other conventional liquids.

2.5 | Nusselt number

The Nusselt number is another dimensionless parameter that affects the performance of the microchannel heat exchangers. Hosseini et al. researched magnetic nanofluids in microchannel heat exchangers. The researchers stated that the Nusselt number is associated with the particle size of the nanoparticles in the nanofluid. As the nanoparticle size decreases, the temperature between the coolant and the wall decreases, which increases the Nusselt number. However, the concentration of nanoparticles at the channel wall improves the Nusselt number for the magnetic field Al_2O_3 as a nanofield.[26]

Abubakar and Sidik studied rectangular microchannel heat exchangers with magnetic nanofluids and straight channels. The outcomes exemplified that the Nusselt number maximizes at the inlet of the channel.[27] In contrast, Dehghan et al. conducted research on

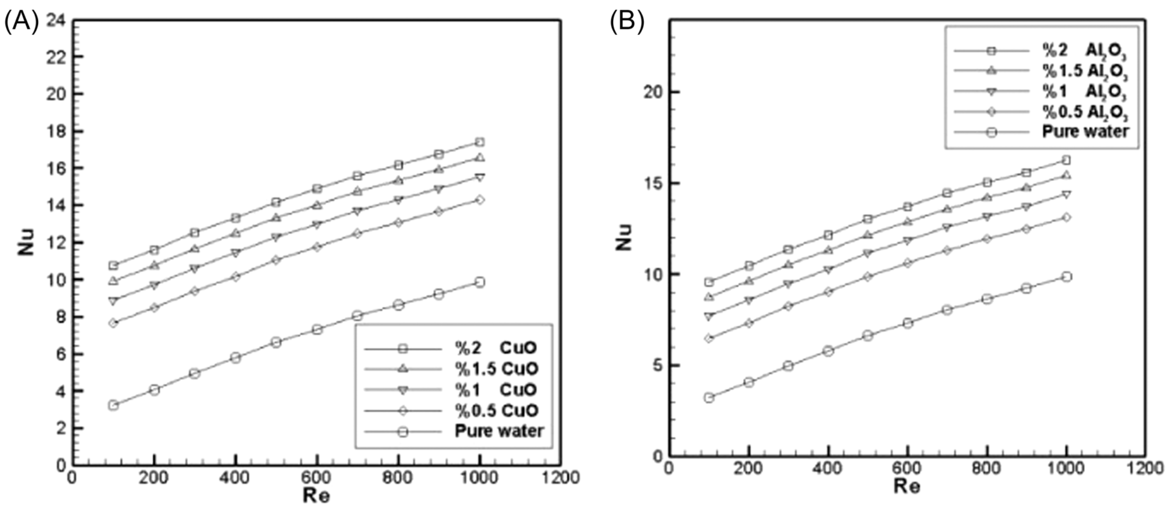

FIGURE 1 Nusselt number variation with Reynolds Number: (A) CuO nanofluid and (B) Al_2O_3 nanofluid.

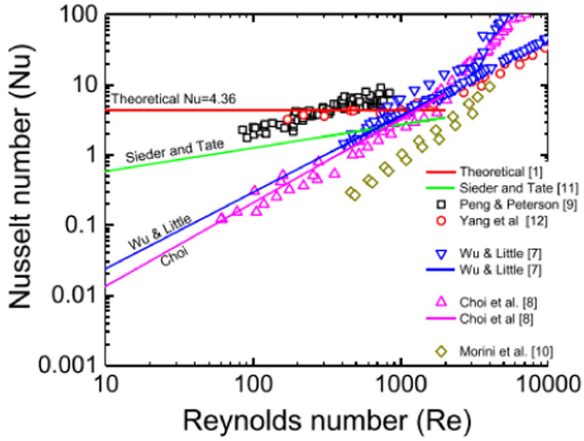

FIGURE 2 Inconsistency of Nusselt number with Reynolds number from different experimental results compared with the theoretical results.[30]

tapered channels and observed that the inlet of the tapered duct, the Nusselt number has no effect. However, the Nusselt number surges with the increase in tapering of the duct.[28]

In comparison, researchers reported that within the laminar regime, the Nusselt number and Reynolds number are independent of each other.[29] While the measurement of heat-transfer coefficients has been thoroughly studied, macrochannel research and microchannel measurements exhibit dissimilar results in the research.[3] These inconsistencies are particularly prevalent in the laminar flow area as shown in Figure 2.

By giving the small size of the microchannels, it is difficult to measure their heat-transfer coefficient. The axial conduction effect, an integral mechanism, is often ignored in traditional studies. However, this mechanism must be considered in new measurements as for microchannels both the Nusselt number and Reynolds number are not dependent on each other, especially in the laminar flow regime.

A numerical model is designed and adopted to evaluate the heat-transfer properties in the microchannel heat exchangers with a special focus on the conduction phenomenon across the walls of the channels. The model predicts the wall temperature variation across a point at the end of the heater and a specified distance away from the end of the heater. The temperature variation is experimentally measured and validated with the numerical model. The comparative analysis showed that the Nusselt number and Reynolds number are not dependent on each other, especially in the laminar flow area.[30] The literature survey shows that no scholar has reported a constant Nusselt number or Reynolds number in the region of laminar flow.

2.6 | Knudsen number

In addition to the influence of dimensionless parameters, the Knudsen number also affects the performance of microchannel heat sinks. Maqableh et al. reported that when the Knudsen number rises, the wall temperature correspondingly increases. But the number of transfer units (NTUs) increases when the Knudsen number decreases. In addition, the researchers hypothesized that wall resistance affects the NTU, with wall temperature analogous to the Knudsen number.[31] However, the wall resistance is insignificant to the effectiveness of the counter and parallel flow heat exchangers.

2.7 | Gravity

Microchannel heat exchangers are installed in either a horizontal or vertical position in compact areas with limited space. There was a lapse to identify the impact of gravity on the vertical and horizontal configuration of the microchannel heat exchangers. Dang et al. analyzed microchannel heat exchangers to predict the effect of gravity on heat transfers.[32] Vertical and horizontal channels were used with hot and cold water as the fluids. For the vertical channel, the hot water was set to flow against the gravitational field in the upward direction while the cold water was set to flow in the downward direction of gravity. The horizontal heat exchanger was tested with hot and cold water. The results indicated that both the straight channel and vertical channel have the same performance indicators with little difference. As such, gravity does not affect the microchannel heat exchanger flow and the microchannel exchangers can be installed either vertically or horizontally.[32]

2.8 | Inlet and outlet arrangements of sink

Another important factor for microchannel devices is the inlet and outlet arrangement (i.e., different shapes of the channel geometry at the inlet/outlet), which affect the performance. As outlined in Figure 3, Chein and Chen worked on the inlet and outlet designs of different types (D-, I-, N-, S-, U-, and V-type inlet/outlet designs) by utilizing the finite volume method. The authors reported that the temperature distribution and resultant flow fields were different for various inlet/outlet arrangements across the heat sink for a specific pressure drop. Additionally, Chein and Chen

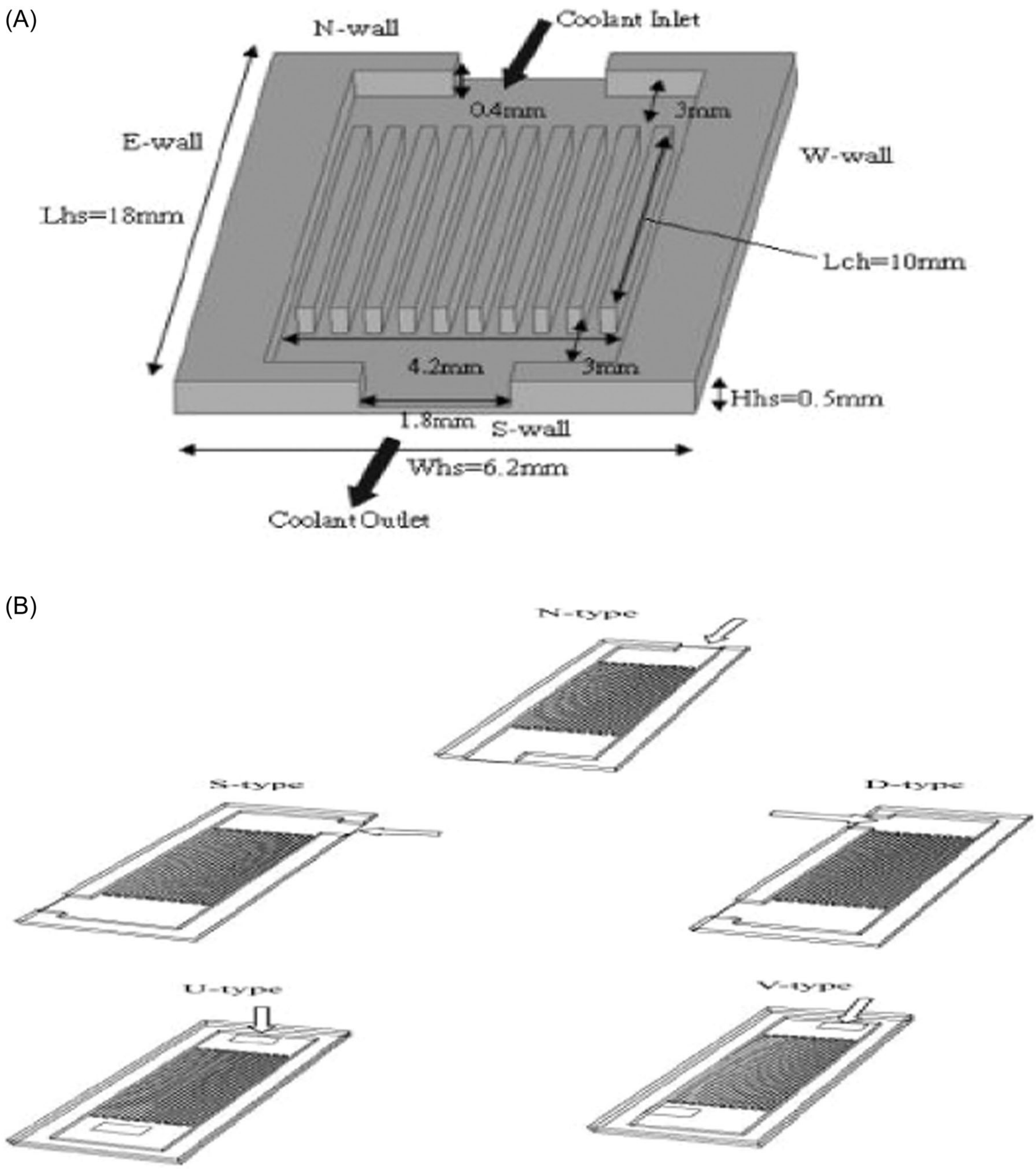

FIGURE 3 (A) Dimension and demonstration of the heat sink and (B) N-, S-, D-, U-, and V-type intel/outlet configuration.[30]

analyzed the microchannel heat exchanger performance using the pressure-dropping coefficient, thermal resistance, and overall heat-transfer coefficient. Among the analyzed heat sinks, it was evident that the V-type sink shows maximum performance compared with the other heat sinks inlet/outlet arrangements.[33] V-shaped heat sinks show excellent velocity and temperature uniformity with a coolant supply and vertical collection.[16] Hung et al. also noted that the thermal resistance is affected due to changes in the channel geometry, with the V-type sinks having the greatest thermal resistance.[34]

3 | MANUFACTURING ASPECTS

Using different materials in microdevices is dependent upon advancements in fabrication methods. Presently, the manufacturing of microchannels by using a diversity of materials is difficult, and further research is needed to achieve an accurate and precise microchannel geometry as well as to develop more efficient fabrication methods. Microchannels are fabricated using many different methods, which are dependent upon the material and dimensions used. These methods are categorized into two main categories: conventional technologies and

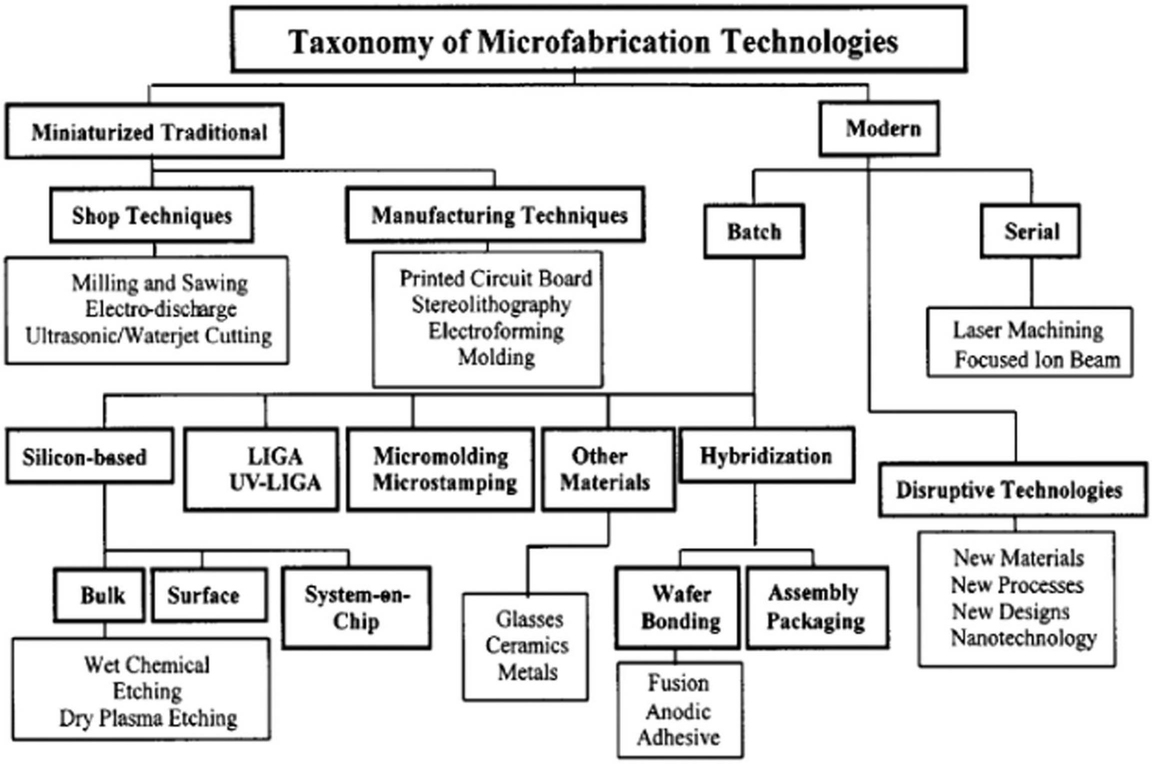

FIGURE 4 Taxonomic chart for microfabrication technologies.[32] LIGA, lithography, electroplating, and molding; UV, ultraviolet.

nonconventional technologies. Figure 4 provides a taxonomic chart of microchannel fabrication technologies. The advantages, disadvantages, and constraints of each fabrication method are discussed in the subsequent sections and summarized in Tables 3 and 4.

3.1 | Mechanical cutting

The technology of mechanical microcutting is an important one of the important methods for microchannel fabrication. It provides a good surface finish and accuracy of channels using high-precision machine tools to enhance heat transfer in microducts. Microturning and micromilling are two of the most commonly used methods of mechanical cutting. In comparison to micromanufacturing technologies, Pan et al. asserted that mechanical cutting is advantageous because of its high machining speed. Additionally, a variety of materials can be fabricated with the help of mechanical cutting such as plastics, polymers, steel, brass, and aluminum.[63] In comparison to lithographic techniques and laser beam machining, Prakash and Kumar found that mechanical cutting has an inexpensive setup that allows for the fabrication of channels at a lower cost.[41] However, it was reported that the process has limitations, including its inability to be used for batch production. Mechanical cutting is better suited for the fabrication of individual components. Moreover, Prakash and Kumar observed that the wearing of the tool and Burr formation at the ends is disadvantageous for the process as it leads to further processing steps, which can impact the precision of the microchannels. Similarly, cracks generated due to mechanical stress can negatively affect the strength of the microchannels.[41] Despite its advantages, micromilling has not been fully explored and there is minimal experience with its introduction into industries.[64]

3.2 | Chemical etching

Generally, the common subtractive technique for micromachining is etching. For this technique, a pattern is transferred by physical or chemical subtraction of material from a substrate. Typically, the pattern is made up of protecting mask films like oxide or a resist. For substrates of metallic nature, wet chemical etching (WCE) is commonly used because metal reacts well with chemicals. Vangbo and Bäcklund discussed how WCE can only produce a limited number of microchannels because of its dependence on crystal orientation (i.e., anisotropic), which can only remove materials in some directions.[65] Additionally, Kikuchi et al. found that fabricating microchannels with WCE using glass can result in irregular boundaries on the microchannel surface.[66] Puers and Sansen also discussed how WCE is limiting for features produced by plane interactions, which are only stable for angles of corners less than 180°.[67] Conversely, Gaikwad[68] and Bhardwaj et al.[69] highlighted Deep Reactive Ion Etch (DRIE), a recent advancement in the etch process, which is more suitable for silicon, glass, and polymers due to the requirement for low reactive energy and low manufacturing uncertainty. Importantly, the DRIE etch process can be easily masked with a variety of polymer and dielectric films like silicon dioxide and photoresist. However, DRIE is not well-suited for industrial use because of the time-consuming process.[69]

3.3 | Lithography

Photolithography is the most commonly used method of lithography. Microchannel fabrication industries often use photolithography to take a pattern from a mask onto thin films. A recent advent is the introduction of X-ray lithography to create polymer microchannels. In contrast to other lithographic processes, X-ray lithography is faster and cheaper because it does not require a vacuum and a clean room facility.[70] Though, Kandliker et al. asserted that lithography, electroplating, and molding (LIGA) have all the advantages of X-ray lithography. LIGA is considered a high aspect ratio manufacturing process which is based on the lost wax process. In LIGA, mold is filled with metal using high-energy X-rays and galvanizing processes.[71] Various different materials can be fabricated with a wider variety of profiles and dimensions.

However, Feinerman et al. noted that LIGA is not a popular method due to its difficulty to produce appropriate X-ray masks for microchannels, its limited availability, and the cost of exposure equipment.[72] Moreover, most lithographic processes require postprocessing steps like etching and other chemical processes for the fabrication of high-resolution microchannels. Postprocessing makes this method more expensive for fabrication. Though, this issue is not limited to lithographic methods; most microchannel fabrication techniques require specialized equipment and mask preparation, which is an expensive and time-consuming process that restricts its use on a larger scale.

As such, there is a need to make simple and fast techniques for the speedy prototyping of microchannels. Whiteside et al. introduced the rapid prototyping of poly dimethyl siloxane, which is a microfluidic device that uses masks comprised of laser-printed commercial sheets. For this method, microchannel designs were

TABLE 3 Fabrication method used versus heat transfer.

References	*Wc* (mm)	*Hc* (mm)	*Dh* (mm)	*Hc/Wc*	*u* (kW/m^2 K)	U_v (MJ/m^3 K)	Fluids/flowrate (L/min)	Manufacturing method
Tuckerman et al.[35]	0.05	0.3–0.32	0.086	6	21.2		Water 0.3–0.5	Silicon etching
Cross and Ramshaw[36]	0.4	0.3	0.343	0.75	4.0	7	Water 2.16	Copper, photo etched plates
Bier et al.[37]	0.1	0.078	0.088	0.78	22.8	324	Water maximum 12.5	Precision machining
Friedrich and Kang[38]	0.26	0.08	0.122	0.3	6.44	33.344.3	Water 0.84–2.7	Diamond machining
Jiang et al.[39] MCHE/MPHE	0.2	0.6	0.3	3	13.3/60.4	38.5/86.3	Water 20.4/4.02	Copper plates wire cutting
Kang et al.[40]	0.04	0.2	0.067	5	24.7	188.5	Water	Silicon etching

Abbreviations: MCHE, microchannel heat exchanger; MPHE, microporous-media heat exchanger.

TABLE 4 Comparison of fabrication techniques for microchannels with their advantages/disadvantages.[41–60]

Laser-evolved microchanneling	Main area of application	Materials	Key references	Advantages/disadvantages
UV laser microchanneling	Inkjet nozzles, chemical applications, mechanical and electronic cooling applications	Almost all sorts of materials	Molian et al.,[44] Heng et al.,[42] Srinivasan and Braren,[61] Kitsara et al.,[46] Fernández-Pradas et al.,[47] and Waddell et al.[48]	Burrs and redeposition of ablated material are minimum, very low fabrication time, specially designed optics, beam delivery and diagnosis, high initial investment, and fit for mass production
IR laser microchanneling	Chemical applications, mechanical and electronic cooling applications, fits for all kinds of applications	Almost all sorts of materials, including PMMA, polyimides	Lim et al.,[49] Gadag,[62] Snakenborg et al.,[50] Yu et al.,[45] and Qi et al.[51]	Higher heat-affected zone, burrs, low aspect ratio channels, and nonuniformity of the shape of microchannels
Microchanneling by short and ultrashort pulse laser	Chemical applications, mechanical and electronic cooling applications, fits for all kinds of applications	Transparent plastics, glass, and other difficult-to- cut materials	Joglekar et al.,[52] Sokolowski-Tinten et al.,[53] Kuršelis et al.,[54] Liu et al.,[55] and Zheng et al.[56]	Negligible heat-affected zone, well controlled (atomic level), tough to maintain, high initial investment cost, and channel shape limitations
Laser microchanneling in different environments	Chemical applications, mechanical and electronic cooling applications, fits for all kinds of applications	Metals and polymers	Morita et al.,[57] Kruusing,[58] Choo et al.,[59] and An et al.[60]	Initial research stage, very low heat-affected zone, repository materials, precise cutting, and higher power consumption

Abbreviations: IR, infrared; PMMA, polymethyl-methacrylate; UV, ultraviolet.

printed instead of using expensive chrome masks. However, high-resolution lines (i.e., 10 μm/dot) were difficult to achieve using this approach.[73] Anderson modified a liquid crystal display projector to develop a photolithography system for the speedy production of microchannels consisting of the following distinct features: no requirement for photomasks, no requirement for an exterior optical system, and no requirement for clean rooms. The required time consumption was reduced with the introduction of mask-free photolithography. Though, as the method is not fully automated, the precision of the fabrication is dependent upon the manufacturer's skills.[74]

3.4 | Embossing or imprinting

Typically, microchannel fabrication by embossing uses a dried plastic material placed over a metal or silicon stamp. Lin et al. found that the accuracy of the microchannel depth and width is significantly impacted by the embossing time, temperature, and embossing load. In this process, force is applied to the plastic material in a hydraulic press for approximately 10 min.[75] It was. found that embossing at very high temperatures and pressures has been found to significantly reduce manufacturing time and extend substrate life. Conversely, Prakash and Kumar found that the embossing process required replicating fine features on the mold, which gradually wore away over time, resulting in inaccurate channel dimensions. For fabrication of replicating devices needs additional processes such as lithography, which further increased the cost of fabrication. As such, the researchers found that the embossing technique results in a low surface finish, required high temperatures, large lead time, and is most appropriate for individual needs.[41]

3.5 | Injection molding

Whiteside et al. argue that cost is a major factor in determining which method is needed to adopt for microchannel fabrication. The injection molding technique was developed for its low-fabrication cost and high-precision results.[73] The micromolding injection machine is comprised of a piston, heater, shut-off valve, nozzles, extrusion screws, and sprues.[76] Researchers at "ACLARA Biosciences Inc." used injection molding operation to produce microchannels for the first time. The polymer for injection molding must be less viscous and have greater interaction with the walls of the mold to produce accurate features during microchannel fabrication. There are two main parameters that determine the quality of injection-molded microchannels: mold temperature and polymer relaxation after releasing.[77] A major advantage of injection molding is that the preformed element is embedded into the plastic. However, one of the major drawbacks of the process is the occurrence of weld lines while fabricating complex microchannels. As the mold fills, weld lines begin to appear, which reduces the strength of microchannels.[78,79] Alternatively, researchers have studied hybrid techniques for the fabrication of microchannels. Though, manufacturers do not consider these to be the best choice because of the lack of standardization among these processes. More research is necessary to achieve high precision and accuracy in microchannel fabrication.

3.6 | Laser fabrication

Laser fabrication for microchannels is a recent technological development that has been converted into a powerful tool for handling different materials and complex microstructure shapes. Researchers have used neodymium-doped yttrium aluminum garnet and excimer lasers, while others have tried CO_2 lasers for microchannel fabrication.[42,43] Khan Malek discussed how the laser fabrication process for microchannels has significant advantages, including minimal time consumption, ease of fabrication, and low cost.[80] These advantages make laser fabrication an attractive choice for manufacturers. In comparison to other processes, laser fabrication is scrap-free, environmentally friendly, and simple to operate. Unlike the photolithographic and etching processes, this method does not need a clean room facility and mask preparation. Additionally, a variety of materials including metal, nonmetal, and ceramic can be easily cut down into any type of shape.[80] However, Wan et al. found that laser fabrication causes surface damage to the microchannels due to its thermal nature.[81] On some occasions, the surface becomes so damaged that it cannot be used for the required purpose.[81] Molian et al. also discussed how fabricating microchannels via laser methods can result in the formation of heat affected zones and burr.[44] Given that, the process conditions must be optimized to achieve better-quality microchannels. Moreover, substantial research is needed to help control and curb surface damage caused by the thermal nature of laser fabrication, either with the use of postprocessing or by altering the process itself.

TABLE 5 Laser-evolved methods for fabrication of microchannels.[41,63,64,66,73,75–79,81,89–104]

Fabrication methods	Main area of application	Materials	Key references	Advantages/disadvantages
Micromechanical cutting	Heat sinks, metallic microparts	Especially suitable for metals	Qin,[89] Pan et al.,[63] Wan et al.,[81] and Liow[64]	Individual/personalized component, not suitable for mass/batch production, wear of cutting tool, crack generation, high accuracy and good surface finish, and burr formation at the ends
Wet and dry etching	Biomechanical applications	Mostly metals and reactive materials only	Madou,[90] Brugger et al.,[91] Kikuchi et al.,[66] Belloy et al.,[92] Park et al.,[105] and Maselli et al.[93]	Nonparallel walls, exact control of dimensions is not possible, and selective material removal
Lithography	DNA analysis, blood, protein synthesis, and chemical applications	Polymers and silicon	Peng Yao et al.,[94] Pal and Sato,[95] McDonald et al.,[96] Becker,[97] Xia and Whitesides,[98] Ueno et al.,[99] and Delamarche et al.[100]	Able to fabricate most complex topography, requires clean room facility, large lead time, needs skilled human resources, and able to fabricate very high aspect ratio microchannels
Embossing and imprinting	Biomechanical applications, and chemical applications	Polymers and silicon	Michel et al.,[101] Martynova et al.,[102] McCormick et al.,[77] and Lin et al.[75]	Generally, needs a higher degree of temperature, low surface finish, large lead time, suitable for individual needs
Injection molding	Electrochemistry, cell trapping, and DNA elongation	Polymers, silicon, and metals	Whiteside et al.,[73] Ganz,[76] Thomas et al.,[103] Piotter et al.,[78] Tosello et al.,[79] and Matteucci et al.[104]	The presence of weld lines, can fabricate structures having very small sizes, low strength

TABLE 6 Relation between fabrication methods and factors affecting microchannels.[106]

Summary of some fabrication methods for microchannels				
	Microdeformation technology	**Micromachining**	**MEMS (deep reactive ion etching)**	**Laser micromachining**
Geometries	Rectangular	Rectangular	Rectangular, circular, triangular, and trapezoidal	Unlimited
Materials	Metal and nonmetal	Metal and silicon	Metal, silicon, and glass	Metal and glass
Channel range	250 Channels/in.	0.1–10 mm	Nanometer scale to millimeter scale	Nanometer scale to millimeter scale
Advantages	Low cost and fast	High or low aspect ratio, inexpensive, and fast	Low manufacturing uncertainty	Low manufacturing uncertainty
Disadvantages	Some materials required posttreatment	Complex design is impossible	Slow process (1 day)	Too expensive

Abbreviation: MEMS, microelectromechanical system.

3.7 | Effect of fabrication methods on the performance of microchannel heat exchangers

Research was carried out by Nageswara Rao and Deepak Kunzru considering three different solutions of $FeCl_3$, HCl, and HNO_3 as etchants and using WCE to fabricate stainless steel microchannels. The study illustrated that by increasing the ratio of the HCl as an etchant not only rises the etch rate but also the etch factor and has a significant impact on the duct roughness. Thus, the dropping of pressure occurs more in the rough channels as compared with the smooth channels. Furthermore, the results show that by obtaining the smooth and uniform channels it is essential to increase the concentration of the HNO_3. It is further evident from the study that the composition of the etchant and the operating temperature have a significant impact on the smoothness of the channel walls. The study further shows that using the etchant having 10% of $FeCl_3$, 10% of HCl, and 5% of HNO_3 by weights at a temperature of 40°C gives the smooth channels that have minimum pressure drop.[82] The advantage of high wall roughness is increased heat transfer from the surface.[83]

In addition, Keramati et al. worked on manufacturing of microchannels by considering additive manufacturing techniques. In this work, direct metal laser sintering is utilized to fuse metal powders layer by layer to produce three-dimensional geometries. Apart from this, three different parameters were utilized, that is, power of laser, size of powder, and thickness of the layer. A $3'' \times 3'' \times 3''$ microchannel heat exchanger was successfully generated by using the metal laser sintering. The new design of the manifold microduct heat exchanger showed an improved rate of heat transfer and reduced the pressure drop as compared with state-of-the-art heat exchangers. The short flow length and the wall smoothness achieved through this method of fabrication reduced the pressure drop by a considerable amount as compared with the chemical etching method and increased the heat transfer by forcing the flow easily to the developing region. Moreover, it has been reported that the method of fabrication of the microchannel has also a considerable effect on the performance of the microchannel heat exchangers.[84] Moreover, the impact of the fabrication method under different studies is presented in Table 3. Where "u" is the heat-transfer coefficient and "U_v" is the volumetric heat capacity.

3.8 | Materials

Various types of substrates have been used for microchannel fabrication. Polymer is a commonly used material for microchannel production. However, Castanoalvarez et al. found that microchannel fabrication using polymer is challenging for manufacturers because it is brittle and has unrestrained crack generation.[85] In comparison to other polymers, microchannel fabrication with metal is easier, though it does not have properties such as optical transparency and a nonreactive nature, which makes it unsuitable for some applications. Kamitani et al. assert that silicon is a good choice for microchannel fabrication as it has a high thermal conductivity. Though, sensitive devices are not suited for thermal-based fabrication processes because the heat is absorbed during the process, which reduces their sensitivity.[86] Researchers also focused on the use of materials such as ceramics and semiconductors for the manufacturing of microchannels but their usage is limited because of the greater cost.[87] Furthermore, Kee et al. proposed a new technique, Pressure Laminated Integrated Structures (PLIS), as a cost-effective fabrication method for ceramic-based devices (Tables 5 and 6).[88]

During the PLIS fabrication technique, ceramic powders and suitable binders are combined. The unfired green films that form the channel geometry are produced using a hydraulic press and custom dies. The green layer is formed close to the final shape, reducing process complexity. In comparison, other methods build up the structures from several individual thin sheets. Then, the prototype is machined from pressed green blocks, which avoids incurring costs for fabricating production dies. When laminating with a hydraulic press, the green layer is inserted and assembled. After laminating, the assembled part is fired, which turns out to be a single polycrystalline ceramic part without bond lines between the laminated layers.[88] Additionally, the axial partitions in the channel ribs, as shown in Figure 5, have three purposes: to enable equal pressure between channels to improve flow distribution, reduce the longitudinal wall conduction, and create a local entry length.

In comparison to metal, ceramic withstands high temperatures and is chemically inert. The PLIS also has low manufacturing costs for complex microchannels because it requires the fabrication and handling of very few parts. On the other hand, other methods use diffusion bonding for the fabrication of multiple thin metal shims. However, the PLIS is brittle and can break with high thermal mechanical stress. These breaks can lead to fluid leaking or the mixing of fluids. Importantly, at low and moderate thermal–mechanical stresses, the PLIS provides promising thermal performance characteristics.

In addition, Paul and Kanlayasiri presented a manufacturing technique to manufacture a parallel flow microchannel heat exchanger from nickel–aluminum (Ni–Al) arrays. Figure 6 highlights how the researchers used NiAl laser machining and NiAl bonding to synthesize the microchannel.[107] NiAl was fabricated by reacting and homogenizing NiAl foils from Ni and Al foils. Ni foil was placed between two Al foils to make NiAl. Then, the foils were held at a level of temperature 500°C and corresponding pressure of 4 MPa for almost 10–15 min. It was further heat treated to change the elemental Ni and Al to intermetallic NiAl. Then, with the use of laser machining NiAl foils were cut into the desired patterns. Next, diffusion bonding was performed between the Ni film and NiAl in which Ni foils were used as filler metal for bonding the NiAl foils. The NiAl has a high heat-transfer performance because of its high melting temperature (>1600°C),[108–110] while other metallic substances cannot sustain more than 650°C. Additionally, the chemical inertness of NiAl is another reason for its high heat transfer. In comparison to Ni_3Al, NiAl is more favorable to form a protective oxide coating due to its high Al contents.[108]

Brandner et al. thoroughly discussed the different methods of manufacturing microchannel heat exchangers and their properties. The researchers found that a variety of materials can be used, including copper, stainless steel, and nickel-based alloys, which can be used in different shapes, sizes, and numbers to obtain the desired properties of heat transfer.[111] Kee et al. fabricated a microchannel crossflow heat exchanger using ceramic material because of its ability to be used at high temperatures. The authors used the PLIS technique for fabrication because of its low cost and the channel geometry was formed with custom dies.[88]

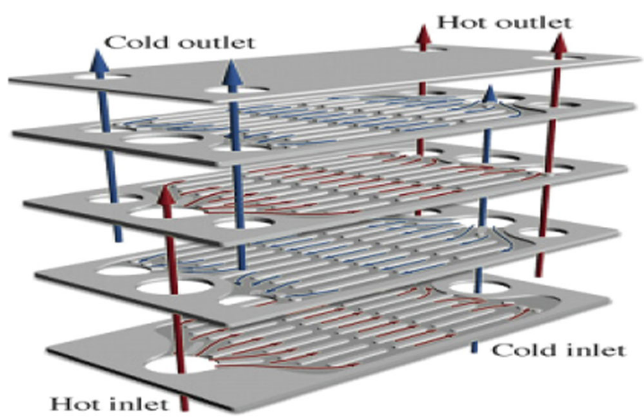

FIGURE 5 Channel structure with internal manifold.[88]

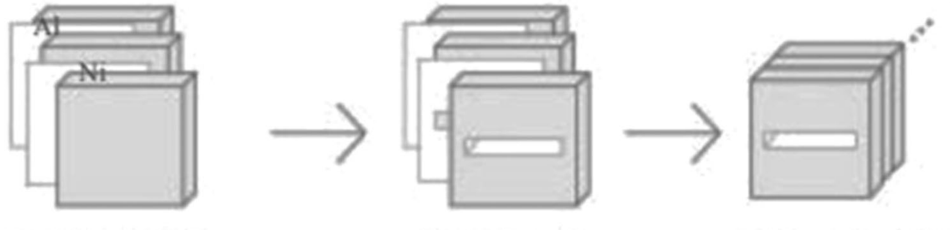

FIGURE 6 Fabrication procedure used to yield Ni–Al microchannel arrays.[108]

4 | CONCLUSION

Microchannel heat exchangers exemplified excellent performance with compact, effective, and dynamic properties. This section summarizes the available research as well as reiterates where further research is needed to maximize the use of microchannels as well as heat exchangers made of microchannels.

Nanofluids improve heat transfer but cause a significant pressure drop. When the number of nanoparticles increases, the pressure drop also increases, reaching a limit beyond which additional nanoparticles no longer affect the performance. The optimum number of particles for different fluids is identifiable.

The literature review indicates that the pressure drop is linked with the channel geometry. The circular shape channel geometry exhibited the maximum thermal performance, whereas the pressure drop was recorded lowest for the square shape channel geometry.

Research indicated that the Reynolds number behaves differently for nanofluids and conventional fluids. For nanofluids, when the Reynolds number rises, the heat transfer correspondingly rises. Conversely, for conventional fluids such as pure water, when the Reynolds number rises the heat transfer declines. Importantly, the Reynolds number affects the performance irrespective of the channel geometry. When pure water is added with nanoparticles, like, Al_2O_3 and CuO with different volume fractions (φ) of 0%, 0.5%, 1%, 1.5%, and 2%, the performance of the microchannel showed enhancement with increasing the Reynolds number but conversely when the fluid is used in pure form the performance decreased with the increase of Reynolds number. Moreover, for CuO–water nanofluids, we observe that the overall enhancement is achieved at $\varphi = 2\%$ and $Re = 100$. It was observed that for both nanofluids, improved heat transfer could be achieved at $\varphi = 0.5\%$ and $Re = 1.000$. No significant increase in friction factor was observed with the addition of nanoparticles to pure water.

The Nusselt number affects the performance of microchannel heat exchangers and depends on the particle size of the nanoparticles. A smaller nanoparticle size increases the Nusselt number and at the same time improves the performance of the heat exchanger. We also observed that the Nusselt number increased when the nanoparticles accumulated on the walls of the heat exchanger. For conical/tapered tubes, the Nusselt number increases with increasing taper.

However, studies have shown that gravity does not affect the performance of microchannel heat exchangers.

Changing the geometry of the sink entrance and exit has been shown to affect performance. It has also been observed that a V-shaped inlet/outlet arrangement provides the best performance. However, the thin tubes experience corrosion and fouling of channels.

There remains a need for more research on microchannel heat exchangers. Further study is needed to identify the optimum number of nanoparticles for different base fluids as it disturbs the performance of the microchannel heat exchangers. In addition, the stability of nanofluids under different flow conditions and the performance of microchannel heat exchangers with and without channel fins inside and outside the channels should be further considered. Further studies are also needed to better understand why heat transfer in microchannels increases with increasing pressure drop. In addition, various methods of measuring temperature, pressure, and velocity within microchannel heat exchangers should be developed. Despite modern nanotechnology, microchannel heat exchangers and nanofluids are currently the only solutions for cooling. Overall, this field has room to grow, and greater attention should be given to the aforementioned issues.

Conventional technologies such as mechanical cutting and photolithography are not appropriate for the mass production of channels because of their time-consuming processes. The size and flexibility of microchannel fabrication were also limited because of the difficulty of the processes. For instance, conventional fabrication processes are not economical because they often require postprocessing. Similarly, WCE has directional removal (i.e., anisotropic behavior), which limits the number of microchannels produced by the process. However, the creation of the DRIE technique enabled flexibility with different materials and low manufacturing uncertainty. Though similar to conventional technologies, DRIE is not well-suited for industrial use because of its time-consuming process. On the other hand, embossing or imprinting processes undergo wearing to the stamp during the replicating of microfeatures for the channels, which can result in improper channel dimensions. For these techniques, further processing is needed to fabricate the replicas, which adds an extra cost.

In comparison to the embossing process, injection molding is advantageous as the preformed elements are embedded into the plastic during the process. Though, a major drawback of this technique is the appearance of weld lines during the fabrication of channels, which reduces the strength of the channels. A variety of hybrid techniques have also been tested. However, manufacturers are not keen to utilize these methods because of a lack of process standardization. As such, more research is needed to achieve greater accuracy in the fabrication of channels.

The laser method for microchannel fabrication has numerous advantages. For example, the laser method is low cost, easily used for fabrication, less time-consuming than other methods, and does not require a clean room facility or the preparation of masks. Importantly, the laser method can be used with a variety of materials, including ceramic, metal, and nonmetal as well as cut into any shape. However, the primary disadvantage of the laser method is that it can damage the surface of the microchannels due to its high thermal nature. As such, further study is required to control the surface damage either through postprocessing or by altering the process parameters.

In the fabrication process, materials play an integral role in the cost control and quality of the produced microchannels. The most widely used material is a polymer. Unfortunately, this material is challenging for manufacturers to use for microchannel fabrication due to its uncontrollable fracturing and brittleness. Alternatively, metal is easier to fabricate than polymers, but it is not suitable because it lacks optical transparency and is nonreactive. Another material, silicon, has high thermal conductivity but is a sensitive material that is not appropriate for fabrication processes. Moreover, the heat that is absorbed during the process greatly reduces the sensitivity of the silicon. More recently, researchers have examined the use of ceramic and semiconductor materials. However, their use is limited due to the high-cost output. Research dedicated to investigate cost-effectiveness and easy-to-fabricate materials is essential as it will help bring about greater innovations to the field of microchannels.

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