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Review on Effect of Geometrical Parameters used in Microchannel Heat Exchanger on its Thermal Performance

Dhrumil Nimesh[a], Alvis Thomas[a], Saurav Patel[a], Mohit Singh[a], Diptesh Patel[b] , Jay Chauhan[c]
[a] *Student, Mechanical Engineering, L. J. University, Ahmedabad, India*
[b] *Associate Professor, Mechanical engineering department, L.J. University, Ahmedabad, India*
[c] *Assistant Professor, Mechanical engineering department, L.J. University, Ahmedabad, India*

Abstract: Microchannel heat exchangers (MCHE) have gained significant attention due to their high thermal efficiency, compact size, and enhanced heat transfer capabilities. This review paper examines the influence of various geometrical parameters on the thermal performance of MCHE. Key design modifications, such as wavy channels, ribbed surfaces, cavities, and pin-fin arrangements, have been analysed to determine their impact on heat transfer efficiency, pressure drop, and flow characteristics. Studies indicate that wavy and ribbed microchannel enhance heat transfer by promoting secondary flows and vortex generation, while cavity-based modifications improve thermal performance with minimal pressure loss. Additionally, the shape and arrangement of pin-fins significantly influence heat dissipation, with denser configurations improving heat transfer at the cost of increased pressure drop. Furthermore, comparative studies on cross-sectional geometries suggest that rectangular channels offer the best thermal resistance and heat transfer efficiency, whereas triangular shapes exhibit the lowest pressure drop. Despite extensive research on geometric optimization, limited studies focus on the effect of different working fluids on these configurations. Future research should explore fluid-geometry interactions to further enhance MCHE performance across diverse applications.

Keywords: Microchannel heat exchanger, Microchannel heat sink, Thermal performance, Geometry, Parameters.

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I. INTRODUCTION

Microchannel heat exchangers (MCHE) are widely recognized for their superior heat transfer performance, compact design, and high surface area-to -volume ratio. Originally introduced by Tuckerman and Pease in 1981 for cooling microelectronic circuits, MCHE technology has since evolved and found applications in aerospace, automotive, chemical processing, and electronics cooling.

Microchannel Heat Exchanger (MCHE) is a heat exchanger having a really low volume-to-surface-area ratio, generally ranging from 10µm to 500µm. This low value of this ratio is possible due to MCHE's design which mainly involves numbers of microchannel having Hydraulic Diameter of less than 1mm, which helps in increasing the surface area exposed to working fluid in it significantly. As the primary mode of heat transfer in MCHE is convectional heat transfer and due to the direct dependency of convective heat transfer on the surface area involved in heat transfer, the MCHE have a really good thermal performance compared to normal heat transfer mechanisms.

Microchannel heat exchangers mainly contain 3 parts, which are Microchannel, Manifolds and Fins (Fig.1). The working fluid is pumped in input manifolds by using a pump, through manifolds fluid enters microchannel and exits from output manifolds. The fins increase the surface area available for heat exchange with outer atmosphere of MCHE.

There were many geometries that were studied in different research paper that we reviewed. We can categorize these geometries in 3 parts, first geometries on side walls of micro channels, second pattern of micro channels, and third pin fins used in the micro channels.

Further we can categorize these 3 parts into different geometries like, the geometries used for side wall of micro channel was Ribs and Cavities. In which different shapes of ribs and cavities were used and also different combination and patterns of these ribs and cavities were used.

Next multiple types of pattern were used for micro channels. In which wavy pattern of multiple wavelength, zigzag pattern with multiple types of nooks i.e. positive and negative variants of different shapes were used.

And lastly different types of pin fins and the effect of their geometrical parameters like height, diameter, spacing, etc were observed. The height of pin-fins in a microchannel heat exchanger (MCHE) determines the extent to which they extend from the base, influencing both heat transfer and pressure drop. Taller pin-fins provide a larger surface area for heat dissipation but also increase flow resistance, while shorter ones reduce pressure drop but may not enhance heat transfer as effectively.

The spacing between pin-fins plays a crucial role in fluid dynamics; closely spaced pin-fins improve thermal performance by increasing turbulence but can lead to higher pressure drop, whereas wider spacing allows smoother flow with reduced thermal enhancement.

The diameter of pin-fins affects both heat transfer and flow behaviour, as larger diameters provide more surface area for heat exchange but may obstruct fluid movement, leading to increased resistance, while smaller diameters allow better flow circulation but might not be as effective in dissipating heat. An optimal balance among height, spacing, and diameter is essential for maximizing the efficiency of MCHEs while minimizing energy losses.

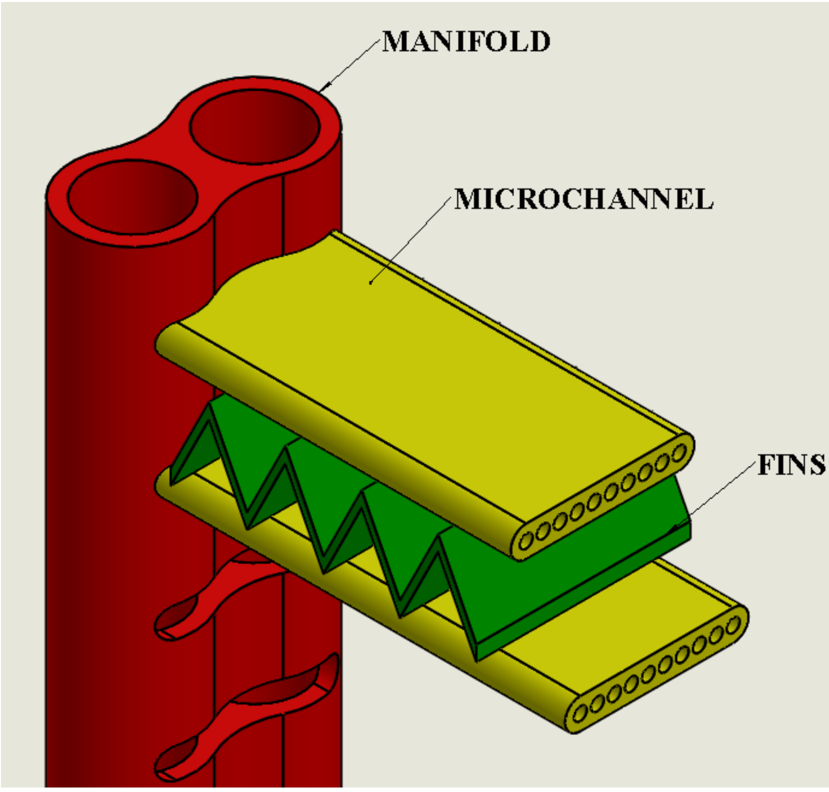

Fig.1 Microchannel Heat Exchanger

II. LITERATURE REVIEW

1.1 Yousef Alihosseini et al [1], review multiple papers having different geometrical patterns of MCHEs, which includes wavy patterns, patterns with corrugated shapes, zigzag patterns with nooks.

First in case of wavy pattern, the parameters studied were, wavelength was taken constant for all pattern that is 2000µm and the 5 different values of amplitude which are, 125µm, 250µm, 375µm, 437.5µm, 500µm. And the results were observed that when the amplitude was increased from 125µm to 437.5µm the thermal performance of also increased but when amplitude was increased further to 500µm, thermal performance decreased.

Next 3 patterns of corrugated shaped MCHEs were observed. The shapes were trapezoidal, triangular and sinusoidal. And the results were that the MCHEs with corrugated shaped performed better than straight MCHEs. And the trapezoidal shape had best performance followed by triangular and sinusoidal shape respectively. The reason for this was given that in case of trapezoidal shape, the swirl generation was much higher than other shapes. This swirl generation increases the heat transfer because of better fluid mixing and hence the thermal performance increases.

Next in case of zigzag pattern 6 different patterns of different nooks were observed. The patterns were with flat nooks, triangular nooks in positive direction, triangular nooks in negative direction, rectangular nooks in positive direction, rectangular nooks in negative direction, circular nooks in positive direction, circular nooks in negative direction (Fig.2). And the results were given that the number and intensity of vortices in the negative oriented nooks were higher than positive oriented nooks. Which means that the negative nook zigzag pattern had higher thermal performance than positive nooks. Also highest heat transfer coefficient and pressure drop was seen in negative triangular and negative circular nooks.

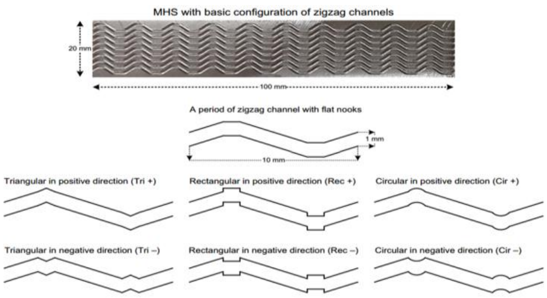

Fig.2 Zigzag patterns and nooks used [1]

1.2 Ergin Bayraka et al [2] performed experiment using cavities and ribs and their combinations on the side walls of microchannel. The different type of MCHE microchannel used are shown in Fig.3, this microchannel are named, a) Microchannel with No Cavities and Ribs (MC-NCR), b) Microchannel with Asymmetric Cavities (MC-AC), c) Microchannel with Asymmetric Ribs (MC-AR), d) Microchannel with Symmetric Cavities and Ribs (MC-SCR), e) Microchannel with Asymmetric Cavities and Ribs (MC-ACR).

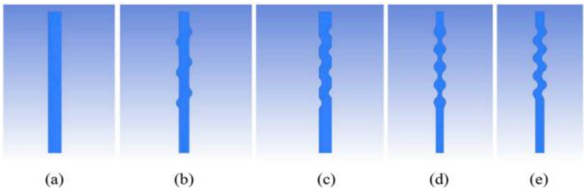

Fig.3 Multiple combination of cavities and ribs used [2]

The results were observed that by using cavities in MCHE the heat transfer performance was increased. It ensures low pressure drop and high thermal performance compared to straight channels. A rib has ability to interrupt and redevelop boundary layer and ensure forming of vortices, which cause increase of flow mixing in a channel by which thermal performance enhances. Using a combination of rib and cavity, the pressure of jetting and throttling can increase the flow mixing because of intensive vortices.

The thermal performance of MC-SCR was highest followed by MC-AC, MC-AR and MC-ACR. The thermal performance of MC-AR was same as the straight channels (MC-NCR) and the thermal performance of MC-ACR was even lower than straight channels (MC-NCR) (Fig.4).

This means that using ribs and cavities enhances the thermal performance until and unless we use asymmetrical cavities and ribs (MC-ACR) type microchannel which reduces the thermal performance or the microchannel with asymmetrical ribs (MC-AR) which does not affect the performance compared with straight channel (MC-NCR).

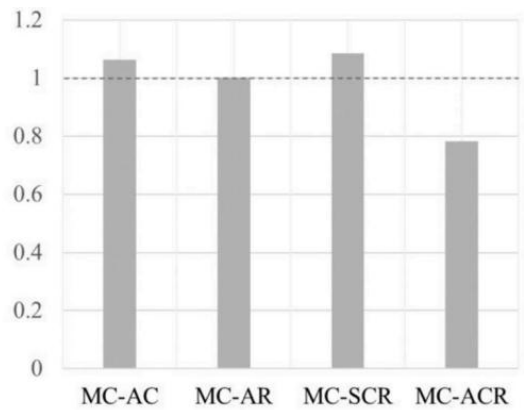

Fig.4 Thermal performance of different type of ribs and cavities compared with no ribs and cavities [2]

1.3 Lei Chai et al [3] performed experiment on MCHEs having fan shaped ribs on their side walls. In which they used 2 orientation of ribs placement which were aligned fan ribs (MC-AFR) and offset fan ribs (MC-OFR) (Fig.5).

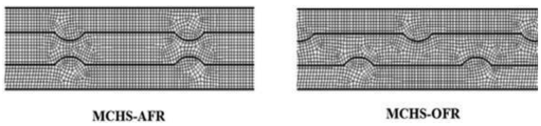

Fig.5 Orientation of ribs used [3]

And the results were observed that the fan-shaped ribs in MCHE can effectively prevent the increase of wall temperature along the flow direction. This helps maintain a higher Nusselt number and improves the heat transfer rate. Increasing the rib height and decreasing the spacing can significantly improve both local and average heat transfer coefficients. The width of the ribs has a less pronounced impact on the heat transfer compared to the height and spacing. For microchannel heat sinks with lower rib height and larger spacing, an aligned arrangement of the fan-shaped ribs provides a higher heat transfer coefficient compared to the offset arrangement.

Influence of width of ribs was observed by taking values of width 0.1mm, 0.2mm,0.3mm and 0.4mm and keeping spacing between ribs as 0.4mm for all 4 widths. And the results were seen that by increasing w/s ratio from 0.25 to 1, the wall temperature increased by 9.5 K to 10.6 K for aligned ribs and 9.9 K to 11.5 K for offset ribs respectively. The Nu in the flow direction in aligned ribs due to expansion and contraction, showed significant fluctuations. But in offset ribs Nu decreased smoothly for higher w/s ratio.

Next the influence of height of ribs was observed by taking values of height as 0.005mm, 0.015mm and 0.025mm and the width was same for all three as 0.1mm. And the results were seen that when H/W ratio increases from 0.05 to 0.25, the wall temperature decreases from 17.4K to 9.5K for MC-AFR and from 17.6K to 9.9K for MC-OFR. Which means that wall temperature decreased by increasing H/W ratio. Nu in flow direction increased as H/W ratio increased due to enhanced boundary layer disruption.

Next the influence of spacing of ribs was observed by taking values of spacing as 0.25mm, 0.5mm, 1mm and 2mm, and keeping the value of width as 0.1mm. And the results were seen that when S/W ratio increases from 2.5 to 20, the wall temperature increases from 9.3K to 15.1K for MC-AFR and from 9.8K to 16.2K for MC-OFR. Wall temperature decreased by decreasing S/W ratio due to more frequent boundary layer disruption. Also it was seen that Nu in flow direction decreased continuously for S/W 20 and 10, but for S/W 5, Nu drops slightly at inlet, then stabilizes at a higher level. And for S/W 2.5, Nu remains consistently high throughout the channel.

And lastly the influence of alignment or orientation of ribs were observed that for aligned ribs (MC-AFR), Heat transfer was higher but the Nu fluctuations were seen. And for offset ribs (MC-OFR), Heat transfer was low but the Nu profile was smooth.

1.4 Hongtao Wang et al [4] performed experiment on 3 type of shapes of cross section of microchannel which were trapezoidal, triangular and rectangular. The microchannel used were made up of oxygen free copper and the working fluid was deionized water.

The results were observed that lowest thermal resistance and highest thermal efficiency was in rectangular followed by trapezoidal and triangular respectively. pressure drop was seen highest in rectangular followed by trapezoidal and triangular respectively and lastly the temperature difference between wall and fluid was 26K (which was most uniform) in rectangular, 30K in trapezoidal (better than triangular) and 70K for triangular which was highest among them.

The conclusion found was that Rectangular shape offers the best overall performance in terms of thermal resistance, heat transfer efficiency, and temperature distribution, despite the higher pressure drop. Trapezoidal shape performed better than triangular in terms of thermal resistance but at the expense of higher pressure drop. Triangular shapes are more suitable for applications where low pressure drop is prioritized, but they exhibit the worst thermal performance

1.5 Binghuan Huang et al, [5] compared different types of cavities with no cavity microchannel in MCHE. The samples used in this paper are shown in Fig.6 in which section (a) is straight (no cavities), section (b) is short expansion and long contraction (triangular cavities), section (c) is short expansion and long contraction (fan-shaped cavities), section (d) is Long expansion and short contraction (triangular cavities) and lastly section (e) is Long expansion and short contraction (fan-shaped cavities).

In this paper, the heat transfer in section (a) was taken as baseline for comparison. The pressure drop of section (a) is lowest. In section (b), moderate heat transfer enhancement was seen at lower values of Reynolds number. The heat transfer in section (c) was better than section (b), and for section (d), strong heat transfer enhancement was seen at higher Reynolds number and the section (e) had same heat transfer enhancement as section (d).

The pressure drop was slightly higher than section (a) for section (b) followed by section (c), section (d), section (e) respectively. And the optimal value of Reynolds number for section (b) and section (c) was observed lower than 80 and for section (d) and section (e) it was higher than 80.

From the given work we concluded that test Sections 2 and 3 showed better overall performance for low Reynolds numbers due to their shorter expansion cross-section geometry. Test Sections 4 and 5 showed better heat transfer enhancement at higher Reynolds numbers because of the longer expansion cross-section, which ensures smoother flow reattachment and sustained mixing. Fan Shaped Cavities generally outperform triangular cavities due to better flow redirection and reduced stagnant zones.

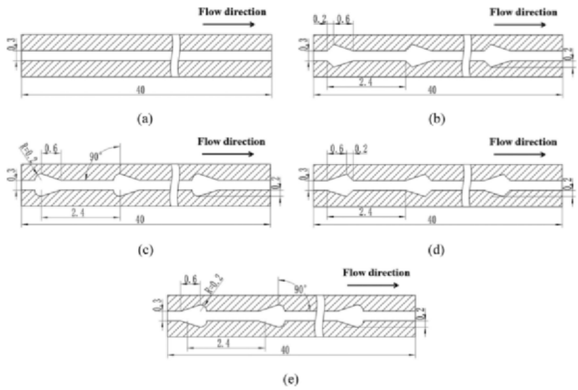

Fig.6 Type of cavities used [5]

1.6 M.P. Vasilev et al [6] performed experiment on different geometrical circular pin fin MCHEs, in which the variable parameters are height spacing and width of circular pin fin (Fig.7).

The influence of height of pin (hp) was observed for constant vale of ratio of spacing to diameter (sp/dp) = 6. And 4 values of height were taken which were 0.1mm, 0.25mm, 0.4mm, 0.5mm. And the results were observed that the thermal resistance for hp = 0.1mm was highest, for 0.25 it reduced by 32% followed by hp = 0.4mm by 47% and for hp = 0.5mm by 55%. The pressure drop for hp = 0.1mm was lowest which was 13% followed by hp = 0.25 36%, for hp = 0.4mm 43%, and for hp = 0.5mm 53% which was highest.

Next influence of spacing was observed for hp = 0.5mm as constant parameter. when the ratio of spacing to diameter, sp/dp was 3, the thermal resistance was 1.25 K/Watt and thermal performance was highest and after increasing it to 24, the thermal resistance was seen 1.96 K/Watt and the thermal performance was highest.

It was seen that higher pins improve thermal performance significantly but increase pressure drop. The densest pin arrangement (sp/dp=3) enhances heat transfer but at the cost of higher pressure drop. For maximum performance: hp=0.5, sp/dp=3 is the optimal values and for balanced performance: hp=0.25, sp/dp=6 is the optimal values.

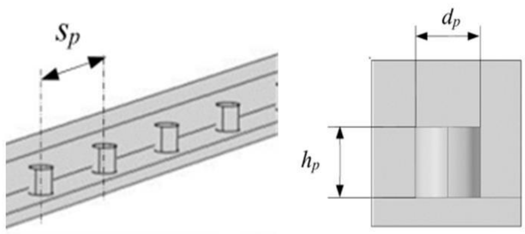

Fig.7 Variable parameters of circular pin fin [6]

1.7 Zhenfei Feng et al [7] performed experiment on interrupted MCHEs with circular pin fins. The experiment was done by finding influence of pin fin's height, diameter and spacing. The Fig.8 shows the MCHE design that was used.

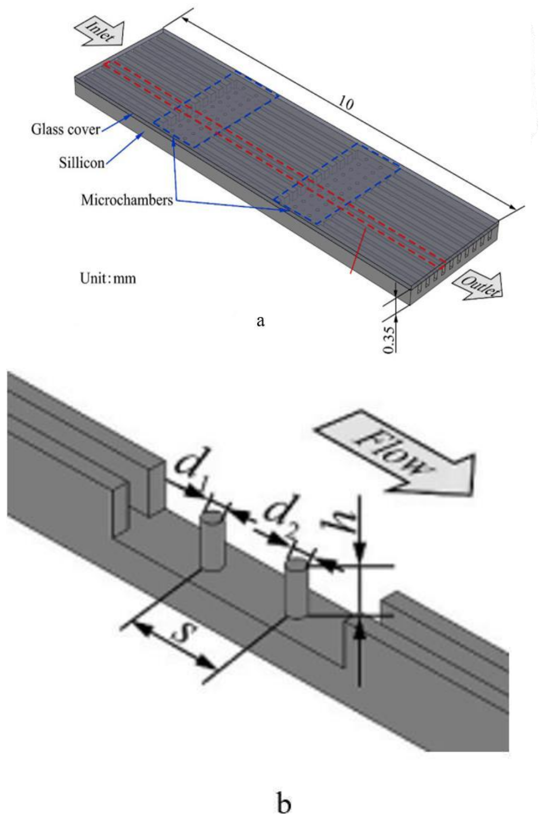

Fig.8 Schematic diagrams of (a) an interrupted microchannel heat sink and (b) a single microchannel [7]

When the spacing was 0.25mm, there was higher local temperature near entrance, but lower temperature in the micro-chamber's centre. For spacing 0.55mm, best uniformity of wall temperature throughout the micro-chamber was observed and for spacing 0.85mm, local temperature increased in the centre but decreased near the entrance. And the pressure drop was lowest for spacing 0.25mm followed by 0.55 and 0.85 respectively.

In case of diameter, when both the diameters were 0.08mm, higher local wall temperature and low pressure drop was observed because smaller diameters result in lower pressure drop but worse heat transfer performance. For 0.1mm moderate improvement in wall temperature uniformity and moderate pressure drop was observed because moderate diameters show a balance between heat transfer and pressure drop. For 0.12mm lower local wall temperature and better heat transfer and noticeable pressure drop due to flow blockage was observed because larger diameters enhance heat transfer but also cause higher pressure drop. And lastly for 0.14mm, maximum reduction in wall temperature and maximum pressure drop was observed because maximum diameter provides the best thermal performance but at the cost of higher pressure drop.

Lastly, in case of height of pin fin, when the height was taken 0.04mm, higher local temperature and less heat transfer surface area and low pressure drop was seen, when height was 0.16mm, optimal wall temperature distribution and moderate pressure drop was seen and for height was 0.2mm, higher temperature in the chamber due to less effective flow near the fin's top and slightly higher pressure drop was seen.

So we can say that, larger diameters improve heat transfer and wall temperature uniformity due to stronger vortex generation but result in higher pressure drops. Increasing height improves vortex intensity and heat transfer area but also increases flow resistance.

1.8 Prabhakar Bhandari and Yogesh K. Prajapati, [8] performed experiment on the open channel pin fin MCHE and compared it with closed channel MCHE by taking different values of height of pin fin. The Fig.9 shows the MCHE diagram that was used

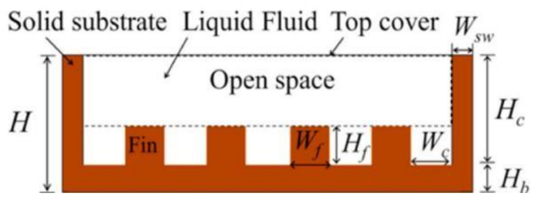

Fig.9 Open spaced MCHE with square pin fin [8]

The results were observed that for open channel, heat transfer was improved by 5–10% compared to a closed channel configuration and optimal coolant flow patterns with improved mixing and reduced obstruction was observed. And for closed channel (hf = 2mm), lower heat transfer performance due to restricted coolant flow and larger pressure drops and it was observed that closed channel was less effective, even with larger convective surface area.

Next the influence of square pin fin was that it promotes vortex formation and mixing behind fins which enhanced heat transfer. And it was observed that vortex effects vary with fin height and Reynolds number, influencing heat dissipation potential. And in case of no pin fin, reduced heat transfer performance due to the absence of vortex enhanced mixing was seen and it was also concluded that plane surfaces underperform compared to pin fin configurations.

1.9 Qifeng Zhu et al [9] performed experiment to find out effect of groove shape on side walls of MCHE. Different types of groove shapes used are shown in Fig.9.

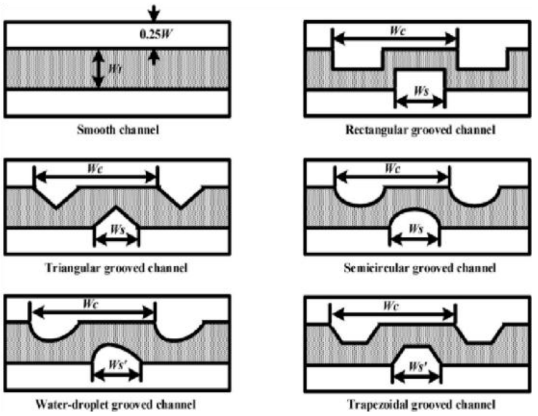

Fig.10 Groove shapes used [9]

The MCHE with no groove had stable and continuous thermal boundary layer and the lowest heat transfer efficiency and the pressure drop was higher than most grooved shapes. In triangular grooved shape, highest heat transfer efficiency and largest Nu number was observed and also high pressure drop was seen when Reynolds number was higher than 430. For rectangular grooved shape lowest heat transfer efficiency among all grooved shapes and smallest Nu number was seen, minimum pressure drop when Reynolds number higher than 480. For semi-circular grooved shape, Heat transfer efficiency was similar to trapezoidal groove and also some to water droplet shape groove for Reynolds number less than 300 and pressure drop slightly better than trapezoidal for Reynolds number more than 350. And lastly, for droplet shape, minimal pressure drop for Reynolds number less than 480.

1.10 Minqiang Pan et al [10], performed experiment on 3 arrangements of fan shaped cavities which are shown in Fig.10. DFSB means dense forward spaced backward, it has cavities with less spacing at entrance of MCHE and more spaced cavities at the exit, EFB means equally in forward and backward, it has equal spacing throughout the MCHE and SFDB means spaced forward and dense backward, it has cavities with less spacing at the exit of MCHE and more spaced cavities at the entrance.

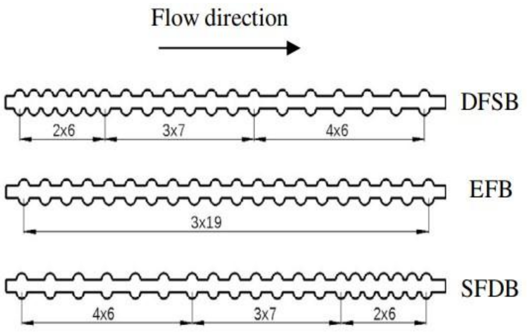

Fig.11 arrangements of cavities [10]

Heat transfer performance was best at high flow rate (>40 ml/min) for SFDB, for EFB it was similar to DBSF at low flow rates. The effectiveness of SFDB was highest at flow rate > 30 ml/min and for EFB it has minor differences at low flow rates and the DFSB had lowest effectiveness. The heat transfer impact was enhanced due to spurt, throttling and boundary layer redevelopment for SFDB and for EFB it was same as SFDB and for DFSB enhancement was there but it was slightly less than SFDB.

III. RESULT TABLES

3.1 Table1: Results found on the basis of Pattern of MCHE :-

Pattern	Thermal Performance
Wavy	When the amplitude of wave keeping the wavelength constant increases, the thermal performance also increases, but upto a certain limit and after that it decreases [1]
Corrugated Shapes	Best thermal performance in Trapezoidal shape, followed by triangular and sinusoidal respectively [1]
Zig-Zag (with nooks)	- The negative oriented nooks had better thermal performance than positive oriented nooks [1] - Highest thermal performance was seen in negative triangular and negative circular nooks [1]

3.2 Table:2 Results found on the basis of cavities and ribs :-

Parameters	Thermal Performance
Alignment	Symmetrical alignment of cavities and ribs have greater thermal performance than straight (with no ribs and cavities) and asymmetrical alignment [2]
Fan Shaped Rib's height and spacing	Increasing the Rib height and decreasing the spacing between them improves thermal performance [3]

3.3 Table:3 Results on the basis of parameters of Pin Fin :-

parameters	Effect
Height	Increasing the height increases the thermal performance but only for small values, after a certain limit the thermal performance decreases. [7, 8] The pressure drop increases when height of pin fin increases [6]
spacing	Increasing the spacing, decreases the thermal performance. [6]
Diameter	Increasing the diameter of pin fin, the thermal performance increases [7]

IV. PIN FIN PRAMETERS

4.1 Pin fin height:

In one paper the result of increasing the height was that it decreased the thermal performance [6], but in another 2 papers, increasing the height upto certain limit increased the thermal performance but decreased after that. [7, 8]

This means that the effect of height of pin fin on the thermal performance depends up on certain other parameters and those parameters should be considered before considering the height.

One of those parameters is the shape of that pin fin. Like in the circular pin fin, the increasing height decreased the thermal performance [6]. But for square shape pin fin used in an open channel MCHE, the height increased the thermal performance when increased upto a certain limit but then decreased. [8]

Also for the placement of pin fin is also a considerable parameter. When the circular pin fins were through all the MCHE, the thermal performance was decreased when height of pin fin increased [6]. But in case of interrupted MCHE which has 2 in fin in the middle of MCHE and the other part of MCHE is straight without pin fin, the thermal performance increased when height increased upto a certain limit [7].

But in case of pressure drop, it was same for all two cases of circular pin fin. When height of the pin fin increased, the pressure drop was also increased [6, 7]. This was because the area in which the working fluid was flowing become less when height of pin fin increases, which lead to pressure drop in the microchannel.

The observations of the height of pin fin clearly highlights that flow behavior is equally important as surface area for heat transfer. Because the height increment decreases the flow and the optimal value of height which have an optimal flow of fluid is different for all cases and should be considered before manufacturing a MCHE with pin fins

4.2 Pin Fin spacing:

When Pin Fin spacing is increased, the thermal performance decreases in case of circular pin fin through all the microchannel. The pressure drop decreased when the pacing increased [6].

But in case of interrupted MCHE with circular pin fin, when the spacing was lowest, higher local temperature near entrance, but lower temperature in the micro chamber's centre was observed. When the spacing was moderate, best uniformity of wall temperature throughout the micro chamber was observed. And when the spacing was highest, local temperature increased in the centre but decreased near the entrance was observed. The pressure drop was increased when the spacing was increased. [7]

As we can see that the pressure drop depends upon the basic type of MCHE. So it should be considered which type of MCHE is best for the specific application before manufacturing.

V. CONCLUSIONS

- The literature review highlights that optimizing the geometry of MCHEs— whether through channel shape, cavities, ribs, or fins—plays a crucial role in enhancing heat transfer efficiency. The best design depends on the application requirements, balancing thermal performance and pressure drop. Rectangular and corrugated patterns, structured cavities, and optimized fin geometries provide the highest efficiency for most applications.

• Increasing the amplitude increases the thermal performance but it has a limit. This limit varies according to other parameters.

• The vortices generated in negative nooks in zigzag pattern were much higher than positive nooks which increased the thermal performance. The negative triangular and negative circular nooks had best performance.

• The aligned cavities and ribs are more efficient than offset cavities and ribs.

• In case of fan shape ribs, the increasing of height and decreasing the spacing improved thermal performance.

• The height of pin fin depends upon the basic structure and shape of pin fin and many other parameters. But it can be concluded that after a certain limit, the increasing of height decreases the thermal performance for most of the cases no matter what type of MCHE or shape of the pin is used.

• Same can be said for the spacing of pin fin but for the pressure drop. The effect of spacing on pressure drop is uncertain. But in case of thermal performance, it decreases when spacing is increased.

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