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Cooling Performance of a Single-Phase Truncated Cone Shaped Fins Array in a Microchannel Heat Sink: A Numerical Analysis

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Abstract

The presence of fins in a microchannel tends to enhance the heat sink's heat transfer performance. Heat transfer is increased by disruption of flow by fins in the channel creating swirls, whereas pressure drop across the channel increases with fin density and fin size, requiring more powerful pumps to create flow across the channel. Truncated Conical Fins arrays with varying fin density are created and compared to cylindrical pin fins at various Reynolds numbers. For this, various performance parameters such as T_{max}, T_{min}, T_{ave} of the chip's top surface, and Uniformity of Chip's Top Surface (UCTS) are measured, as well as the pressure drop across the fin array. At higher Reynolds numbers (Re), Cylindrical Pin Fins outperform Truncated Conical Fins in thermal performance in but pressure drop across fins is more in cylindrical fins. At lower Reynold's Numbers, sparsely dispersed truncated conical fins performed the best thermally while pressure drop remained comparable. UCTS was similar for all arrays at greater Re, but UCTS did rise for all arrays as Re decreased, with the least increment for sparsely distributed truncated conical fins.

Keywords

Heat Sink, Micro-Pin Fin, Truncated Conical Fins

1. Introduction

Computer computing performance has surged in recent decades, and computers have grown increasingly prevalent in many facets of modern life. The semiconductor industry has successfully doubled transistor density every two years by following Moore's law [1]. One of the implications of improved electronic chip performance is an increase in heat generation. The failure factor of electronic equipment increases drastically as device temperature rises [2]. The power density of the devices has increased due to their smaller size and improved performance, necessitating the use of appropriate cooling.

Heat sinks were initially passive cooling solutions that used natural convection via plates and fins to distribute the produced heat. Passive cooling has the advantages of energy efficiency and reduced financial expenses, making it an efficient system design solution for electronic device thermal control. Air-cooling technology has reached its limit [3] and is no longer adequate for today's electronic devices with high heat dissipation demands in a slim-form-factor design, necessitating the current trend of cooling via liquid circulation. Water is employed as a coolant to remove heat from the heat sink due to its high specific heat capacity and low cost.

Tuckerman and Pease's pioneering discovery paved the door for investigations of micro-channel-based liquid cooling to handle high-performance electronics, especially silicon chips in integrated circuits [4]. Another effective approach for increasing microchannel heat transfer is the use of micro pin-fins.The Pin-fins increase heat removal by increasing surface area and breaking the continuous fluid flow. In the literature, a wide range of pin-fins with varying shapes, sizes, and combinations have been utilized to improve thermal and hydraulic performance [5].

The heat transfer capacity of microchannel heat sinks with five distinct pin-fin geometries was studied computationally and experimentally. Triangle, square, pentagon, hexagon, and circle geometries were investigated as pin fin cross-sections to study the impact of pin fin cross-sections [6]. Six small micro pin fin shapes – circle, square, triangle, ellipse, diamond, and hexagon – are employed in a staggered array and connected to the bottom heated surface of a rectangular mini channel and examined to study the effect of fin width and spacing on thermal and hydraulic performance [7]. A three-dimensional square channel with pin fins is numerically analyzed to determine the effect of fin shape and height on microchannel performance [8]. A three-dimensional analysis is done to numerically investigate the heat transfer and fluid flow characteristics of a combined microchannel with a cone-shaped cross-section of micro pin fins (MCPF) for low inlet Reynolds number [9].

Many research has been conducted to investigate the thermal and hydrodynamic behaviour of MPFHS, as described above. The research by Yang et al. [6]'s was chosen for model verification because it provides both numerical and experimental findings for the parameters that portray the performance of the heatsink, namely, the temperature of the chip's top surface and pressure drop. These analyses ignore the existence of fins with a larger convective area than cylindrical fins. There have been very few studies about variable area cross-sectional fins. Convective area is directly proportional to the amount of heat transfer through convection, and increasing convective area improves fin thermal efficiency while increased open space in variable cross-sectional area fins generates less pressure drop. There is no literature on the effect of fin geometry and density on the thermal and hydraulic performance of fin arrays. The thermal and hydrodynamic performance of truncated conical fins in an array of 14, 15, and 16 staggered rows at varying Reynolds numbers are investigated in this study.

2. Materials and Methods

2.1 Materials

Because Yang et al. [6]'s work is being used as a reference for model verification and performance comparison, it is critical to keep all other parameters constant except those of interest while examining the impact of fin density and fin shape. So, for the sake of comparison, the materials used, the fluid flow characteristics, and the geometry of the sink (except the shape of the fins) are all kept unchanged. Silicon is used for the chip, aluminium nitride for the top plate, and copper for the baseplate and fin, with water serving as the cooling fluid.

2.2 Methods

2.2.1 Model Verification and Grid Independence test

For model verification, geometry is created in CATIA and numerical simulations are conducted in ANSYS FLUENT 19.2. The microchannel heat sink was constructed in the manner shown in Figure 2. 218 micro pin fins are staggered in the heat sinks. Eight of these rows have 15 micro pin fins, whereas the other seven contain 14 micro pin fins. The centre distance between two adjacent pin fins is 0.5 mm, pin fin height is 0.5 mm, and the cross-section area of a single pin fin is 0.0625 mm^2. The flow path's inlet and outlet diameters are 1mm. When the maximum flow rate of 100 ml/min is provided to the heat sink, the coolant flow velocity is 2.122m/s, and the corresponding Reynolds number (Re) is 2122. Water was selected as the coolant because it is incompressible and has homogeneous and constant thermal physical properties, and the flow was steady and laminar. The exterior surfaces' convective heat transfer coefficient is considered to be 10 W/m^2K. When the results are compared, they show that they are consistent with the numerical and experimental results presented in the literature.

Table 1: Dimensions of Different Parts of Heat Sink in mm

Parts	Length	Breadth	Thickness
Chip	6	6	0.2
Top Plate	10	10	0.5
Fin Base	10	10	0.5

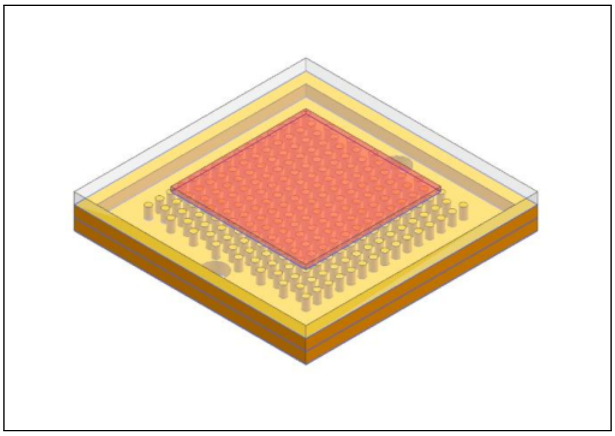

Figure 1: Heat Sink used for Comparison

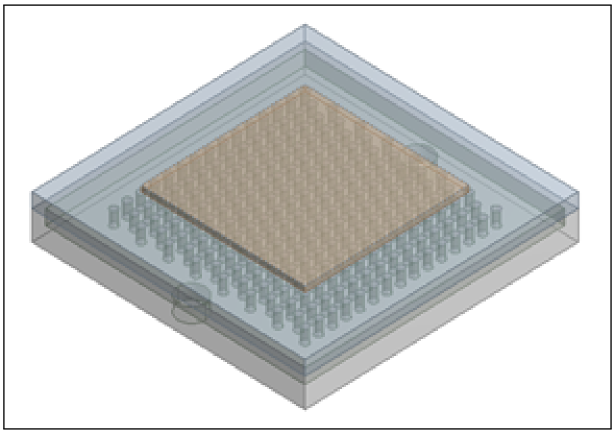

Figure 2: Heat Sink used in the present study

Assembled geometrical model of different parts is shown above.

Table 2: Comparison of Performance Parameters of Current Study with Literature

Parameters	Current Study's Findings	Results in Literature (Numerical)	Results in Literature (Experimental)
Pressure Drop (Pa)	14395.00	14783.18	–
T_{max} (K)	325.968	326.347	323.55
T_{min} (K)	311.625	310.742	310.25
T_{ave} (K)	321.167	321.102	320.65
UCTS (percent)	4.46	4.87	4.14

The size of the meshes used in numerical simulations has a significant impact on the results. Different meshes generate various results, but as the meshes get finer, the variation in results decreases and becomes inconsequential. The grid independence test is used to demonstrate that the variability in results produced by the meshes employed is within an acceptable margin of error. Mesh 3, Mesh 2, and Mesh 1 are constructed, with mesh sizes of 0.0002mm, 0.0004mm, and 0.0006mm, respectively, and results are achieved. The result difference between meshes 2 and 3 is less than 0.5 percent. Mesh 2 is chosen since its simulation duration is much less than Mesh 3.

2.2.2 Truncated conical fin geometry and its array

The fin's geometry is set to Truncated Conical Geometry. For the sake of comparison, the cone angle is set to 20^0 and the fin height remains constant. Because height is an important factor in heat dissipation, and varying height may increase heat transfer and pressure drop more, causing the effect of geometry change to be lost, height is kept constant. The figure below shows the geometry of the fin with its dimensions. Three different staggered arrays of 248, 218 and 189 truncated conical fins (16, 15 and 14 rows of staggered fins) are created and their performance is evaluated under various Reynold's number ranging from 100 to 2122 keeping all the other conditions same as the cylindrical pin fin.

3. Results and Discussion

3.1 Performance Comparison of Truncated Conical and Cylindrical Fin

An array of 15 rows of truncated conical fins and another of 15 rows of cylindrical pin fins were prepared to compare the performance parameters of truncated conical fins and cylindrical fins. By means of a straightforward relationship, the rate of heat transfer must increase as the area of the fin increases, but the results show that the maximum temperature of the chip increases. The maximum temperature of the chip at Reynold's Number 2122 is lower for cylindrical pin fin array than that of a truncated conical fin heat sink with the same number of fins implying that the rate of heat transfer in truncated conical fins decreases.The lower separation in fluid flow in the microchannel generated by truncated conical fins, which is smaller than that caused by cylindrical pin fins, accounts for the reduced heat transfer.

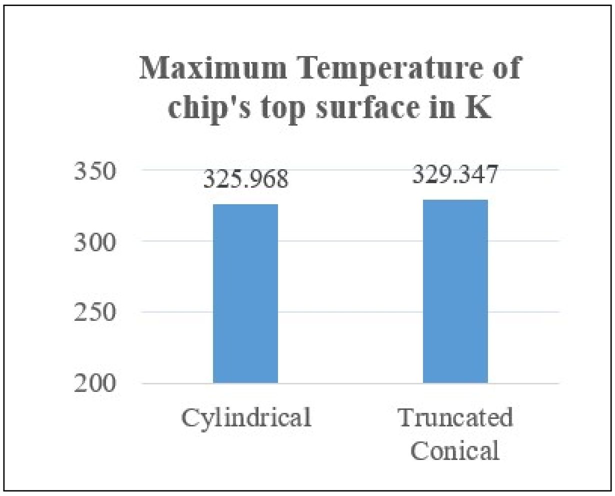

Figure 3: Comparison of Maximum Temperature of chip's top surface while using cylindrical and truncated conical fins in heat sink at Re 2122

The existence of more open spaces lets the fluid move through the heat sink with limited exposure to the heated surface, resulting in unfavourable heat transfer conditions and a higher substrate temperature [10]. Because of the greater open space in truncated conical fins, more coolant passes the heat sink without actively participating in the heat transfer process, shown by the lower pressure drop over the heat sink at higher Reynold's numbers. At Reynold's number 2122, pressure drop is larger in cylindrical fin array due to larger and more frequent wakes formation in cylindrical fins than in truncated conical fin array.

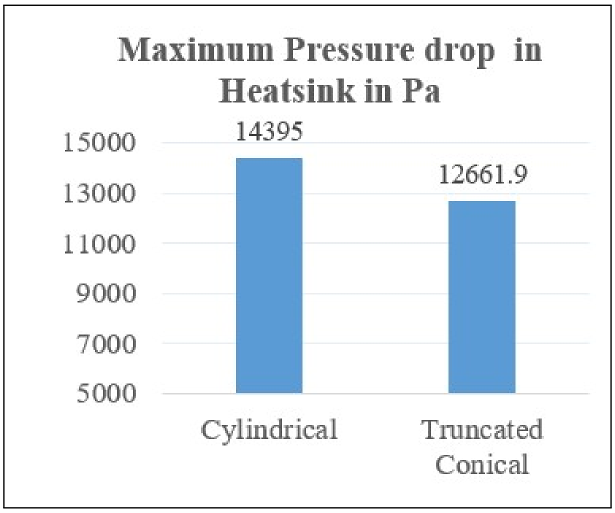

Figure 4: Comparison of Pressure drop across the heat sink while using cylindrical and truncated conical fins in heat sink at Re 2122

3.2 Performance Comparison of Truncated Conical and Cylindrical Fin Array

Decreasing of the space between fins promotes heat transfer because the reduction of the fins space causes the number of fins to increases which lead to the enlargement of the heat transfer area and the disturbance of the flow and the breakup of boundary layer become more frequent as a result of fins increase. The performance parameters for heat sinks of various arrays of fins are recorded at various Reynolds Numbers, and the findings are as follows.

3.2.1 Effect on T_{max}

Because the maximum temperature of the chip at Reynold's Number 2122 is least, cylindrical fin arrays display improved thermal performance, implying that the rate of heat transfer decreases in truncated conical fins due to more fluid running through fins without participating in heat transfer. Also, at higher Reynold's Numbers, the denser array of truncated conical fins performed better than sparse fins because when the fins spacing is reduced, the number of fins increases, resulting in an increase in heat transfer area. Furthermore, as the number of fins increases, the flow disruption and boundary layer breakdown become more frequent, resulting in improved heat transfer [9].

At Reynold's Number 200, T_{max} for all arrays becomes nearly equal, and all truncated conical fins outperform the cylindrical pin fin array, with the sparsely packed array being the best of all at Reynold's Number 100 at the inlet. This demonstrates that at Reynold's number, less restriction to the flow promotes more heat transfer, enabling more fluid to pass through without overheating or maintaining a bigger temperature differential towards the exit. The cylindrical fin array performs the worst due to its increased resistance to flow.

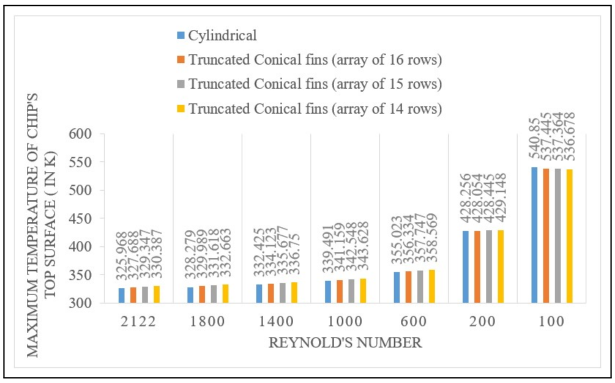

Figure 5: Maximum Temperature of Chip's Top Surface (in K) variation with Reynold's Number

3.2.2 Effect on Pressure Drop

Because of the disturbance in the flow pattern, pressure drop and differential in pressure drop are greater as Reynold's Number increased. This also indicates higher heat transfer at higher Reynolds Numbers since higher disruption of flow equals more fluid participating in heat transfer. It is also clear from the results that at higher Reynold's Numbers, convective area plays little role compared to flow disruption because truncated conical fins have a significantly higher surface area than conical fins, but heat transfer through truncated conical fins is smaller than heat transfer through cylindrical fins.

Pressure drop and pressure drop difference are very low at lower Reynolds numbers due to very low velocity at the intake of the heat sink, leading in lower velocity in the bank of fins and less disturbed and smooth flow, resulting in a reduced possibility for wakes formation. While maintaining the same number of fins, the pressure drop over the cylindrical pin fin is greater. Even when the number of fins is increased by 30, the pressure loss across the array of truncated conical fins is smaller.

A denser array of truncated conical fins has a larger pressure drop than a sparse array due to enhanced flow disturbance across the range of Reynold's Number. Pin fins with a high fin density have a greater friction factor. This is because wakes occur behind pin fins as a result of flow separation.

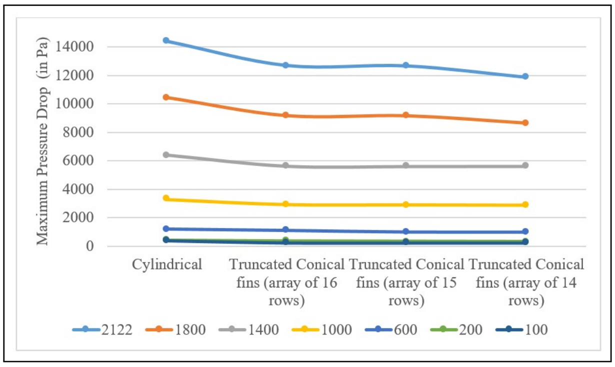

Figure 6: Maximum Pressure drop in heatsink (in Pa) variation with Reynold's Number

3.2.3 Effect on UCTS

The table of UCTS shows that when Reynold's Number decreases, UCTS(percent) increases, implying that there is more variation in temperature at the top surface, which is undesired. This is due to the fact that the temperature in the chip top surface is lower towards the entrance and higher towards the exit. From the figure below, it can be seen that with decrease in Reynold's Number UCTS(percent) increases which implies that there is a larger variation in temperature at the top surface which is undesirable. This can be because the temperature towards the inlet in the chip top surface is lower and the temperature towards the outlet is higher. Fluid gets more time to heat up at lower Reynolds Number because of their slower flow velocity, and as a result, they get hotter. The decrease in heat dissipation capabilities of the liquid as it travels towards the exit is caused by a decrease in the temperature difference between the liquid and the fin. Hence, the chip surface will be warmer near the outlet.

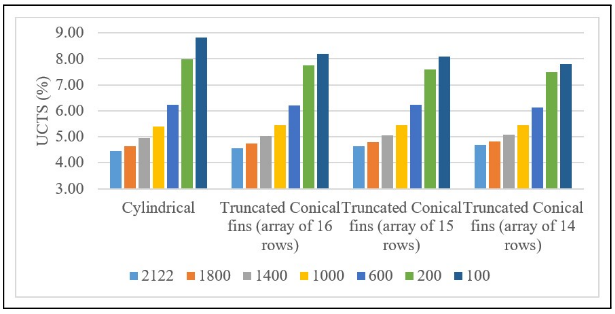

Figure 7: Uniformity at Chip's Top Surface (UCTS) (in percent) variation with Reynold's Number

Observations also demonstrate that when Reynold's Number is low, denser arrays exhibit larger UCTS due to more flow blockage. Furthermore, the sparsely dispersed fins had lower UCTS, indicating temperature homogeneity at the chip's top surface. Because of the bigger gaps and faster flow of the fluid, more liquid may pass through the bank of truncated conical fins, giving less time for the liquid to heat up and maintaining a greater temperature difference. Though the UCTS is similar at higher Reynold's Numbers, the truncated conical fin was able to maintain better temperature uniformity at the chip's top surface than cylindrical fins at lower Reynold's Numbers.

4. Conclusions

The effect of Truncated Conical Fin in Microchannel on maximum temperature, UCTS and pressure drop across the fin array is investigated in this study using the commercial CFD software ANSYS FLUENT 19.2. At various fin density and Reynolds numbers, the performance of Truncated Conical Fins is compared to that of Cylindrical Pin Fins.

The use of Truncated Conical Fins reduces heat transfer at higher Reynolds numbers, as evidenced by an increase in the maximum temperature of the chip's top surface. The maximum temperature of the chip's top surface rises by 1.03 percent, while the pressure drop across the fin array is reduced by 12.04 percent, lowering the pump's driving cost. When the arrays of truncated conical and cylindrical pin fins were examined, it was discovered that at higher Reynolds numbers, the cylindrical pin fin has better thermal performance as evidenced by the lowest T_{max}, although the temperature drop is greater. The pressure drop was lowest with sparsely dispersed truncated conical fins, while the T_{max} was largest among the arrays exhibiting poor thermal performance. UCTS were identical, and pressure drop was greatest for cylindrical fins, whereas pressure drop for truncated conical fins decreased with fin density.

Using sparsely distributed truncated conical fins resulted in the lowest UCTS of 7.81 percent. At Reynold's Number 100, dense truncated conical fins had 8.19 percent and cylindrical fins had the greatest UCTS of 8.81 percent. Pressure drops were similar across the board for all arrays, with sparsely dispersed truncated conical fins providing the best thermal performance.

5. Recommendations

While the classical fin analysis method is a simple way to describe the heat transfer performance of a microchannel heat sink, its accuracy is severely limited by its simplifying assumptions. As a result, two-dimensional heat transfer and turbulent models at higher Reynolds numbers can be considered for greater accuracy, because the flow in the channel between the fins tend to become turbulent. Further studies using cooling fluid properties such as viscosity, thermal conductivity density, and so on temperature-dependent can also be performed.

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