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EXPERIMENTAL INVESTIGATION FOR FLOW AND HEAT TRANSFER OVER PIN FIN HEAT EXCHANGER

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ABSTRACT

In the present work fluid flow and heat transfer characteristics of a micro pin fin heat sink were investigated both experimentally. The heat sink was fabricated from Aluminium and fitted with a polycarbonate plastic cover plate. The heat sink consist of staggered and inline arrangement of square pin fin of size 0.5mm X 0.5mm X 0.5mm. Water was employed as the working fluid subjected to heat flux 10W/cm^2. The study was carried out for Reynolds number ranging 60 to 900. Later the performance of square pin fin heat sink was compared with parallel pin fin heat sink. Pressure drop, friction factor and maximum thermal resistance were employed to access the characteristic of heat sink. Significant amount of heat transfer enhancement was observed in staggered square pin fin heat sink compared to other heat sink with penalty in pressure drop.

KEYWORDS: Heat sink, pin fin.

I. INTRODUCTION

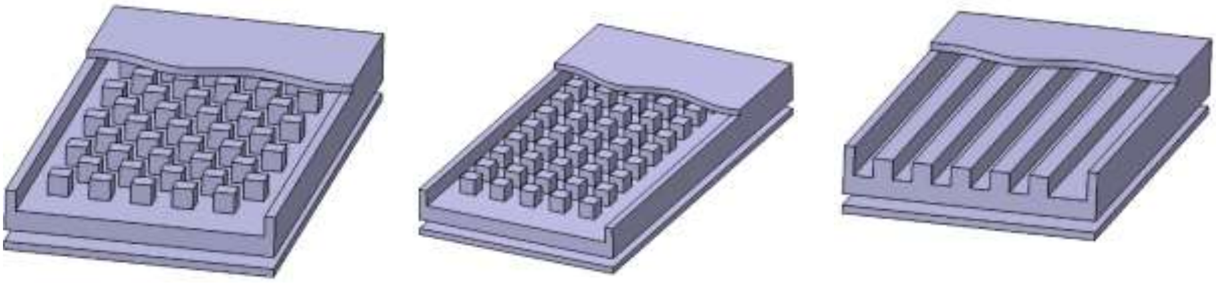
Micro-pin fin heat sinks is an innovative cooling technology for removing large amount of heat from a small area. Micro pin fin heat sink is usually made from materials with high thermal conductivity solid such as silicon or copper fabricated by either precision machining or micro-fabrication technology. These have characteristic dimensions ranging from 10 to 1000 µm, and act as flow passages for the cooling liquid. These have the advantages of very high surface area to volume ratio, large heat transfer coefficient, small mass and volume, and minimum coolant inventory. These advantages render the heat sinks suitable for cooling such devices as high-performance microprocessors, laser diode arrays, radars, and high-energy-laser mirrors. With the Recent advancements in machining techniques, highly complex three-dimensional geometries of micro dimensions can be directly fabricated into high-thermal-conductivity solid materials which can be used as the substrates for miniature heat sinks. This allows to explore structures which are highly effective in enhancement of heat transfer compared to plate fins. One such enhanced structure is pin fin arrays with characteristic dimension of tens to hundreds of micro meters. In the present study, the miniature heat sinks that incorporate staggered and aligned micro size short pin-fin arrays are referred to as micropin-fin heat sinks. Compared to their micro-channel heat sink counterparts, micropin-fin heat sinks have the potential to provide larger heat transfer area to volume ratios as well as higher heat transfer coefficients due to boundary layer disruption and mixing effects.

D.B. Tuckerman and R.F.W. Pease [1], were the first to introduce the concept of micro channel heat sink. Since then, several researcher have carried out theoretical and experimental work, thereby providing significant amount of information in the field of micro scale fluid flow and heat transfer process. Poh- seng lee [2] et.al conducted experiments and validated the experimental results with classical correlation for predicting heat transfer through rectangular micro channel for Reynolds ranging 300 to 3500 using deionized water. Weilin Qu [3] et.al experimentally studied hydrodynamic characteristic of water flowing through trapezoidal micro channel for hydraulic diameter ranging between 51µm to 161µm.Measured pressure drop and friction factor from the present work were slightly higher than computed values from conventional flow theory and linear variation was observed for pressure drop at low Reynolds number. Welin Qu [4] et.al experimentally investigated hydrodynamic characteristic of fluid inside trapezoidal micro channel and compared hydrodynamic characteristic for flow inside a trapezoidal channel with conventional theory , they observed conventional theory for friction and pressure gradient over predicts the experimental results . Hasan et.al [5] numerically studied flow and heat transfer behavior of micro pin fin heat sink using water . Sohail et al. [6] proposed pin fin array of various shapes to reduce maximum surface temperature. Later Abdoli et al. [7] numerically studied the effect of different pin fin shapes for electronic chip cooling and concluded pin fin with convex and hydrofoil shape perform better compared to circular cross section. Carlos et al. [8] proposed variable fin density heat sink of different shapes to maintain uniform temperature of integrated chips. Flat shaped pin fins were observed to be superior compared to other shapes. Liu et al. [9] experimentally showed pin fin shape has large effect on heat dissipation at larger Reynolds number. Yavo poles et al. [10] experimentally proved thermal resistance can be greatly reduced by using pin fin heat sink. Zhao et al. [11] experimentally showed elliptical pin fin has better stream line with low thermal resistance and triangular pin fin has larger flow resistance compared to other shapes. In the present work, experiments are carried out with staggered arrangement of square micro-pin-fin heat sink using liquid water. The experimental setup is configured for measuring pressure drop and heat sink temperature measurements. Friction factor, temperature drop and maximum thermal resistance are evaluated. The results provide new, fundamental insight into the thermal/fluid characteristics of liquid-cooled single-phase micro-pin-fin heat sinks.

II. Test Section Design

Heat Sink

The top surface of the heat sink was 6.0 mm wide and 11.5 mm long. 50 square pin fin heat sink of size 0.5mm X 0.5mm was machined in the top surface of heat sink by precision sparking technique. The pin fins were equidistantly placed both inline and staggered arrangement with spacing 0.5mm in both longitudinal and transverse direction. The height of the pin fin is 0.5mm. Ten pin fins were placed in longitudinal direction and five in transverse direction as shown in figure 1a and figure 1b. Parallel pin fin heat sink was also constructed with top area of 6mm wide and 11.5mm length. Five straight fins of thickness 0.5mm thick and 0.5mm height was fabricated on the top surface as shown in figure 1c.



a) Staggered *b) Inline* *c)Parallel*

Figure 1: Schematic arrangement of pin fin heat sink

Design

To characterize heat transfer and pressure drop, Maximum Thermal Resistance and friction factor was obtained for various reynolds number. Measured Pressure drop was represented in terms of non dimensional term.

Friction factor
$$f = \frac{\Delta P}{\frac{\rho \times \mathrm{u}^{2}_{\max}}{2}} \qquad (1)$$

Maximum Thermal Resistance
$$R_{th} = \frac{T_{s,\max} - T_{f,in}}{q} \qquad (2)$$

Reynolds number
$$\mathrm{Re} = \frac{\rho u d_h}{\mu} \qquad (3)$$

Pressure drop and temperature are measured using differential digital manometer and thermocouple respectively, heat flux is recorded using DC power supply and mass flow rate is measured using measuring jar and stop watch.

Based on the construction of pin fin heat sink discussed above the test section consist of aluminium heat sink with pin fin as shown in figure 2 .Below the top surface K-Type thermocouples were inserted to measure the surface temperature of the heat sink. A hole was drilled at the bottom surface of heat sink for accommodating the DC cartridge heater powered by DC power supply. The centre part of housing was cut for inserting pin fin heat sink. Rubber gasket was placed at the interface between housing and heat sink to overcome leakage.

The housing consist of six number of plenums along the length of the housing. A digital manometer used for measuring differential pressure drop across the flow was connected at two plenums close to heat sink. Two K-Type thermocouples were located in other two deep plenum for measuring inlet and outlet temperature of the working fluid. Two more plenum were used for inlet and outlet of the working fluid. A cover plate of acrylic sheet was joined to the housing using adhesive. A small slot of size equal to heat sink width was machined in to the cover plate. The slot in cover plate and top surface of heat sink containing the pin fin provides a flow passages for coolant used in the present work. A small groove was machined into the heat sink, where a rubber gasket was placed to produce better leak proof seal. The Extended portion of heat sink ensures the top surface of pin fin heat sink was in line with top surface of the housing. A silicon paste was applied around the heat sink which acts as thermal insulation to minimize the heat loss.

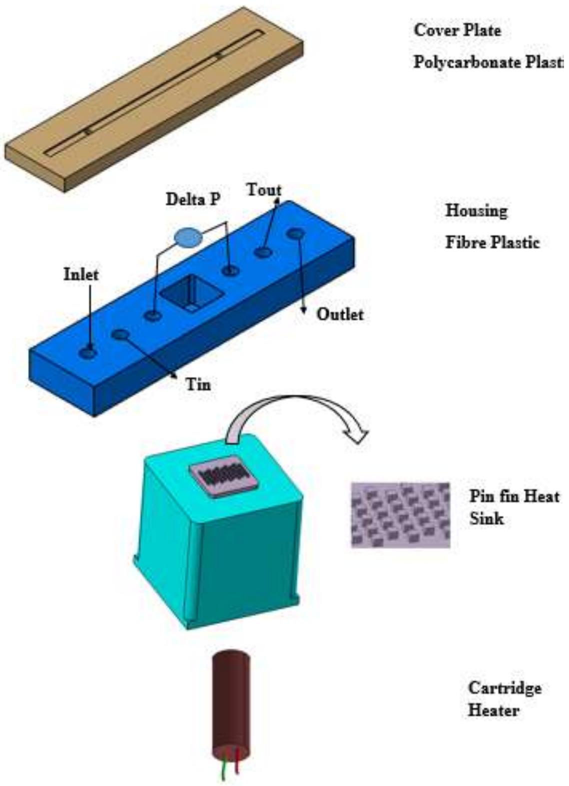


Figure 4: Test Module Construction

Flow Loop

To ensure reliable quality of data, experimental procedures were consistently and methodically executed. Figure 5 represents the flow loop constructed to supply water to the heat sink at a desired Pressure, Room temperature, and flow rate. At the beginning of each trial, atmospheric temperature were recorded using K Type Thermocouple. The water is pumped from a liquid reservoir using micro pump or fluid controller and circulated through the flow loop. Power is supplied to cartridge heater using DC supply. The water enters the heat sink test module, the electric power supplied to the heat sink was removed by the water. Measuring jar is used to determine flow rate. Once the heat sink reaches constant heat flux, power supply is turned off, measurements for surface temperature, fluid temperature and pressure drop across the heat sink are recorded. The experiment is conducted for different flow rate and different heat input.

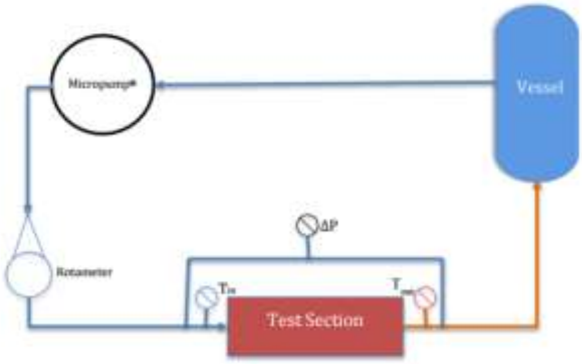


Figure 5: Flow Loop

Validation of experimental setup

To validate the experimental results obtained, tests were conducted over a plain surface. The temperature drop (T_{out} -T_{in}) obtained from the theoretical equations were compared with experimental values obtained from present work subjected to 10W/cm^2. The comparison between experimental data obtained from the present work and theoretical values are shown in figure 6. The Mean error in the temperature drop was calculated to be 15%.

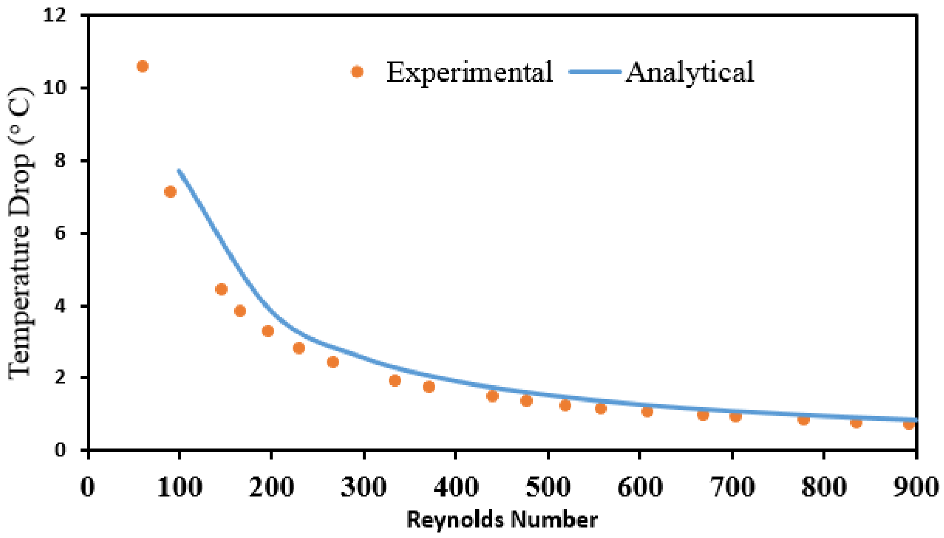


Figure 6: Comparion for temperature drop for plain micro channel heat sink subjected to 10W/cm^2

III. RESULTS AND DISCUSSION

Pressure Drop

Figure 7 clearly indicates at low reynolds number (For Reynolds number less than 200) the rise is pressure drop remain almost same for all shapes and arrangement of pin fin. Whereas pressure drop for parallel fin heat sink was on lower side compared to both the arrangement of micro square pin fin heat sink. This indicates resistance offered by parallel fins as well as, viscous and blocking effect are negligible compared to square pin fin. Once pressure drop is measured friction factor was calculated, friction factor was observed to be very minimum for straight pin fin.

Once pressure drop is obtained, the average friction factor across the staggered and inline pin fin heat sink can be evaluated and is validated with moores and joshi correlation [4]. The fluid properties are evaluated based on water inlet temperature. To validate the present experimental method the measured friction factor was compared with moores and joshi correlation. The comparison between measured values and correlation values are illustrated in figure 8, it is observed measured friction factor decreases with Reynolds number and slightly under predicts the correlated values with MAE around 8.2%.

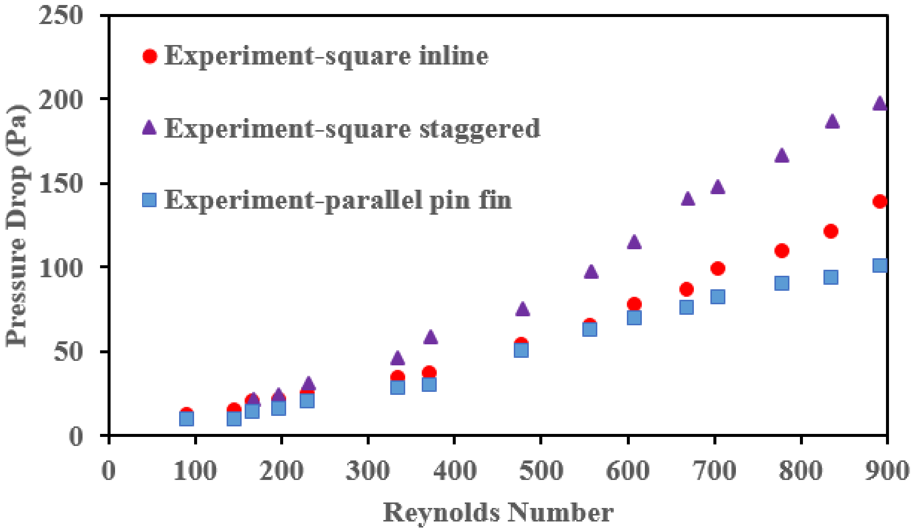


Figure 7: Variation of measured pressure drop with reynolds number for different arrangement of micro pin fin heat sink.

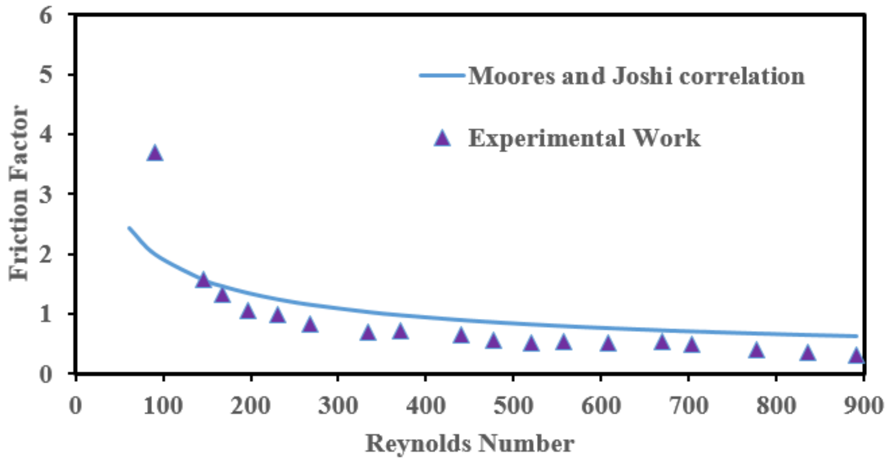


Figure 8: Comparison of measured friction factor with Moores and Joshi correlation for different Reynolds number

Friction Factor

Due to more fluid interaction in square pin fin heat sink with staggered arrangement, friction factor is slightly on the larger side compared to inline arrangement and parallel pin fin heat sink as shown in figure 9. The short et al [4]. correlation for friction factor over predicts the measured friction factor by a large margin. This may be due to the fact that the short et al correlation was developed using air as working fluid, while water was used in the present work. The mean absolute error for short et al correlation is around 41.56% with 14 data points.

Moores and Joshi correlation $f_{pin} = 19.04\left(\frac{H_{fin}}{d_{fin}}\right)^{-0.742} \mathrm{Re}^{-0.542}$

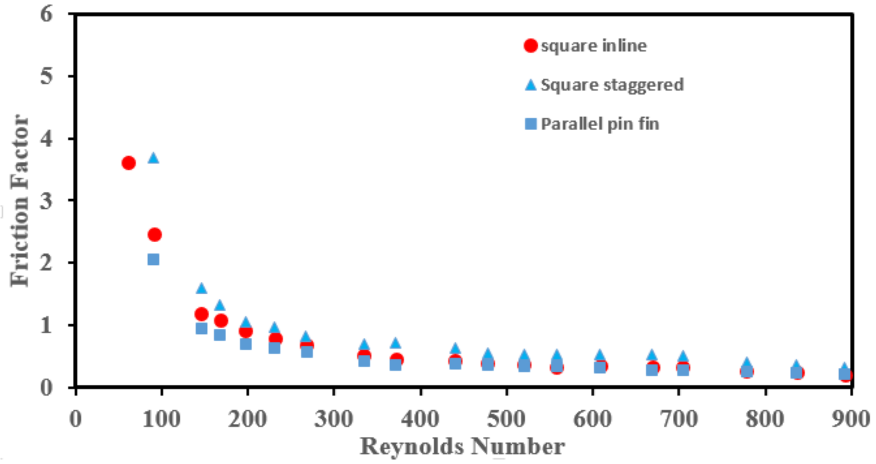


Figure 9: comparison of measured friction factor with reynolds number for different micro pin fin heat sink.

Maximum Thermal Resistance

Figure 10 represent variation of maximum thermal resistance against Reynolds numbers for 10W/cm^2. Maximum thermal resistance decreases with reynolds number for both inline and staggered arrangement of micro pin fin heat sink. However maximum thermal resistance is slightly on the lower side for staggered arrangement compared to inline arrangement indicating enhanced heat transfer due to more fluid interaction. In case of inline arrangement fluid travels in straight path with minimum pin fin interaction resulting in larger thermal resistance with minimum heat transfer. Maximum thermal resistance for staggered arrangement is 6.3% less than inline arrangement. As expected maximum thermal resistance decreases with increasing reynolds number for parallel pin fin heat sink also but it is on the higher side compared to square pin fin heat sink (both inline and staggered arrangement). Compared to all the three cases discussed above square pin fin with staggered arrangement shows higher pressure drop and outperforms other cases in terms of heat transfer enhancement.

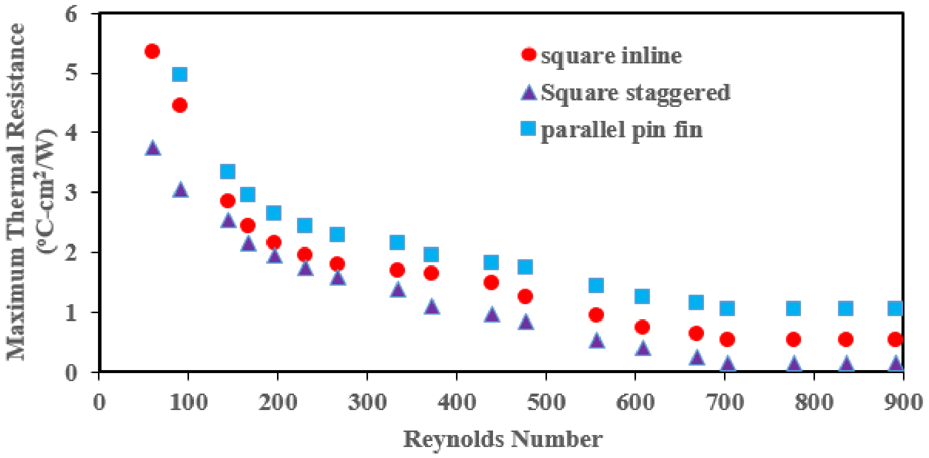


Figure 10: Variation of Maximum thermal resistance with Reynolds number for different arrangement of pin fin heat sink subjected to 10W/cm^2.

IV. CONCLUSION

The measured friction factor under predicts Moores and Joshi correlation with MAE of around 8.2%. Friction factor is maximum for staggered pin fin heat sink compared to other two cases

Measured temperature drop decreases with Reynolds number and are in good agreement with analytical

High heat transfer enhancement is obtained with staggered micro pin-fin arrays, which illustrates that staggered micro pin-fin heat sinks are very effective in meeting the needs of heat-flux electronic cooling applications.

Nomenclature

Symbols

A - Cross sectional area (m^2)

d - Diameter (m)

Re - Reynolds Number

p - Pressure

T-Temperature

V-Velocity component (m/s)

Greek Symbols

ρ - Density (Kg/m^3)

Δ – Delta

μ - Dynamic Viscosity (Kg/m-s)

Subscripts:

h – Hydraulic

in – Inlet

out – Outlet

avg – Average

Sur – Surface

f-fluid

max-maximum

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