American Journal of Engineering Research (AJER)
e-ISSN: 2320-0847 p-ISSN : 2320-0936
Volume-4, Issue-7, pp-73-82
www.ajer.org
Research Paper Open Access

Comparative Study for Improving the Thermal and Fluid Flow Performance of Micro Channel Fin Geometries Using Numerical Simulation

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ABSTRACT : *There is a continuous quest for improving the performance of micro channels for handling the increased dissipation of heat from electronics circuits. The Oblique fin micro channels are attractive as they perform better than plate fin & pin fin configurations. There are scopes for further improvements in oblique fin micro channels. Hence this work is about the investigation for the performance enhancement by modifying the oblique fin geometry. Seven variants of micro channel geometries have been explored using three dimensional numerical simulations. The variants are plate fin, in-line pin fin, staggered pin fin, oblique fin, oblique fin with two slit angles, oblique with nozzle type slit and improved oblique fin. The simulation results are validated using the published data. To ensure a common reference for comparison, hydraulic diameter, inlet flow conditions, heat loads and the boundary conditions are kept identical across all the geometries. The results of simulation are compared for the thermal & fluid flow performances. Heat transfer correlations have been developed using the simulation data. The proposed modification is found to enhance the performance significantly.*

Keywords - *Micro channels, heat sinks, Electronics cooling, Single phase cooling, Forced convection cooling, CFD simulation*

I. INTRODUCTION

The operational effectiveness of electronic circuits depends mainly on the thermal handling capability of their cooling system. Most often, it is required to achieve higher heat transfer coefficient in compact volume. Hence micro channel heat sinks are prospective options which can handle enhanced levels of heat flux due to its higher surface area to volume ratio. Micro channel research has been under active consideration since the work of Tuckerman and Pease [1]. Li and Peterson [2] have optimized the plate fin micro channel geometries for the constant pumping power criterion. They achieved 20% lower thermal resistance than Tuckerman & Pease. Lee and Garimella [3] studied the plate fin micro channels by varying the aspect ratios. They proposed a generalized correlation for predicting Nusselt number. There was uncertainty over the applicability of conventional heat transfer theory for micro channel system. Hence the liquid flow in the micro channels were investigated both experimentally & numerically [4]. They concluded that the conventional theory is applicable for predicting the flow behavior.

Lee P S et al. [5] proved that it is possible to increase the local heat transfer coefficient by creating a small recess at the cover lid near the hot spot region. They found that the small recess caused the breakage and re-initialization of boundary layer resulting in the increased heat transfer coefficient. This concept was pursued further by many researchers. As an extension of this Lee, Y. J. et al., [6] have experimentally studied the heat transfer from silicon chips using oblique fins. They have proposed to vary the oblique fin pitch for the mitigating local hot spots in silicon chips. Xu et al. [7-8] have carried out experimental and numerical studies to enhance heat transfer rate by using the concept of boundary layer redevelopment. They found that the interruption in the fins leads to boundary layer redevelopment thus increasing the heat transfer coefficient. These interruptions induced pressure recovery at the exit & pressure loss at the entrance. Qu [9] has reported that the pin fin heat sinks are thermally efficient than the conventional plate fin micro channels of the same hydraulic diameter but with a penalty of higher pressure drop. The performance of the Pin fin heat sink was reported to degrade at lower flow rates [10]. Liu et al. [11] have conducted experiments on square pin fins keeping the diagonal of the fin aligned to the flow direction. They have developed heat transfer correlations from the experimental data. However it is observed that the numerical simulations have been extensively used by many researchers to predict the performance of micro channel heat sinks. Rubio-Jimenez et al. [12] used numerical analysis to propose the concept of variable fin density for maintaining more uniform temperature of the IC chip junction. They reported to have achieved an overall temperature gradient lesser than 2°C/mm by varying the pitch. Fan et al. [13] have numerically simulated the performance of oblique fins on the cylindrical surfaces. The results of simulation were compared using a performance index. Lee Y J et al. [14-16] have studied the performance of oblique fin micro channels both experimentally & numerically. They were able to study the thermal & flow behavior inside the channel by carrying out detailed numerically simulations which are not otherwise possible by experimentation. Danish et al. [17] have carried out a comparative study using numerical simulation for optimizing the parameters of rectangular & oblique fin micro channel heat sinks. The Oblique fin micro channel is reported to enhance the thermal performance with a reasonable pressure drop when compared with pin fin & plate fin micro channels. This shows that there are scopes for the improvement of performance of the oblique fin micro channel geometry using the numerical simulation.

The present study consists of two parts. In the first part, the laminar flow through plate fin and oblique finned micro channel heat sinks are simulated. The results are validated using the published experimental data. In the second part, seven different micro channel fin geometries are investigated for performance enhancement using numerical simulation while imposing certain common criteria. Theoretical heat transfer correlations are developed using simulation data. The results are compared on the basis of performance index.

II. MICRO CHANNEL HEAT SINK DETAILS

The micro channel geometry consists of inlet, repetitive fluid passages & outlet. Seven micro channel fin geometries have been considered for simulation studies. To ensure a reasonable basis for comparison, some of the dimensional parameters such as the hydraulic diameter, inlet flow conditions, heat load and boundary conditions are held common across all the geometries. The details of the common parameters are shown in Table1. The specific dimensional details pertaining to six of seven geometries are presented in Table 2. The rectangular plate fin micro channel is considered as the seventh geometry. Other than the pin fins & staggered pin fins, three different modifications are proposed for the oblique fin micro channels. In the first type the angle of the secondary flow passage is modified to have two angles for the smooth injection fluid in the main channel. This modification is termed as the oblique fin with two angles. In the second type the secondary flow passage is modified like a convergent nozzle. This is termed as nozzle type micro channels. In the third type fluid entering the secondary flow passage is given an entry and exit angle for smoother diversion & injection of secondary flow with the main flow. This modification is termed as the improved oblique fin micro channels.

III. COMPUTATIONAL DOMAIN & BOUNDARY CONDITIONS

The micro channel heat sinks have periodically repeating fin and channel pairs. This periodic nature is exploited in order to reduce the computational load. Hence only one pair of a fin and a channel has been chosen as the computational domain. The typical computational domains for the plate fin and the oblique fin micro channels are indicated as the dashed line in Fig 1 and Fig 2. The governing equations relevant to the present computational domain are continuity equations, Navier-Stroke equations and the energy equations in their incompressible form. These equations are not reproduced here as they are well known. A commercially available computational fluid dynamics software ANSYS CFX v.14.5 [19] has been employed for the numerical simulation which has the capability to solve the above equations using finite volume techniques.

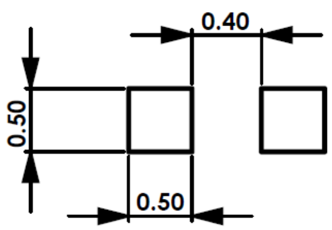
Table 1 Common parameters of the micro channels heat sinks

Feature	Details
Width of main channel in micrometers	500
Depth of channel in micrometers	1500
Width of fin in micrometers	500
Size of heat sink in mm X mm	25 X 12.5
Aspect ratio	3
Single fin length in mm	25
Heat sink material	Copper
Coolant fluid	Water
Heat flux in W/cm^2	65

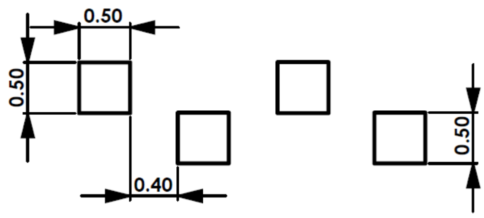
Table 2 Micro channel fin geometries with specific dimensional details

Plan view of the micro channels fin geometries. All dimensions are in mm

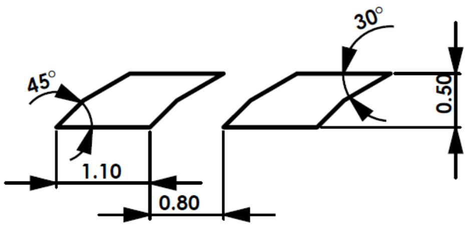
1.In Line Pin fin



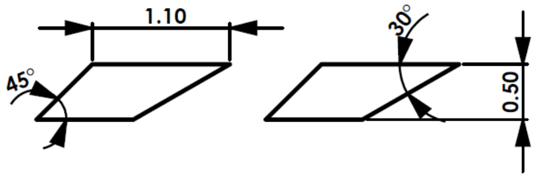
2.Staggered Pin fin



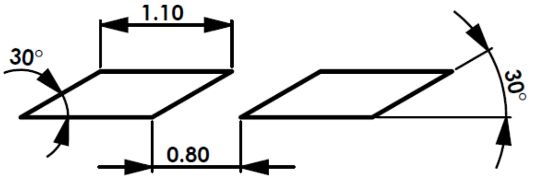
3.Oblique with Two Angle



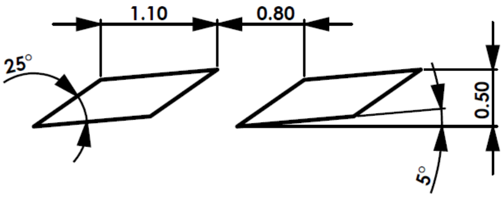
4.Nozzle type



5.Oblique fin



6.Improved Oblique fin



Fully developed velocity profile is assigned to the inlet. Periodic boundary condition is assigned to the sides. A uniform heat flux of 65 W/cm^2 is applied to the heat sink surface at the bottom. The top of the micro channel heat sink is considered to be bonded with adiabatic cover. Pressure boundary condition is assigned to the outlet, where the flow reaches atmospheric pressure. The approach velocity of the fluid is varied from 0.4 m/s to 1.2 m/s. The Reynolds number ranged from 391 to 1130. The temperature dependent materials properties of water [16] have been used for the simulation with the help of CEL expressions in the ANSYS CFX[19].

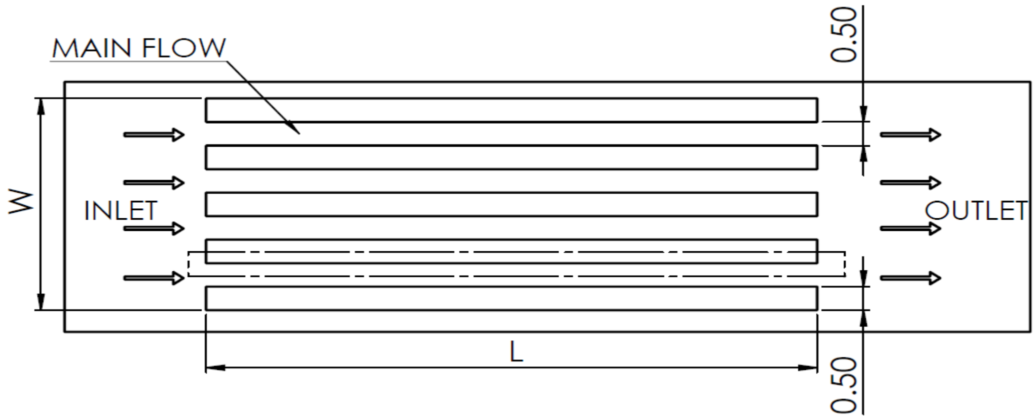


Fig. 1 Plan View of Plate fin Micro channels with dimensions in mm

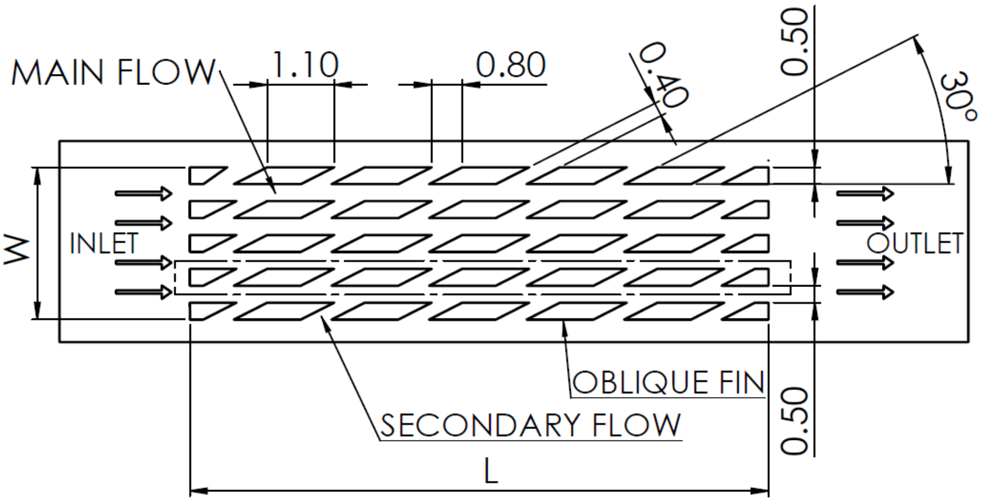


Fig. 2 Plan view of Oblique fin Micro Channels with dimensions in mm

IV. GRID INDEPENDENCY CHECKING

To ensure grid independent results the model has been meshed at four different grid levels consisting of 676982, 1599592, 23277930 and 4257452 elements. All solid to fluid interfaces have been inflated to a thickness of 100 micrometers with 8 layers. The Face spacing of 50 micrometers to 20 micrometers has been applied to fluid region for better resolution. High resolution scheme is selected as solver option. Double precision has been activated for improving the accuracy. The convergence criterion of 10^{-6} is set for residues. Nusselt numbers are found to be in close proximity of to each other except the mesh of 676982. The average Nusslets number varied by 1.3 % from the first to second mesh level and only by 0.8 % for the second to third meshes level. The fourth mesh level varied by 0.15% from the third level. Hence the mesh level of 2327790 has been used. In the similar manner grid dependency check was carried out for each type of simulation.

V. VALIDATION

The plate fin micro channel and the oblique fin micro channel have been selected for the validation purpose. The geometric details are chosen in the similar lines of the work carried out by Y.J.Lee et al [16] which is considered as the reference data for validation. The dimensional details are shown in Table 3. The computational fluid dynamic analysis was carried out using ANSYS CFX by varying the inlet velocity. The heat load of 65 W/cm^2 was applied. Figure 3 presents the variation of Nusselt number with Reynold number. It is observed that the Nusselt number calculated using ANSYS CFX matches closely with that of published experimental as well as Fluent data for both plate fin and oblique fin micro channels.. The simulated results of the present study matched closely with that of Fluent results[16] and the experimental data [16]. Hence the simulation procedure is validated and the same is adopted for the rest of the analysis.

Table 3 Dimensional details used for validation

Parameter	Plate fin	Oblique fin
Size of heat sink	25mm X25 mm	25mm X 25mm
Main channel width (micrometers)	547 micron	539
Fin width (micrometers)	458	465
Channel depth (micrometers)	1482 micron	1487
Oblique channel width (micrometers)	-	298
Oblique angle (degrees)	-	27
Oblique fin pitch (micrometers)	-	1995
Oblique fin length (micrometers)	-	1331
Hydraulic diameter (micrometers)	799	792
Heat sink material	Copper	Copper
Coolant fluid	Water	Water

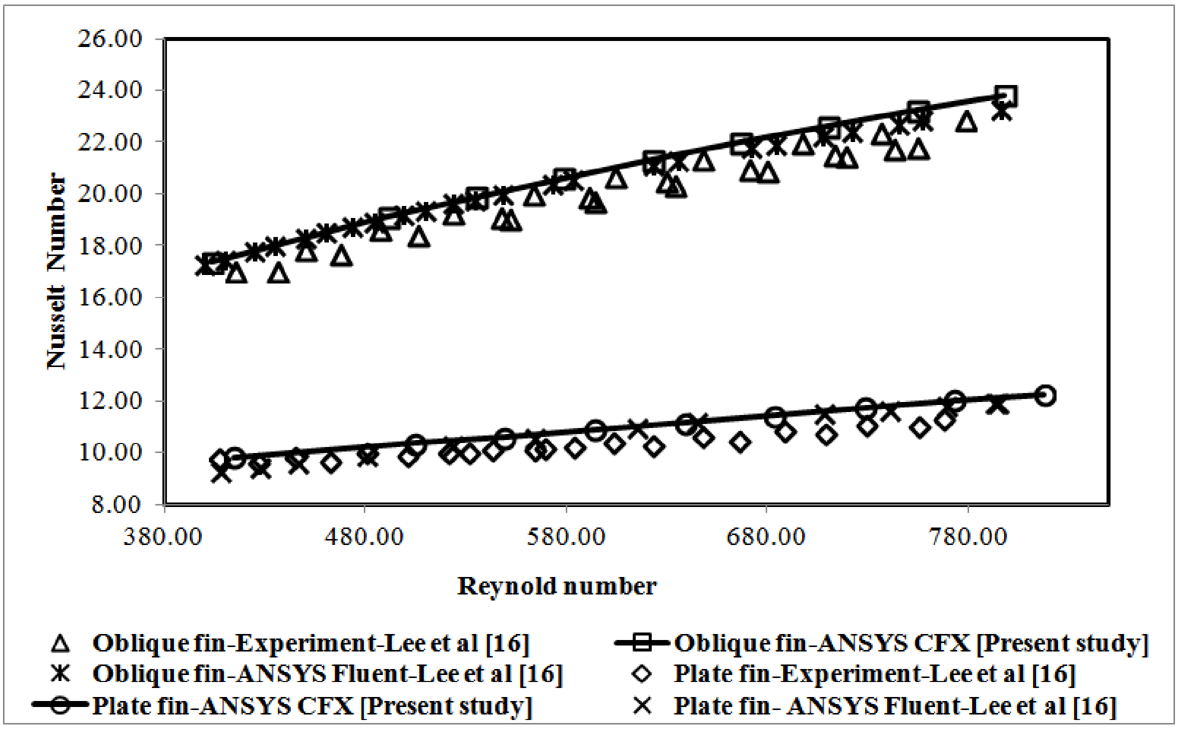


Fig. 3 Validation of Simulation

VI. RESULTS AND DISCUSSIONS

The effect of inlet flow velocity over the pressure drop is presented in two different plots for the sake clarity which are shown as Fig 4 & Fig 5. The effect of velocity on the pressure drop incurred by all the micro channel geometries under consideration excluding staggered pin fin configuration is presented as Fig 5. It is seen that the pressure drop increases with respect to the inlet flow velocities for all the micro channel geometries. The pressure drop of the plate fin micro channel is the least of all. The pressure drop of the nozzle type micro channel is the highest as the main channel flow is interrupted by accelerated fluid from the secondary channel. Whereas the pressure drop of the improved micro channel is the second lowest and is lower than the oblique micro channel due to the presence of entry exit angles in the secondary flow passage. The pressure drop of in line pin fin & Oblique with two angles is intermediate between oblique & improved oblique fin. The comparison of fluid flow performance of all the micro channel geometries with respect to staggered pin fin is presented in Fig 5. The pressure drop of staggered pin fin is found to be around 4 to 8 folds higher that of the other types.

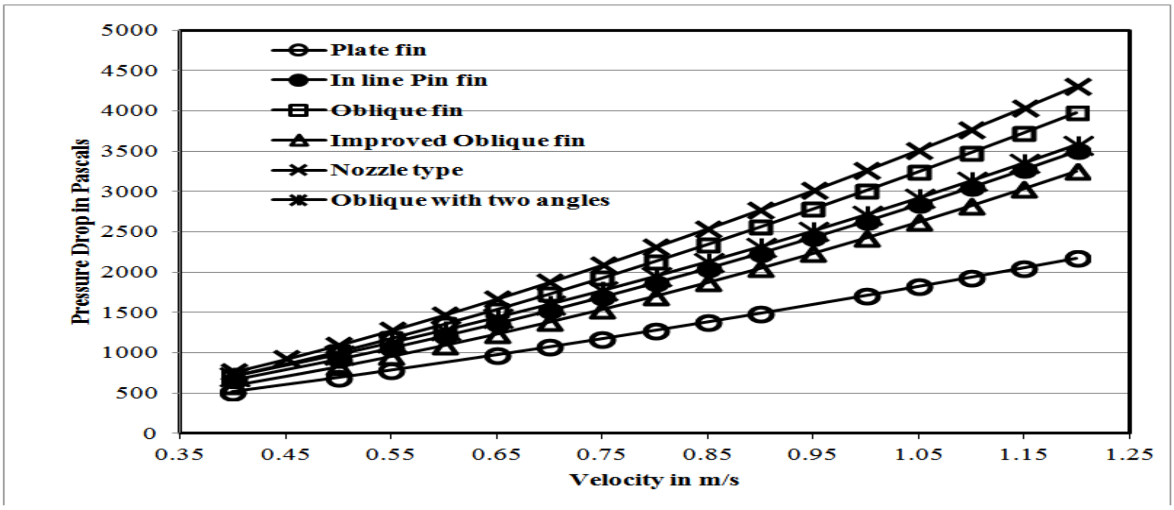


Fig. 4 Comparison of Pressure drop

The effect of inlet flow velocity over the heat transfer coefficient is presented in two graphs which are illustrated as Fig 6 & Fig 7 for the sake of clarity. Figure 7 depicts thermal performance of all the micro channels except staggered pin fin micro channel. The boundary layer breakage & redevelopment concept is used by all types of micro channels except the plate fin. Since the boundary layer grows steadily, the heat transfer coefficient of plate fin is the lowest for the same sets of boundary conditions. The nozzle type micro channel is found to have higher heat transfer coefficient for the entire range of inlet velocities. The performance of inline pin fin & improved oblique fin is found to be nearly equal. The performance of the oblique fin & oblique fin with two angles are found to be lesser than that of the improved oblique fin. Figure 8 compares the performance of staggered pin fin with that of all other geometries. It is observed that the staggered pin performs better.

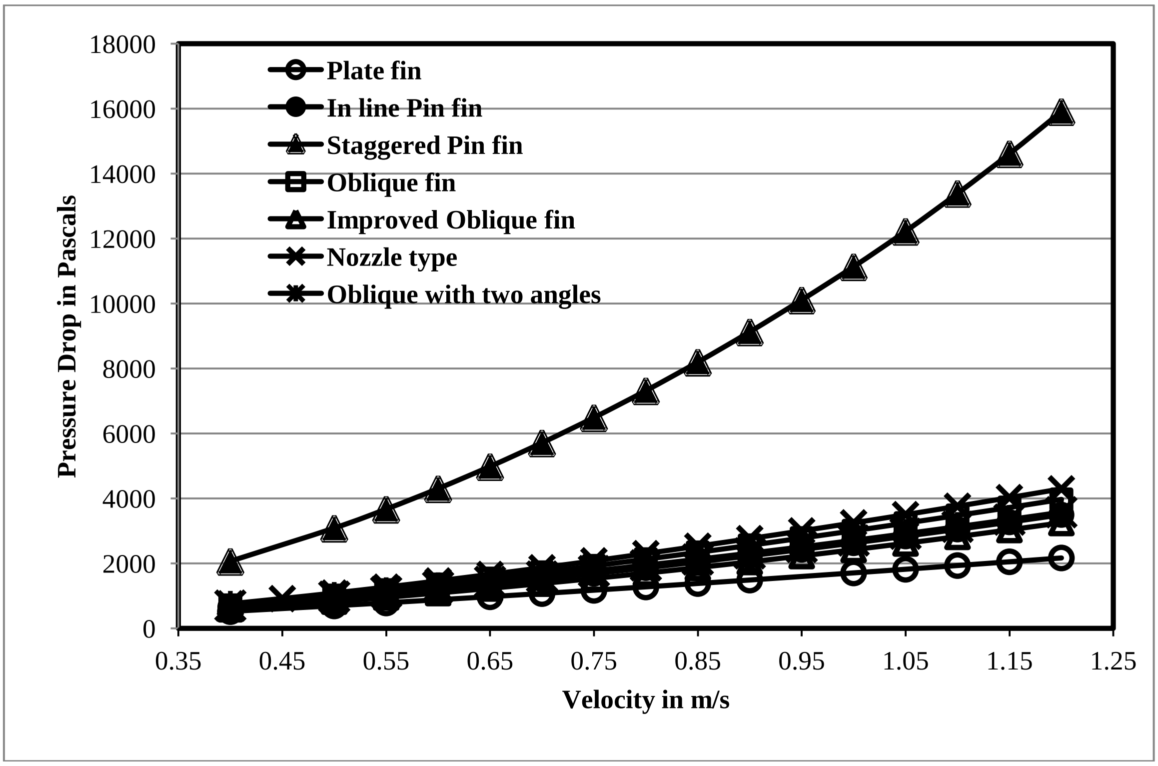


Fig. 5 Pressure drop Compared with Staggered Pin fin

It is important to verify the thermal performance considering the available the wetted surface of the micro channel fin geometries. The heat transfer coefficient is directly proportional to the available heat transfer area & velocity of flow. The comparison of the wetted surface area is presented in Fig 8. The plate fin geometry has the lowest wetted surface resulting in the lower thermal performance. The pin fin geometries and the oblique fin geometry found to have higher wetted surface area leading to higher thermal performance than the plate fin geometry.

4.1 Discussion on the Performance improved Oblique fin micro channel

The wetted surface area of the improved oblique fin is lesser than inline pin fin & oblique fin geometries. But the thermal performance of improved oblique fin is found to be closer to that of inline pin fin and oblique fin geometries. The wetted surface area of the improved oblique fin and nozzle type micro channel is lesser than oblique fins but the thermal performance is better than oblique fins due to the accelerated secondary flow.

The flow impinges the corner of the oblique fin encountering a shock which will results in early separation from the fin surface . The wetted surface will not be effectively utilized in the oblique channel. The performance improvement of improved oblique fin can be attributed to smoother branching of secondary flow. The flow gets modulated without encountering any shock. This delays the flow separation on the trailing end of the oblique fin leading to the effective utilization of the wetted surface.

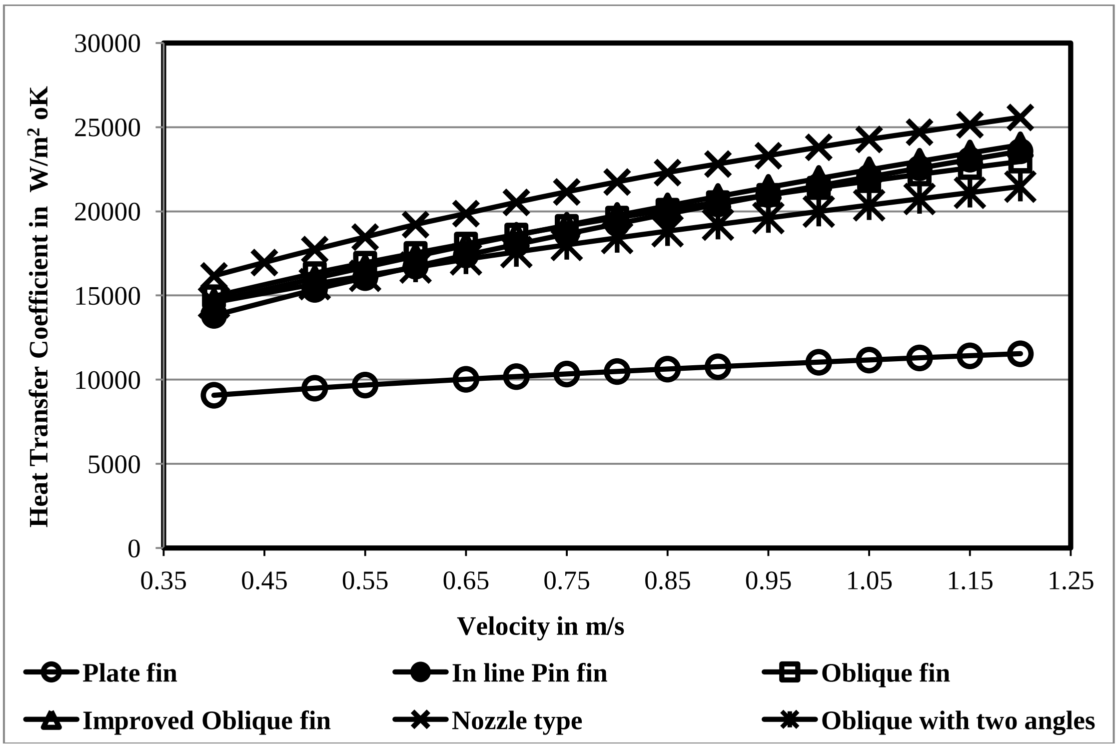


Fig. 6 Comparison of Heat Transfer Performance

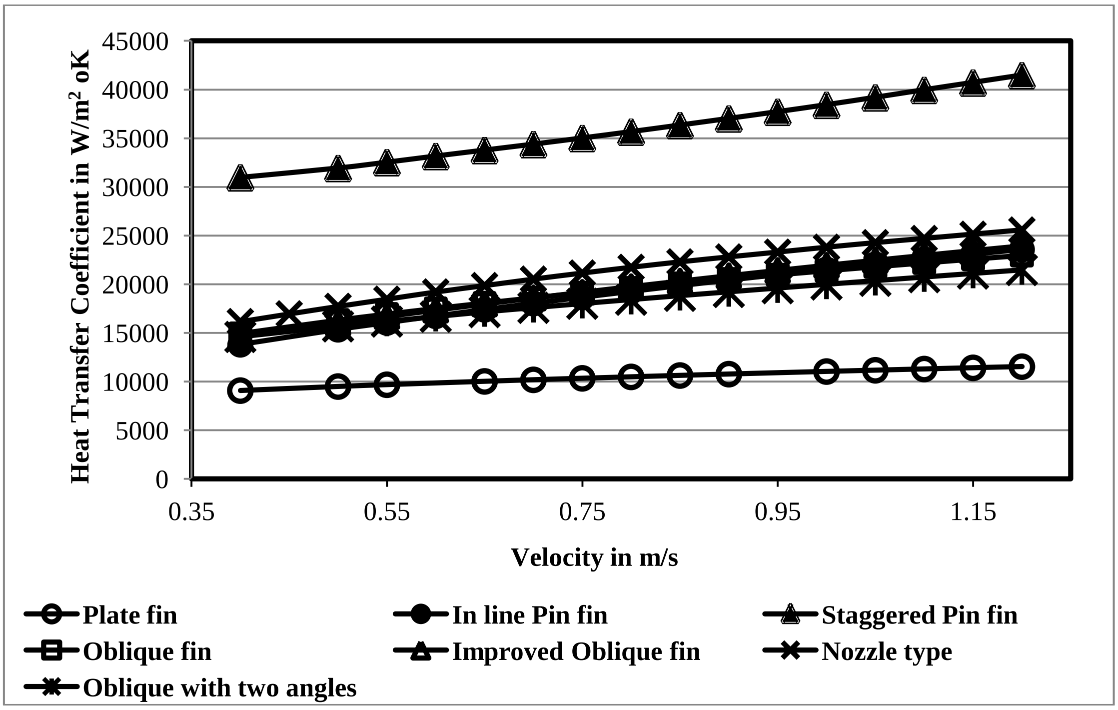


Fig. 7 Heat Transfer Performance Compared with Staggered fin

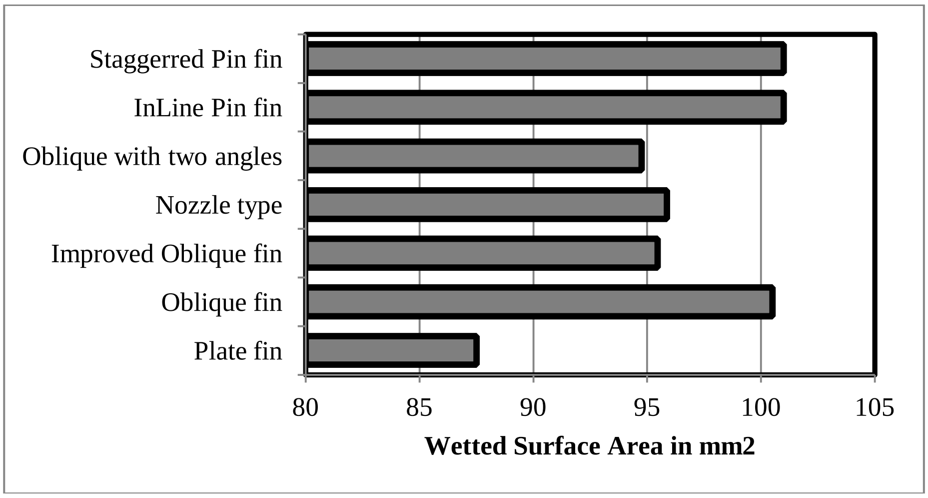


Fig. 8 Comparison of Wetted Surface area

4.2 Performance index

To get a meaningful insight, the above results are compared using a performance index. The ratio of heat transfer coefficient (h) per unit pressure drop (p) is considered as the performance index. The pressure drop is proportional to the pumping power as the mass flow at the inlet is held constant. The ratio of h/p is an indication of heat transfer coefficient per unit pumping power. Figure 9 below presents the h/p ratio for different inlet velocities. It is observed that the performance index of the staggered pin fin is the lowest of all. This implies that the staggered pin demands higher pumping energy to achieve higher heat transfer coefficient. The performance index of the improved oblique fin is the highest which implies that the higher thermal performance is achievable with lesser pumping power.

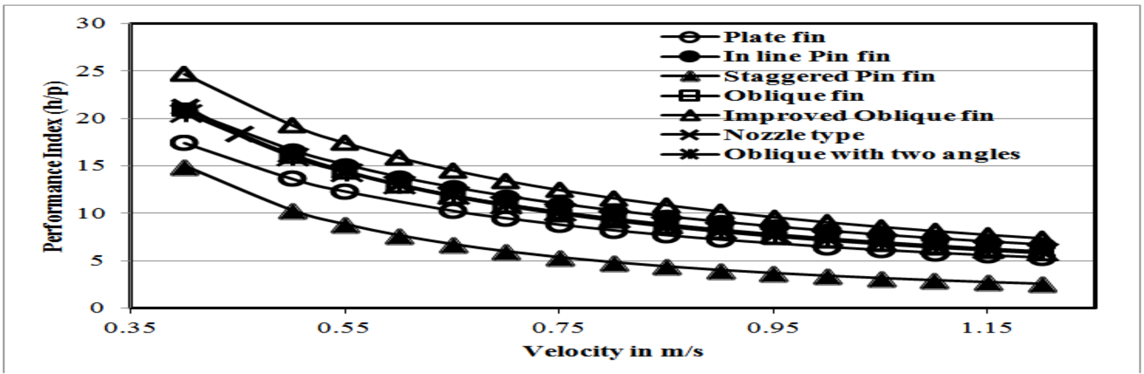


Fig. 9 Comparison of Performance Index

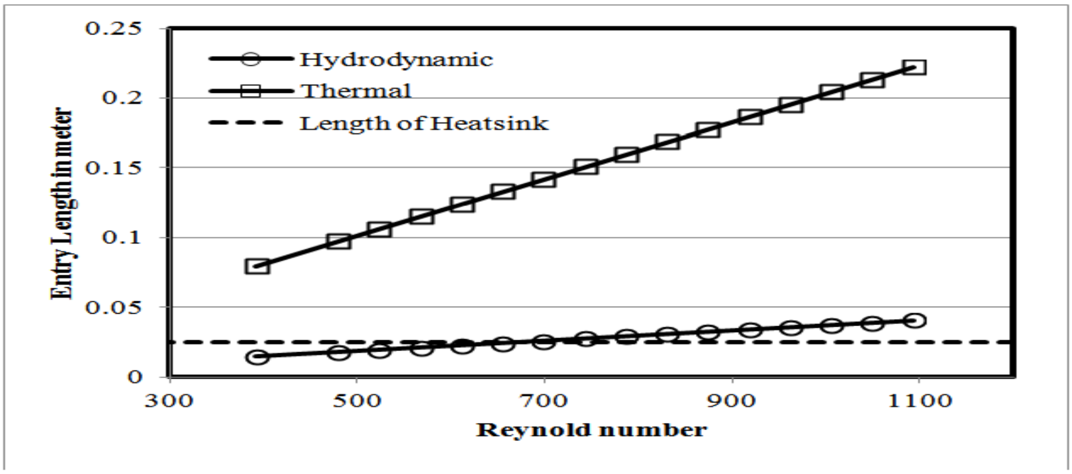


Fig. 10 Effect of Reynolds number on Hydrodynamic and Thermal entry lengths

4.3 Heat Transfer Correlations

The thermal performance of plate fin micro channels decrease along the flow direction due to the thickening of the boundary layer. In order to understand whether the flow is in developing or developed region, the hydrodynamic & thermal entry lengths have been calculated for the plate fin micro channels using the following relations [18].

$L_h = 0.05\ Re\ D_h$

$L_T = 0.05\ Re\ D_h\ Pr$

Figure 10 shows that the hydro dynamically developed flow is not feasible if the Reynolds number is beyond 700. But the flow is always in thermally developing zone for all the flow rates. The conventional heat transfer correlations are not applicable for these flow conditions as they are based on the developed flow assumption. For all the fin geometries excluding plate fins, the boundary layer gets re-initialized repeatedly along flow direction, so that the flow is always in the developing region. In view of the above, it is required to evolve indicative heat transfer correlations. The heat transfer correlations were evolved through curve fitting using the above simulated results. The list of proposed heat transfer correlations is presented in Table 4. The heat transfer correlation for the inline pin fin is found to be closely matching to that of the one reported in the published literature [11]. Therefore the other heat transfer relations proposed in this work is considered to be reasonable.

Table 4 Heat transfer correlations from simulation

Sl No	Micro channel type	Heat Transfer Correlation
1.	Plate fin	$Nu = 2.415\ Re^{0.250}$
2.	In line Pin fin	$Nu = 0.642\ Re^{0.543}$
3.	Staggered Pin fin	$Nu = 5.499\ Re^{0.314}$
4.	Oblique fin	$Nu = 1.348\ Re^{0.434}$
5.	Improved Oblique fin	$Nu = 0.943\ Re^{0.491}$
6.	Nozzle type	$Nu = 1.186\ Re^{0.468}$
7.	Oblique with two angles	$Nu = 1.784\ Re^{0.382}$

VII. CONCLUSION

A comparison study has been carried out to investigate for performance enhancement of micro channel fins by modifying the secondary flow passage of the oblique fin micro channel. Thermal & flow performance is compared based on the performance index. The staggered pin fin geometry is able to thermally perform better with higher penalty of pressure drop. But the improved oblique fin geometry which is a variant of modified oblique fin geometry has shown a notable improvements in the performance. In the oblique fin micro channel the main flow branches out to the secondary flow with sharp angle leading to considerable pressure drop. The modification incorporated in the improved oblique fin geometry has helped the smooth entry and exit of secondary flow while ensuring the frequent boundary layer redevelopment leading to an enhancement in performance. The staggered pin fin is the best choice, if thermal performance alone considered as the criteria irrespective of the pumping power. Indicative heat transfer correlations have been developed using numerical simulation.

This numerical study has demonstrated that the augmented heat transfer coefficient is achievable with lesser pressure drop penalty than the oblique fins micro channel. Hence it can be concluded that the improved oblique fin micro channel has better advantage than the other types of micro channel configuration.

VIII. Acknowledgements

The authors acknowledge Microwave Tube Research & Development center, Bangalore, India for extending technical support in carrying out this work.

Nomenclature

Nu	=	Nusselt number
Re	=	Reynolds number
Pr	=	Prandtl number
h	=	Heat transfer coefficient in $W/m^2\ {}^oK$
p	=	Pressure in Pascals
L_h	=	Hydrodynamic entry length in m
L_T	=	Thermal entry length in m
D_h	=	Hydraulic diameter in m

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