Heat Transfer Enhancement in Oblique Finned Channel

Badyanath Tiwary, Ritesh Kumar and Pawan Kumar Singh

Abstract In the modernistic day, cooling is one of the predominant challenges of electronic and automobile industry. The demand for faster and smaller devices increases the thermal load, and at the same time, conventional cooling techniques that use extended surfaces (fins, microchannel, heat sink, heat pipe, etc.) reached their limits. Recently, oblique fin heat sink has been found as an alternative to conventional heat sink because of their improved heat transfer performance and a marginal increase in pressure drop. The reason behind this improved heat transfer is the breakage of the continuous fin into oblique fin which keeps the flow in developing condition. Also, the secondary flow through oblique channel diverts a small fraction of flow and enhances mixing. The present paper tries to capitalize the advantage of the oblique fin with the benefits of nanofluid by carrying out a detailed numerical simulation. Alumina–water nanofluid has been used for numerical analysis using single-phase and discrete phase modeling approaches through oblique fin microchannel. Conjugate heat transfer between the oblique fin heat sink and nanofluid is computed numerically. Approximately, 115 and 145% heat transfer enhancement has been observed in oblique channel compared to rectangular microchannel in single-phase modeling and discrete phase modeling, respectively.

Keywords Nanofluid · Enhanced microchannel · Oblique fin · DPM

Nomenclature

P	Pressure (Pa)
C_p	Specific heat capacity (J/kg K)
T	Temperature (°C or K)

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k	Thermal conductivity (W/m K)
t	Time (S)
F_D	Drag force (N)
g	Gravitational acceleration (m/s^2)
F	Force term
h	Heat transfer coefficient (W/m^2 K)
D_h	Hydraulic diameter (mm)
ΔP	Pressure drop (Pa)
Re	Reynolds number
f	Friction factor
DPM	Discrete phase model

Greek Symbols

∇	Del (operator)
ρ	Density (kg m^{-3})
μ	Dynamic viscosity (Pa s)
ϕ	Nanoparticle volumetric fraction

Subscripts

eff	Effective
f	Pressure drop penalty factor
NF	Nanofluid
BF	Base fluid
P	Particle
l	Liquid
avg	Average

1 Introduction

The continuous growth in the direction of miniaturization and advancement in electronics and automobile industries have been pushed to boost the system performance which often comes up with high heat generation which needs to be dissipated within limited space. International Technology Roadmap for Semiconductors (ITRS) forecast in 2012 that the integrated circuits demand high power density up to 100 W/cm^2 in 2020 [1]. Moreover, power density in microscale with elevated packing density in the field such as weapon, laser, and radar could generate 1000 W/cm^2 of heat flux [2]. The conventional cooling methods are not enough to fulfill the present-day cooling requirement. The cooling achieved by microchannel has been pushed to its limit, and there is a need for novel microchannels which can enhance heat dissipation with marginal or no increase in the pressure drop compared to the conventional microchannel. One of the microchannels is oblique fin channel. The reason behind this is the breakage of the continuous fin into oblique fin keeps the flow in developing condition and also the secondary channel diverts flow in a small fraction and enhances mixing. The efficiency of these microchannels can be further increased by using a better cooling liquid having higher thermal conductivity compared to a conventional cooling fluid, which is a colloidal suspension of nanoparticle in a base fluid having magnificent thermo-physical properties named as nanofluid. The nanoparticle is made up of metal, oxides, carbide, carbon nanotube (CNT), etc [3–5].

As early, Tuckerman and Pease [6] suggested the concept of liquid cooling with the microchannel to enhance the heat transfer performance by accomplishing greater heat transfer rate up to 800 W/cm^2 with microchannels in single-phase and discrete phase flows. This landmark work paved the door for further research in the field of microchannel heat transfer.

Wang and Peng [7] investigated experimentally the single-phase forced convective heat transfer characteristics of water/methanol flowing through the rectangular microchannel. The results show considerable insight and significant data into the nature of forced-flow convection in microchannels.

Lee et al. [8] made oblique fin in a microchannel heat sink in order to modulate the flow. This results in the local and global heat transfer enhancement. Numerical analysis of laminar flow and heat transfer showed that heat transfer enhanced significantly with negligible pressure drop. The mixing of primary and secondary flow effect gives much improved heat transfer performance by 80%. Also, there is a decrement of maximum wall temperature and temperature gradient.

Lee et al. [9] investigated the outcome of heat transfer performance on the secondary channel in the oblique fin microchannel. The secondary flow was introduced by parting a small channel in the straight channel at a certain angle. Simulation results are validated by conducting an experiment. The width of 100 and 200 μm is used in this study for a different flow range of 100 to 500 mL/min. It was found that heat dissolution potential in the oblique fin is much improved than the straight channel. However, edge effect caused a large fluctuation in the distribution of temperature and decreased the thermal performance. The present study has been validated with this research paper for water before taking alumina–water nanofluid as working fluid.

From the detailed literature survey, it has been noticed that very few studies have been conducted on the novel oblique fin micro-/minichannel heat sink with nanofluid as cooling fluid may result in good heat transfer performance. Thus, in the present study numerical simulation on heat transfer performance using an oblique finned channel with the use of nanofluid is to be performed using both single-phase and discrete phase modeling.

2 Mathematical Modeling

The two main approaches which are to be considered for numerical simulation of nanofluid are mixture rule or single-phase modeling and discrete phase modeling (DPM). In mixture rule, nanofluid is assumed to be single-phase homogeneous fluids, whereas in DPM the fluids are assumed to have continuous phase and for this continuous phase, flow and heat transfer are governed by general Navier–Stokes equation and energy balance equation. It is also called Eulerian–Lagrangian approach. The particles are injected in this flow field, and the motion of these particles is governed by Newton's second law which depends on various forces acting on the particles.

For the purpose of the numerical study, a single row of the rectangular and oblique channel has been designed in SOLIDWORKS and meshed in ANSYS 15 [10]. Meshing for both fluid and solid domains is done separately. The simulation domain has been meshed using face sizing, body sizing, and sweep method in ANSYS mesh (Figs. 1, 2, and 3; Table 1).

To simplify the analysis, certain assumptions are considered in the analysis of flow such as steady state, laminar, negligible radiative heat transfer, negligible convective heat transfer, negligible viscous dissipation from the oblique fin heat sink, and constant fluid properties.

Solution Method

The governing differential equations for alumina nanofluid using mixture rule are

1. Continuity equation

$$\nabla \cdot (\rho \vec{v}) = 0 \tag{1}$$

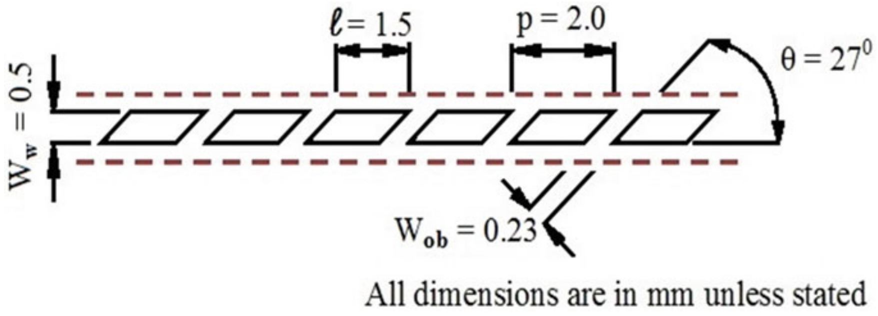

Fig. 1 Schematic diagram of oblique fins

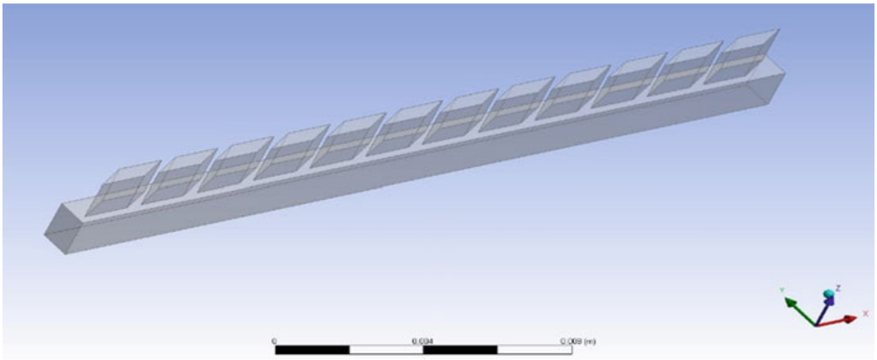

Fig. 2 Geometry of oblique fin channel

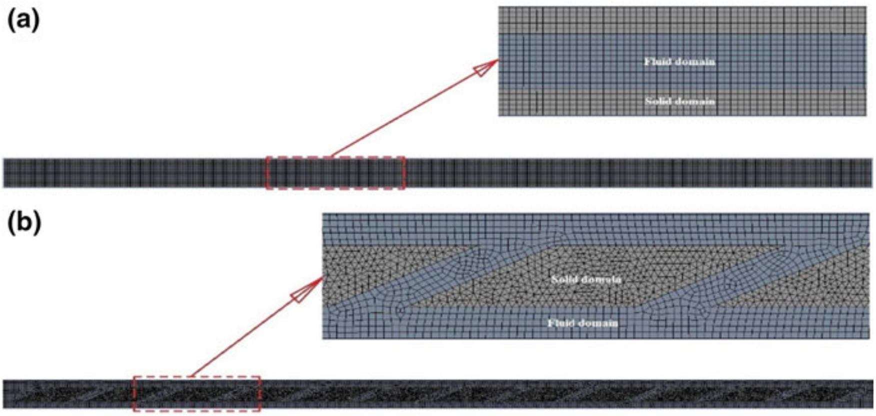

Fig. 3 Meshing of **a** straight channel and **b** oblique finned channel

Table 1 Dimension of oblique finned channel

Characteristics	Dimensions
Material	Aluminum
Channel width, W_{ch} (μm)	500
Fin width, W_w (μm)	500
Channel depth (μm)	1500
Fin length, **l** (μm)	1500
Fin pitch, p (μm)	2000
Oblique angle, θ (°)	27
No. of fins	12

2. Momentum equation

$$\nabla \cdot (\rho \vec{v}\vec{v}) = -\nabla P + \nabla \cdot (\mu \nabla \vec{v}) \tag{2}$$

3. Energy equation

$$\nabla \cdot \left(\rho \vec{v} C_{\mathrm{p}} T\right) = \nabla \cdot (k \nabla T) \tag{3}$$

The thermo-physical properties of alumina-based nanofluid at 1, 2, and 4% volumetric concentration in this analysis, for mixture rule, have been calculated by the following equation.

The thermal conductivity of the alumina nanofluid is given by Hamilton–Crosser model [11],

$$k_{\mathrm{eff}} = k_{\mathrm{f}}(1 + C_{\mathrm{k}}\varnothing) \tag{4}$$

where C_{k} is taken as 4.

The viscosity of the suspension is given by:

$$\mu_{\mathrm{NF}} = \mu_{\mathrm{BF}}\left(1 + C_{\mu}\varnothing\right) \tag{5}$$

where C_{μ} is viscosity coefficient. The value of C_{μ} is taken as 5 for alumina–water nanofluids.

The effective density of nanofluids is given by:

$$\rho_{\mathrm{NF}} = \rho_{\mathrm{BF}}(1 - \varnothing) + \rho_{\mathrm{P}}\varnothing \tag{6}$$

The specific heat of nanofluids is defined as (Tables 2 and 3):

Table 2 Thermo-physical property of nanofluid using mixture rule

ϕ (%)	ρ (kg/m^3)	C_{p} (J/kg K)	K (W/m K)	μ (Pa s) × e-03
1	1027.01	4147.94	0.632	0.933
2	1055.83	3938.73	0.656	0.978
4	1113.47	3720.73	0.705	1.067

Table 3 Thermo-physical property of alumina

Properties	Value
Density (Kg/m^3)	3890
Specific heat capacity (J/Kg K)	776.42
Thermal conductivity (W/m K)	37.717

$$C_{\mathrm{pNF}} = \frac{\rho_{\mathrm{f}} C_{\mathrm{pf}}(1-\varnothing) + \rho_{\mathrm{P}} C_{\mathrm{p_P}\varnothing}}{\rho_{\mathrm{f}}(1-\varnothing) + \rho_{\mathrm{P}}\varnothing} \tag{7}$$

For discrete phase modeling, differential equations are as follows [12]
Continuity equation

$$\nabla \cdot (\rho \vec{v}) = 0 \tag{8}$$

Momentum equation for base fluid

$$\nabla \cdot (\rho \vec{v}\vec{v}) = -\nabla P + \nabla \cdot (\mu \nabla \vec{v}) + S_{\mathrm{m}} \tag{9}$$

Momentum equation for nanoparticle

$$\frac{\mathrm{d}\overrightarrow{v_{\mathrm{P}}}}{\mathrm{d}t} = F_{\mathrm{D}}\left(\vec{v} - \overrightarrow{v_{\mathrm{P}}}\right) + \frac{g(\rho_{\mathrm{P}} - \rho_{\mathrm{l}})}{\rho_{\mathrm{P}}} + \vec{F} \tag{10}$$

F term represents the additional thermophoretic force, Saffman lift force, Brownian motion, etc.

3 Results and Discussion

Figure 4 shows pressure drop in flow through the rectangular channel and oblique finned channel. Both are nearly same at lower Reynolds number, but at higher Reynolds number, a significant change in pressure drop has been observed in the oblique finned channel due to irregular flow.

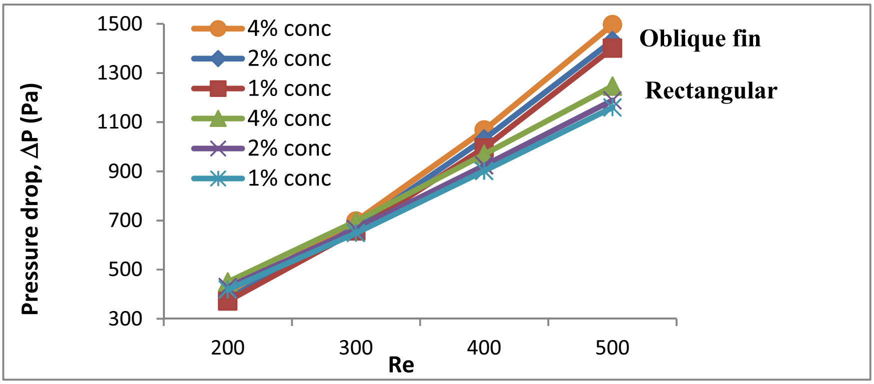

Fig. 4 Pressure drop versus *Re* in oblique fin and rectangular channel using mixture rule

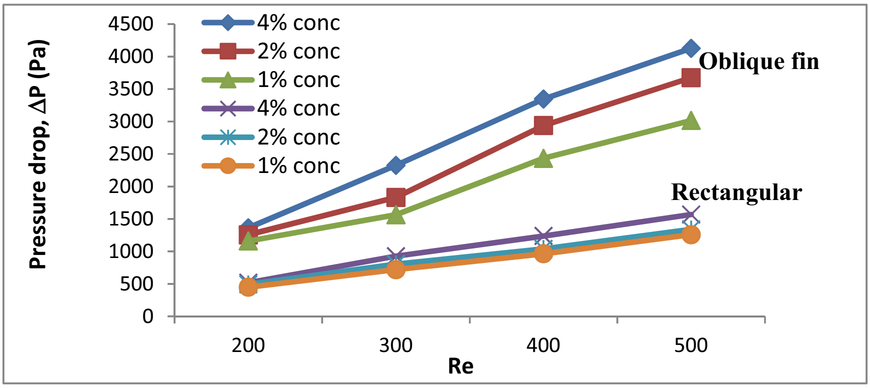

Fig. 5 Pressure drop versus *Re* in oblique fin and rectangular channel using DPM

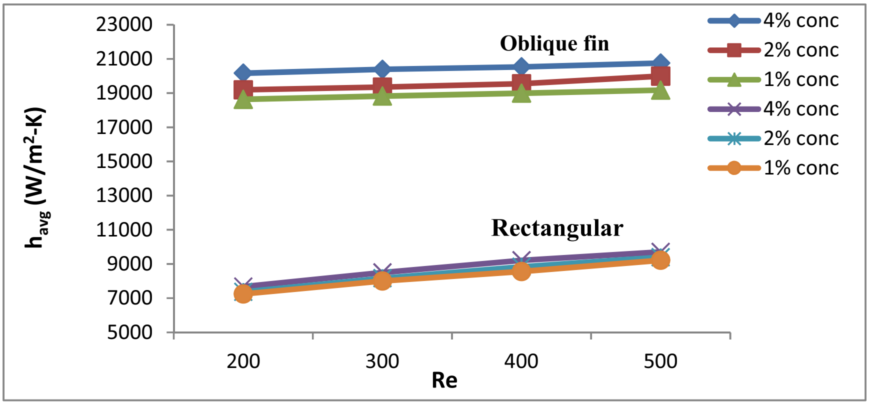

Fig. 6 Heat transfer coefficient versus *Re* in oblique fin and rectangular channel using mixture rule

Figure 5 shows the variation in pressure drop with Reynolds number in discrete phase modeling. Oblique finned microchannel shows more pressure drop at higher concentration due to more number of particles and individual particle behavior considered in DPM.

Figure 6 shows the variation of h_{avg} with Reynolds number in the rectangular and oblique channel. There is high heat transfer enhancement observed in oblique finned microchannel compared to rectangular channel as there is continuous breakage of the thermal boundary layer at the end of every oblique fin.

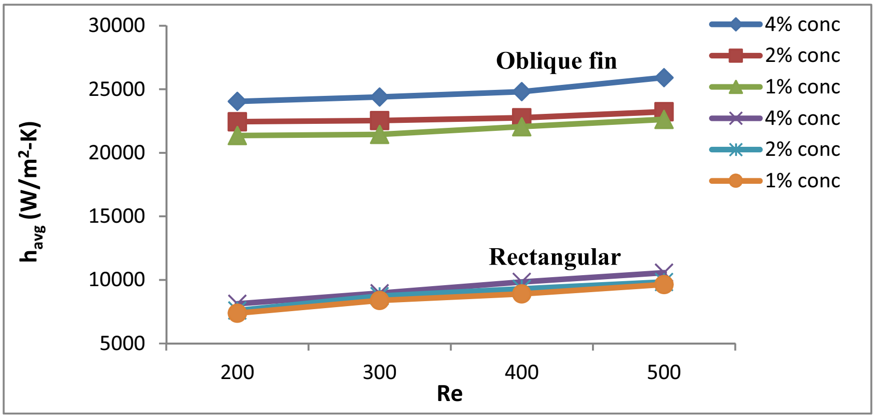

Fig. 7 Heat transfer coefficient versus *Re* in oblique fin and rectangular channel using DPM

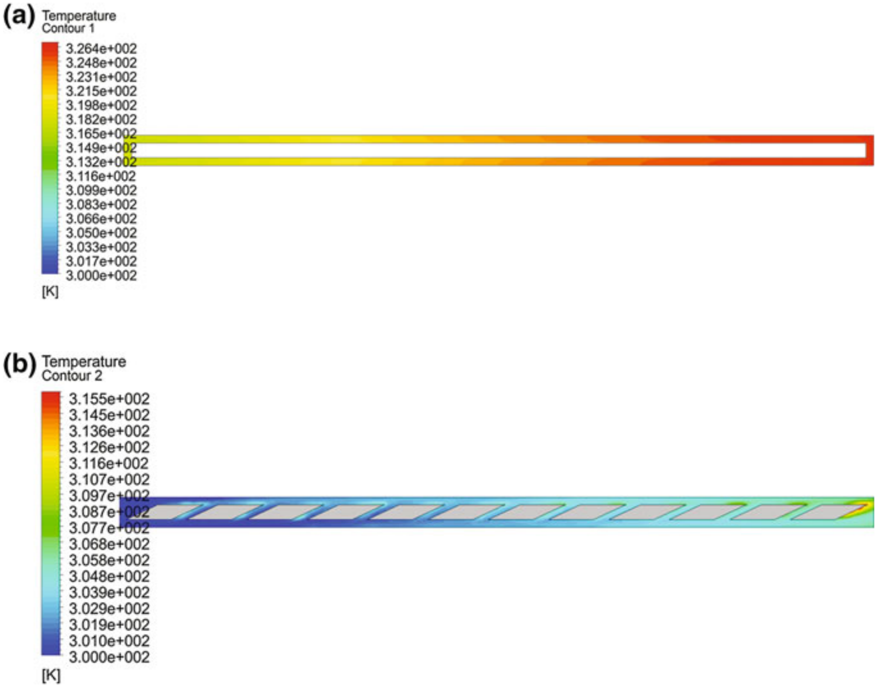

Fig. 8 Temperature contour at the base of **a** rectangular channel and **b** oblique fin channel

Figure 7 shows less variation in the h_{avg} value at lower Reynolds number. In oblique finned microchannel, there is 145% enhancement in heat transfer coefficient compared to rectangular microchannel due to more mixing of nanofluid particles at 500 Reynolds number.

Temperature Contour

Figure 8 shows the temperature variation at the base in the rectangular and oblique finned channels. In oblique geometry, there is more uniform temperature distribution compared to that of a rectangular channel. Also, the temperature near the end of the rectangular channel is 10 °C more than the oblique channel. Thus, it acts as a better alternative to rectangular microchannel for cooling purpose.

4 Conclusion

In the present study, hydrodynamic and heat transfer behaviors of Al2O3-water-based nanofluid are studied in an oblique finned channel. The result is obtained for laminar flow Reynolds numbers 200, 300, 400, and 500 and nanoparticle volume fraction of 1, 2, and 4%. At 4% volumetric concentration and $Re = 500$, there is an enhancement of 115% heat transfer coefficient that has been observed in oblique channel compared to rectangular microchannel in mixture rule, whereas 145% enhancement has been observed in discrete phase modeling. Therefore, oblique finned channel can be a potential alternative to microchannel heat sink application.

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References

1. Gong L, Zhao J, Huang S (2015) Numerical study on layout of microchannel heat sink for thermal management of electronic devices. Appl Therm Eng 88:480–490
2. Khan JA, Morshed AKMMM, Fang R (2014) Towards ultra-compact high heat flux microchannel heat sink. Procedia Eng 90:11–24
3. Choi SU, Eastman JA (2016) Enhancing thermal conductivity of fluids with nanoparticles (No. ANL/MSD/CP–84938; CONF-951135–29). Argonne National Lab, IL (United States)
4. Buongiorno J (2016) Convective transport in nanofluids. J Heat Transf 128(3):240–250
5. Yu W, France DM, Routbort JL, Choi SU (2008) Review and comparison of nanofluid thermal conductivity and heat transfer enhancements. Heat Transf Eng 29(5):432–460
6. Tuckerman DB, Pease RFW (1981) High-performance heat sinking for VLSI. IEEE Electron Device Lett 2:126–129
7. Peng XF, Wang BX (1995) Experimental investigation of heat transfer in flat plates with rectangular microchannel. Int J Heat Mass Transf 38(1):127–137
8. Lee YJ, Lee PS, Chou SK (2009) Inter PACK 2009-89059. In: International conference on energy sustainability, Proceedings 2009, San Francisco, California, USA, 19–23 July
9. Lee YJ, Singh PK, Lee PS (2015) Fluid flow and heat transfer investigations on enhanced microchannel heat sink using oblique fins with parametric study. Int J Heat Mass Transf 81:325–336
10. Fluent ANSYS (2016) Fluent 15 users guide. Lebanon, USA

11. Hamilton RL, Crosser OK (1962) Thermal conductivity of heterogeneous two component systems. Ind Eng Chem Fundam 1(3):187–191
12. Goutam S, Paul MC (2014) International conference on advances in civil, structural and mechanical engineering—CSM 2014, Birmingham, UK, 16–17 Nov