Received: 11 March 2019 | Revised: 17 April 2019 | Accepted: 11 June 2019

DOI: 10.1002/htj.21520

RESEARCH ARTICLE

HEAT TRANSFER Asian Research

WILEY

Thermal intensification of heat transfer characteristics on the plate-fin heat sink with piezoelectric fan

Santosh K. Gugulothu[1] | **Ali J. Chamkha**[2]

[1]Department of Mechanical Engineering, National Institute of Technology Hamirpur, Harimpur, Himachal Pradesh, India

[2]Mechanical Engineering Department, Prince Mohammad Bin Fahd University, Al Khobar, Saudi Arabia

Correspondence
Santosh K. Gugulothu, Department of Mechanical Engineering, National Institute of Technology Hamirpur, Himachal Pradesh 177001, India.
Email: santoshgk1988@nith.ac.in

Abstract

This study applied the computational fluid dynamic (CFD) code, ANSYS Fluent for simulating the effect a piezoelectric fan installed inside the rectangular channel by numerical simulation method for transient flow field and investigating the influence of each parameter. To remove the disorganized form of energy from the electronic components, the reversible piezoelectric effect is employed to energize the piezoelectric fan. To observe the variation of fan characteristics and to predict the convective heat transfer coefficient, CFD code ANSYS Fluent 15.0 is used. The numerical simulation parameters included are Nusselt number, number of fins (n = 12 and 14), and counter-shift (inward and outward-phase), and distance between the upper portion of the fan tip to the front part of the low thermal reservoir. Numerical analysis was carried out to evaluate the effect of thermal flow fields on the heat sink and piezoelectric fan employed in a flow domain. the results showed that by varying the height from channel bottom to the center of piezoelectric fan improves the performance of the piezoelectric fan, piezoelectric fan swinging in a transient phenomena and also simultaneously influences fluid flow behavior on the heat source surface, the fan vibration at counter-phase has a better rate of heat transfer than vibration in in-phase.

KEYWORDS
CFD, fins, piezoelectric cooling, plate-fin heat sink

1 | INTRODUCTION

The demand for growth in science and technology enhances the electronics industry to develop efficient electronic components with high functionality and portability. The demand for smaller, more functional and portable electronic devices has resulted in a large number of powerful electronic components being packed into smaller spaces. The resulting reduction in size and mass density of electronics components has improved the rate of heat generation and wall heat fluxes over their components. The heat generated in the electronic devices is gradually increasing which affects the efficiency and lifetime of devices. Hence the necessity of implementing the sophisticated cooling techniques to improve the performance of electronic components is increasing significantly. Piezoelectric fans are considered as an alternative cooling mechanism for electronic components. In this study, piezoelectric fans are investigated as an active cooling technique for the thermal management of portable electronics.

Various investigations have been done to improve the cooling of electronic components. Liu et al[1] have studied the influence of geometric parameters, location of piezo fan, and so forth. Results found that in vertical arrangement the heat transfer enhancement is gradually increasing and reaches the maximum at the center and gradually decreases whereas in the horizontal retarded peaks are observed at the inception stage. Lin[2] has done the numerical and experimental analysis on vibrating fan by considering a three-dimensional (3D) fluid domain. From the analysis, it was observed that experimental and numerical results indicate that fan improves the rate of heat transfer by 25% to 50% and simultaneously local heat transfer coefficient can be achieved by 2.85 times. Ma et al[3] have established a driving source to drive multistage fan by a cooling system that uses a piezoelectric magnetic force. The results have shown that the MPMF system is efficient consuming low power with an improved thermal resistance performance compared with natural convection. Fairuz et al[4] have done numerical analysis on the effect of different piezoelectric fan shapes driven at the frequency and the tip amplitude of the first mode to investigate their effects on the performance of heat transfer characteristics. The results showed that the increase in mode number decreased the induced air flow velocity on the top of the heating surface, thus impeding the cooling capabilities at the higher model number. Shyu et al[5] have investigated the enhancement of a piezoelectric fan-cooled plate-fin array by varying fan position, height of the fan, fan material. From the results it was observed that the fin heat transfer with an aluminum fan at $x = 0$ was higher than that of $x = 0.25$ L. Sufian et al[6] have done the analysis of the influence of dual vibrating fans on flow and thermal fields by conducting numerical and experimental investigations. Good comparison results were achieved by accurate modeling of the salient features of the fan. Abdullah et al[7] have investigated the cooling capability for possible use in electronic devices by using a piezoelectric fan. By using particle image velocimetry, measurements are carried out for fluid flow at different heights. The results show that the fan height of $h_p/l_p = 0.23$ can reduce the temperature of the heat source surface as much 68.9°C. Li et al[8] have performed experimental and numerical analysis to investigate the effect of convective heat transfer coefficient in a dual piezoelectric fan by adopting three different aspects, that is, 3D computational analysis to study the effect of the piezoelectric fan, heat transfer measurement, and vibration tests. Results reported that the heat transfer coefficient is approximately similar in the case of a dual piezoelectric fan when compared with a single fan. Jeng et al[9] have performed the experimental analysis to study the influence of the piezoelectric fan on forced convective heat transfer in a pin-fin heat sink. The analysis was carried out with a combination of three different pin-fin arrays, that is, 5×5, 7×7, and 9×9. Results reported that of the three pin-fin arrays used, 9×9 units have slightly higher heat transfer coefficient. Sufian et al[10] have performed experimental and numerical analysis to study the influence of tip and side gaps of a piezoelectric fan applied in a microelectronic cooling. Results reported that the impact of tip gap has higher significance than the side gap. Lin[11] has performed the experimental analysis to enhance the heat transfer of a cylindrical surface by using a piezoelectric fan. Results reported that heat transfer coefficient improved by 1.2 to 2.4 times. Li et al[12] have conducted the experimental analysis to study the influence of the piezoelectric fan on the micro pin-fin heat sink. Results reported that for improving thermal performance, the integration of piezoelectric fan into micro heat sink is an effective method. Sufian et al[13] have performed numerical analysis on two vertically oriented piezoelectric fan study the effect of vibrating fans on flow and thermal fields. Computed results emphasize that enhancement in heat transfer in case of a single fan was approximately 2.3 times for the heated surface. Li et al[14] has performed experimental investigations to study the influence of the piezoelectric fan on plate-fin heat sinks. The effects on thermal resistance were evaluated in the form of fan configuration, location of the fan, reservoir dimensions, and so forth. Results showed that better thermal performance factor was observed in the case of a vertical piezoelectric fan when the tip of the fan blade is at the center of the heat sink. Sufian et al[15] investigated the thermal characteristics of resistance, intermediate temperature, and average heat transfer coefficient for different fans experimentally and numerically. Results reported that the performance of dual fans increased to 3.2 times, while in the case of quadruple fans 3.8 times compared to natural convection. Only a few literatures are available in the thermal intensification of heat transfer characteristics in a plate-fin heat sink. In this analysis, we intended to enhance the heat transfer effect by utilizing a piezoelectric fan which is set in front of the radiator to mix the air surrounding radiator and the fins and also simultaneously develop a design with lower thermal resistance and to provide a new direction for the plate-fin heat sink. The rest of the paper is organized as follows: Geometrical model with different boundary conditions are discussed in Section 2. The numerical method is discussed in Section 3. The performance of the piezoelectric fan with different fins and inward and outward phases are discussed in Section 4 followed by conclusions are discussed in Section 5.

2 | GEOMETRIC MODEL

The model used in this simulation consists of a rectangular channel in which piezoelectric fans are installed in front of the heat sink attached with the extended surfaces known as "FINS" as shown in the Figure 1. Numerical simulation parameters considered are the size of the rectangular channel is $320\,mm \times 45\,mm \times 100\,mm$, the size of the heat sink is $31\,mm \times 31\,mm$, and the number of fins (n) are 12 and 14. Dimensions of piezoelectric fan is 65 mm length and width of 12 mm, the distance between two fans is 30 mm. Vibrations phase: in-phase and counter-phase.

To carry out the process, the thermodynamic system is assumed to be a steady state, flow as incompressible, gravity forces and effects of thermal radiation are neglected. Following are the boundary conditions are considered. Here, L_g is the distance from the tip of the fan to the heat

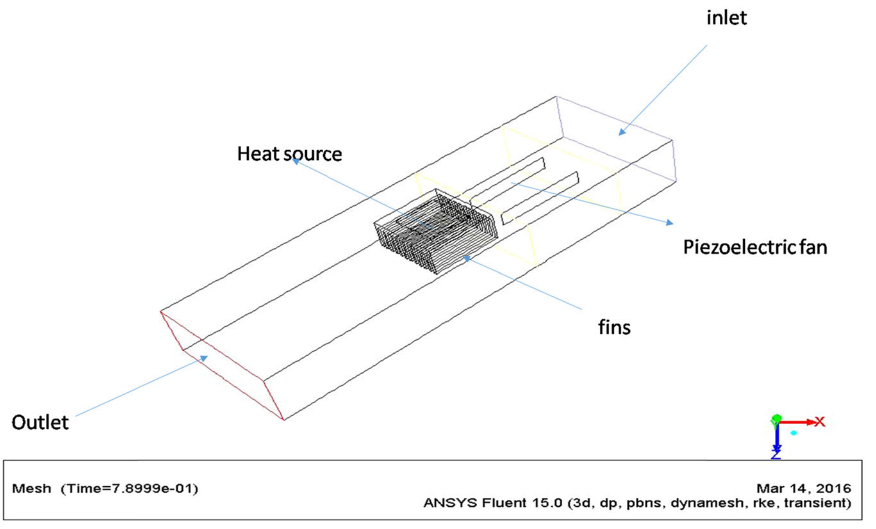

FIGURE 1 Schematic diagram of the experimental setup [Color figure can be viewed at wileyonlinelibrary.com]

sink and H_w is the distance from the center of the fan to the channel bottom. At inlet and outlet pressure is treated to be atmospheric.

Inlet: $U = U_\varphi,\ V = W = 0,\ T = T_\varphi = 293\,K$; wall: $U = V = W = \frac{\partial T}{\partial n} = 0$; outlet: $\frac{\partial \phi}{\partial n} = 0,\ \varnothing = (U,\ V,\ W,\ K,\ \in, \mathrm{T})$

The heat sink is thermally isolated at the bottom except for the surface of heat. The heat transfer coefficient of the heat sink is 168 W/(m^2·K) and it is kept at an operating temperature of 350 K. Approximately 2.5 m/s maximum flow velocity produced by a single fan is considered, other parameters included are fan length of 65 mm, breadth of 12 mm, and amplitude vibration of 23 mm. A maximum velocity of 2.5 m/s was assumed to produce by a single fan. A single fan of length 65 mm and width of 12 mm with a vibration amplitude of 24 mm are considered.

3 | NUMERICAL METHOD

The numerical analysis is done by using ANSYS fluent 15.0 with a 3D computational model. To predict the flow fields, the dynamic mesh is used where the shape of the domain is changing with time due to the motion of the domain boundaries. For maintaining the movement of fan, smoothing and remeshing are done. The hybrid mesh is used in which mesh is constructed by tetrahedral and hexahedral mesh. For reducing the number of elements, coarse mesh, that is, the hexahedral mesh is chosen for piezoelectric fan and for flow domain flow along with heat sink hexahedral mesh is chosen.

The governing equation applied in this simulation is the conservation of energy. The equation can be written as

$$\iiint \rho c_p\, \partial T/\partial t^{\mathrm{dxdydz}\, +\, h_c A_t (T_{\mathrm{ave}} - T_\infty)} = \dot{E}_{\mathrm{in}} \tag{1}$$

The first and second terms on the left side are the change in internal energy with respect to time and convective energy. The term on the right is energy conducted into the system. Where ρ is density,

TABLE 1 Simulated data and calculations

Fins	Phase	Time step	Heat transfer coefficient, W/(m^2·K)	Nusselt number
12	In-phase	1.875	2.8	117.82
	Counter-phase	1.84	4.46	184.66
14	In-phase	0.76	1.06	43.92
		1.2	1.17	48.3
		2.5	1.24	51.3
		3.6	1.28	52.85
	Counter-phase	1.25	1.4	57.93
		1.6	1.38	57.1

C_p is specific heat, $\frac{\partial T}{\partial t}$ is the energy per unit volume with the rate of change of time, dxdydz represents the control volume, h_c is proportionality constant, $(T_{\text{ave}}-T_\infty)$ is the temperature gradient of the wall surface and fluid particles. The assumption in the 3D computational model includes turbulent flow, incompressible flow with buoyant forces and radiation phenomena are neglected. Energy equations are solved by using differential equations, pressure forces by using simple mechanism although a second order would yield better accuracy. To capture the flow domain precisely, the lesser time gap is required. The time step taken in this simulation is 0.001 seconds.

4 | RESULTS AND DISCUSSIONS

In the present study, numerical analysis was carried out to evaluate the effect of thermal flow fields on the plated heat sink and piezoelectric fan installed in a rectangular channel. To

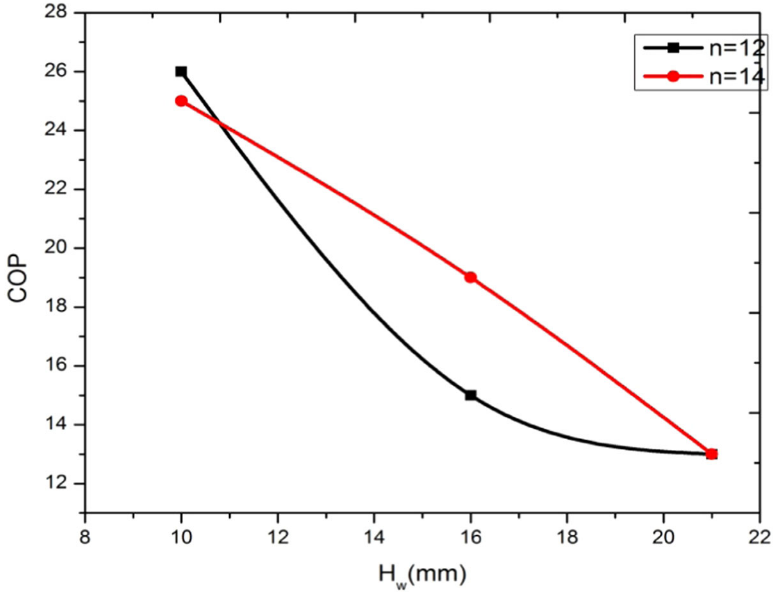

FIGURE 2 Effects of the COP on H_w. COP, coefficient of performance [Color figure can be viewed at wileyonlinelibrary.com]

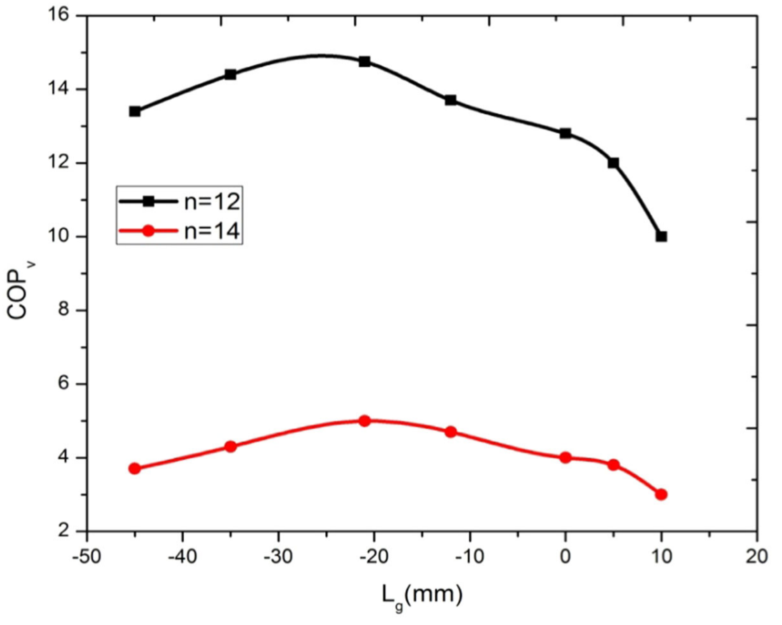

FIGURE 3 Effects of the COP on H_w. COP, coefficient of performance [Color figure can be viewed at wileyonlinelibrary.com]

investigate the performance of the thermal flow efficiency of heat sink under operating conditions with various parameters. From the present analysis, it is assumed that temperature gradient in plate-fin heat sinks is neglected, defines the distribution of unsteady temperature per energy balance and simultaneously defines the distribution of unsteady temperature per energy balance as the objective as mentioned in Table 1.

4.1 | Fin number

For doing the analysis on heat sink under natural convection, to assess the performance coefficient of performance (COP) is considered. Using COP the thermal resistance provided by a piezoelectric fan and the convective resistance of the thermal reservoir under natural convection with different fins (n = 12 and 14) are discussed as shown in the Figures 2 and 3. The result has shown that COP at n = 12 is greater than that of n = 14 at a given distance $L_g = -45$. From the graph, it is observed that

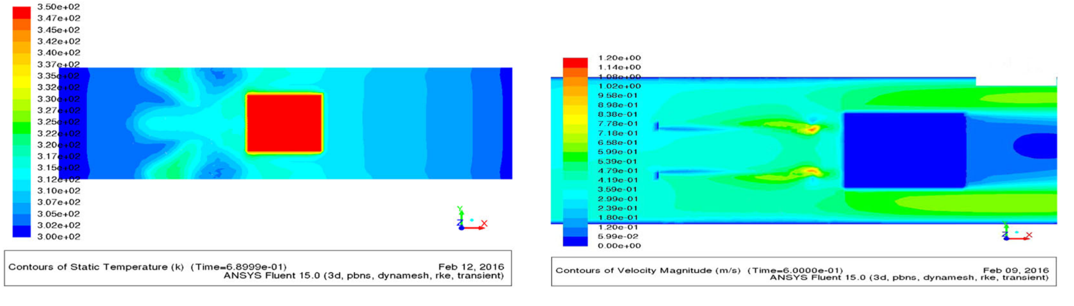

FIGURE 4 Contours of temperature and velocity magnitude with $y = 0$ and $z = 0$ (n = 12 fins; counter-phase) [Color figure can be viewed at wileyonlinelibrary.com]

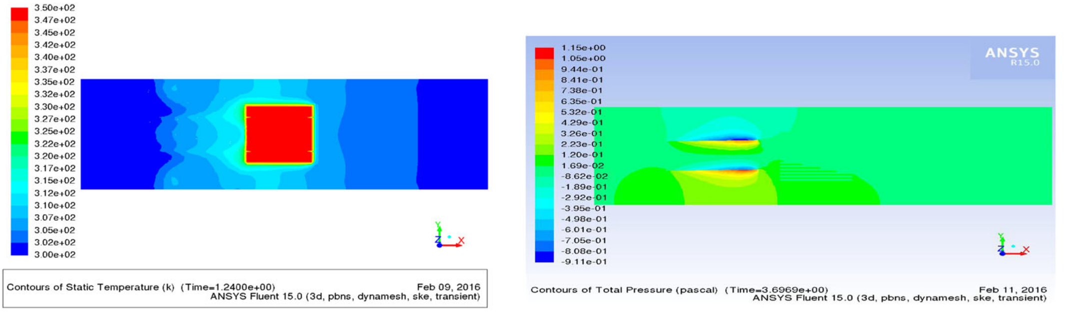

FIGURE 5 Contours of temperature and velocity magnitude with $y = 0$ and $z = 0$ (n = 14 fins; counter-phase) [Color figure can be viewed at wileyonlinelibrary.com]

for both the fins (n = 12 and 14) at a distance of $L_g = 5$, similar COP is identified, that is, the length between thermal reservoir to piezoelectric fan tip.

Figures 2 and 3 represents the comparison plot between the effect of COP and length between piezoelectric fans to flow. It is observed that the distance from the fan tip to a heat sink (H_w) is reducing, the COP is observed to be higher. It is also observed from the figure that there is no significant influence of increasing both cop and number of fins at $H_w = 10$. Even

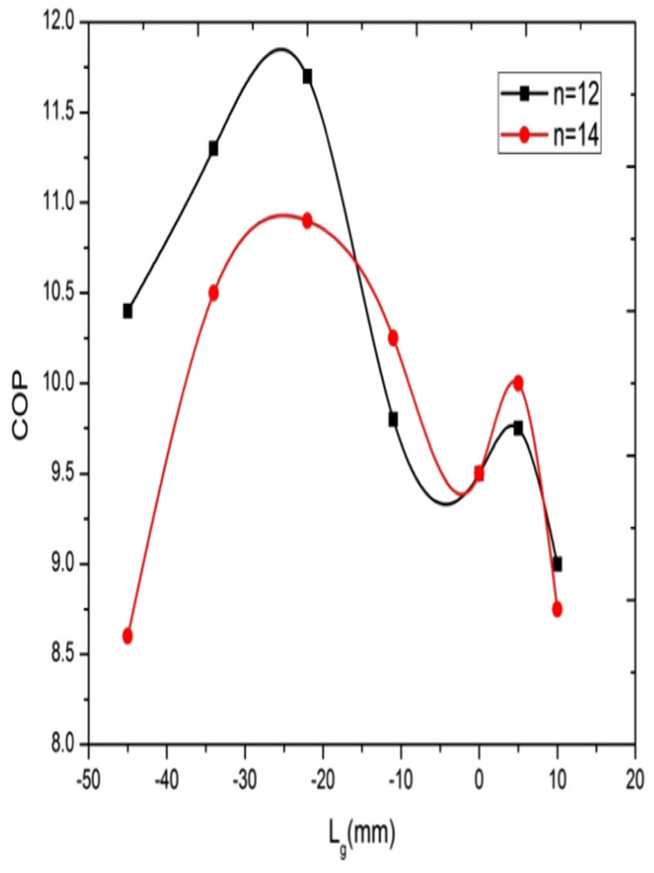

FIGURE 6 The effects of the COP number on L_g. COP, coefficient of performance [Color figure can be viewed at wileyonlinelibrary.com]

though twin fan has an effective performance on the rate of heat transfer on the thermal reservoir but due to its higher maintenance cost it may not be considered to helpful in the electronic cooling system. Figures 4 and 5 represents the temperature distribution and velocity contours with different fins with a constant distance from the tip of the fin to the heat sink, respectively. It is reported that the fluid in contact with the heat sink absorbs the energy and transfer it to the fluid domain and distributes the energy transfer in y and z directions, respectively.

4.2 | Compare with in-phase and counter-phase

From the analysis, it was observed that the thermal efficiency of the single piezoelectric fan is lesser than that of counter-phase twin fan, even though the velocity of fan tip is observed to be similar for both twin and single piezoelectric fan, but the mass flow rate of twin fan is higher than a single fan. In this analysis, the investigation has been carried out to draw the comparison between the counter and in-phase with different L_g, which convective heat transfer phenomena occurred on the surface which gives greater scope to compare the relative fluid flow. Figures 6 and 7 compares COP and Nusselt number at a different distance for the vibration of fan at opposite phase and in-phase. In counter-phase, the convective performance of flow is greater than in-phase of the heat sink surface. For $L_g = 0$, the convective flow drops away from the heat sink at in-phase vibration and there is no effect when compared with counter-phase vibration.

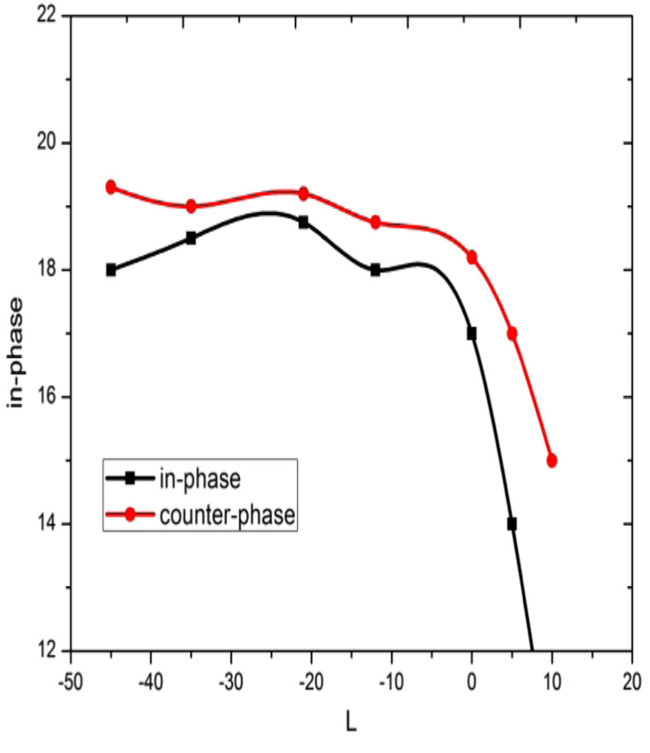

FIGURE 7 The effects of the Nu on L_g. Nu, Nusselt number [Color figure can be viewed at wileyonlinelibrary.com]

5 | CONCLUSIONS

In the present study, numerical analysis was carried out to evaluate the effect of thermal flow fields on the plated heat sink and piezoelectric fan installed in a rectangular channel. To investigate the performance of the thermal flow efficiency of heat sink under operating conditions with various parameters. From the present analysis, it is assumed that temperature gradient in plate-fin heat sinks is neglected, defines the distribution of unsteady temperature per energy balance and simultaneously defines the distribution of unsteady temperature per energy balance as the objective.

- On the basis of the numerical analysis following are the observations drawn on the performance of the piezoelectric fan associated with different angle of inclinations, with extended surfaces on the low-temperature reservoir with perpendicular flow evaluated heat capacitance and fluid efficiency.
- If fins are placed below the center of the piezoelectric fan, the entrained flow area is prioritized of consideration in study with the most effect of entrained flow is at $L_g = -0.5$ and $H_w = 21$.
- It is observed that if the piezoelectric fan center is higher than that of the fins, the entrant flow area is a priority in consideration whereas if piezoelectric fan center is lower than fins, the impact flow area is in consideration.
- With the increase in the distance between the thermal reservoir and fan is increasing, it is observed that there is a decrease in the flow efficiency.

From the observation, it is evident that only advantage of inward flow, twin fan is that convective flow is developed only around the fan with better performance away from the fan gradually reduced.

ORCID

Santosh K. Gugulothu http://orcid.org/0000-0003-1255-4134

REFERENCES

1. Liu S-F, Huang R-T, Sheu W-J, Wang C-C. Heat transfer by a piezoelectric fan on a flat surface subject to the influence of horizontal/vertical arrangement. *Int J Heat Mass Transfer*. 2009;52(11–12):2565-2570.
2. Lin C-N. Heat transfer enhancement analysis of a cylindrical surface by a piezoelectric fan. *Appl Therm Eng*. 2013;50(1):693-703.
3. Ma HK, Tan LK, Li YT, Liu CL. Optimum thermal resistance of the multiple piezoelectric–magnetic fan system. *Int Commun Heat Mass Transfer*. 2014;55:77-83.
4. Fairuz ZM, Sufian SF, Abdullah MZ, Zubair M, Abdul Aziz MS. Effect of piezoelectric fan mode shape on the heat transfer characteristics. *Int Commun Heat Mass Transfer*. 2014;52:140-151.
5. Shyu J-C, Syu J-Z. Plate-fin array cooling using a finger-like piezoelectric fan. *Appl Therm Eng*. 2014;62(2):573-580.
6. Sufiana SF, Abdullaha MZ, Mohamedb JJ. Effect of synchronized piezoelectric fans on microelectronic cooling performance. *Int Commun Heat Mass Transfer*. 2013;43:81-89.
7. Abdullah MK, Abdullah MZ, Ramana MV, et al. Numerical and experimental investigations on effect of fan height on the performance of piezoelectric fan in microelectronic cooling. *Int Commun Heat Mass Transfer*. 2009;36(1):51-58.

8. Li X, Zhang J, Tan X. Experimental and numerical investigations on convective heat transfer of dual piezoelectric fans. *Sci China Technol Sci*. 2018;61:232-241. https://doi.org/10.1007/s11431-017-9084-2
9. Jeng T-M, Tzeng S-C, Liu C-H. The effect of a piezoelectric fan on forced air heat transfer in a pin-fin heat sink. *Smart Sci*. 2015;3(1):1-6. https://doi.org/10.1080/23080477.2015.11665629
10. Sufian SF, Abdullah MZ, Abdullah MK, Mohamed JJ. Effect of Side and Tip Gaps of a Piezoelectric Fan on Microelectronic Cooling. *IEEE Trans Compon Packag Manuf Technol*. 2013;3(9):1545-1553.
11. Lin C-N. Heat transfer enhancement analysis of a cylindrical surface by piezoelectri fan. *Appl Therm Eng*. 2013;50(1):693-703.
12. Li X-J, Zhang J-Z, Tan X-M. Effects of piezoelectric fan on overall performance of air-based micro pin-fin heat sink. *Int J Therm Sci*. 2018;126:1-12.
13. Sufian SF, Abdullah MZ, Mohamed JJ. Effect of synchronized piezoelectric fans on micro electronic cooling performance. *Int Commun Heat Mass Transfer*. 2013;43:81-89.
14. Li H-Y, Chao S-M, Chen J-W, Yang J-T. Thermal performance of plate-fin heat sinks with piezoelectric cooling fan. *Int J Heat Mass Transfer*. 2013;57(2):722-732.
15. Sufian SF, Abdullah MZ. Heat transfer enhancement of LEDS with a combination of piezoelectric fan and a heat sink. *Microelectron Reliab*. 2017;68:39-50.

SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

How to cite this article: Gugulothu S, Chamkha AJ. Thermal Intensification of Heat Transfer characteristics on Plate-Fin Heat Sink with Piezoelectric Fan. *Heat Transfer—Asian Res*. 2019;48:2629-2638. https://doi.org/10.1002/htj.21520