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Heat Transfer Study of Perforated Fin under Forced Convection

M. S. Sundaram, M. Venkatesan*

School of Mechanical Engineering, SASTRA University, Tirumalaisamudram, Thanjavur, Tamilnadu, India

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ABSTRACT

Fins are protrusions on a heat transfer surface to augment heat transfer rate from it. The increase in area exposed to convection in case of finned surfaces results in increased heat transfer rate. In this study heat transfer characteristics of a pin fin with perforation is numerically analyzed. A pin fin is fabricated and experiments are done under forced convection conditions. The experimental results are used for validating the numerical model. The numerical analysis of perforated pin fin with varying parameters such as diameter of perforation, location of perforation and number of perforations is done. The perforated pin fin is found to enhance heat transfer rate compared to ordinary pin fin with a lesser material requirement.

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1. INTRODUCTION

Fins under forced convection conditions are used for enhancing heat transfer from electronic and mechanical components to dissipate excess heat from the source. Rectangular fins which were initially used under forced convection conditions were found to have higher pressure drop thereby increasing the power requirement of the pumps. Pin fins provide lower pressure drop for air flow and hence the pumping requirements are minimized. The following literature works are reported on heat transfer of fins. Harahap and McManus [1] studied the effect of rectangular fins on free convection and proposed correlation for finding average heat transfer coefficient for the experimented fin model. Bejan and Morega [2] calculated the optimal parameters for pin fins and plate fins to augment heat transfer rate. El-Sayed, et al. [3] studied the effect of orientation of rectangular fins on heat transfer characteristics. The parallel orientation of the fin resulted in increased efficiency when compared to the other orientations. Ojha [4] performed heat transfer analysis on micro channel heat fins using a commercial code (ANSYS Fluent). The average Nusselt number and average convective heat transfer coefficient along the length of the channel was calculated. It was concluded that the values dropped at 1/10th of channel length due to merging of boundary layer from the channel sides. Hannani et al. [5] studied the heat transfer characteristics of horizontal cylindrical pin fin confined between two vertical walls and found an optimal value for enhanced heat transfer. Kameoka et al. [6] studied the performance of a pin fin placed in a vertical plate for forced convection conditions. The relationship between fin dimensions and flow velocities to have enhanced heat transfer was analyzed. Balachandar et al. [7] studied the performance of a closed top fin under natural convection conditions. The effective fin parameters for augmented heat transfer were found out. Sparrow et al. [8] compared the performance of a pin fin with a rectangular fin to establish the advantage of pin fin over rectangular fin. Khoshravan et al. [9] studied the performance of a vertical pin fin placed over a horizontal base plate under convection and radiation. The 'modified box method' used resulted in a faster solution when compared to a fully implicit finite difference method. The effects of convection-conduction, radiation-conduction type boundary conditions were studied. Huang et al. [10] studied the

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*Corresponding Author's Email: *mvenkat@mech.sastra.edu* (M. Venkatesan)

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performance of a rectangular fin with perforations on the base of a fin. It was found that fin with perforation had lower temperature than a plate fin. Yu et al. [11] studied the performance of a plate pin fin apparatus with that of a plain plate fin apparatus. It was found that plate pin fin apparatus resulted in 30% less thermal resistance compared to a plain plate fin apparatus. Chapman et al. [12] compared the performance of a elliptic pin fin with cross cut fin and rectangular fin. Elliptic fin was found to operate efficiently because of less resistance to air flow. Yang et al. [13] studied the effect of porosity on heat transfer characteristics of a porous pin fin and an ordinary pin fin. The porous pin fin was found to work efficiently at lower weight than an ordinary pin fin. Shaeri et al. [14] studied heat transfer of perforated plate fin in forced convection. The perforated plate fin is found to be more effective than an ordinary plate fin. Taghilou et al. [15] optimized a double pipe fin-pin heat exchanger using entropy generation minimization. Recently Bailin et al. [16] analyzed the performance of electric vehicle insulated gate bipolar transistor (IGPT) pin fin heat sink. The above mentioned literature shows that a lot of work had been done in the area of fins. Works on solid pin fins are available in literature. Works have been published on perforations in rectangular fins. However, works on perforated pin fins are limited. The present work aims at analyzing heat transfer characteristics of a perforated pin fin. Experiments are done on a solid pin fin and the results are used for validating the numerical model. The effect of diameter of perforation, location of perforation and number of perforations on heat transfer characteristics of a pin fin is studied using a commercial code ANSYS Fluent.

2. PROBLEM DESCRIPTION

An experimental set up designed to carry out forced convection experiments on a solid aluminum pin fin is shown in Figure 1. The fabricated pin fin is placed vertical to air flow under forced convection conditions. The fin is placed over a copper base plate. The copper base plate is placed on a surface filled with MgO powder. A cartridge type heater (250 W) is placed inside the MgO powder. The heater and MgO powder is surrounded by wooden box to prevent loss of heat.

The MgO powder ensures uniform heating of copper plate. The copper plate is of dimension 70×60×1 mm. The pin fin is placed at the center of the copper base plate. The dimensions of the pin fin are shown in Figure 2. The pin fin is attached to the copper plate by means of a thermal paste to avoid any contact resistance. The 12V DC fan for air flow is placed at a distance of 11cm from the copper base plate. Holes of 1.2 mm diameter are drilled at five locations on the surface of the fin to insert thermocouples.

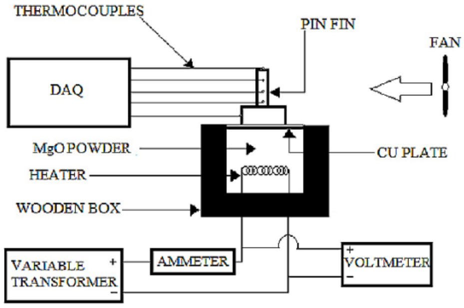

Figure 1. Experimental setup.

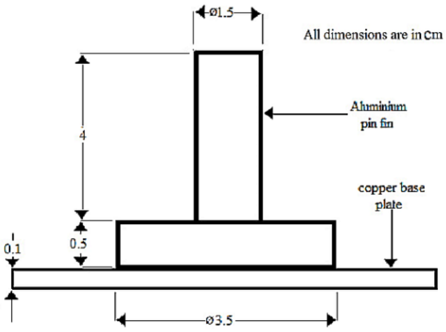

Figure 2. Pin fin dimensions

K-type (Chromel-Alumel) thermocouples of 1mm diameter are inserted and used for measuring the temperatures of pin fin. The thermocouples are accurate to ±1 °C. They are connected to a NI cDAQ9174 chassis with NI 9203 high speed temperature module to collect the temperature data in a computer. The velocity of air is measured at the same distance of 11cm by a digital anemometer (MASTECH MS6252B) with ±3% accuracy. The heater is connected to a dimmer stat whose voltage can be varied between 0-240V. This experimental setup is placed in a room temperature of 27°C and the heater is supplied with a heat flux of 10W. The properties of the material used are shown in Table 1. The power supplied to the heater in terms of volts and current are measured using a digital voltmeter and ammeter respectively. The experimental value of temperature of pin fin at various locations is obtained by thermocouples attached to data acquisition (DAQ). The readings of the five thermocouples are averaged.

TABLE 1. Materials Used

S.no	Component	Material name	Thermal conductivity(W/mK)
1	Pin fin	Aluminum	130
2	Copper base plate	Copper	401
3	Wooden box	Wood	0.17

3. NUMERICAL VALIDATION

The numerical model has got the same dimensions as that of the experimental work and is analyzed using a commercial CFD package ANSYS Fluent. The entire pin fin and copper base plate setup is placed in a domain of dimensions 220×100×120 mm. Reynolds number for a velocity of 1.5m/s is found to be greater than 2000 for the modeled domain. Enhanced RNG turbulent model is chosen in the solver since turbulent flow conditions are reached. This model is found to be accurate compared to other turbulent models. The numerical simulation is carried out on a computer with core-i5 processor with 4GB ram. Each numerical simulation took approximately 1 hour. Grid independency is performed for the developed numerical model. The purpose of this test is to identify the optimum number of mesh elements which is a tradeoff between numerical errors and computational time. The optimal number of grid volumes for this numerical model is found to be greater than 7, 02, 000 which can be inferred from Figure 3. Table 2 represents the comparison of experimental values with the numerical ones.

4. PARAMETRIC VARIATION

In order to augment the heat transfer characteristics of a pin fin, perforations are made on the pin fin. Perforations are provided on the pin fin along the direction of air flow. The heat transfer characteristics of a perforated fin is studied by varying diameter (d), location (x), number of perforations (n) and velocity of air flow. The range of the considered parameters is shown in Table 3.

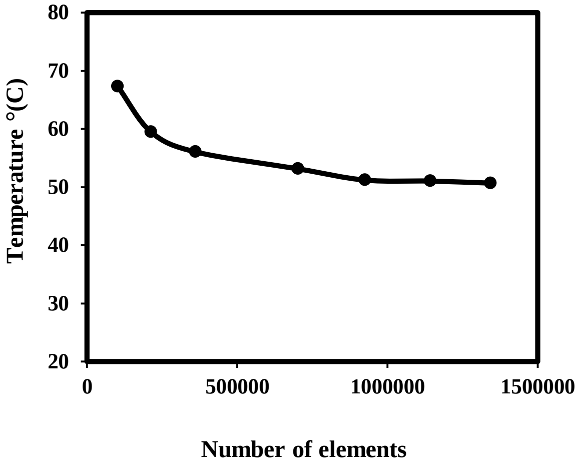

Figure 3. Grid independency

TABLE 2. Numerical Validation

S.no	Heat flux Q (W)	Velocity (m/s)	Average Temperature (°C)	Numerical value (°C)	Error (%)
1	10	1.5	53.30	53.1428	0.3

TABLE 3. Parameters of pin fin.

S.no	Parameters of perforated fin	Value of parameters
1	Diameter of perforation d (mm)	2, 5, 8
2	Location of perforation x (mm)	10, 20, 30
3	Number of perforations (n)	1, 2, 3
4	Velocity of air (m/s)	1.5, 3, 5

5. GOVERNING EQUATIONS

The continuity, momentum and energy equations are shown in Equations (1) (2) and (3). SIMPLE algorithm (pressure, velocity coupling equation) is used.

$$\nabla v = 0 \tag{1}$$

$$\nabla ku = \frac{\nu_t}{\sigma_k}\nabla^2 k + P_k - \varepsilon \tag{2}$$

$$\rho c_p v \nabla T = \nabla.(k\nabla T) + Q \tag{3}$$

where k- Turbulent kinetic energy, ε- Turbulent dissipation rate, u- Velocity, ν_t- eddy viscosity, P_k- production term, ∇-laplacian operator and $C_{\varepsilon 1}, C_{\varepsilon 2}, \sigma_k, \sigma_\varepsilon$- constants of value. The following boundary conditions are used in ANSYS Fluent to solve the equations - velocity and temperature of fluid at the inlet, heat flux at the base plate and atmospheric pressure at the outlet. First order upwind scheme is used for convection terms. No slip condition was assumed for walls.

6. RESULTS AND DISCUSSION

6. 1. Effect of Perforation on the Pin Fin The modeled solid pin fin is supplied with a heat load of 10 W. The heated pin fin is exposed to air at different velocities of 1.5, 3 and 5 (m/s) and its base plate temperature is calculated. Perforations of different diameters are made on the solid pin fin. The perforated pin fin is exposed to air at same velocities and same heat flux as that of a solid pin fin. The comparison between a solid pin fin and a perforated pin fin is shown in Figure 4.

It can be inferred from Figure 4 that the perforated pin fin has a lower base plate temperature compared to a solid pin fin. The reason is the increased exposed area for convection because of provision of perforation. A perforated pin fin is lighter compared to a solid pin fin. Total number of perforations in all the cases of diameters considered is taken as three (n=3). Figures 5, 6 and 7 represents the temperature contours of a solid pin fin and a perforated pin fin for the same heat load and air velocity. The temperature contour shows that the perforated fin has got a lower base plate temperature when compared to a solid pin fin.

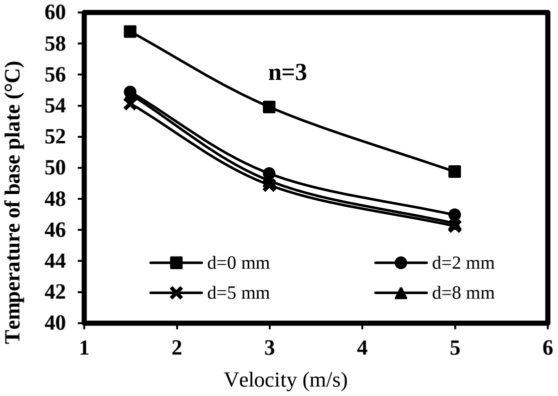

Figure 4. Effect of perforation on maximum base plate temperature of perforated pin fin compared to ordinary pin fin.

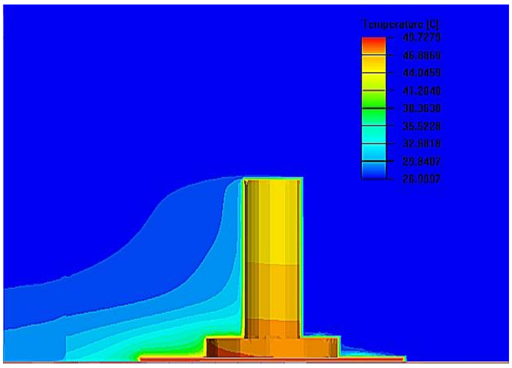

Figure 5. Temperature contour of pin fin (q=10 W, v=5 m/s)

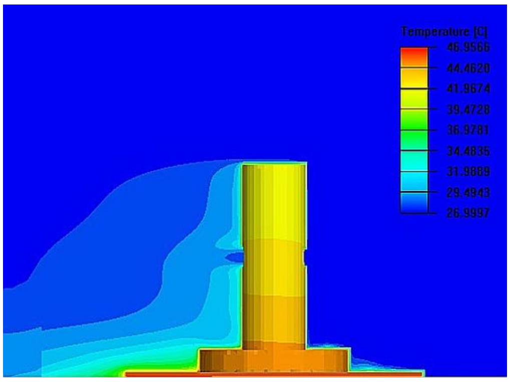

Figure 6. Temperature contour of perforated pin fin (q=10 W, v=5 m/s, d=5 mm, x=20 mm, n=1).

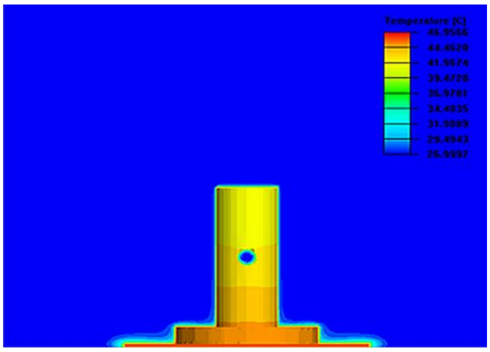

Figure 7. Temperature contour of perforated pin fin (q=10 W, v=5 m/s, d=5 mm, x=20 mm, n=1).

6. 2. Effect of Perforation Diameter (d) The diameter of the perforation provided on the pin fin is varied in this study. Three different diameters (d = 2, 5 & 8 mm) are used for the same heat load and different air velocity conditions. The number of perforations (n) is also varied from (1-3). The results are shown in Figures 8, 9 and 10. The temperature contours of perforated pin fins with different perforation diameters are shown in Figures 11, 12 and 13.

It can be inferred from these plots that the perforated pin fins with d=5 mm has maximum heat transfer compared to fins of other diameters. The reason is that at low perforation diameter of 2 mm, the area exposed to the convection is reduced compared to a diameter of 5 mm. However, with further increase in diameter (d=8 mm), there is a reduction in cross section area which reduces the area in which conduction heat transfer takes place from base to the top.

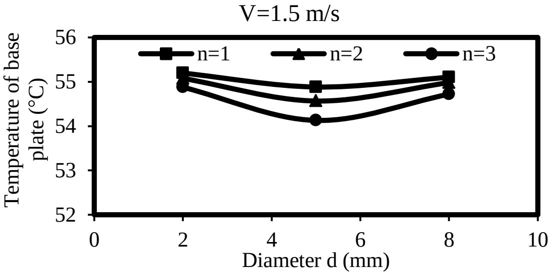

Figure 8. Effect of perforation diameter (q=10W, V=1.5m/s).

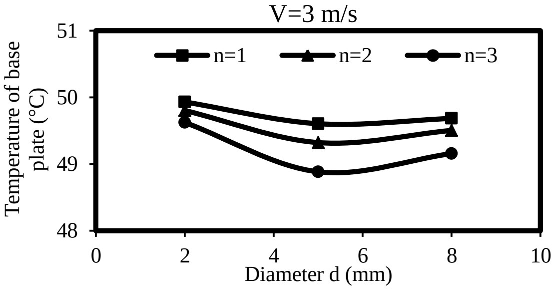

Figure 9. Effect of perforation diameter (q=10W, V=3m/s).

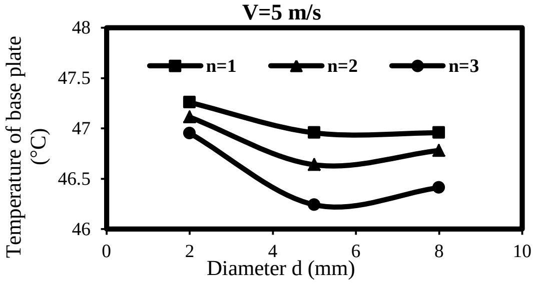

Figure 10. Effect of perforation diameter (q=10W,v =5m/s)

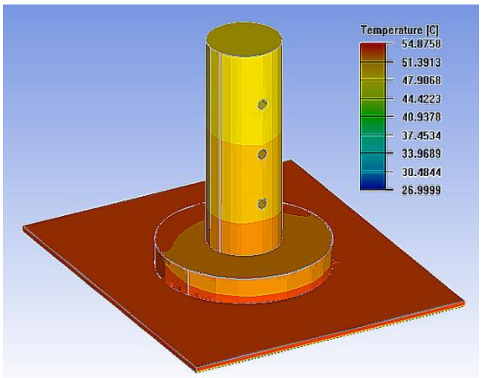

Figure 11. Temperature contour of perforated pin fin (d=2 mm, n=3).

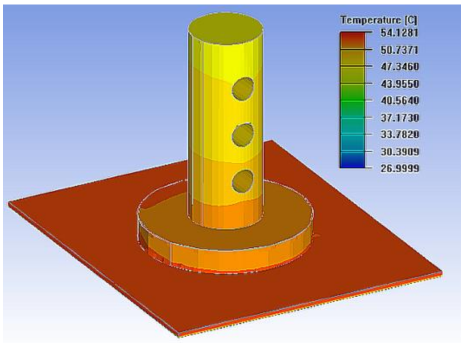

Figure 12. Temperature contour of perforated pin fin (q=10 W, v=1.5 m/s, d=5 mm, n=3).

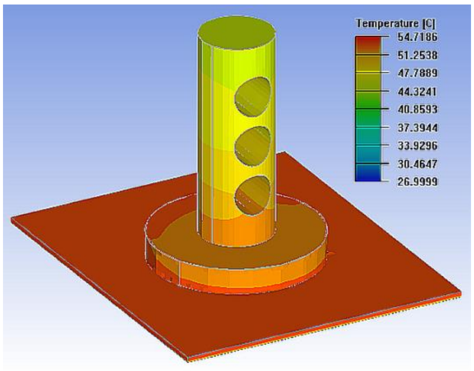

Figure 13. Temperature contour of perforated pin fin (q=10 W, v=1.5 m/s, d=8 mm, n=3).

6. 3. Effect of Number of Perforations (n)

The number of perforations on the pin fin is varied to study the heat transfer characteristics. Heat flux is maintained constant at 10W. Air velocity is varied and diameter of the perforation d is also varied. The results are shown in Figures 14, 15 and 16. It is evident from the graphs that the temperature decreases with the total number of perforations. The effect of location of a single perforated fin is analyzed by varying the distance x. The perforation location (x) is varied for the fin with perforation of d=5 mm since it is the optimal diameter of the perforation. The velocity of air is varied and heat flux is kept constant. It is seen from Figure 17 that to have enhanced heat transfer, the optimal value of location of perforation (x) is 20 mm. The location is at the correct place by a tradeoff between conduction resistance and surface area exposed to air. The trend of other graphs for different diameter (2, 8 mm) is found to be straight, so the effect of location of perforation is negligible for diameters other than the optimal value. In a perforated pin fin there is a reduction of wake area compared to solid pin fin. This reduction in wake area will help in uniform temperature distribution and avoid hot spots in ordinary pin fin and there is a reduction of form drag. A 19% weight reduction is obtained in addition to augmented heat transfer rate.

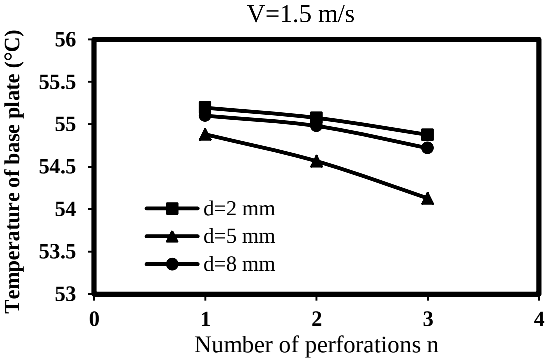

Figure 14. Effect of number of perforations (V=1.5m/s).

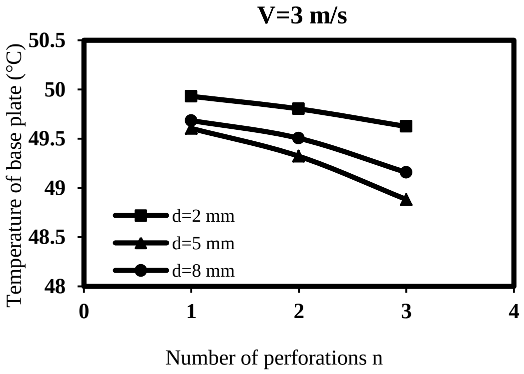

Figure 15. Effect of number of perforations (V=3m/s).

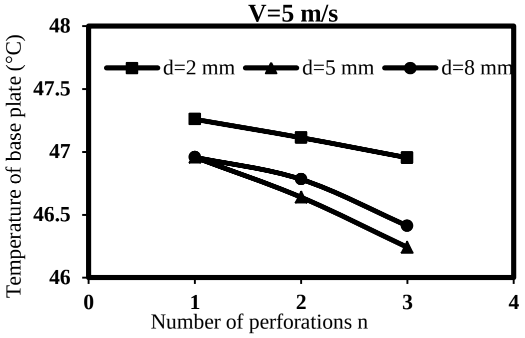

Figure 16. Effect of number of perforations (V=5m/s).

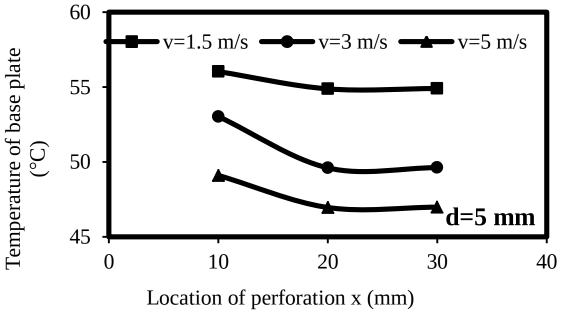

Figure 17. Effect of location of perforation.

7. CONCLUSION

In the present work heat transfer characteristics of a perforated pin fin is analyzed. Experiments are done on a solid pin fin and the results are used for validating the numerical model. Parametric studies such as the effect of diameter of perforation, location of perforation and number of perforations on heat transfer characteristics is done using a commercial code ANSYS Fluent. The perforated pin fin is found to enhance the heat transfer with lesser weight compared to a solid pin fin. The variation of different parameters revealed the optimal dimensions for perforated fin in order to augment the heat transfer. The study can be further extended by analyzing the profile of perforation on the fin.

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M. S. Sundaram, M. Venkatesan

School of Mechanical Engineering, SASTRA University, Tirumalaisamudram, Thanjavur, Tamilnadu, India

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چکیده

باله (پره)ها برآمدگی‌هایی بر روی یک سطح انتقال حرارت هستند که به منظور افزایش نرخ انتقال حرارت از آن سطوح ایجاد می‌شوند. افزایش مساحت در معرض همرفت در سطوح پره‌دار موجب افزایش سرعت انتقال گرما می‌شوند. در این مطالعه ویژگی های انتقال حرارت از یک باله‌ی میله‌ای سوراخ‌دار به صورت عددی تحلیل شده است. در این پژوهش یک باله‌ی میله‌ای ساخته و آزمایش‌ها تحت شرایط همرفت اجباری بر روی آن انجام می‌شود. از نتایج تجربی برای اعتباربخشی مدل عددی استفاده می‌شود. تحلیل عددی سوراخ باله با پارامترهای مختلف از جمله قطر ، محل و تعداد سوراخ‌ها انجام شده است. نتایج نشان داد که باله‌ی میله‌ای سوراخ‌دار در مقایسه با نوع عادی منظور نرخ انتقال حرارت بیشتر دارد مواد کمتری در آن به کار رفته است.

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