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Natural Convection around a Cylindrical Heat Sinks with longitudinal plate fins

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Abstract- In this study, we investigated natural convection heat transfer from horizontal cylinders with longitudinal plate fins adapted for dissipating heat on a LED (light emitting diode) light. The numerical results were validated with experimental results and a good agreement was found. Parametric studies are conducted to compare the effects of three geometric parameters and a single operating parameter (heat input) on the thermal resistance and the average heat transfer coefficient for the heat sink array.

Keywords- Natural convection, Heat sink, Cylinder, Heat transfer, Laminar flow

Nomenclature

L	Fin length(mm)
H	Fin height (mm)
t	Fin thickness (mm)
n	Fin number
D	Outer cylinder diameter (mm)
d	Inner cylinder diameter (mm)
g	Gravity acceleration (m/s^2)
T	Temperature (K)
h	Heat transfer coefficient (W/m^2 K)
k	Thermal conductivity (W/m ^{0}C)
q	Heat input (W)
$\dot{q}$	Heat flux (W/m^2)
R_{th}	Thermal resistance (^{0}C/W)
u	x-component of velocity (m/s)
v	y-component of velocity (m/s)
w	z-component of velocity (m/s) Greek symbols
μ	Dynamic viscosity (N/m^2 s)
ρ	Density (kg/m^3) Subscripts
avg	Average
fluid	Fluid (air)
solid	Solid (heat sink)
a	Air (ambient)
b	Base

1. INTRODUCTION

In the past few years, Light-emitting diode (LED) lighting is emerging technology in the illumination industry, because of low power, long life, small size, more durable structure and emission of superior visible light than conventional lighting system. However, about 85% of total electric power consumption of the light-emitting diodes (LEDs) is emitted as waste heat. If the dissipation of waste heat is not a proper way, it occurs a thermal problem, which reduces luminous efficiency and also its service life. The transfer of heat of LEDs is generally from the LED substrate to the fined heat sink by thermal conduction mode, and then finally from the fins by the air-flow thermal convection mode. So, there are two cooling mechanisms used for thermal. One is the passive cooling of natural convection in which the temperature difference between the high-temperature fins and the ambient is employed due to advantageous nature as, no additional power element required, high reliability and energy saving; the other is the active cooling of forced convection in which the air-driven device is used, and it is especially suitable for high power LEDs. Thus, a cylindrical heat sink is employed for cooling of LED lighting applications.

Due to the rapid development of the LED lighting market, there have recently been reported several studies which focused on radial heat sinks for cooling LED lights [1-10]. These studies were concerned to the natural convection heat sinks with vertical fins attached to a horizontal circular base, and observed the thermo-flow characteristics around these radial heat sinks, and also optimized their cooling performance and mass. However, these studies were related only with heat sinks for down lights, which are horizontally attached to the ceiling. Therefore, the results are inappropriate to cylindrical heat sinks employed for other types of LEDs, such as the light bulb assumed in the present study. Many previous studies have concentrated on cooling through natural convective heat transfer using a cylindrical heat sink. This type of heat sink in which fins are attached in a cylindrical body, as summarized in the books well presented by Martynenko and Khramtsov [11] and by Raithby and Hollands [12]. Sparrow and Bahrami [13] observed an experiment based naphthalene sublimation technique in which the fin heat-transfer rate from the square vertical fins attached to a horizontal tube was reported. They reported that the fin heat-transfer rate remains constant for small fin-to-fin spacings but increases for large fin-to-fin spacings, when the fin dimensions are fixed.

Chen and Chou [14] developed the Nusselt number correlation and to predict the impact of the heat transfer coefficient of square vertical fins attached to a horizontal tube. Yildiz and Yüncü observed on an experimental investigation of the heat transfer from annular fin arrays attached on a horizontal cylinder [15]. In addition, they reported that maximize condition of the heat transfer rate from the fin array occurs at an optimum fin-to-fin spacing. Hahne and Zhu carried out an experimental study on horizontal cylinders with annular fins [16]. They reported that the better heat transfer for smaller fins occur in terms of fin height; and also a correlation is proposed to predict the Nusselt number on the basis of visualized and measured the temperature field of fin surfaces. An et al. [17] developed a Nusselt number correlation for estimating the thermal performance of a natural convective cylindrical heat sink with vertically oriented plate fins. For this purpose, extensive experimental investigations are conducted for various fin numbers, fin heights, and base temperatures. Kim et al. [18] observed to investigate the effect of various fin numbers, fin heights, and base temperatures on natural convection from horizontal cylinders with longitudinal plate fins experimentally. From these experimental results, a Nusselt number correlation was developed. Park et al. [19] performed extensive experiments for various branch angles, fin numbers, and base temperatures to investigate natural convection heat transfer from vertical cylinders with branched plate fins.

Also they developed a Nusselt number correlation. Jang et al. reported to investigate the orientation effect for cylindrical heat sinks employed to cool an LED light bulb. They suggested that the orientation effect was intensified when the number of fins and the fin length increased; on the other hand the influence of fin height on the orientation effect was relatively insignificant, and also developed a Nusselt number correlation around an inclined cylindrical heat sink[20]. Also, Jang et al. [21] studied to investigate cross-cut cylindrical heat sinks to enhance the orientation effect of a conventional plate-fin cylindrical heat sink for LED light bulbs. They showed that the orientation effect of the cross-cut heat sink was smaller than that of the plate-fin heat sink. In addition, they developed a correlation to predict the degree of enhancement in the thermal resistance compared with a conventional plate-fin heat sink as a function of the heat sink design parameters, the installation angle, and the Rayleigh number.

In this study, natural convection heat transfer from horizontal cylinders with longitudinal plate fins is numerically investigated. Parametric studies are carried out to compare the effects of geometric parameters, and also heat input on the thermal resistance and the average heat transfer coefficient are investigated.

2. MATHEMATICAL MODELING

2.1. Numerical model

Fig. 1 shows a cylindrical heat sink in which present work is investigated. This type of heat sink consists of a cylindrical base with the longitudinal plate fins. The fins are circularly arrayed at regular angular intervals. The cylindrical heat sink base and fins are made of aluminum alloys whose thermal conductivity as 136.8 W/(m·K). The assumed heat transfer medium is air.The surrounding air temperature is maintained constant as 300 K. In the analysis, the thermophysical properties were evaluated at the mean of the base and ambient air temperatures.

2.2. Governing equations and boundary conditions

For the numerical simulation, the computational domain is shown in Fig. 2. The assumptions for the numerical simulation are as follows:
(1) The flow is three dimensional, laminar and study.
(2) Except for density, fluid properties are independent of temperature.
(3) The density of air is calculated from the ideal gas law.
(4) Radiation heat transfer is neglected.

The governing equations and boundary conditions is shown in Table 1.

TABLE 1 - GOVERNING EQUATIONS AND BOUNDARY CONDITIONS FOR THE COMPUTATIONAL DOMAIN.

	DOMAIN	WALL	CONTINUITY EQUATION	MOMENTUM EQUATION	ENERGY EQUATION
Governing equation			$\nabla.(\rho v) = 0$	$\rho \frac{Dv}{Dt} = -\nabla P + \mu\nabla^2 v + F$ (here,for x-direction F= $-\rho g$)	$\rho C \frac{DT}{Dt} = \nabla.(k\nabla T) + \frac{DP}{Dt}$
Boundary conditions	Fluid domain	Periodic face [22]		$u_i(\vec{r}_i) = u_i(\vec{r}_i + \vec{L})$,	$T_i(\vec{r}_i) = T_i(\vec{r}_i + \vec{L})$
		Outer face		Pressure inlet/ Pressure outlet condition	$T_{inlet} = T_{outlet,\ back\ flow} = T_a$
	Solid domain	Heat sink base		$u_i = 0$	$-k_{solid} \frac{\partial T_{solid}}{\partial n}\Big\vert_{heat\ sink\ base} = \dot{q}$
		Symmetric face		$u_i = 0$	$\frac{\partial T_{solid}}{\partial n}\Big\vert_{sectional\ wall} = 0$
	Interface between fluid and solid domain	Interface		$u_i = 0$	$T_{fluid,wall} = T_{solid,wall}$, $-k_{fluid}\frac{\partial T_{fluid}}{\partial n}\Big\vert_{wall}$ $-\ k_{solid}\frac{\partial T_{solid}}{\partial n}\Big\vert_{wall}$

The interface conditions are comes from the energy balance across the fin–air interface and it is solved simultaneously as a conjugate problem. Periodic condition occurs when the flow geometry has a periodically repeating nature. Such a periodic flow was analyzed with the FLUENT [23]. In this simulation, only a single set of fins was analyzed, because of the number of grids and the computational time involved. Especially, a constant heat input was applied to the inner surface area of the cylindrical heat sink, that is, the area of πdL which can be evolved from Fig. 1.

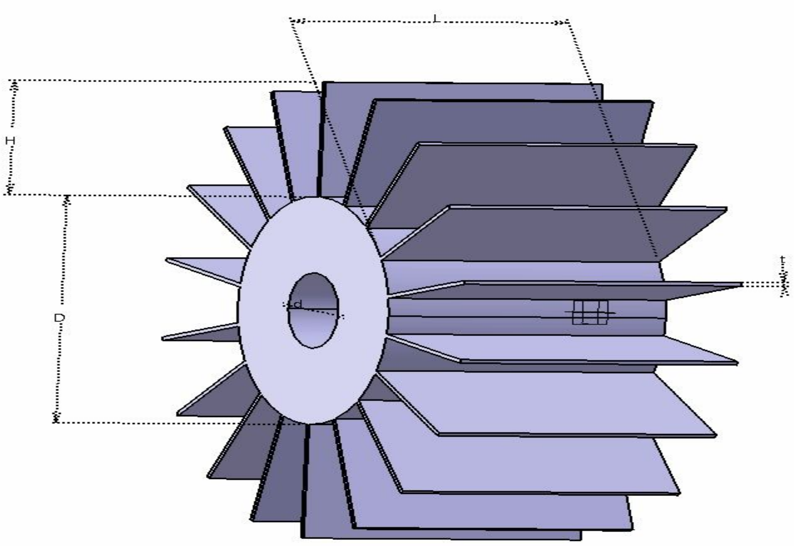

Fig. 1. *Cylindrical heat sink with the longitudinal plate fins.*

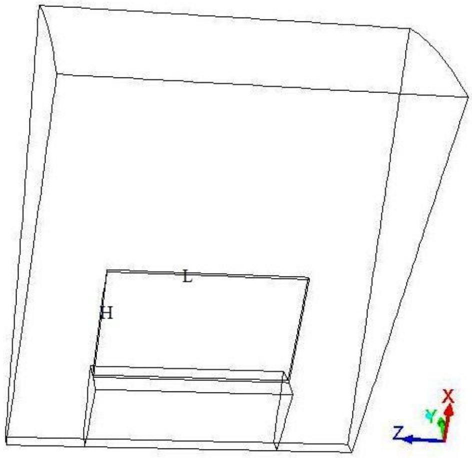

Fig. 2. *Computational domain.*

2.3. Numerical procedure and validation

For simulation, three-dimensional steady-state laminar flow model was considered. The Computational Fluid Dynamics (CFD) package FLUENT which is based on the finite volume method, and it is important tool to solve the fluid flow and heat transfer problems. A segregated solver was employed to the governing integral equations for the conservation of mass, momentum, and energy. Also, ANSYS ICEM was applied for the boundary conditions to create the computational mesh. The semi-implicit method for pressure-linked equations (SIMPLE) algorithm was applied to couple the velocity and pressure, and also it employed to solve the basic conservation equations .To obtain the complete solutions for flow and heat transfer model, the solver iterated the procedure until the convergence criteria were satisfied. A second-order upwind scheme was used to the convective terms of the governing equations by which accuracy of the analysis was improved.. The convergence criterion for all dependent variables was a relative error with an order of 10^{-5}. Considering both convergence of the heat-sink temperature and computational time, the radius of the computational domain was two to four times that of the heat sink. When the radius of the computational domain increased beyond three times that of the heat sink model, the average temperature of heat-sink reasonable changed by less than 0.5%, and thus the size of the computational domain was obtained. Also, the grid sensitivity was checked by increasing the number of grid points from 25,000–700,000. We selected 70,880 grid points as a reference heat sink model, and additional grid points produced a change of less than 0.5% in the average heat-sink temperature of the reference model, which had n = 18 and D = 60 mm.

The numerical results were validated with experimental data, if comparing the differences between the ambient and heat sink base temperatures was done. The geometric parameters of the experimental model were n = 18, D = 60 mm, L = 50 mm, H = 30mm, and t = 1 mm [18]..

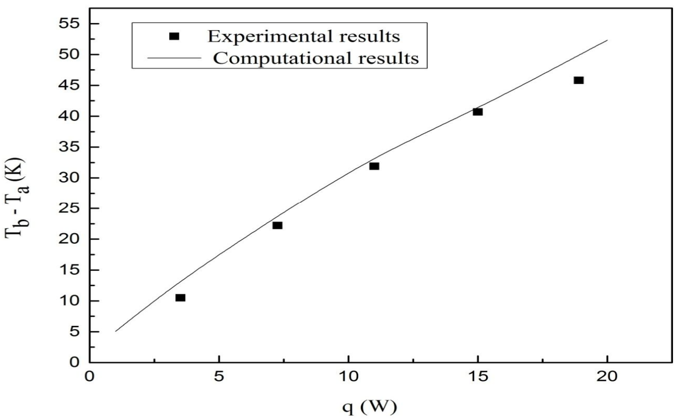

Fig. 3. *Comparison between experimental and computational results.*

Fig. 3 exhibits the temperature differences between the experimental and numerical results in terms of the heat input applied to the heat sink base. It can be shown that the agreement between the experimental and numerical data is good, when comparison was done. This implies that the present numerical model can accurately predict the natural convection flow around cylinderical heat sink with the longitudinal plate fins

Fig. 4 shows temperature contours at z = 0.01 m in xy plane .This contours exhibited more clearly to understand the temperature distributions in the cylindrical heat sink with the longitudinal plate fins.

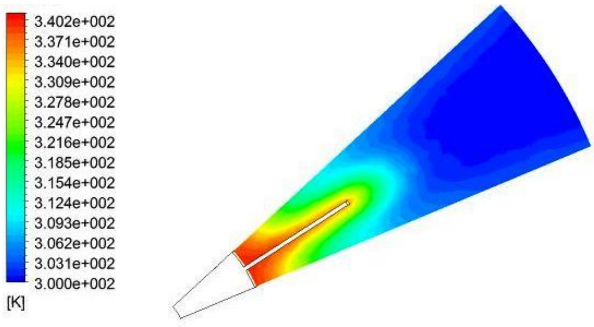

Fig. 4. *Temperature contours at at z = 0.01 m in xy plane*

3. RESULTS AND DISCUSSION

Parametric studies were reported by numerically investigating the effects of the number of fins, fin height, and heat input on the thermal resistance and the heat transfer coefficient for the heat sink array. The reference model is n = 18,D = 60 mm, L = 50 mm, H = 30 mm, t = 1 mm, and q = 15 W.

Fig. 5(a) exhibits the effect of the number of fins on the thermal resistance and heat transfer coefficient. The average heat transfer coefficient decreases as the number of fins increase due to overlap the boundary layer and the effective surface area increases, so the total surface area also increases. As a result, the minimum thermal resistance occurs. It can be shown that the thermal resistance of the heat sink decreased with increasing the number of fins (less than 36), since the effect of the heat transfer surface area was more impact than the effect of the decreased heat transfer coefficient. Also, when the number of fins was greater than 36, the thermal resistance of the heat sink increased significantly with increasing the number of fins, since the heat transfer coefficient was very small. Finally, optimum number of fins occurs which gives the minimum thermal resistance, and the performances of heat sink are enhanced.

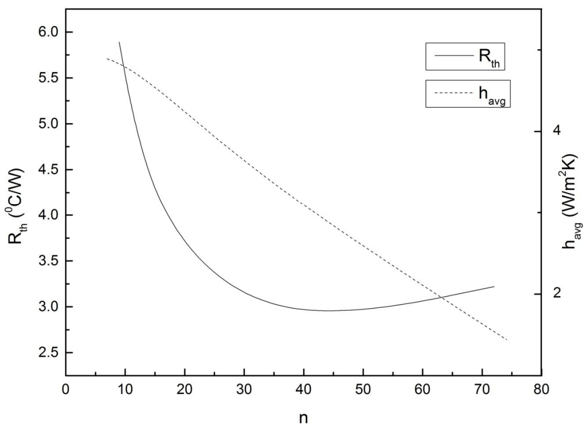

Fig.5 (a). *The effect of the number of fins.*

Fig. 5(b) shows the effect of the fin height. The thermal resistance decreases as the height of the fin increases because of the increased heat transfer surface area. Although, the variation in the heat transfer coefficient was comparatively small, since the air velocity entering from outer region increased significantly small with increasing fin height.

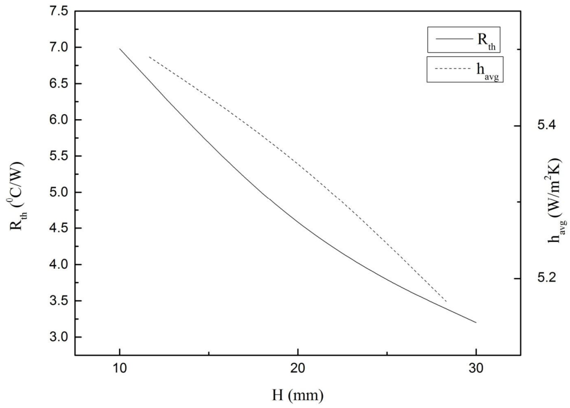

Fig.5 (b). The effect of the fin height

Fig. 5(c) exhibits the effect of the heat input applied to the heat sink base. The thermal resistance decreases with increases heat input owing to a more rising air velocity, which in result the flow rate of the cooler air entering from outer side increased. Also, the average heat transfer coefficient increased which showed to the enhanced effect of natural convection.

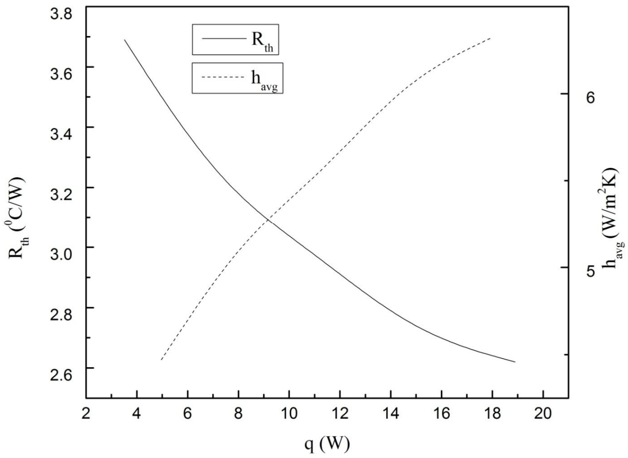

Fig.5 (c). The effect of the heat input

4. CONCLUSIONS

Natural convection from a horizontal cylindrical heat sink with the longitudinal plate fins was numerically investigated. It was comparing with experimental work, and showed a close agreement between them. Parametric studies were observed to compare the effects of the number of fins, fin height, and heat flux on the thermal resistance and the heat transfer coefficient. As the thermal resistance and heat transfer coefficient generally decreased with increasing the number of fins and fin height. Although, optimal values of the number of fins occurred to obtain an effective low heat sink temperature. The thermal resistance decreased and the heat transfer coefficient increased in proportion to the heat flux applied to the heat sink base.

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