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Optimization of Fins Arrangements for the Square Light Edding Diode (LED)

Cooling through Nanofluid-Filled Microchannel

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Abstract

In current paper, a finned micro-channel is designed for the cooling application in Light Edding Diode (LED), numerically. Selected materials for LED-chip is GaN, Die from Si, Die-attach is made by Au-20Sn, substrate is copper and heat sink material is considered to be Al. To make a convection heat transfer for cooling process, Al₂O₃-water nanofluid is used as the cooling fluid flow through the micro-channel and tried to maximize the heat transfer efficiency by optimized geometry. For this aim, there geometry variables from the microchannel were selected and minimum possible geometry cases (11cases) were proposed by Central composite design (CCD) and variables were optimized by the Response Surface Method (RSM). As a main result, parameter *B*, *i.e.* fin length had the most effect on the Nusselt number and Al₂O₃ nanoparticles with $\phi=0.01$ stated greatest heat transfer value.

Keywords: LED cooling; Al₂O₃-water nanofluid; Optimization; Finned Micro-channel; Response Surface Method.

1. Introduction

Light Edding Diode or LED lamps have taken the place of discharge lamps such as mercury discharge lamps [1, 2] and metal halide lamp[3, 4] due to better energy efficiency,

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small size, environmental friendliness, low UV radiation, easy control and low maintenance. So, due to this advantages of LED lamps, many researchers focused on its improvements and optimizations. For instance, Ben Salah and Ben Hamida [5, 6] investigated the heat transfer in LED geometries using air and PCM as alternative cooling materials. They also compared the results based on Ha and Graham [7] study for a chip-on-board packing of LED arrays with high power. So, Ben Hamida et al. [8] optimized some parameters such as: thickness, material and size of all subcomponents for single-chip LED to reduce the junction temperature and increase light output as well as device reliability. They considered six parts for the case modeling named die, die-attach, metallization, thermal interface material, substrate and heat sink to find the best material and concluded that GaN as LED-Chip material, SiC for Die material, Au as material metallization, 100In for Die-attach material, AlN DBC was the greatest substrate package, Copper for heat sink was the most suitable material and 100In solder as thermal Interface Material for designated parts. Also, other suitable materials are proposed by researchers such as CsPbBr₃ as the perovskite light emitting diodes proposed by Jia et al. [9]. Yu et al. [10] investigated the LED performance covered by cesium lead halide perovskite CsPbBr₃ through a small organic molecule material named 1, 3, 5-tri (m-pyrid-3-yl-phenyl) benzene (TmPyPB) as a chemical stabilizer. In an experimental study about the LED cooling, Pan et al. [11] used the cutting copper fiber oriented sintered heat sinks (CCFOSHS) and found that by decreasing the porosity, heat transfer efficiency of CCFOSHS was improved slightly, but pressure drops were increased, noticeably. Lin et al. [12] used the nanofluid-cooled microchannel heat sink for the light-emitting diodes (LEDs) and concluded that nanofluids reduced the thermal resistance more than 42.4% where 0.5% TiO₂ nanofluid

improved the heat transfer efficiency up to 38.6% compared to pure water. Another study on LED cooling improvements is performed by Lin et al. [13] using Taguchi parametric study for the micro-channel. Also, Huang and Wang [14] found the optimal fins geometry for the circular micro-channel of LED lighting heat sinks, numerically. They found that thermal resistance of systems for the optimum design were decreased by 16.8% and 11.0% than the “initial” and “Type 2” design heat sinks, respectively.

There are also some researchers focused on the novel designs for LED heat sink applications to improve the thermal managements. Wang et al. [15] designed novel tubular oscillating heat pipe with sintered copper particles for this application and reported that the temperature of LED array was inversely related to the illumination intensity. Tang et al. [16] developed an integrated heat sink with vapor chamber for LED thermal managements and showed that the high-power LED yields a favorable performance using proposed unit. Kim et al. [17] proposed the using copper-oxide (CuO) composite coating on aluminum-alloy heat sink to enhance the heat dissipation of LED module and observed good results due to the improved thermal radiation property. In a different study, Park et al. [18, 19] designed a chimney over a circular heat sink in a downlight LED and reported that installing chimney can increase the cooling efficiency of heat sink up to 20%. Microchannels not only is applicable for LED cooling, but also they are very useful instruments for thermoelectric generators [20], natural circulation loops [21] and etc. which different base fluids such as PCM [22] and nanofluids [23] are widely used to improve their performance.

Nanofluids due to improvements thermal properties have wide applications and motivated researchers to use them in various aspects. Ben Hamida et al. [24] used Ethylene

Glycol-Copper Nanofluid under magnetic fields in an enclosure. Ben Jaballah et al. [25] applied the hybrid nanofluid for the performance enhancement of bubble absorber for cooling applications. Hatami and Ganji [26], Hatami et al. [27] and Tang et al. [28] used the nanofluid in porous media between two coaxial cylinders, wavy microchannel and wavy cavity, respectively. Also, Hatami et al. [29-32] used the optimization techniques such as Response Surface Methodology (RSM) to find the optimize geometries including nanofluids in heat transfer applications. Massoudi et al. [33, 34] also investigated the nanofluids application in free convection under the influence of magnetic field.

Based on discussed short literature review, here it is tried to enhance the cooling efficiency of a LED by using the Al_2O_3 -water nanofluid and finned arrangements in a microchannel, simultaneously. Also, RSM is used to find the optimized dimensions for the fin numbers, lengths and thicknesses, numerically.

2. Problem Description

A 3D microchannel filled by Al_2O_3 –water nanofluid is considered as shown in Fig. 1 for LED cooling by fin arrangements. Microchannel dimensions are: Height = 100 mm; Width = 80 mm and Depth = 50 mm and the Power of LED = 1, 2 and 3W as shown in Table 1 in details. The velocity of inlet of nanofluid was considered as 0.001 m/s where the temperature of inlet of nanofluid considered to be 25 °C. The micro-channel is equipped with fin arrangements for better cooling performance. The main objective of current research is finding the optimum values for fin numbers, lengths and thicknesses, respectively as shown in Fig. 1 for the micro-channel geometry. For modeling the problem, a transient flow, incompressible three-dimensional flow from the laws of conservation of

mass, momentum, and energy is considered. The governing equations represent the transient flows are [8]:

Mass conservation equation:

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho u)}{\partial x} + \frac{\partial(\rho v)}{\partial y} + \frac{\partial(\rho w)}{\partial z} = 0 \quad (1)$$

Where ρ refers to the mass density and u, v, and w represent the velocities according to x, y, and z, respectively.

Momentum conservation equation according to x:

$$\frac{\partial(\rho u)}{\partial t} + \frac{\partial(\rho uu)}{\partial x} + \frac{\partial(\rho uv)}{\partial y} + \frac{\partial(\rho uw)}{\partial z} = -\frac{\partial p}{\partial x} + \left[\frac{\partial}{\partial x} \left(\eta \frac{\partial u}{\partial x} \right) + \frac{\partial}{\partial y} \left(\eta \frac{\partial u}{\partial y} \right) + \frac{\partial}{\partial z} \left(\eta \frac{\partial u}{\partial z} \right) \right] \quad (2)$$

Momentum conservation equation according to y:

$$\frac{\partial(\rho v)}{\partial t} + \frac{\partial(\rho uv)}{\partial x} + \frac{\partial(\rho vv)}{\partial y} + \frac{\partial(\rho vw)}{\partial z} = -\frac{\partial p}{\partial y} + \left[\frac{\partial}{\partial x} \left(\eta \frac{\partial v}{\partial x} \right) + \frac{\partial}{\partial y} \left(\eta \frac{\partial v}{\partial y} \right) + \frac{\partial}{\partial z} \left(\eta \frac{\partial v}{\partial z} \right) \right] + \rho g \quad (3)$$

Momentum conservation equation according to z:

$$\frac{\partial(\rho w)}{\partial t} + \frac{\partial(\rho uw)}{\partial x} + \frac{\partial(\rho vw)}{\partial y} + \frac{\partial(\rho ww)}{\partial z} = -\frac{\partial p}{\partial z} + \left[\frac{\partial}{\partial x} \left(\eta \frac{\partial w}{\partial x} \right) + \frac{\partial}{\partial y} \left(\eta \frac{\partial w}{\partial y} \right) + \frac{\partial}{\partial z} \left(\eta \frac{\partial w}{\partial z} \right) \right] \quad (4)$$

In above equations, p denotes the pressure, g shows the gravity, and η is related to the dynamic viscosity.

Energy conservation equation:

$$\frac{\partial(\rho CT)}{\partial t} + \frac{\partial(\rho uCT)}{\partial x} + \frac{\partial(\rho vCT)}{\partial y} + \frac{\partial(\rho wCT)}{\partial z} = \left[\frac{\partial}{\partial x} \left(\lambda \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left(\lambda \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left(\lambda \frac{\partial T}{\partial z} \right) \right] \quad (5)$$

Where, T and C are the temperature and the specific heat capacity, respectively and λ is the thermal conductivity.

The practical boundary conditions are assumed as follows:

- There is a uniform heat flux on top of the die, and other surfaces are adiabatic.

- The microchannel inlet boundary condition is considered to be the uniform temperature of T_{in} with a uniform velocity of U_{in} .
- At microchannel outlet, Pressure outlet boundary condition with zero gradients is assumed.
- No slip condition is imposed on the surface of microchannel walls.
- All the microchannel outer walls are insulated.

In this study, the thermal conductivity of the materials used in the LED package as well as the water properties are considered dependent on temperature [8]. For water temperature-dependent properties:

a) Dynamic viscosity:

273.15 K < T < 473.15 K :

$$\eta = 1.3799566804 - 0.021224019151 \cdot T + 1.3604562827 \cdot 10^{-4} \cdot T^2 - 4.6454090319 \cdot 10^{-7} \cdot T^3 + 8.9042735735 \cdot 10^{-10} \cdot T^4 - 9.0790692686 \cdot 10^{-13} \cdot T^5 + 3.8457331488 \cdot 10^{-16} \cdot T^6 \quad (6)$$

473.15 < T < 553.15 K :

$$\eta = 0.00401235783 - 2.10746715 \cdot 10^{-5} \cdot T + 3.85772275 \cdot 10^{-8} \cdot T^2 - 2.39730284 \cdot 10^{-11} \cdot T^3 \quad (7)$$

T in K and dynamic viscosity in Pa.s

B) Thermal Capacity:

273.15 < T < 553.15 K

$$C = 12010.1471 - 80.4072879 \cdot T + 0.309866854 \cdot T^2 - 5.38186884 \cdot 10^{-4} \cdot T^3 + 3.62536437 \cdot 10^{-7} \cdot T^4 \quad (8)$$

T in K and Thermal Capacity in J/(kg*K)

D) Mass density

273.15 < T < 293.15 K

$$\rho = 950.704055329848 - 0.000063092789034 \cdot T^3 - 0.060367639882855 \cdot T^2 + 18.9229382407066 \cdot T \quad (9)$$

293.15 < T < 373.15 K

$$\rho = 0.000010335053319 \cdot T^3 - 0.013395065634452 \cdot T^2 + 4.969288832655160 \cdot T + 432.257114008512 \quad (10)$$

T in K and mass density in kg/m³

E) Thermal conductivity

273.15 < T < 1000 K

$$\lambda = -0.869083936 + 0.00894880345 \cdot T - 1.58366345 \cdot 10^{-5} \cdot T^2 + 7.97543259 \cdot 10^{-9} \cdot T^3 \quad (11)$$

T in K and Thermal conductivity in W/(m*K). For the nanofluid properties, following equations are applied [35]:

$$\rho_{nf} = (1 - \phi) \rho_{bf} + \phi \rho_p \quad (12)$$

$$C_{p_{nf}} = \frac{(1 - \phi)(\rho C_p)_{bf} + \phi(\rho C_p)_p}{\rho_{nf}} \quad (13)$$

$$\frac{k_{nf}}{k_{bf}} = 0.991 + 0.276T\phi + 77.6\phi^2 + 3641.231T\phi^2 + \frac{0.00217}{\sin(T - \phi)} - 6.01 \times 10^{-6} T^2 - 3647.099T\phi \sin(\phi) \quad (14)$$

$$\mu_{nf} = \mu_{static} + \mu_{Brownian} \quad (15)$$

$$\mu_{nf} = \frac{\mu_f}{(1 - \phi)^{2.5}} + 5 \times 10^4 \beta \phi \rho_f (C_p)_f \frac{\mu_f}{k_f \text{Pr}} \sqrt{\frac{k_b T}{\rho_p d_s}} f(T, \phi) \quad (16)$$

where

$$f(T, \phi) = (2.8217 \times 10^{-2} \phi + 3.917 \times 10^{-3}) \left(\frac{T}{T_0} \right) + (-3.0669 \times 10^{-2} \phi - 3.91123 \times 10^{-3}) \quad (17)$$

$$\beta = 8.4407 (100\phi)^{-1.07304} \quad (18)$$

3. Methodology of Solution

In this study, COMSOL-Multiphysics 5.4 commercial finite element method (FEM) software is applied for the modeling of problem. FEM is a numerical method to discretize and solve the coupled partial differential equations governed on any physical phenomenon. FEM by COMSOL not only is accurate and adaptable, but also it is simple in modeling the

complicated physics as well as the time-dependent simulation of physical problems in environment, chemical, energy, electrical, heat transfer and other multi-physic problems. Actually, FEM with COMSOL can help the user to solve the problems with multi-physic such as electrical-mechanical systems easily, while the solution of these problems by other commercial software (such as FVM based ANSYS-FULENT) or by hand is not possible [8]. During the modeling process, user must define the boundary conditions after the geometry modeling to show the conditions which must be responded during the solution. Boundary conditions can be defined as the distributed forces, point forces, positional constraints and thermal effects such as temperature changes or applied heat energy. Additionally, the FEM user can certainly spot any vulnerability in design with the complete visualizations FEM produces and then use the novel data to have a new design [8].

Central Composite Design or CCD is a technique of Design of Experiment (DoE) to achieve the suitable points of each independent variable based on their possible values (level). CCD contains an imbedded factorial or fractional factorial design with center points which is improved by a “star points” group and let’s estimate of curvature. After introducing the minimum number of cases with CCD, RSM must be applied to find the optimum values for the fin numbers, lengths and thicknesses. Actually, RSM find a first or second-order polynomial relation between the response (here temperature) and independent variables (fin numbers, lengths and thicknesses). This polynomial equation consider the interaction between the and surface curvatures and fitted in the shape of [31, 32]

$$y = A_0 + \sum_{i=1}^n A_i x_i + \sum_{i=1}^n A_{ii} x_i^2 + \sum_{i=1}^n \sum_{j=1}^n A_{ij} x_i x_j \Big|_{i < j} \quad (19)$$

where x_i and x_j indicate the geometry independent variables (fin numbers, lengths and thicknesses) and A is the coefficient of polynomial equation. The essential parameter for RSM optimization is “Desirability” which returns the desirable ranges of responses (d_i). Actually, objective function can be altered from zero outside of the limits to unity at the aim and the point with the maximum desirability function by following equation is the optimized case obtained by numerical solutions:

$$D = (d_1 \times d_2 \times \dots \times d_n)^{\frac{1}{n}} = \left(\prod_{i=1}^n d_i \right)^{\frac{1}{n}} \quad (20)$$

where n indicates the number of responses. If each of responses or factors drops outside their desirability range, the overall function will be zero. More details about this optimization method can be found in [31, 32].

4. Results and Discussions

As described in above sections, it is tried to obtain an optimized geometry for the nanofluid microchannel for LED cooling. Dimensions of LED package as well as the materials are presented in Table 1. Based on previous study in [8], the best materials for LED-chip is GaN, Die from Si, Die-attach is made by Au-20Sn, substrate is copper and heat sink material is considered to be Al. LED had 1, 2 and 3 W power and the microchannel dimensions was Height = 100 mm; Width = 80 mm and Depth = 50 mm. In order to find a suitable mesh grid, numerous mesh numbers (from extremely coarse to finer mesh) were used for this 3D model as demonstrated in Table 2. This values confirm that fine mesh is a suitable grid type for this study due to its accuracy and acceptable time of

calculations. Here, CCD is applied to have the proposed geometries for the considered parameters as shown in Table 3. Fin number, fin diameter and fin thicknesses are three main parameters under the study which their levels are presented in Table 3. CCD proposed 11 cases as shown in Table 4 in details.

To validate our generated 3D model with the previous model of Ha and Graham [7], the temperature distribution of the LED package is simulated with the equivalent settings modeled by Ha and Graham [7] as presented in Fig. 1 and generated mesh is depicted in Fig. 2. Fig. 3 shows the 3D model simulated by Ha and Graham [7] using the commercial ANSYS-FLUENT software where Power of LED lamp was 1W, heat transfer coefficient was $10 \text{ W/m}^2/\text{K}$ and the temperature of ambient was 25°C . From the Fig. 3 (a,b) it can be observed that current code has similar results where the minimum and maximum temperatures are around 53.22°C and 60.37°C , respectively for both methods. Actually a minor temperature difference between the two models is existed which does not exceed than 0.001%. Also, the vertical temperature profile along the LED package centerline is plotted in Fig. 3 (c), which a good agreement between current 3D COMSOL-Multiphysics model and 3D ANSYS-FLUENT model of Ha and Graham [7] was evident.

Figs. 4, 5 and 6 show the temperatures, velocities and streamlines of nanofluid in both LED and microchannel domains and the results of junction temperature for three LED powers (1, 2 and 3 W) of all 11 designed cases are shown in Table 5 at final time, $t=620\text{s}$. Fig. 7 and Fig. 8 shows the 2D contours of velocity and streamlines of 11 cases, respectively. It can be observed that cases 6, 8 and 9 due to greater fin numbers (8 fins) has more compact microchannel and the velocity between the fins is smaller. But for the cases 2, 3 and 5 nanofluids easily flow between the fins due to more free spaces. So, this

parameter has an important role in heat transfer. Also, the cases which have lengthy fins (Cases 1, 5 and 9) have smaller region of maximum velocity in micro-channel (red area) due to making obstacles against the flow. Because these three parameters has influence on each other, a parametric study is required to find the most important parameter among them. Fig. 9 shows the average temperatures during the time for $P=3W$. Cases 3, 10 and 6 have maximum temperatures (worst cooling performance) and cases 9, 1 and 5 have the minimum temperatures or best cooling performances. From Table 4 it can be seen that Cases 3, 10 and 6 are in lowest level of fin length, while cases 9, 1 and 5 are in upper level of fins length. Fig. 10 and Fig. 11 also present the temperatures during the time when LED power is 2W and 1W, respectively which confirm the same results. Also, it can be found that number of fins is the next important parameter while the fins thickness is the last parameter due to its small effect of the cooling performance. Fig. 12 shows these descriptions in 2D and 3D contours to find the effect of each parameter on the results. As seen, slope of curves and surfaces for the parameter B is greater than parameter A and greater than parameter C . Also the minimum temperatures (best cooling) is occurred when all the parameters are in upper levels, so desirability function of optimized case in Fig. 13 is depicted which illustrate that better case (desirability=1) occurs when $B=20$ and $A=8$. Based on these results, RSM proposed the best cases which is presented in Table 6 as optimized geometries. Fig. 14 compares the Nusselt number and pressure drops of all cases. Since the pressure drops are very small, so they can be negligible in optimization and single objective is performed for this case of study. The results of optimized case is depicted in Fig. 15, while the effect of different nanoparticles volume fraction is presented in Fig. 16

which says that smaller nanoparticles volume fraction has greater Nusselt number due to temperature dependent properties of base water.

5. Conclusion

In this study, the geometry of a finned microchannel is optimized for application in LED cooling by nanofluids, numerically. COMSOL-Multiphysic commercial code was used and Al_2O_3 -water as the cooling nanofluid flow was selected as the working fluid. Three powers (1, 2 and 3W) are used for the LED power output and to find the optimized arrangement of fins for reaching the minimum temperature (as cooling efficiency), Central composite design (CCD) was applied to propose minimum possible geometries (11 Cases). Finally, FEM results of modeling were optimized by the Response Surface Method (RSM) which confirmed that the optimized case include parameters as Fin numbers=8, Fin length=20 and Fin thickness=4 where nanoparticles with $\phi=0.01$ caused maximum cooling efficiency for this case.

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Tables and Figures

Table 1. Properties of dimensions and materials of LED package

	Thickness	Size	Materials
LED-chip	4 μm	1 mm $\times$ 1 mm	GaN
Metallization:	10 μm		Au-Si eutectic bonding
Bonding Layer			
Die	375 μm		Si
Die-attach	50 μm		Au-20Sn
Substrate	127 μm	1 cm $\times$ 1 cm	Copper
	381 μm		AlN
TIM	50 μm	1 cm $\times$ 1 cm	Thermal grease
Heat sink	-	-	Al

Table 2. Mesh independency of the micro-channel

Predefined mesh size	Mesh elements	Junction Temperature (°C) (max. temperature)	Temperature of Heat sink (°C) (min. temperature)
Extremely coarse	3641	60.165	52.416
Extra coarse	6019	60.231	52.623
Coarser	10766	60.254	52.794
Coarse	17989	60.273	52.931
Normal	26436	60.289	53.087
Fine	45255	60.370	53.222
Finer	136857	60.968	53.568

Table 3 Geometry parameters of fins arrangement for microchannel and defined levels

Parameter	Description	Level 1	Level 2	Level 3
A	Fin number	4	6	8
B	Fin Length	10	15	20
C	Fin thickness	2	3	4

Table 4 CCD proposed cases for finned geometry with Power of LED = 1, 2 and 3W
Microchannel dimensions: Height = 100 mm; Width = 80 mm and Depth = 50 mm

Case Number	Level of parameters		
	Parameter, A	Parameter, B	Parameter, C
1	6	20	3
2	4	15	3
3	4	10	2
4	6	15	3
5	4	20	4
6	8	10	4
7	6	15	2
8	8	15	3
9	8	20	2
10	6	10	3
11	6	15	4

Table 5 Results of final temperature (t=620s) for designed geometries

Case	P=1W	P=2W	P=3W
1	25.52701	26.05767	26.58474
2	25.74088	26.50567	27.26295
3	26.05708	27.14766	28.22671
4	25.68918	26.38428	27.07537
5	25.83996	26.11025	26.66800
6	25.75795	26.69111	27.53490
7	25.62041	26.52071	27.27858
8	25.51977	26.24666	26.86830
9	25.95494	26.04184	26.56050
10	25.64296	26.92147	27.88059
11	25.54928	26.29494	26.94251

Table 6 Optimized geometry proposed by RSM

Number	A	B	C	
1	8	20	4	Selected
2	8	19.64	3.89	
3	6	19.83	3.17	
4	8	18.84	2.63	
5	8	19.06	2.51

Fig. 1 (a) Structure of the LED package; (b) Sample Dimensions of heat sink, (c) Geometry of LED cooling by finned micro-channel filled by nanofluid

Fig. 2 Mesh generated in the domain and LED finned section

Fig. 3 Temperature distribution of the LED package: (a): Our 3D code (b): Ha and Graham code [7] (c), Comparison of vertical temperature profile along the center line (z axis) [8].

Fig. 4 Temperature contours for the finned micro-channel of different geometries (11 Cases)

Fig. 5 Velocity contours for the finned micro-channel of different geometries (11 Cases)

Fig. 6 Streamline contours for the finned micro-channel of different geometries (11 Cases)

Fig. 7 2D Velocity contours for the finned micro-channel of different geometries (11 Cases)

Fig. 8 2D Streamline contours for the finned micro-channel of different geometries (11 Cases)

(a)

(b)

Fig. 9 Average Temp. when $P= 3\text{W}$ for different 11 cases a) complete view, b) zoomed view

(a)

(b)

Fig. 10 Average Temp. when $P= 2W$ for different 11 cases a) complete view, b) zoomed view

Fig. 11 Average Temp. when $P=1\text{W}$ for different 11 cases a) complete view, b) zoomed view

Fig. 12 2D and 3D contour of geometry parameters on temperature

Fig. 13 Desirability function of optimized geometry

(a)

(b)

Fig. 14 a) Nusselt number b) Pressure drops graphs for $P=3W$ for all designed cases

Fig. 15 Velocity, temperature and streamline for optimized case

Fig. 16 Effect of different nanoparticles concentration on Nusselt number of the optimized case

Figures

Figure 1

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Figure 2

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Figure 5

Velocity contours for the finned micro-channel of different geometries (11 Cases)

Figure 6

Streamline contours for the finned micro-channel of different geometries (11 Cases)

Figure 7

2D Velocity contours for the finned micro-channel of different geometries (11 Cases)

Figure 8

2D Streamline contours for the finned micro-channel of different geometries (11 Cases)

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Average Temp. when $P= 3\text{W}$ for different 11 cases a) complete view, b) zoomed view

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(b)

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Average Temp. when $P = 2W$ for different 11 cases a) complete view, b) zoomed view

(a)

(b)

Figure 11

Average Temp. when P= 1W for different 11 cases a) complete view, b) zoomed view

Figure 12

2D and 3D contour of geometry parameters on temperature

Figure 13

Desirability function of optimized geometry

Figure 14

a) Nusselt number b) Pressure drops graphs for P=3W for all designed cases

Figure 15

Velocity, temperature and streamline for optimized case

Figure 16

Effect of different nanoparticles concentration on Nusselt number of the optimized case