IREEE

International Journal of
Advanced Thermofluid Research

ISSN 2455-1368
www.ijatr.org

Experimental Investigation of Heat Transfer Enhancement in Grooved Plates under Natural Convection

Abdul Razak R. Kaladgi [1*], G. Ramachandran [2], Mohammed Aneeque [1], Fazlur Rahman [3] Mohammed Kareemulla [1], Mohammed Avvad [1], Navaneeth I. M. [1], Rayid Muneer [1] and Chandrasekhar A [4]

[1]P. A. College of Engineering (Affiliated to Visvesvaraya Technological University, Belgaum), Mangalore, India.
[2]B Vinayaka Mission's Kirupananda Variyar Engineering College, Vinayaka Mission's Research Foundation (Deemed to be University), Salem, Tamil Nadu, India.
[3]Anjuman Institute of Technology and Management, Bhatkal, India.
[4]Bangalore Institute of Technology, Bangalore, India.

Abstract

Due to the extreme miniaturization of devices, enhancing the heat transfer rate has been a challenging task in the electronic industry. Several researchers have conducted experiments to gain maximum heat transfer rate in small spaces. So, the current study focuses mainly on improving the thermal dissipation characteristics from the surface by creating grooves across the substrate of aluminium plates with different ranges of length to depth (L/D) ratio and width to depth (W/D) ratios. The experiment was conducted by varying the heat flux under steady state with free convection conditions. It was seen from the experiments that the L/D ratio and W/D ratio have significant effect on heat transfer rate and friction factor. The Response Surface Methodology gave a good prediction of the interaction factors. A large value of R2adj (0.9981) was projected. This result suggests that the designated model can signify 99.81 per cent of the total variation on Nusselt number data. The "Lack of Fit F-value" of 0.74 indicates that the lack of fit compared to the pure error is not significant. It could be concluded that heat transfer enhancement does occur with the creation of grooves on surfaces but at the cost of pumping power.

Keywords
Miniaturization •
Groove •
Augmentation •
Natural Convection.

Received
Sep 26, 2019
Revised
Oct 28, 2019
Accepted
Nov 20, 2019
Published
Dec 29, 2019

***Corresponding email**: arkmech9@gmail.com (Abdul Razak R. Kaladgi).

DOI: https://doi.org/10.51141/IJATR.2019.5.1.3

1. Introduction

Heat transfer analysis of flat vertical plates (with and without heat generation) has gained significant interest in the recent past since they are extensively used in many engineering systems such as vertical electronic board, other electronic devices, nuclear applications, and plate heat exchangers (Abdul Razak et al., 2018; Afzal et al., 2017, 2019; Afzal, Kareemullah, et al., 2018; Afzal, Mohammed Samee, Abdul Razak, & Ramis, 2020; Afzal, Mohammed Samee, Abdul Razak, Khan, et al., 2020; Afzal, Samee, et al., 2018, 2020, 2020; Akthar et al., 2015; Kaladgi et al., 2020; Rahiman et al., 2014; Samee AD et al., 2018) . If enhancement in the heating or cooling cycle is needed, improved design of the compactness of the plate and spatial dimension is very much necessary. For this purpose, the heat transfer augmentation techniques have become very popular in the recent years. The main aim of these augmentation techniques is to minimize the dimension and cost of the devices. These techniques can be divided into active and passive augmentation techniques. Active augmentation is less popular since additional source needs to be applied to induce a desired change in flow. Passive augmentation, on the other side, comprises of modification of the substrate surface or integration of a system whose existence leads to the alteration of the flow field(Afzal, Saleel, et al., 2020; Rogovyi et al., n.d.) . The implementation of grooves is one of the most common improvements. The obvious benefit of grooved plates is that they enhance the rate of heat transfer by having extra contact area.

Given the above evidence, the literature is rare on the flat plate with grooves. Dixit & Patil, (2015) conducted experiments on various types of grooves built on extended surfaces and observed that the transmission of heat was more for fins that had angled grooves (Dixit & Patil, (2015). Chang et al. (2004) performed an experimental analysis on fin channels with 900 ribs to study the effect of Reynolds number and L/B on heat transfer rate. They also established a correlation and proposed the optimal L/B ratio required to enhance the heat flux. The authors found that using 900 ribs, the heat transfer enhancement was up to 140–200 percent. An experiment was carried out on tubes containing grooves of different geometry by Bilen et al. (2009). The L/D ratio was kept constant throughout the experiments. They primarily established a relation for heat transfer and friction factor. Their analysis showed that significant heat transfer improvement occurred for tubes with grooves relative to tubes without grooves. Free convection through 2D vertical plates containing rectangular grooves was explored experimentally and numerically by Kwak and Song (1998). In their test set-up, a Mach-Zehnder interferometer has been used and the local Nusselt number was quantitatively determined from the interferograms for each groove surface (external, underside, internal and upper surface). The influence of the Rayleigh number was analysed for each aspect ratio. Using the mean Nusselt number vs Rayleigh number relations, the findings were summarized (Afzal et al., 2017; Pinto et al., 2017). These relations could be used to choose the correct aspect ratio and size. The influence of free convection on the cooling of vertical flat board with spherical grooves was analyzed by Sakai et al. (2010). In their test set-up, two flat plates, one having periodic groves and another without periodic grooves were tested. They plotted the heat transfer features of both the plates. They found that heat transfer due to free convection is suppressed by using grooved plates. The thermal performance features in the channel provided with grooves on one surface were computationally analyzed by Ghaddar et al. (1986). They computationally solved the N-S and energy equations and displayed complicated flow behavior of separation of the flow, recirculation flow, etc. Xinyi and Dongsheng (2012) performed experimental and numerical research on rectangular channels attached with grooves and ribs. To solve the equations and do the further computations, they employed the SST turbulence model. In contrast to the channels having just ribs, they observed that the Nu ratio and C_f were high for the channels having ribs and grooves. An experiment was performed by Layek et al. (2007) to examine the influence of heat transfer on a duct that has ribs and grooves on one side. Compared to plain surface, they found a rise in Nu by around 3.24 times. Al-Shamani et al. (2015) analysed the heat transfer features of a channel attached with ribs and grooves on one surface using a numerical approach. The STD K-epsilon turbulence model was used to crack the governing equations. They used different types of ribs and grooves along with nanofluids to carry out the analysis. They found highest heat transfer in a groove of trapezoidal shape. Eiamsa-Ard and Promvonge (2009) carried out an experimental study to find thermal performance features in a duct having 3 types of grooves. A heat transfer enhancement was found for the duct having groves as compared to plain duct.

It is clear from the literature review that grooves play a very important role in the enhancement of heat transfer. So, this paper focusses on the enhancement of convective heat transfer of vertical plates having rectangular grooves.

2. Description of the experimental setup

In this research, a simple natural convection set-up was designed as shown in Figure 1. It is made up of a rectangular duct with dimensions of 260 × 150 ×310 (in mm), open at both ends. A clamp was provided on one side of the hollow duct to support the wooden box that holds the heater and test plates in a vertical position. The pressure-drop occurring during the air flow inside the channel was measured by a digital manometer (accuracy ±0.5%) to calculate the friction factor. The test-plates were produced from aluminium and rectangular grooves of various lengths of 25 mm, 50 mm, 75 mm, and 100 mm were created on each of them with the assistance of CNC machine. The plate was of 100 mm in length, 60 mm in width and 10 mm in thickness. The breadth of the groove was 10 mm. Figure 2a and Figure 2b represent the four plates used for the present analysis. In these figures, the cross symbol (X) indicates the measurement points for the temperature.

Figure 1: The experimental setup.

2.1 Uncertainty analysis

Uncertainty in the experiment was estimated considering the accuracies of all the measuring equipment's by using the method described by Moffat (1988), as given in Table 1.

Table 1. Uncertainties of different parameters

Parameter	Uncertainty
Heat transfer coefficient	±6---±11
Overall heat transfer coefficient	±2---±05
Nusselt number	±3---±08

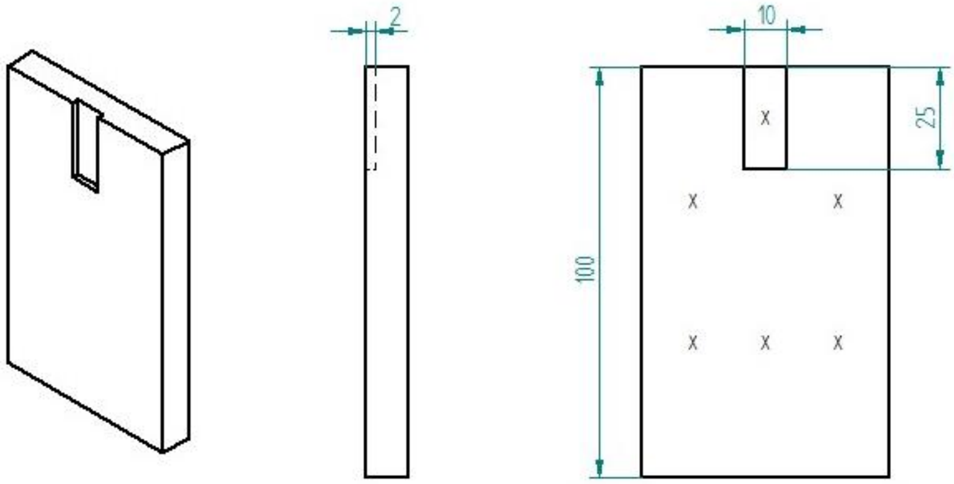


Figure 2a. Schematic diagram of plate 1 with location of equidistant thermocouples (shown by cross). All dimensions in mm.

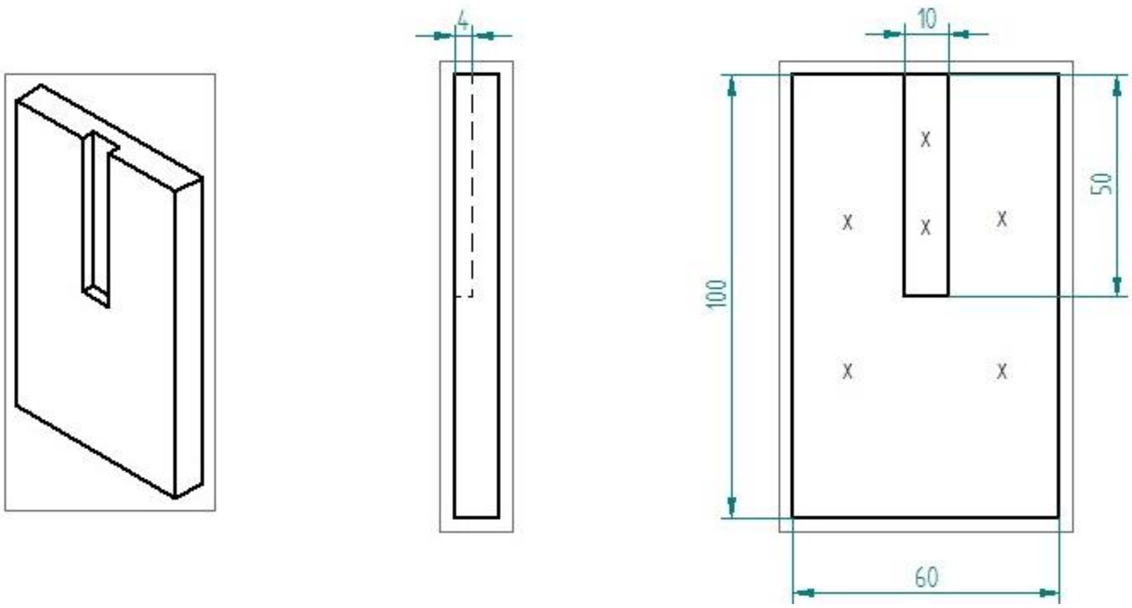


Figure 2b. Schematic diagram of plate 2 with location of equidistant thermocouples (shown by cross). All dimensions in mm.

Figure 3. Pictorial view of Four Test Plates Used.

3. Results and Discussion

In this paper, an experimental analysis was carried out to find the various thermal performance features of flat vertical plate having grooves of different aspect ratio. The experiment was conducted by varying the W/D ratio and L/D ratio, under steady state conditions in natural convection mode by varying the heat flux.

3.1 Variation of Nusselt number different W/D and L/D ratio.

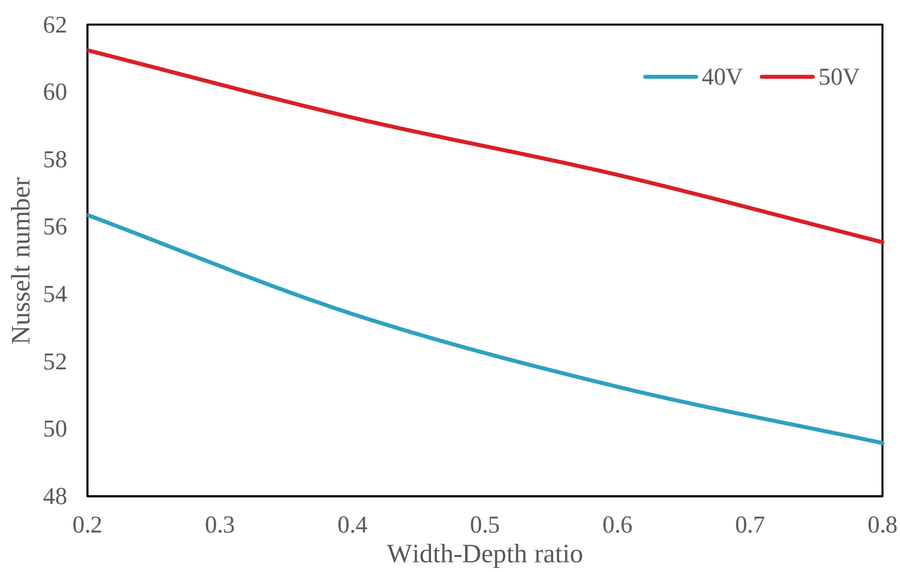


Figure 4. Nusselt number Vs. W/D ratio.

Figures (4) and (5) depict the impact of the W/D ratio and L/D ratio on the plate *Nu*, for various heat flux inputs. It was noted that the *Nu* raised as the depth of the groove increased. This is due to intense flow impingement on the downstream boundary and enhanced flow mixing at the downstream by vortices. The development of vortex pairs regularly shedding off the grooves, a wide wash area with some liquid coming from the central regions of the grooves were the key factors of augmentation of *Nu* and was more prominent around the downward rims of the dimples (Zhang et al., 2014). It was also seen that the values of *Nu* were high when heat flux was high.

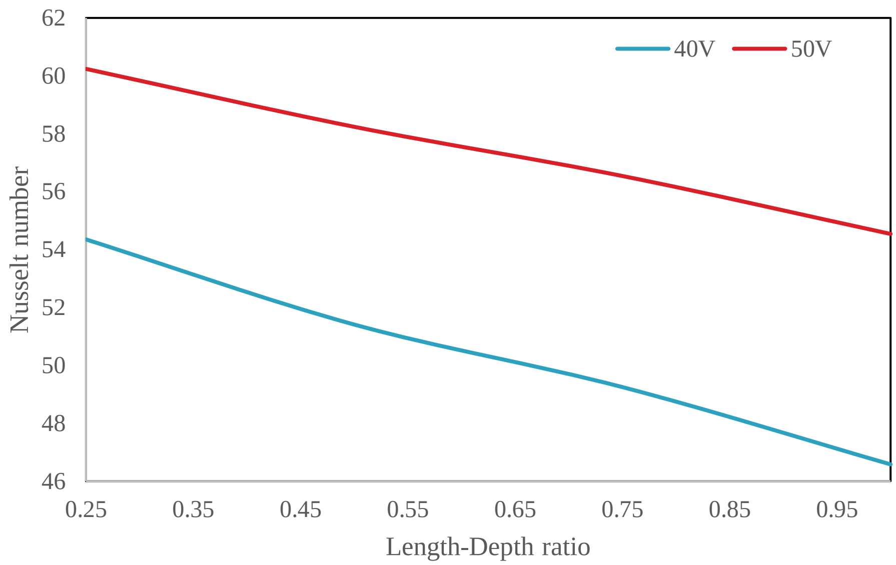


Figure 5. Nusselt number Vs. L/D ratio.

3.2 Variation of Grashoff number for different W/D and L/D ratio

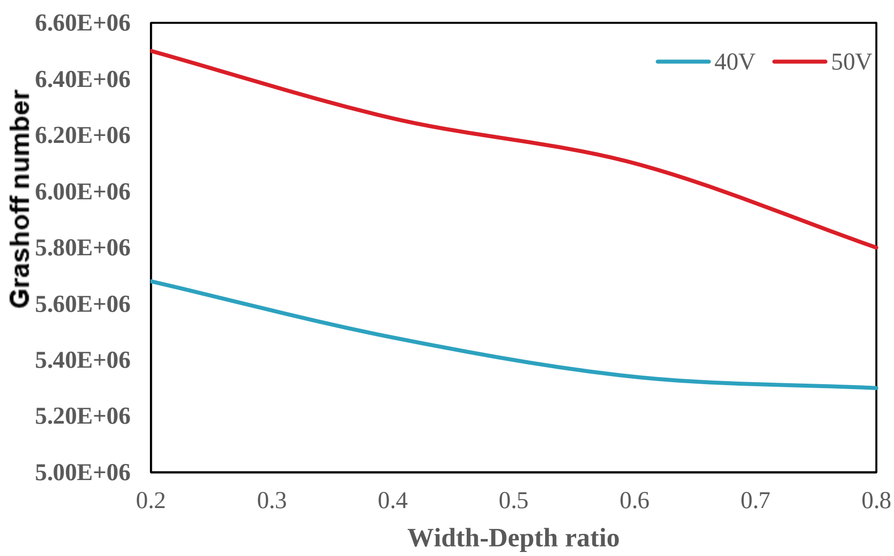


Figure 6. Grashoff number Vs. D/W ratio.

Figure 6 and Figure 7 show the variation of Grashoff number with W/D and L/D ratios for two types of heat flux input. For all cases, with increase in the depth of the groove, the Grashoff number increased, which leads to an increase in heat transfer rate. It is also evident from the graphs that Grashoff number was high for Figure 7 as compared to Figure 6, indicating that the L/D ratio is a prominent factor in increasing the Grashoff number and hence the heat transfer rate.

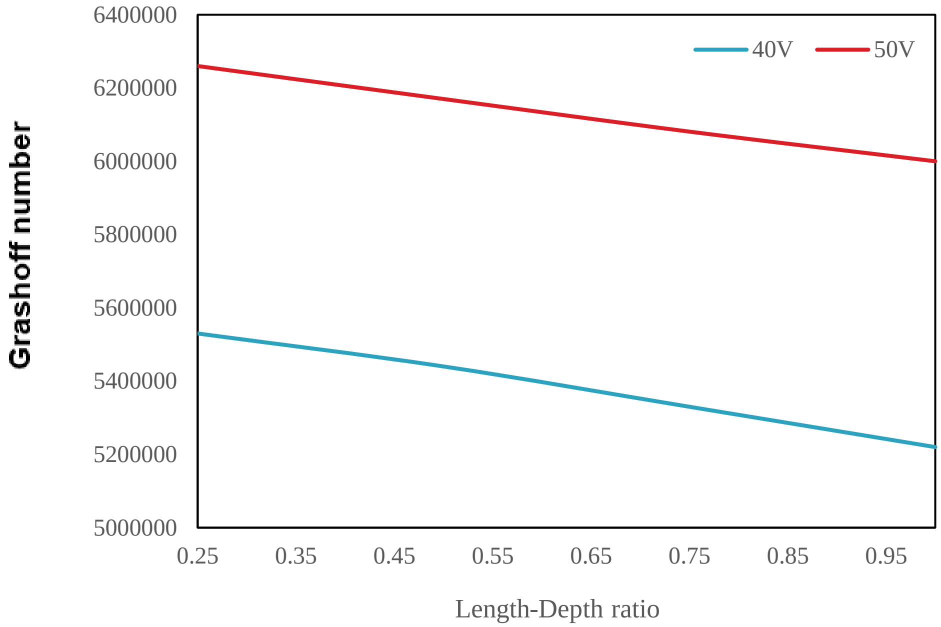


Figure 7. Grashoff number Vs. L/W ratio.

3.3 Variation of friction factor with Grashoff number

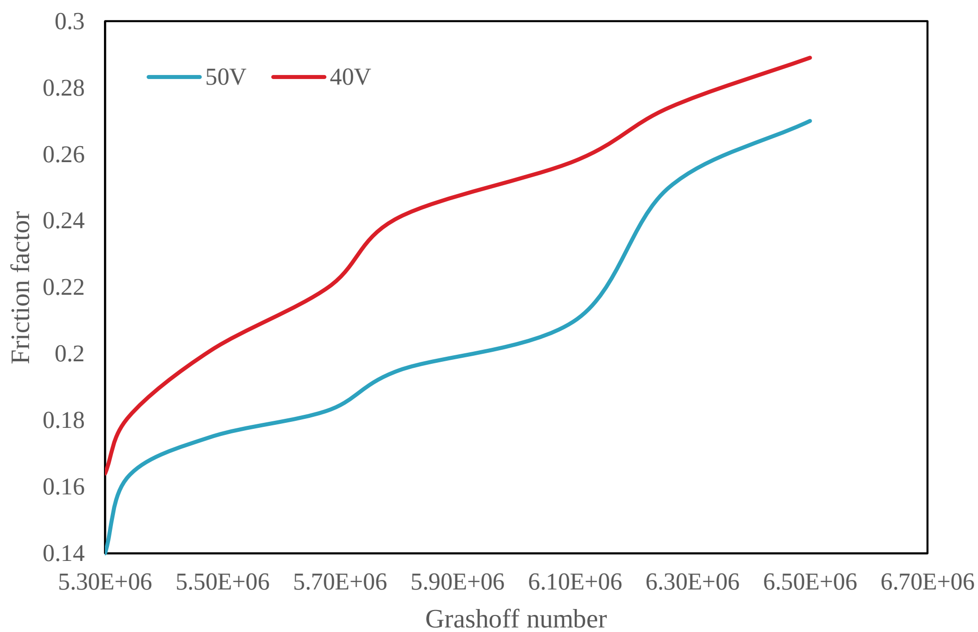


Figure 8. Variation of friction factor with Grashoff number.

Figure 8 shows the variation of friction factor with Grashoff number. The friction factor increased as Grashoff number increased. Similar nature was observed when the heat flux was increased. As fluid get circulated through the grooved surface, the re-circulation caused the fluid to lose energy, resulting in an enhanced drop in pressure and hence increased friction.

3.4 CCD studies

Three significant parameters, W/D ratio, L/D ratio, and Voltage (V) (Table 1), were proposed as input in the present research (Table 2). Consequently, the independent variables were designated as A, B, and C, while the non-dimensional Nusselt number and Grashoff number were chosen as the response (dependent) variables. As suggested by the design, the final *CCD* acquired for the Nusselt number and Grashoff number with important terms was quadratic and is given in Eq. (1).

Regression equation:

NU= -132.108 + -39.3466 * W/D + 95.7424 * L/D + 6.98307 * Voltage + 0.017 * W/D * L/D + 4.11036e-15 * W/D * Voltage + 2.21444e-15 * L/D * Voltage + 32.7355 * W/D^2 + -11.9719 * L/D^2 + -0.0673034 * Voltage^2-------------- (1)

Gr = -1.09422e+08 + -9.63881e+07 * W/D + 4.62563e+07 * L/D + 5.2797e+06 * Voltage + 6.54954e+06 * W/D * L/D + 1.37882e+06 * W/D * Voltage + -967476 * L/D * Voltage + 3.7159e+07 * W/D^2 + 1.13108e+06 * L/D^2 + -59986.8 * Voltage^2-------------- (2)

Eqs. (1) and (2) display how the Nusselt number and Grashoff number are influenced by the independent variables. The negative coefficient indicates that factors with single or double interactions have a negative influence on Nusselt number and Grashoff number (i.e., decline in Nusselt number and Grashoff number with increase in the parameters), while positive coefficient indicates that factors in the tested range rises with increase in Nusselt number and Grashoff numbe*r*. The appropriateness (Table 3) of the models was established by the analysis of variance (ANOVA) (model summary statistics, Table 4). The *Nusselt number* ANOVA is presented in Table 5. The P-value less than 0.0001 of the model indicates that the model is substantial [53]. In this case, the important model variables are A, B, C, AC, A^2, and B^2 where A indicates W/D ratio and B indicates L/D ratio and C indicates Voltage. The "Lack of Fit F-value" of 0.74 indicates that the lack of fit compare to the pure error is not significant. Owing to noise, this value of F may occur. It indicates that the proposed model could draw a better correlation between output and input variables. From diagnostic case statistics, the value of the actual and predicted removal percentage, leverage, DFFITS and Cook's distance of the data can be acquired. The findings indicate that the leverage value was less than 0.1. The limit of residuals internally studentized is $\pm$3 sigma.

Table 2: Variables and levels considered for the study

Factor	**Name**	**Minimum**	**Maximum**	**-alpha**	**+alpha**
A	W/D	0.2000	0.8000	0.2000	0.8000
B	L/D	0.2500	1.0000	0.2500	1.0000
C	Voltage	40.00	50.00	40.00	50.00

Table 3: Adequacy of the model tested

Source	Sequential p-value	Adjusted R^2	Predicted R^2	
Linear	< 0.0001	0.9952	0.9942	
2FI	1.0000	0.9940	0.9922	
Quadratic	**0.0021**	**0.9981**	**0.9959**	**Suggested**
Cubic	1.0000	0.9969	-0.2191	Aliased

Table 4: Model summary statistics

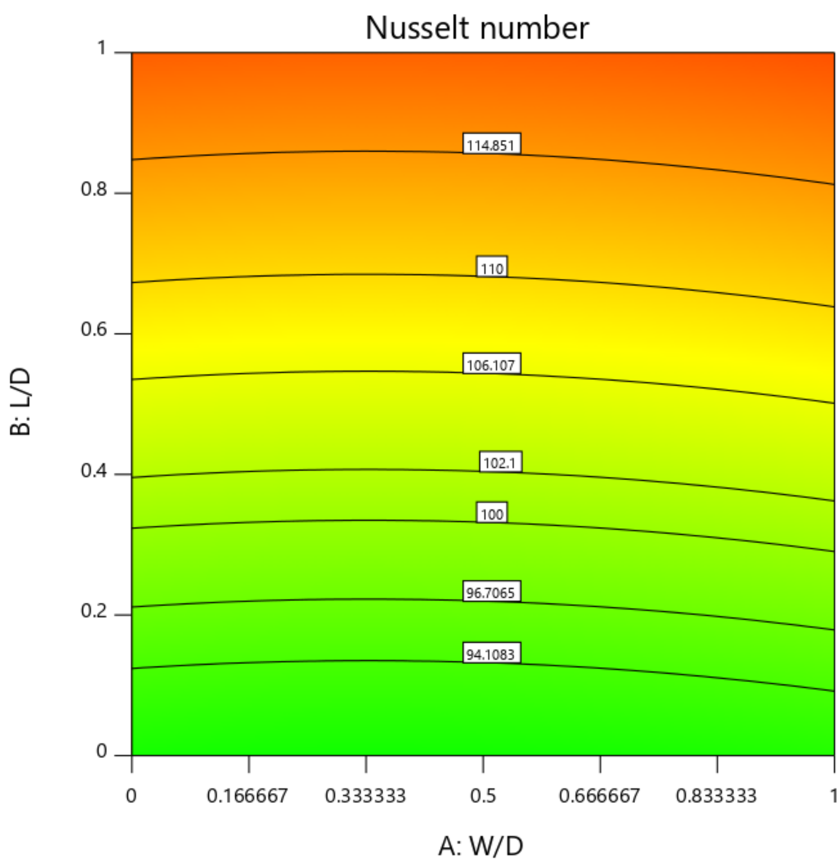
Source	Std. Dev.	R^2	Adjusted R^2	Predicted R^2	PRESS	
Linear	1.55	0.9959	0.9952	0.9942	54.78	
2FI	1.72	0.9959	0.9940	0.9922	73.40	
Quadratic	**0.9693**	**0.9990**	**0.9981**	**0.9959**	**39.23**	**Suggested**
Cubic	1.25	0.9990	0.9969	-0.2191	11544.67	Aliased

Table 5: ANOVA for Quadratic model

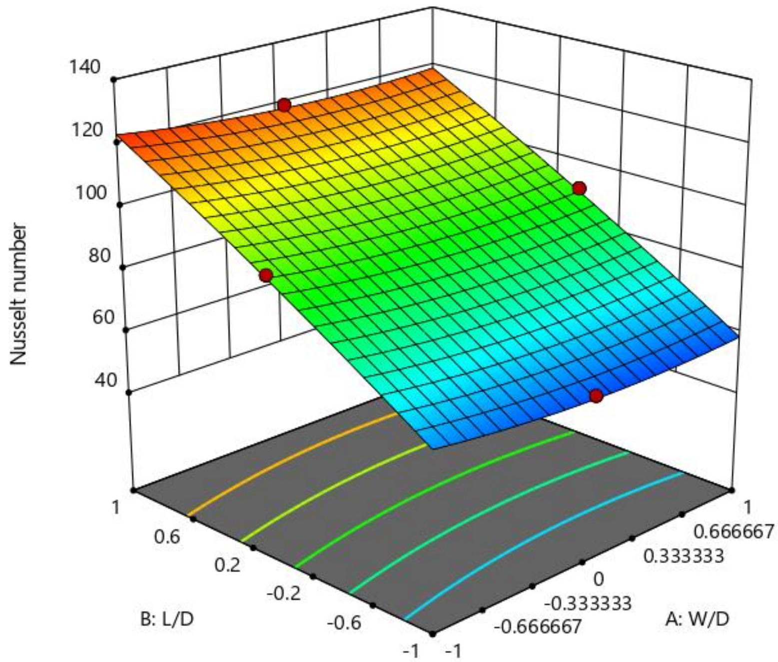
Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	9460.43	9	1051.16	1118.75	< 0.0001	significant
A-W/D	39.21	1	39.21	41.73	< 0.0001	
B-L/D	9177.75	1	9177.75	9767.92	< 0.0001	
C-Voltage	214.26	1	214.26	228.03	< 0.0001	
AB	0.0000	1	0.0000	0.0000	0.9957	
AC	0.0000	1	0.0000	0.0000	1.0000	
BC	0.0000	1	0.0000	0.0000	1.0000	

A^2	23.87	1	23.87	25.41	0.0005	
B^2	7.79	1	7.79	8.30	0.0164	
C^2	7.79	1	7.79	8.29	0.0164	
Residual	9.40	10	0.9396			
Lack of Fit	9.40	5	1.88		0.74	Nonsignificant
Pure Error	0.0000	5	0.0000			
Total	9469.83	19				

A large value of R^2_{adj} (0.9981) was projected. This result suggests that the designated model can signify 99.81 per cent of the total variation on *Nusselt number* data.



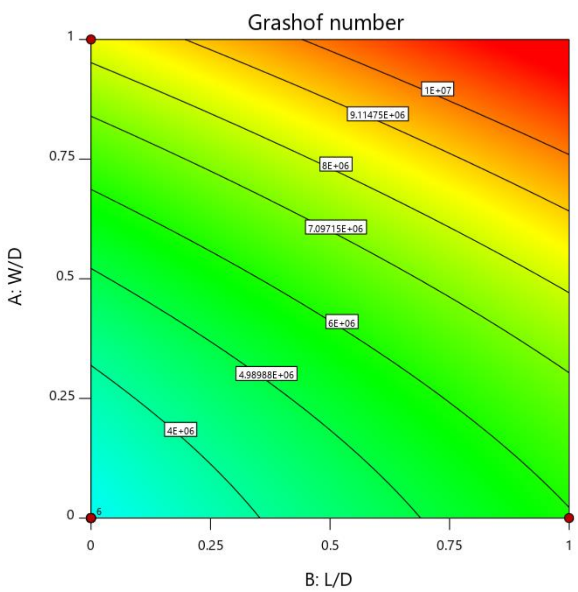
(a)



(b)

Figure 9. Contour and 3D surface plots for Nusselt number.

The impact of the W/D ratio and L/D ratio on the plate *Nu* for various heat flux inputs is shown in Figure 9. It is noted that the *Nu* raised as the depth of the groove increased. It was also seen that the values of *Nu* were high when heat flux was high. Figure 10 displays the Contour and 3D surface plots for Grashoff number. It is observed that as the depth of the groove raised, the Grashoff number also increased, resulting in an increase in the rate of heat transfer.



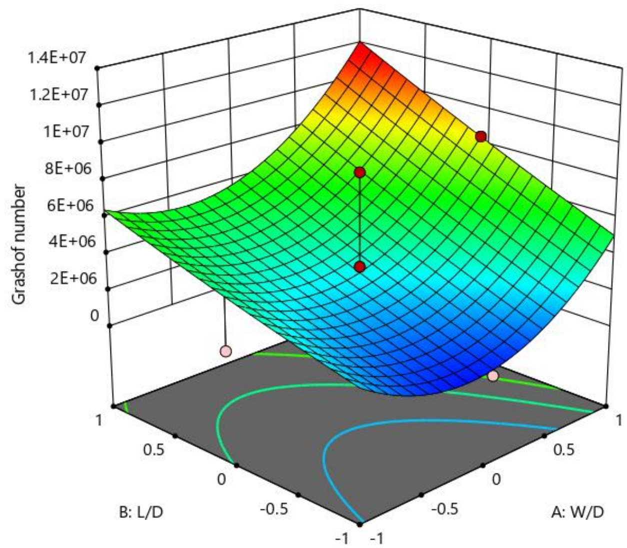


Figure 10. Contour and 3D surface plots for Grashoff number

4. Conclusion

In this paper, experimental research was carried out to improve the thermal performance features of a vertical flat plate mimicking an electronic circuit board. Grooves were provided on the surface and the analysis was carried out by varying the heat flux under steady state and free convection condition. From the results obtained, the following conclusion were drawn:

1. The Nusselt number and hence the heat transfer rate increases as the depth of the grove increases, the length or width of the groove however should be kept constant to achieve the enhancement in heat transfer rate. The reason is that due to intense flow impingement on the downstream boundary and enhanced flow mixing at the downstream by vortices, the turbulence mixing takes place and hence the heat transfer rate increases.

2. The Grashoff number increases with the decrease in the length or width of the plate. This increases further when the heat flux given to the plate increases.

3. Friction factor increases as Grashoff number increases. This is because, fluid gets circulated through the grooved surface and the re-circulation causes the fluid to lose energy, resulting in an enhanced drop in pressure and hence increases the friction.

It can also be observed that heat transfer enhancement does occur with the creation of grooves but at the cost of pumping power.

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