ENCIT-2018-0729
ANALYSIS OF GEOMETRICAL PARAMETERS IN HEAT SINKS UNDER FREE CONVECTION USING DOE

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Abstract. With the increasing miniaturization of electronic equipment, more efficient, long lasting heatsinks are necessary. In this study, analyses of different geometric parameters in rectangular finned heatsinks were performed. The variables studied are: the average heat transfer coefficient, $\bar{h}$, the dimensions of the base, the geometric parameters (height and spacing between fins) and position of heatsinks. In addition, analyses with different heat flux intensities applied to the heatsink bases were accomplished. All possible variations involved in the experiments were developed using the DOE (Design of Experiments) statistical tool, together with Minitab software, in order to obtain a statistical analysis of the results. Tests were carried out with 8 different heatsinks, 4 with 50 mm x 50 mm and 4 with 100 mm x 100 mm base area. Two height and fin space values were analyzed for each heatsink. A sequence of 64 experiments involving all variables was done. Experimental temperature data, $\bar{h}$ obtained experimentally and Nusselt number were used in the analyses. Empirical correlations found in literature were used to validate the results and equally good results were obtained. Finally, a statistical analysis was performed by using Minitab software with the aim of finding the interactions of the variables previously mentioned in relation to Nusselt number.

Keywords: Statistical Analyze, Design of Experiments, Natural Convection, Heat Sinks, Heat Transfer

1. INTRODUCTION

With the advance of the technologies involved in the various branches of today's engineering, heatsinks have become fundamental elements in the design and construction of a wide range of equipment used today in industry. These devices range from heavy machinery to electronic devices that gain more and more ability to perform tasks with the smallest possible space, such as smartphones and laptops. Heatsinks are capable of increasing the lifespan of the equipment by reducing the operating temperature and therefore the ill effects to the equipment in which they are used. In order to investigate which geometric characteristics influence heat transfer in heatsinks, the statistical methodology of experiment planning (DOE) was used to reach conclusions of which characteristics exert greater effects on the heat dissipation capacity. Among the countless applications of heatsinks, some of daily use can be cited, such as, truck radiators, laptops and smartphones. Several authors have studied finned heat sinks by addressing the main geometric characteristics like the height, space between fins, base size as well as horizontal and vertical position. In this work, two different intensities of heat rate were considered besides these characteristics. Among the main characteristics for heatsink analysis, we can cite the average convective heat transfer coefficient $\bar{h}$ which depends on flow conditions, fluid properties and surface geometry. Another feature also studied was the influence of the geometric dimensions and the positions of the base on Nusselt number. Nusselt number is a widely used parameter to determine $\bar{h}$, and is defined as the ratio between the heat transfer of some fluid by convection and by conduction in a given system. With the technological advance of microelectronic equipment and computers, Harahap and Rudianto (2005) called attention to the study of miniaturized heatsinks arranged horizontally. Through some adaptations of correlations proposed by Harahap and Setio (2001), good results were found in the comparisons between experimental and calculated values of Nusselt number. Yazicioglu and Yüncü (2007) performed tests with 30 different combinations of heatsinks, with lengths ranging from 250 to 340 mm; the thicknesses of the fins were kept constant at 3 mm. The height and space between fins were varied, respectively, between 5 to 25 mm and 5.75 to 85.5 mm. The experiments showed that the convective heat transfer rate is dependent on the geometric parameters of the heatsinks and also on the temperature difference between the heatsink base and the room temperature. Yu, Lee and Yook (2011) conducted studies on natural convection around a radial heat sink in circular LED lamps. There were three types of heatsinks, one with only long fins (type L), one with long fins with an intermediate between the others (LM types) and finally with a long fin, an intermediate one and two smaller fins (type LMS). The studies performed compared the effects of the number of fins and heat flux on the thermal resistance and the average heat transfer coefficient. The numerical results were validated with the experimental results and a good agreement was obtained. The authors concluded that LM type heat sinks have the best thermal performance. Tari and Mehrtash (2013)

conducted a numerical study to obtain a suitable model for studying the heat transfer and the effects of slope in heatsinks. Two different heatsink models with different lengths were studied. CFX was used and the results obtained were compared with literature and a correlation to calculate the number Nusselt number was proposed. Li and Byon (2015) numerically and experimentally studied the characteristics of the heat transfer around a radial heatsink made of 6061 T6 Aluminum, with dimensions chosen according to a commercial profile. Two numerical analyses were realized, one to estimate the temperature distribution and another to obtain the average heat transfer coefficient on the heatsink surface. Jang et al. (2014) numerically studied the behavior of natural convection as well as radiation in a cooling system of LED light fixtures. The authors used different slopes to evaluate the influence of the geometric parameters of the heatsink in the heat transfer. An analysis of experiments was performed for different slopes and a correlation for the number of Nusselt was found.

In literature, there is still not much work about the use of Design of Experiments (DOE) in free convection experiments involving heatsinks; nonetheless this methodology is used in several areas of knowledge. Design of Experiments is a technique used to plan experiments, that is, to define which data, in what quantity and in what conditions should be collected in a given experiment, basically seeking to satisfy two major objectives: the highest possible statistical precision of the response and the lowest cost. Montgomery (2010) defines the experimentation as a fundamental part of the scientific method in the analysis of engineering applications. DOE is the process of planning the experiments so that appropriate data are collected and then analyzed by statistical methods, resulting in valid and objective conclusions. Paiva et al. (2005) conducted a study using the DOE tools together with the surface response methodology with the objective of analyzing the lifespan of mixed ceramic tool in a SAE/ ABNT 52100 hardened steel turning process. It was concluded through a combination of the response surface methodology and the full factorial analysis that the best conditions to improve the lifespan of mixed ceramic tools are: cutting speed equal or lower than 200 m/min, feed rate equal or lower than 0.05 mm/rev. and depth of cut equal or lower than 0.15 mm. Ko-Ta Chiang (2005) studied a method for predicting and optimizing the cooling performance of Parallel-Plain Fin (PPF) heatsink using design of experiments based on the Taguchi method. This method was used to seek the best combination of optimized design parameters. The design parameters used were fin height, number of slot, fin spacing and wind capacity of the electric fan. The author also performed a numerical analysis with the objective to reach the lowest value of highest temperature by the heatsink. It was used an aluminum alloy CPU heatsink working under forced convection conditions. Kotcioglu, Khalaji and Cansiz (2018) analyzed experimentally a heat exchanger with different geometric configurations operating under forced convection. The authors investigated the behavior of pressure variables and flow rates of working fluids in different sessions and specific intervals to the Reynolds number. The heat transfer and the pressure drop were discussed in terms of different fin geometries. It was used the Taguchi method for the modeling of the experiments. Among the conclusions of the work, it was said that a pressure change in the heat exchanger input is a fixed number of Reynolds for different types of loops, which causes an increase in the pressure drop with the increase of Reynolds number. Thus, experimentation according to Montgomery (2010) is characterized as a fundamental part for the scientific method in the analysis of the diverse applications of engineering.

2. METHODOLOGY

2.1 Material and manufacturing of heatsinks

All the heatsinks used in the experiments were machined from 6063-T5 aluminum due to its essential properties in the heat transfer process, such as high thermal conductivity, resistance to corrosion, low density and good affinity with the capacitive discharge welding process, which was used to attach the thermocouples on the heatsink surface. The heatsinks were milled to ensure flat and rectangular fins. 8 heatsinks were machined, 4 with base dimensions of 100 mm x 100 mm and 4 others with base dimensions of 50 mm x 50 mm. An analysis of the geometrical characteristics was performed by using different combinations base length, space between fins and height of the fins. All these factors are shown in Fig. 1.
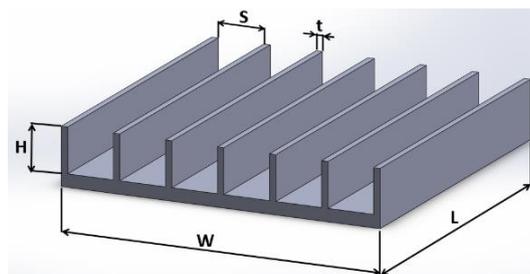

Figure 1. Geometrical parameters of the heatsinks

The heatsinks have similar geometrical characteristics, differing only by the length of the base and consequently the number of fins. The geometrical dimensions of all heatsinks are shown in Table 1.

Table 1. Geometrical dimensions of the heatsinks

	S [mm]	t [mm]	H [mm]	L [mm]	W [mm]
Heatsink	Fin space	Fin thickness	Fin height	Base length	Base width
1	5.55	2.00	7.00	100.00	100.15
2	5.55	2.00	7.00	50.00	47.30
3	14.35	2.00	7.00	100.00	100.10
4	14.35	2.00	7.00	50.00	51.05
5	5.55	2.00	20.00	100.00	100.15
6	5.55	2.00	20.00	50.00	47.30
7	14.35	2.00	20.00	100.00	100.10
8	14.35	2.00	20.00	50.00	51.05

2.2   Experimental bench

Figure 2 presents an experimental apparatus used in the experiments which consists of a MDF (Medium Density Fiberboard) on which the resistive heater and the heatsink are placed (Fig. 3a). This assembly reduces heat losses through the lower surface of the heater and does not restrict the airflow around the fins. Glass wool was used to insulate the sidewalls of the base and MDF was placed underneath the heater in order to keep the heat flux in the direction of the heatsink. Thermocouples T4 and T5, were welded by capacitive discharge to the tip and the base. The capacitive discharge reduces the contact resistance between the surface of the heatsink and the thermocouples. T3 was inserted in the middle of the resistive heater, T2 was placed below the MDF surface and T1 was used to measure room temperature. All the thermocouples used in this work are type T 30 AWG, except in the heater which is type T 40 AWG which have a smaller gauge.
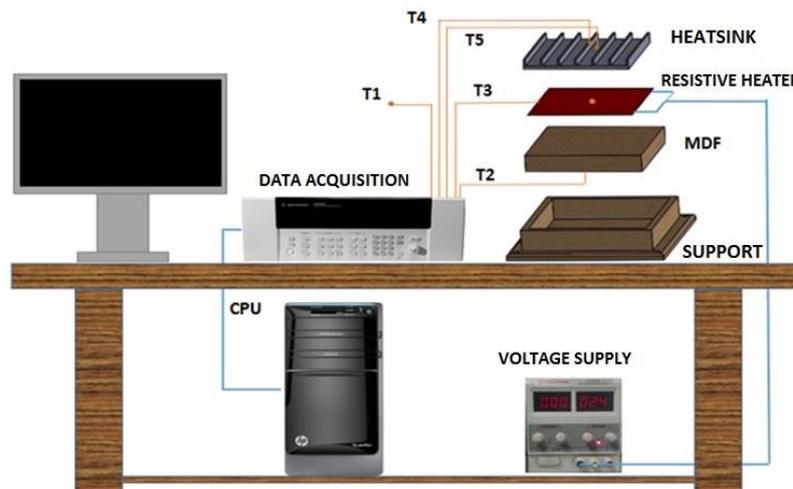

Figure 2. Arrangement of experimental bench

In this study, all the heatsinks were tested in both position, that is, horizontally and vertically. Figure 3b shows the two different ways at which the heatsinks were tested. In order to avoid air between the heatsink and the resistive heater, clamps were used to fix the heatsinks, thus promoting a certain pressure on the assembly and avoiding the presence of air.
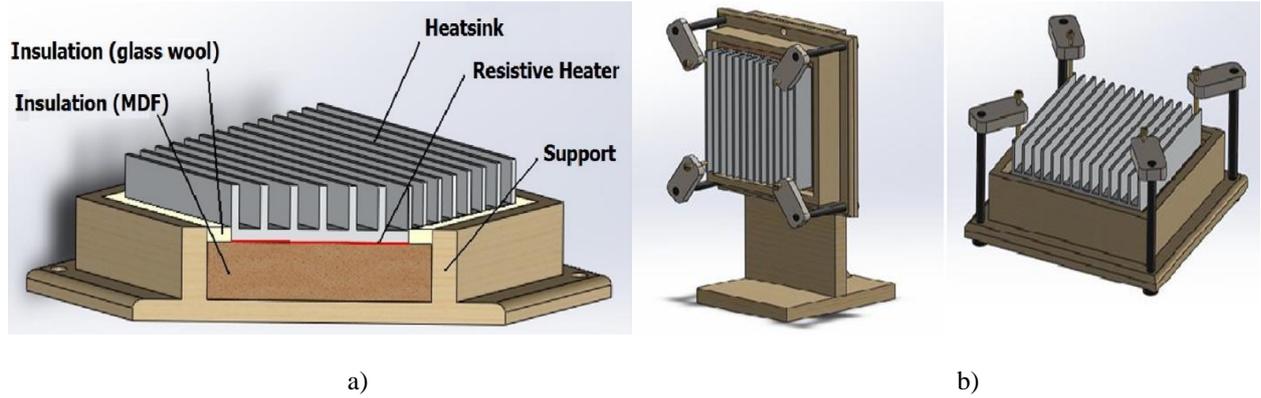
Figure 3. a) Assembly sectional view. b) Vertical and horizontal settings.

According to Figure 2, the heatsinks are then heated through the resistive heater connected to the voltage source. The thermocouples then collect the temperature data in 4-second time intervals in a total of approximately 90 minutes, until the assembly reaches the steady state. After the first measurement with data of the transient regime, 4 other measures were made in permanent regime. With these extra measurements, steady state is ensured and also a better data repeatability. After acquiring the data, the average temperature was calculated and afterwards $\bar{h}$ was obtained.

3. THEORETICAL DEVELOPMENT

3.1 Coefficient of heat transfer by convection

To obtain $\bar{h}$ theoretically, the authors used the empirical correlations proposed by Harahap and Rudianto (2005) for horizontally arranged heatsinks and Harahap and Lesmana (2006) for vertically positioned heatsinks.

3.2 Empirical correlation of Harahap and Rudianto (2005)

The correlation proposed by these authors was used to obtain Nusselt number (Eq. 1). Dimension $l = L/2$ is considered.

$$Nu_{H\&R} = 0.203 \left[Ra\left(\frac{nS}{H}\right) \right]^{0.393} \left(\frac{S}{l}\right)^{0.470} \left(\frac{H}{l}\right)^{0.970} \left(\frac{L}{W}\right)^{0.620} \tag{1}$$

The average heat transfer coefficient by free convection is given in Eq. (2).

$$\bar{h}_{H\&R} = \frac{Nu_{H\&R} \quad k_{ar}}{l} \tag{2}$$

The correlation suggested by Harahap and Rudianto (2005) is suitable for a range of values between $3 \times 10^3 \leq Ra_l \cdot n(S/L) \leq 3 \times 10^5$.

3.3 Empirical correlation of Harahap and Lesmana (2006)

The correlation suggested by these authors uses Nusselt number in relation to dimension L and Nusselt number is calculated from Eq. (3).

$$Nu_{H\&L} = 3.350 \cdot (Ra)^{0.153} \left(\frac{L}{W}\right)^{0.121} \left(\frac{S}{H}\right)^{0.605} \tag{3}$$

This correlation is suitable for values between $2 \times 10^5 \leq Ra_L \leq 5 \times 10^5$. In this case, the average heat transfer coefficient by natural convection is given in Eq. (4).

$$\bar{h}_{H\&L} = \frac{Nu_{H\&L} \cdot k_{ar}}{L} \tag{4}$$

4. FACTORIAL DESIGN ANALYSIS

Factorial design is widely used in industrial experimentation because it promotes better decision-making process through a simple analysis.

According to Montgomery (2010), factorial designs are more efficient for experiments that involve the study of the effects of two or more factors (input variables). A factorial design is an experimental planning strategy with the objective of collecting data and detecting which factors and interactions between factors are most influential in the response of the experiment. The 2^K factorial design refers to designs with k factors where each factor has just two levels. The levels could be qualitative or quantitative, depending on the factors, that is, in case of quantitative factors the levels can be represented by numerical values in accordance with some scale. On the other hand, if the levels assume qualitative values, there is no need for scale, this way the values can be represented by symbols like for example "low" and "high" or "maximum" and "minimum". In this study the factorial design analysis was used to evaluate the effects of each input variable, such as geometrical parameters and heat flux.

In order to obtain better results for this study, of all the experiments were repeated. The replica consists of repeating the experiment under pre-established conditions. A replica is used to estimate the influence of the experimental error in the results and also the possibility to know when the results are statistically different.

The first step to begin the analysis is to choose the input variables and the values of the levels that these variables will assume. Table 2 presents data of each factor that composes the analysis as well as the levels that will be used as parameter.

Table 2. Factors and levels of the factorial analysis

Factors	Symbol	Unit	Low Level	High Level
Base Length	L	mm	50.00	100.00
Fin Space	S	mm	5.55	14.35
Fin Height	H	mm	7.00	20.00
Heat Flux	q"	W/m^2	800.00	1600.00

After a design matrix is generated in Minitab® software. All the possible relations among the factors to conduct the experiments in the right sequence are used (Tab. 3). Every line of the experimental matrix represented in Tab. 3 indicates an experiment using a combination of levels that will be executed and the results collected for further analysis.

Table 3. Experimental matrix with factorial 2^4

Nº	Base Length	Fin Space	Fin Height	Heat Flux	Nusselt
-	[mm]	[mm]	[mm]	[W/m^2]	-
1	50	5.55	7	800	41.59
2	100	5.55	7	800	22.13
3	50	14.35	7	800	37.75
4	100	14.35	7	800	34.62
5	50	5.55	20	800	25.33
6	100	5.55	20	800	13.00
7	50	14.35	20	800	41.53
8	100	14.35	20	800	24.46
9	50	5.55	7	1600	41.66
10	100	5.55	7	1600	24.36
11	50	14.35	7	1600	22.78
12	100	14.35	7	1600	37.00
13	50	5.55	20	1600	29.25
14	100	5.55	20	1600	15.97
15	50	14.35	20	1600	44.71
16	100	14.35	20	1600	27.07

Once the experiments have been performed and the responses obtained, the analysis can be done through the statistical tools and thereby can achieve the conclusions of which factors exert significant influence in the response.

Altogether 64 experiments were carried out, including a replica. 32 experiments for horizontally positioned heatsinks and 32 others positioned vertically. After all the experiments indicated by DOE matrix were accomplished, Nusselt number could be obtained as the answer.

Table 3 shows the results based on the factorial design matrix built for the first 16 experiments. In this case, all results obtained for heatsinks positioned horizontally are shown.

Firstly, with all power and temperature data collected from the experiments, $\bar{h}$ was calculated. The calculation of this coefficient was cited in the theoretical development of this work and is given by Newton's cooling law.

With the values of $\bar{h}$, Nusselt number can be calculated through Eq. (5).

$$Nu = \frac{\bar{h} \cdot L}{k_{ar}} \qquad (5)$$

Nusselt number was analyzed as a response variable and the combinations were made for two different values of space between fins (5.55 mm and 14.35 mm), two values of fin height (7 mm and 20 mm), 2 values for the length of the base (50 and 100 mm) and two values of heat flux (800 W/m^2 and 1600 W/m^2).

5. RESULTS

In this study, a 2^K factorial design for heatsinks was analysed. The experiments were done to verify which factors are significant in the response and how they exert some influence in Nusselt number. The main purpose of this study is to verify how the chosen factor and which iterations affect Nusselt number.

A variance analysis tool (ANOVA) from Minitab was used in the results in order to obtain the main effects of the factors in Nusselt number. First, the results for horizontal heatsink will be presented as shown in Fig. 4a where the space between fins exerts more influence in Nusselt number, that is, the wider the space, the higher the Nusselt number. The other features presented in Fig. 4a show that the heat flux does not affect Nusselt number significantly.
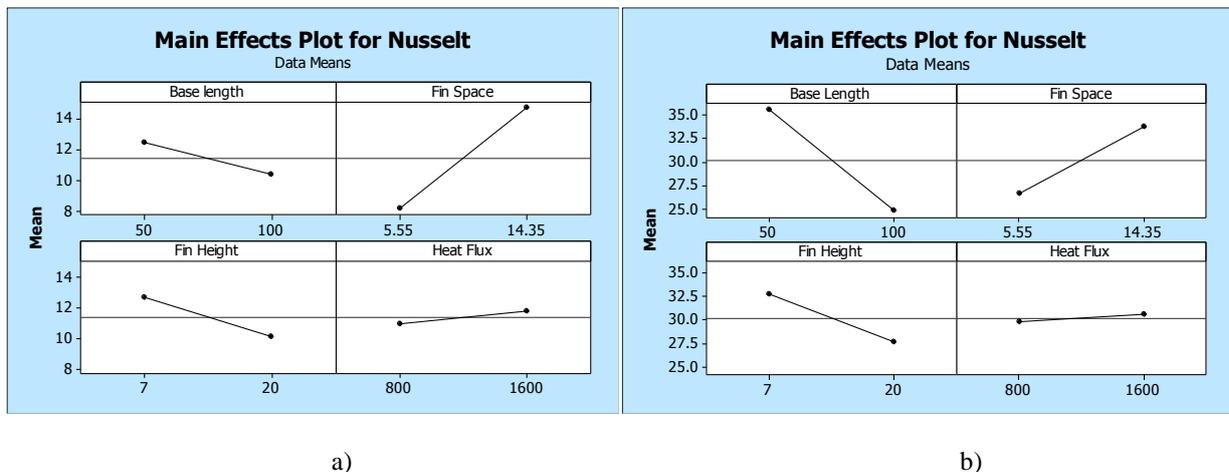

Figure 4. Main effects diagram heatsinks a) Horizontal b) Vertical

Figure 4b also presents the main effect results for vertical heatsinks. When the dimensions of the base and the space between fins are changed, Nusselt number is greatly influenced. However, for the features of height and spacing between fins, when the height is increased from 7 mm to 20 mm, Nusselt number decreases but with a lower intensity. This behavior can be noticed in the slope in the diagram. The last diagram in Fig. 4b, shows that the heat flux line keeps the same inclination, that is, the effect of this factor in Nusselt number is smaller when compared with the other characteristics.

Following the factorial analysis, to better visualize the effects and interactions between the factors in Nusselt number, a Pareto chart was generated. This chart relates all effects and interactions between the input variables and the response in a statistical analysis. The chart shows the absolute effects and describes a reference line in the graph. Any effect that extends beyond the reference line is potentially important. Figure 5 presents the Pareto chart for the horizontal heatsinks. It can be inferred that Fig. 5a is in accordance with Fig 4a. The length of the base and space between fins are the most influent factors in Nusselt number. The results for the vertical heatsinks show the similarity with the behavior in Fig. 5, that is, the most influent factors are base length and fin step.
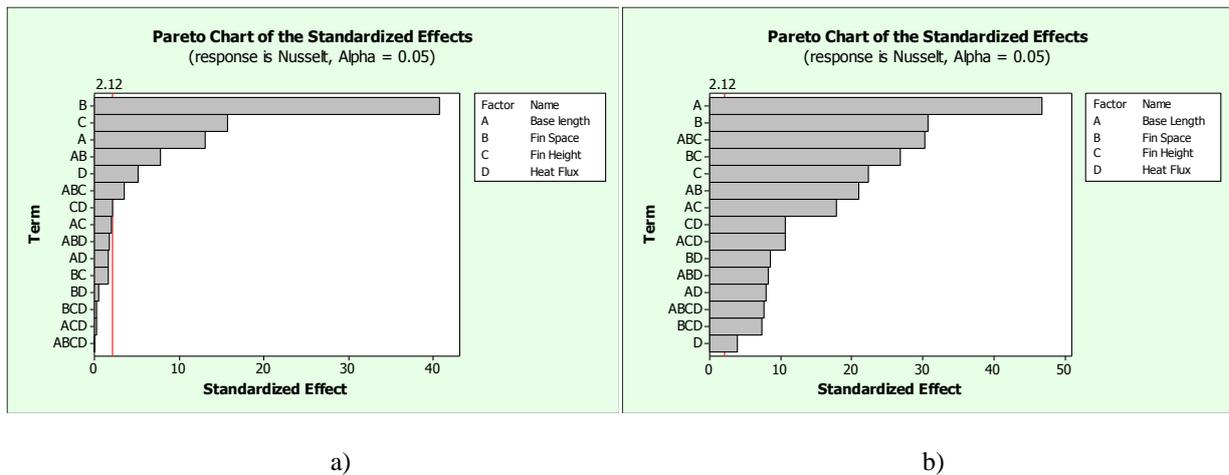
a)   b)

Figure 5. Pareto chart for heatsinks. a) Horizontal b) Vertical

Figure 5b presents the Pareto chart for the vertical heatsinks. The difference in the behavior between the two positions is that in the horizontal position some interactions between the factors can be removed from the analysis without big changes in the results.

A very important analysis in the factorial design is the residual analysis. A histogram of residuals is a graph used to examine the quality of the regression fit and ANOVA. The residual histogram determines whether the data is asymmetric or contains outliers. Figure 6 presents the results of the histogram of residuals of the horizontal heatsinks. The data keeps a Gaussian distribution pattern, which shows that the residual data follows a normal distribution. A large number of residuals means a high incidence of this value in the difference between the actual values and the values statistically adjusted. According to Fig. 6a, it may be noted that there are many residuals equal to zero for Nusselt number, that is, the difference between the actual and adjusted values is close to zero in the center of the graph.
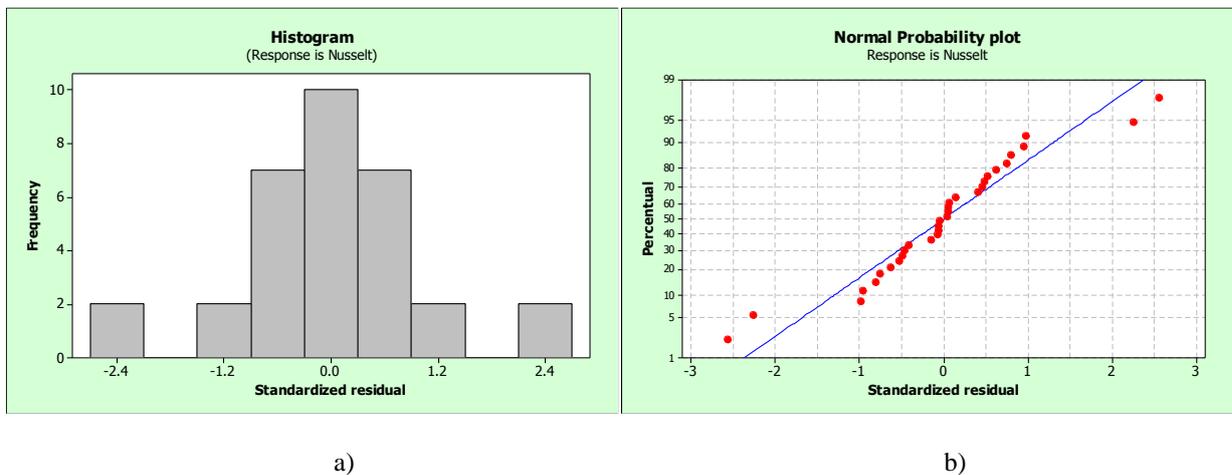

a)   b)

Figure 6. a) Residual histogram for heatsinks horizontally. b) Normal probability plot for heatsinks horizontally.

As a comparison parameter, the normal probability plot in Fig. 6b was also generated and a residual analysis shows that the data are normal and that they have some outliers.

Figure 7a present the residual analysis results for vertical heatsinks. Through the graphical analysis, it is noted that in the vertical position, the behavior of the Nusselt number is different, however the behavior of the graph shows symmetry, approaching a Gaussian.

Figure 7b confirms the normality of the data, since the points follow the normal probability line, but with some outliers.

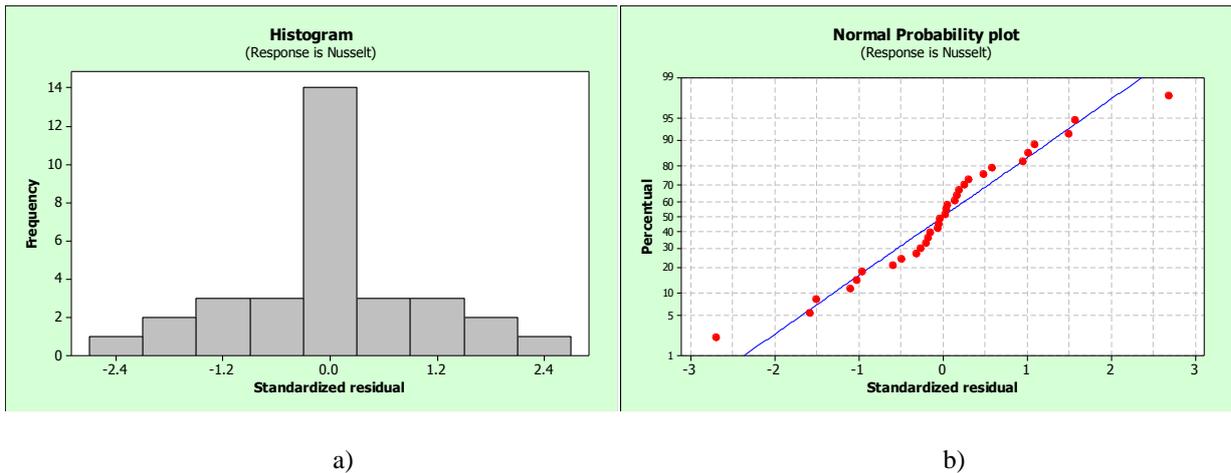a)   b)

Figure 7. a) Residual histogram for vertical heatsinks. b) Normal probability plot for heatsinks vertically

The half-normal probability plot of the effects shows the absolute values of the standardized effects from the greatest effect to the least effect. The standardized effects are statistics t which test the null hypothesis that the effect is 0. The points are presented in relation to an adjustment line of distribution for the case where all the effects are 0. Effects farther from 0 that are in the X axis have higher magnitude. The distance that the points must be from zero to be statistically significant depends on the level of significance (denoted by α or alpha). Figs. 8a and 8b show the results in the half normal graphs.

a)   b)
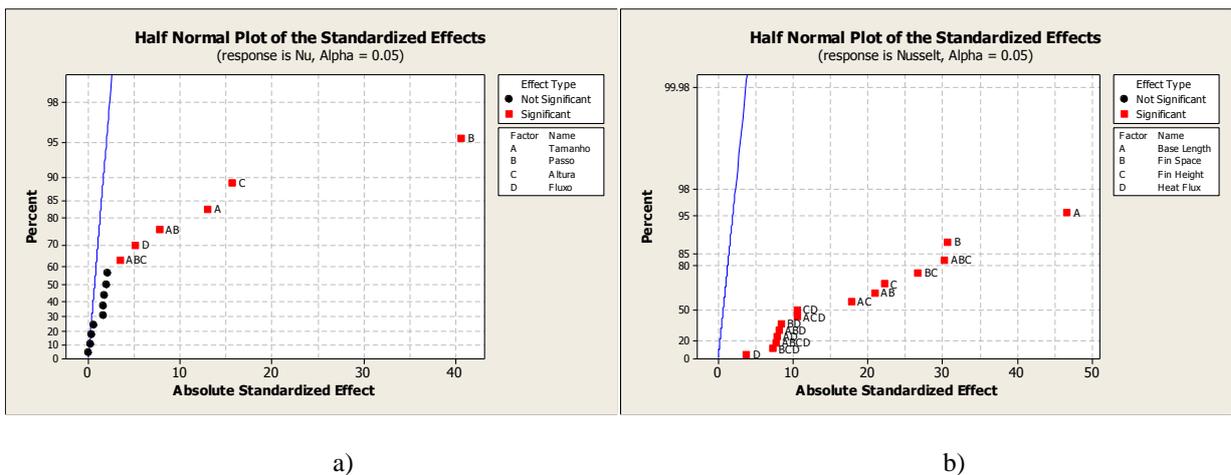
Figure 8. Half Normal plot of the standardized effects a) Horizontally b) Vertically

In the half-normal probability plot of effects, the effects that are furthest from 0 are statistically significant. The color and shape of the dots differs between the statistically significant and statistically insignificant effects. Another ANOVA tool is used to illustrate interactions between factors and response.

The interaction plot helps in visualizing the effects that influence the results of the experiments, encompassing all the parameters involved and a response variable. An interaction plot can be used to show how the relationship between one categorical factor and a continuous response depends on the value of the second categorical factor. This plot displays means for the levels of one factor on the x-axis and a separate line for each level of another factor. When the line is horizontal (parallel to the x-axis), there is no main effect present. The response mean is the same across all factor levels. When the line is not horizontal, there is a main effect present. The response mean is not the same across all factor levels. The steeper the slope of the line, the greater the magnitude of the main effect.

The effects diagram for the horizontal and vertical positions are represented by Figs. 9 and 10, respectively.
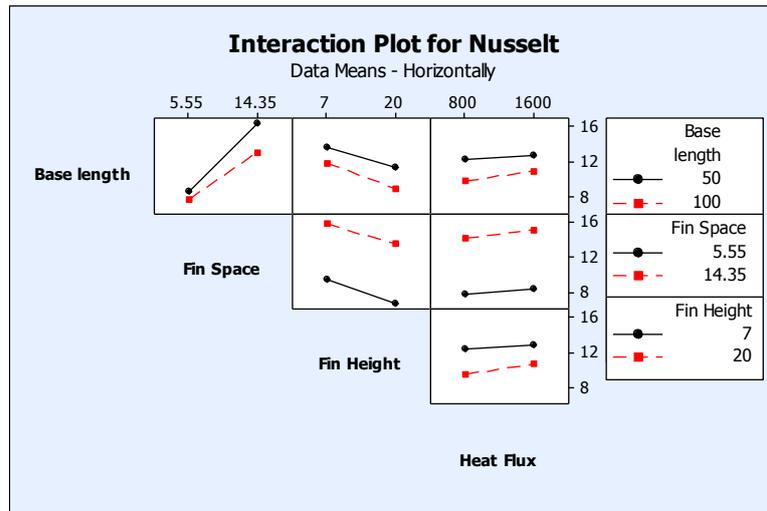
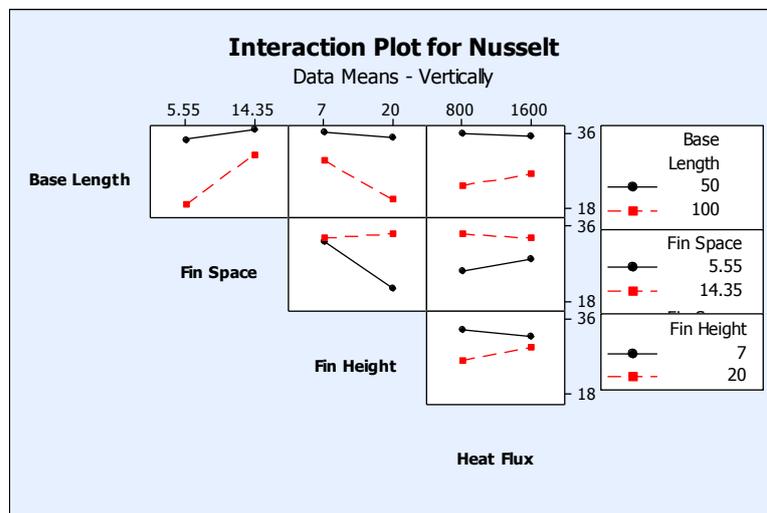Figure 9. Interactions for heatsinks in the horizontal position.

Figure 10. Interactions for heatsinks in the vertical position.

6. CONCLUSÕES

The paper introduced a statistical analysis using factorial design methodology applied to free convection in heatsinks. Altogether 8 heatsinks were tested with different geometric parameters. The effect of each parameter has been analyzed using two positions for the heatsinks. The main objective of this study was to analyze which factors or input variables exert influence in Nusselt number. Results show that in heatsinks positioned horizontally, the greatest influence in Nusselt number was caused by the space between fins, that is, when the space between fins increases, Nusselt number also increases. The factors like base length and height of the fin also exert minor influence when compared with the space between fins. Heat flux has the smallest influence on Nusselt number. Another conclusion about the interactions between the factors is that they did not produce significant effects on Nusselt number. In the case of vertical heatsinks the base length and the space between fins were the most significant factors. When the base length increases, the space between fins decreases, Nusselt number also decreases. The Pareto charts show results in agreement with the main effect diagrams. The histogram of residual analysis showed that there is a difference between the positions of the heatsinks.

Further work should consider a more specific analysis about the data collected with this study. Other analyses could be done with a heatsink in intermediary dimensions. With experiments involving heat sinks with intermediate dimensions it will be possible to notice if there are curvatures between the levels studied in this work. These curvatures can provide information if the characteristics exert more or less influence on the Nusselt number.

7. ACKNOWLEDGEMENTS

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