Heat Transfer Analysis for New Product Development

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Abstract. This project presents an analysis of heat and mass transfer in designing a new product development. The problem in designing of electronic components to be mounted in Printed Circuit Board (PCB) is very complex due to significantly influence to reliability, safety, and cost effective. The objective of this study is to carry out the current problems related with heat and mass transfer analysis. The methodology used is started from cross-sectional heat transfer surface, Reynolds Number, heat transfer coefficient, heat flux, and last the maximum total power required. The result shows that a 15cm x 20cm of Printed Circuit Board (PCB) has an optimal heat and mass transfer coefficient to meet reliability and safety. In addition, the power degeneracy as function of the air velocity and the surface temperature are plotted. The simulation was generated, and it is represent the air velocity is vary from 1 m/s to 15 m/s and the external temperature surrounding on the printed circuit board is identified from 30°C to 100°C. As the result, the comprehensive value of heat and mass transfer coefficient is presented for new product development purposes.

Keywords: Heat transfer, Mass Flow Rate, PCB, Electronic components

1. Introduction
Heat transfer analysis is important step in designing a new product development. Several cases in heat transfer problem influences the performance of product, particularly in reliability and safety. Most of engineers have been practically improve the knowledge by approaching basic science to represent the real model. In determining the mass flow rate and velocity are frequently used in heat transfer analysis. In the field of temperature and heat phenomena, it is necessary to study due to effect the overall manufacturing processes, particularly in casting and injection moulding processes. Moreover, the phenomena of heat transfer could lead the reliability and final product price.

Several researchers have been studied the heat transfer analysis from different perspective. In 2019, the authors described the transient thermal behaviour for thermal battery module, which consists of 13 stacks cells unit [1]. The performance of heat transfer is presented in designing of radiator cooling system. The use of coolants and nanofluids enhanced heat transfer coefficients and to make an effective for the radiator system [2]. Heat flux interface equation is used in describing the heat transfer analysis. This research introduced the integral boundary element method and found a significant advantage for solving multi-medium problems [3]. Most of researchers have been discussed the heat transfer analysis from the mathematical basis to carry out current problems. However, there is room for introducing the heat transfer analysis based on the current method to other engineering applications practically.
Numerical heat transfer has been attracted the researchers due to ability to represent the model and improved the solution to solve a complex problem. The phenomena of thermal analysis at the design process was presented to predict temperature responses of the shielding material. This study found, the numerical investigated the effects and induced by vapour specific [4]. The heat flux based on the numerical model plays an important on the LNG thermal performance under supercritical pressure. This study also found a significant on the heat transfer performance based on thermo physical properties and geometry, led to temperature and heat transfer coefficient [5]. Numerical heat transfer is used on temperature distribution and heat transfer rate in continuous polymer foaming processes. The authors also found that the temperature distribution of polymer process is important [6]. In recent studied in 2020, the numerical heat transfer is obtained for the great critical water flowing in the vertical pipe. This study performed the simulation and validated with experimental works [7]. However, most of cases in numerical methods represent the complex problems and need engineering software in order to calculate the numerical model.

New product development is necessary due to fulfil and response the customer needs in specific area of improvement, such as reliable, safety, and low cost. The study of perceive value of design was presented and it is found three is obstacle to design new products and business to increase the product competitiveness. The innovations and collaboration with multidisciplinary team also play important role in designing of new product development [8]. The use of Quality Function Deployment (QFD) in designing of new product is presented to increase company agility [9]. The recent study in 2020 is the most close to this research. The authors claimed that by applying design for energy efficiency has improved product performance during early design stage. This study also has been implemented the design for energy efficiency for a wind turbine [10].

In designing of new product development, it is required the reliability, safety and cost-effective. In addition, the industry have to consider the use of material and manufacturing processes to achieve minimum cost. Therefore, this paper describes the advantage of heat transfer analysis during the design stage, so the engineer could perform the comprehensive analysis in designing a new product in the perspective of cost effective and increase the reliability. In addition, the performance of heat transfer could be as reference for business aspect to attract the customer with low-cost product.

2. Materials and Methods
In this study, a 15 cm × 20 cm of Printed Circuit Board (PCB) and consists of several electronic components as shown in Figure 1. The air is cooled by passing cool air to be 15 °C from the left side of PCB and through a 20 cm long channel of the rectangular cross section 0.2 cm × 14 cm is drilled into board.

![Figure 1. Printed circuit board (PCB)](image-url)
be insignificant. This study stated that the velocity of the air surrounding the circuit board at the inlet. And the air is filled to the channel with maximum velocity of 4 m/s. In addition, the surface temperature through of the channel is considered below 50°C. The problem of this study is to calculate the maximum total power from the electronic components with required and to ensure be attached on this PCB safely.

The phenomena of heat transfer come from inlet, passing through the printed circuit board, and outlet of the channel. The effect of air velocity in circuit board surrounding at the inlet and the value of maximum surface temperature. This study also shows the maximum total power generation to be assigned for the electronic components. In this study, the air velocity is vary from 1 m/s to 15 m/s and the surface temperature is identified from 30 °C to 100 °C. The current problem is how to plot the power dissipation as function of air velocity and surface temperature, and to find out the optimum heat transfer measurements through the inlet and outlet of the printed circuit board.

The basic science methodology is introduced by Cengel and Ghajar [11], from initial cross-sectional heat transfer surface, determination of Reynold Number and heat transfer coefficient, heat flux, and last the maximum total power can be calculated. Several formulas from Cengel and Ghajar [11] are used such as

\[
D_h = \frac{4A_c}{P} \quad (1)
\]

\[
Re = \frac{V_mD_m}{\nu} \quad (2)
\]

\[
\dot{m} = \rho\dot{V}\quad (3)
\]

\[
hA_c(T_s - T_e) = \dot{m}C_p(T_e - T_i) \quad (4)
\]

\[
Q_{\text{max}} = \dot{m}C_p(T_e - T_i) \quad (5)
\]

3. Results and Discussion
At the first step in this study, is to state the several conditions to be included in the calculation. A part of circuit board is ventilated by transient cool air concluded a channel penetrated into the printed circuit board. In this part, the maximum total power required for the electronic components must be calculated. Several constraints such as this process is assumed the steady state workingcircumstancesthrough the process. For the inner surfaces, the channel are being flat conditions and the air is considered as an ideal gas with constant properties. The heat flux at the top surface of the channel is assumed uniform. Due to some limitations, this study is considered the heat transfer surrounding through other surfaces is insignificant. The pressure of airdetailed the channel is assumed to the value of 1 atm. Figure 2 shows the schematic of electronic components to be mounted in circuit board.

Second step is to identify all the properties included from inlet to outlet. The properties of air at 1 atm and appraised average surface temperatures of 25°C are provided in Table A-15 [11]. It is identified that: density, \( \rho = 1.184 \text{ kg/m}^3 \); thermal conductivity, \( k = 0.02551 \text{ W/m.}^\circ\text{C} \); thermal diffusivity, \( \nu = 1.562 \times 10^{-5} \text{ m}^2/\text{s} \); specific heat capacity \( C_p = 1007 \text{ J/kg.}^\circ\text{C} \); and Prandtl Number, \( Pr = 0.7296 \).

![Figure 2. Schematic of electronic components](image-url)
Third step is to calculate the cross-sectional of printed circuit board. And also to determine heat transfer surface areas are as follow:

\[ A_1 = (0.002 \text{ m})(0.14 \text{ m}) = 0.00028 \text{ m}^2; \quad A_2 = (0.14 \text{ m})(0.2 \text{ m}) = 0.028 \text{ m}^2 \]

In step four, in order to determine heat transfer coefficient, the Reynolds number have to set at the beginning.

\[ D_h = \frac{4A_1}{P} = \frac{4(0.00028 \text{ m}^2)}{2(0.002 \text{ m} + 0.14 \text{ m})} = 0.004 \text{ m}; \quad \text{Re} = \frac{V u D_h}{\nu} = \frac{(4 \text{ m/s})(0.004 \text{ m})}{1.562 \times 10^{-5} \text{ m}^2/\text{s}} = 1024.33 \]

The laminar flow is applied when the Reynolds number calculated maximum 2300. Therefore, in this study the laminar flow is applicable. And for the thermal entry length can be calculated as follow:

\[ L_e = 0.05 \text{ Re Pr } D_h = 0.05(1024.33)(0.7296)(0.004 \text{ m}) = 0.15 \text{ m} < 0.20 \text{ m} \]

This study also have to consider to develop the flow through most of the channel. However, in this study, the conventional method is selected and adopt fully developed flow, and based on Table 8-1 [11] the value of \( \text{Nu} = 8.24 \). At that point, the heat transfer coefficient developed as follow:

\[ h = k D_h \times \frac{0.02551 \text{ W/m°C}}{0.004 \text{ m}} (8.24) = 52.55 \text{ W/m}^2 \cdot \text{°C} \]

Next step is to find out the mass flow rate through the circuit or channel,

\[ \dot{m} = \rho V A_1 = (1.184 \text{ kg/m}^3)(4 \text{ m/s})(0.00028 \text{ m}^2) = 0.00133 \text{ kg/s} \]

Step five is to determine the heat flux. For the heat flux at the exit of channel, it is applied as \( q = h(T_e - T_i) \) where \( T_i = 50°C \) is measured at the temperature exit. The heat transfer rate can be stated by applying energy conservation equation [11] \( \dot{Q} = \dot{q} A_1 = hA_1(T_e - T_i) \). The leaving air temperature from the channel can be determined as

\[ hA_1(T_e - T_i) = \dot{m}C_p(T_e - T_i) \]

\[ (52.55 \text{ W/m}^2 \cdot \text{°C})(0.028 \text{ m}^2)(50°C - T_e) = (0.00133 \text{ kg/s})(1007 \text{ J/kg°C})(T_e - 15°C) \]

The leaving temperature can be found at \( T_e = 33.3°C \)

And last is step six, to calculate the total power of the electronic components in maximum condition to be mounted on this printed circuit board safely suits

\[ \dot{Q}_{\text{max}} = \dot{m}C_p(T_e - T_i) = (0.00133 \text{ kg/s})(1007 \text{ J/kg°C})(33.3°C - 15°C) = 24.5 \text{ W} \]

In step six, the phenomena of heat transfer could refer the power generation as function to determine the optimum level of heat transfer coefficient. In this study, to represent the phenomena of heat transfer of air comes from inlet of the channel, passing through the circuit board, and exit at outlet of the channel. It is necessary to calculate power dissipation as function of air velocity and surface temperature, and to find out the optimum heat transfer coefficients through the inlet and outlet of the channel. By applying the similar method and some calculation in step 1 to step 5, the power dissipation as function of air velocity is listed in Table 1.
Table 1. The power dissipation as function of air velocity

| Air velocity (m/s) | Power Dissipation (W) |
|-------------------|-----------------------|
| 1.0               | 9.5                   |
| 2.0               | 16.1                  |
| 3.0               | 21.0                  |
| 4.0               | 24.5                  |
| 5.0               | 27.6                  |
| 6.0               | 29.9                  |
| 7.0               | 31.8                  |
| 8.0               | 33.4                  |
| 9.0               | 34.8                  |
| 10.0              | 36.0                  |
| 11.0              | 37.0                  |
| 12.0              | 37.9                  |
| 13.0              | 38.7                  |
| 14.0              | 39.4                  |
| 15.0              | 40.1                  |

In representing the power dissipation as function of surface temperature is listed in Table 2, using the similar calculation for developing the power dissipation as function of air velocity.

Table 2. The power dissipation as function of surface temperature

| Surface Temperature (°C) | Power Dissipation (W) |
|--------------------------|-----------------------|
| 30                       | 10.6                  |
| 35                       | 14.1                  |
| 40                       | 17.6                  |
| 45                       | 21.6                  |
| 50                       | 24.5                  |
| 55                       | 28.2                  |
| 60                       | 31.7                  |
| 65                       | 35.2                  |
| 70                       | 38.7                  |
| 75                       | 42.2                  |
| 80                       | 45.7                  |
| 85                       | 49.1                  |
| 90                       | 52.6                  |
| 95                       | 56.1                  |
| 100                      | 59.6                  |

The generated of air velocity is applied from 1 m/s to 15 m/s in order to represent the phenomena of heat transfer in the printed circuit board (Figure 3). It is found that air velocity 1 m/s has the minimum power dissipated with 9.5 W followed by 2 m/s, 3 m/s, and 4 m/s with value of 16.1 W, 21.0 W, and 24.5 W, respectively. For the air velocity reaches at more than 5 m/s to 10 m/s, the power generated is not significant increased. Therefore, the optimum level of air velocity is reached at 4 m/s. It is agreed with the previous calculation as well as from the business aspect to sell the product with
power consumed less than 25 W. In addition, the air velocity less than 4 m/s is intended to reduce the reliability even though the power required is minimum.

Figure 3. Diagram of power dissipation as function of air velocity

Figure 4 shows the relationship between the power dissipation and surface temperature. It shows a linear relation from incremental 5 °C from 30 °C to 100 °C, and the power dissipated similar with the value of 3.5 W. It is found that every incremental 5 °C contributed to increase 5 W power consumed. However, the optimal value of surface temperature in order to remain the safety and reliability for electronic components mounted in circuit board had to maximum at 50 °C [11]. As a result for safety and reliability purposes, the power consumed deals with maximum 25 W.

Figure 4. Diagram of power dissipation v.s. surface temperature

4. Conclusion
The phenomena of heat transfer behaviour is necessity to be studied due to effect on the overall performance of new product development, particularly in reliability, safety, dan low-cost aspects. The result shows that a 15 cm × 20 cm of Printed Circuit Board (PCB) has an optimal heat and mass transfer coefficient to meet reliability and safety. In addition, the power generation as function of the
air velocity and the surface temperature are plotted. The simulation was generated, and it is represent the air velocity is vary from 1 m/s to 15 m/s and the surface temperature is identified from 30 °C to 100 °C. As the result, the comprehensive value of heat and mass transfer coefficient is presented for new product development purposes. It is proposed to develop a new product with the power generated with 24.5 W in order to comply cost effective and safety.

This paper describes the advantage of heat transfer analysis during the design stage, so the engineer could perform the comprehensive analysis in designing a new product in the perspective of cost effective and increase the reliability. In addition, the performance of heat transfer could be as reference for business aspect to attract the customer with low-cost product.

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