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Modelling, simulation and analysis of 2D steady state conduction, convection and radiation heat transfer of moulding on rubber press machine

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Abstract

The equal heat transfer distribution of moulding on rubber press machine was very essential to produce the best moulded product. However, the heat transfer on moulding on rubber press machine was not equally distributed. Therefore, the heat transfer of moulding on rubber press machine are required to be evaluated. Most of previous studies only consider the conduction heat transfer on the moulding while no study investigated the convection and radiation heat transfer which almost occurs in rubber press machine due to the open case of machine. Finite element method was performed to determine the temperature distribution based on conduction heat transfer and analytical method was conducted to calculate the radiation and convection heat transfer on moulding of rubber press machine. The results from finite element method showed that the high temperature only occured on the boundary side while the center of moulding showed lower temperature. The temperature from the boundary sides varied 124.3 ºC, 124.4 ºC, 124.5 ºC, 124.8 ºC, 125.3 ºC, 126.5 ºC, 129.2 ºC, and 134.8 ºC. The convection and radiation heat transfer on the moulding was 13.3 kW and 68.23 kW. The slightly difference between real measurement and finite element method on conduction heat transfer because of the steady state assumption on the model. Future study should consider the transient state on the conduction heat transfer and various view factors on convection and radiation heat transfer on the model.

Keywords: *conduction; convection; radiation; finite element method; analytical method*

Abstract

Distribusi transfer kalor yang seragam pada bagian *moulding* dari mesin *rubber press* sangat penting untuk menghasilkan hasil *moulded* produk yang berkualitas terbaik. Pada kenyataannya, transfer kalor pada *moulding* dari mesin *rubber press* tidak terdistribusi secara seragam. Oleh karena itu, transfer kalor pada *moulding* dari mesin perlu dievaluasi. Sebagian besar penelitian sebelumnya hanya mempertimbangkan transfer kalor secara konduksi pada *moulding* sementara itu tidak ada studi yang menginvestigasi transfer kalor secara konvensi dan radiasi yang hampir terjadi pada seluruh tipe mesin *rubber press* dengan tipe *moulding* yang terbuka. Metode elemen hingga digunakan untuk menganalisis distribusi temperatur berdasarkan transfer kalor secara konduksi dan metode analitik dipakai untuk menghitung transfer kalor secara radiasi dan konveksi pada *moulding* dari mesin *rubber press*. Hasil dari metode elemen hingga menunjukkan bahwa temperatur tinggi hanya terjadi pada bagian *boundary* sementara bagian pusat dari *moulding* menunjukkan temperatur yang lebih rendah. Temperatur pada bagian *boundary* bervariasi sebesar 124.3 ºC, 124.4 ºC, 124.5 ºC, 124.8, 125.3 ºC, 126.5 ºC, 129.2 ºC, dan 134.8 ºC. Transfer kalor secara konveksi dan radiasi pada *moulding* sebesar 13.3 kW dan 68.23 kW. Perbedaan antara pengukuran langsung dan simulasi menggunakan metode elemen hingga diakibatkan adanya asumsi *steady state* pada model simulasi. Penelitian selanjutnya sebaiknya mempertimbangkan kondisi *transient* pada transfer kalor secara konduksi dan *view factor* yang lebih bervariasi pada transfer kalor secara konveksi dan radiasi.

Kata Kunci: konduksi; konveksi; radiasi; metode elemen hingga; metode analitik

1. Introduction

Many industries use polymers as material of their products such as aerospace, aircraft, sports equipment, biomass, automotive, electronics and chemicals [1-2]. Industry of sport equipments used polymers to made hand grip of racket, shoes, ball, appareal, and so on. The production of sport equipments, i.e. the shoes, increased by 20.5% and global export increased by 30.8% in volume and by 80.8% in value [3]. Furthermore, Ahmed and Chowdhury [4] concluded that the efficiency of apparel manufacturing was required to be improved in order to fulfill the escalation of global market. The increasing demand of those products prompted the industry to improve the output of production [5]. Rubber press machine was used to made some sport equipments such as outshole shoes and ball based on polymers materials. The machine would proceed the material using heat from electric or boiler to be molded into desired shape. The heat transfer of moulding on the machine are required to be evaluated because the unequal conduction heat of moulding and heat loss due to convection and radiation heat transfer could affect the quality of moulded product. Therefore, the modelling and simulation were performed in this study in order to investigate the heat transfer process on the moulding of rubber press machine.

Wang and Ni [6] studied about the two dimensional unsteady state heat transfer using inverse heat conduction approach based on finite difference method and model prediction control method. The results showed that the model showed good performance with error from 7.01% to 21.05% on boundary angular point angle. Babenko et al. [7] evaluated the heat transfer at the cavity polymer interface in microinjection moulding. The finite element package moldflow was utilized to simulate the experiment and to find the heat transfer coefficient (HTC) that best to describe the cooling curves which confirmed that the value of HTC ranged from 2500 to 7700 W/m^{2}C as requirements for accurate prediction. Liu [8] studied about heat transfer process between polymer and cavity wall during injection molding. The factors affecting the HTC was analyzed on the basis of the factor weight during injection molding. Finite element method was utilized using HTC from the experimental results. The relative criystallinity and part density were obtained from the simulation. The results showed the HTC from the model showed good aggrement with respect to the HTC from the experiment. Al rwashdeh [9] modelled operating conditions of conduction heat transfer based on 2D simulations which confirmed that the thermal conductivity of metal material had higher conduction heat transfer compared to that of wood material.

Most of previous research only studied about the conduction heat transfer on the moulding without considering the convection and radiation. Current study improves the knowledge and comprehensive understanding of heat transfer on moulding of rubber press machine by investigating the performance of steady state model of conduction based on finite element method and calculation analysis of convection and radiation on the moulding.

2. Materials and methods

The material data of measurement was obtained from moulding of rubber press machine by using thermal image camera based on the secondary datasets [11]. Finite element method was used to simulate the temperature distribution of moulding on rubber press machine. Analytical method was utilized to calculate the magnitude of convection and radiation heat transfer from the moulding.

2.1. Temperature Boundary Condition and Air Temperature

Data for temperature boundary condition would be obtained from rubber press machine which was investigated in this study by using thermal image. Figure 1 shows the typical of rubber press machine dan Figure 2 shows the thermal image of moulding from the machine. The moulding of rubber press machine was opened during the measurement using the thermal image therefore the overall distribution of temperature could be investigated. The data measurement from the thermal data image would be used to determine the initial boundary condition of model simulation using finite element method and analytical calculation. Temperature data from thermal image would be collected six times in order to ensure the accuracy of distribution temperature on the moulding as shown in Table 1.

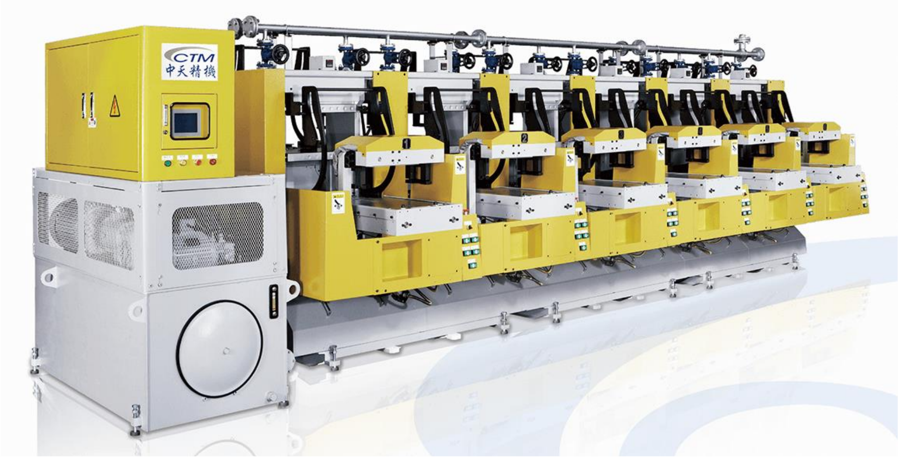

Figure 1. Typical of rubber press machine [10]

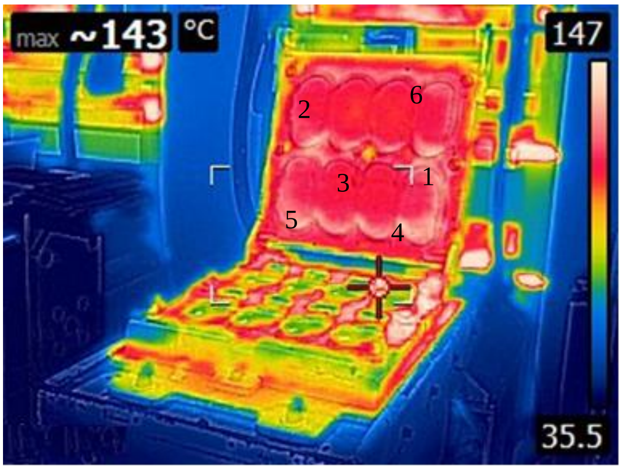

Figure 2. Thermal image of moulding on rubber press machine

Tabel 1. Variation of temperature on moulding

Temperature point	Mold Temperature
Point 1	140 °C
Point 2	143 °C
Point 3	145 °C
Point 4	146 °C
Point 5	147 °C
Point 6	148 °C

Air temperature was measured using temperature hygrometer as shown in Figure 3. The data was collected six times in one day with different hour to investigate the variation of air temperature around the rubber press machine. Air temperature around rubber press machine was assumed uniform because the air temperature was out of the range of thermal boundary layer from the moulding as confirmed by Cengel and Ghajar [13] in the Figure 4.

Figure 3. Typical of temperature hygrometer [12]

Tabel 2. Variation of air temperature (T_∞)

Time	**T∞**
05.00-06.00	34.8 °C
06.00-07.00	35.7 °C
08.00-09.00	36.4 °C
10.00-11.00	36.5 °C
12.00-13.00	37.1 °C
13.00-14.00	37.8 °C

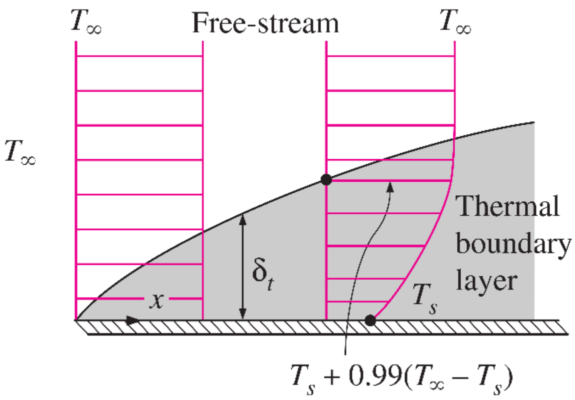

Figure 4. Air temperature was uniform in the outside of thermal boundary layer [13]

2.2. Finite Element Method and Gauss-Seidel Iterative Method

Finite element method (FEM) was used to model the conduction heat transfer on the moulding of rubber press machine. FEM is a numerical analysis technique analyzing the discrete elements of model by using partial differential equations. The FEM method would solve two dimensional poisson equation by assuming steady state in the system as shown in equation (1) [13].

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{q_{gen}}{k} = 0 \quad (1)$$

Surface element analysis would be utilized to solve the two dimensional poission equation as shown in (1) by dividing the plate of moulding into the discrete points which were evenly located throughout the plate and the points would be analyzed using two dimensional (2D) surface elements approach as shown in Figure 5.

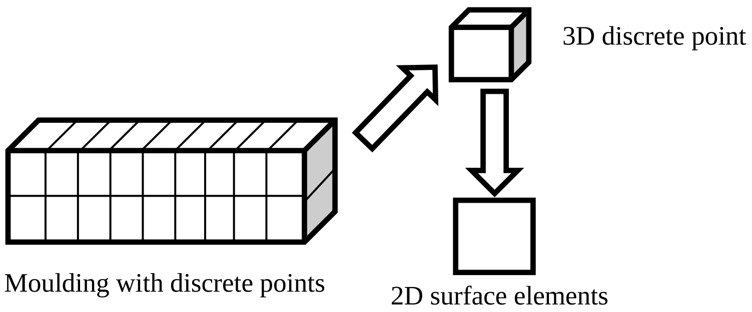

Figure 5. Moulding with discrete points and 2D surface elements

The distribution temperature of each 2D surface elements could be analyzed by using nodes principles as shown in Figure 6 and calculated using Fourier's Law and energy balance principle as shown from equation (2) to equation (5).

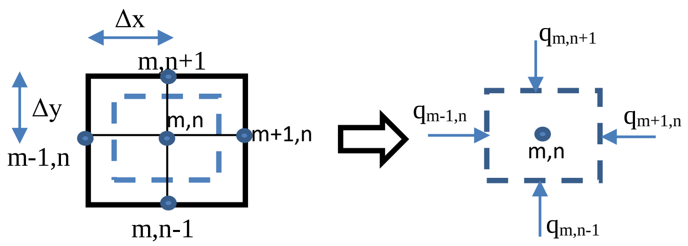

Figure 6. Analysis of 2D surface elements

$$E_{in(m,n)} = E_{out(m,n)} \tag{2}$$

$$q_{m-1,n} + q_{m+1,n} + q_{m,n-1} + q_{m,n+1} + q_{gen} = 0 \tag{3}$$

Equation (3) would be solved by using Fourier's Law of heat conduction as shown in equation (4) [13].

$$Q_{conduction} = -kA\frac{\Delta T}{\Delta x} \tag{4}$$

The result from equation (3) using Fourier's Law of heat conduction is shown in equation (5).

$$4T_{m,n} - T_{m-1,n} - T_{m+1,n} - T_{m,n-1} - T_{m,n+1} - T_{gen} = 0 \tag{5}$$

The equation (5) would be solved by using Gauss-Seidel iterative methods as shown in equation (6).

$$T_m = \frac{1}{a_{mm}}\left[-\sum_{n=1}^{m-1}\left(a_{mn}T_n^{(k)}\right) - \sum_{n=m+1}^{n}\left(a_{mn}T_n^{(k-1)}\right) + b_m\right] \tag{6}$$

The matrix would be created in order to calculate the temperature distribution using Gauss-Seidel iterative method. The matrix would be set from zero as initial value with boundary condition from the mold temperature in the Table 1. The equation (5) would be used to calculate the distribution temperature in each matrix and Gauss-Seidel iterative method would repeat the calculation until reach the tolerance = 1 x 10^{-6} and error = 1 x 10^{-4}.

2.3. Convection and Radiation Heat Transfer

Analytical method would be used to calculate the convection and radiation heat transfer. Convection heat transfer would be calculated by using equation (7) [13].

$$Q_{conv} = h(T_s - T_\infty) \quad (7)$$

where h means the convective heat transfer coefficient (W/m^2.K), T_s means surface temperature (K) and $T\infty$ means air temperature (K). Radiation heat transfer would be calculated by using equation (8) [13].

$$Q_{rad} = \varepsilon\sigma A_s(T_s^4 - T_{surr}^4) \quad (8)$$

where ε means the emisivity of the object, $\sigma = 5.67 \times 10^{-8}$ J/s.m^2.K^4 is the Stevan-Boltzman constant, A is the surface of object, T_s is the surface temperature and T_{surr} is the surrounding temperature. Convection and radiation heat transfer would be calculated based on three different position of moulding on rubber press machine which were horizontal, vertical and inclined as shown in Figure 7 and Figure 8, respectively. L means the length of the moulding, θ is the angle of moulding with respect to vertical line, w means width of the moulding, w_i and w_j means the width of moulding on the first and second surface, respectively.

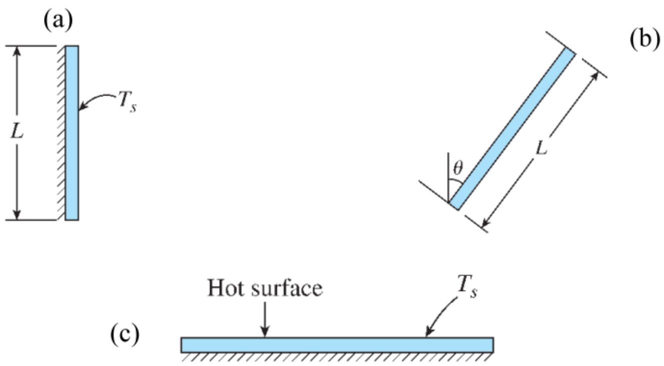

Figure 7. Different position of moulding for convection heat transfer (a). Vertical, (b). Inclined, (c). Horizontal [13]

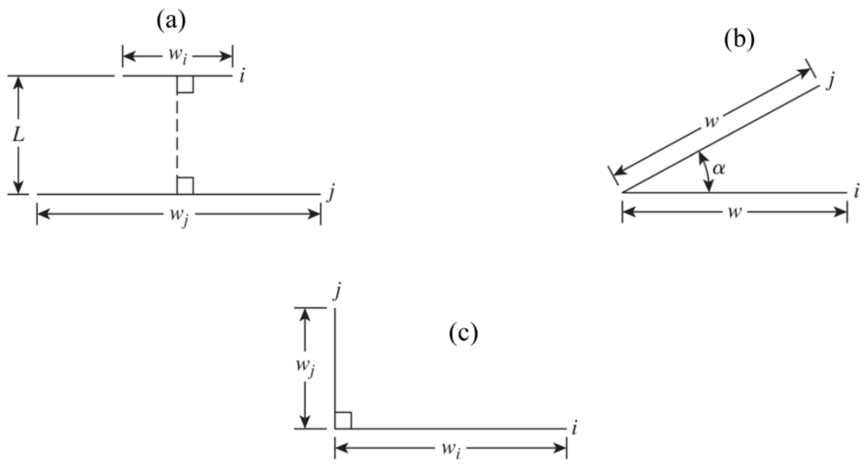

Figure 8. Different position of moulding for radiation heat transfer (a). Vertical, (b). Inclined, (c). Horizontal [13]

2.4. Research Methodology

Figure 9 summarize the research methodology in current study. The boundary condition (BC) and surface temperature (T_s) would be obtained from the thermal image. Air temperature (T_∞) was measured by using temperature

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hygrometer. Finite Element Method (FEM) would be used to model temperature distribution on the moulding based on BC. The Gauss-Seidel iterative method would be repeat the calculation of FEM until the predicted temperature achieved the desired tolerance and error. Countour temperature was the final results of finite element method. The surface temperature and air temperature would be used to calculate convection and radiation heat transfer. Three different position of moulding would be considered in the calculation such as vertical, horizontal and inclined. The results of those positions would be compared to each other in order to determine which positions had high, moderate and low convection and radiation heat transfer.

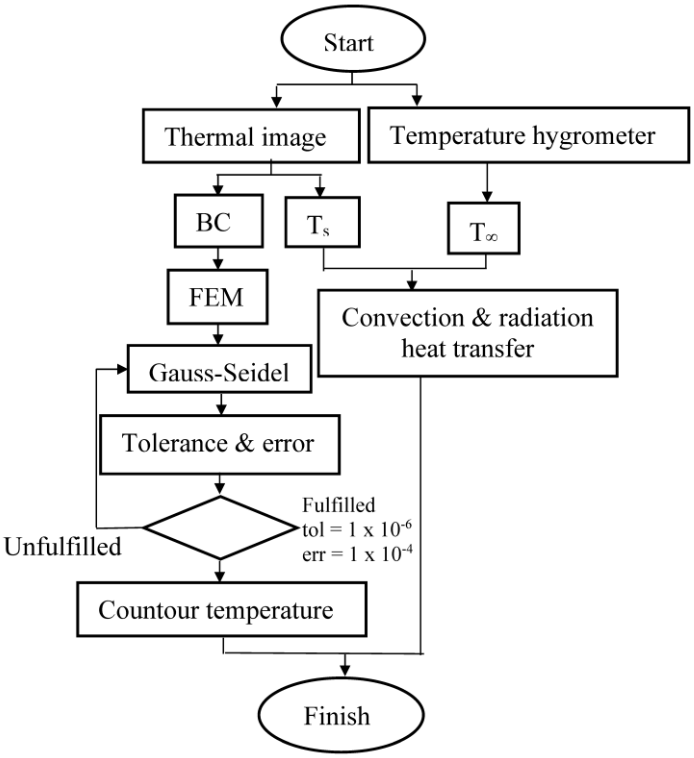

Figure 9. Research methodology

3. Results and Discussion

Results of finite element method would be represented by temperature countour and graphic of moulding on rubber press machine. While, results of calculation of convection and radiation would be presented on the different position of moulding such as horizontal, inclined and vertical. The simulation only focused on the moulding of rubber press machine. Figure 10 shows the position of analyzed moulding on rubber press machine.

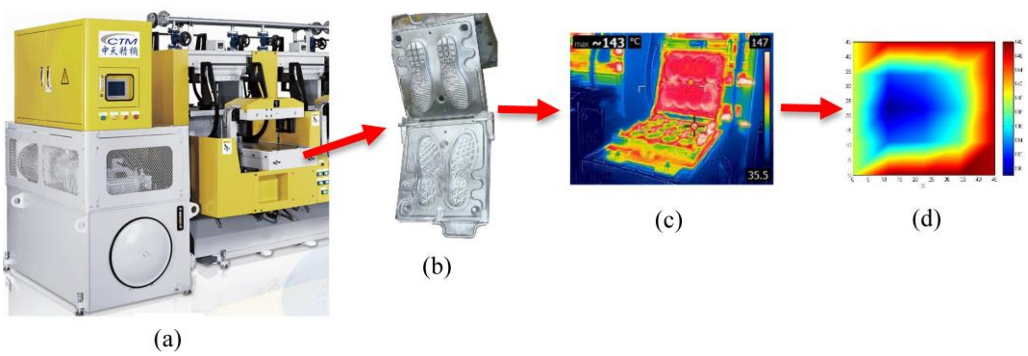

Figure 10. Analyzed moulding on the machine (a). Rubber press machine, (b). Moulding, (c). Thermal image on moulding, (d).Simulation on moulding using finite element method

3.1. Simulation of temperature distribution on moulding of rubber press machine

Figure 11 shows temperature distribution on moulding of rubber press machine based on number of nodes (n=5) with error = 0.001 and tolerance 1 x 10^{-6}. The average simulated temperatures on the middle of moulding were 131.4^{o}C, 132.9^{o}C and 136.8 ^{o}C from left to right position which were lower compared to the temperature on the boundary condition in Table 1.

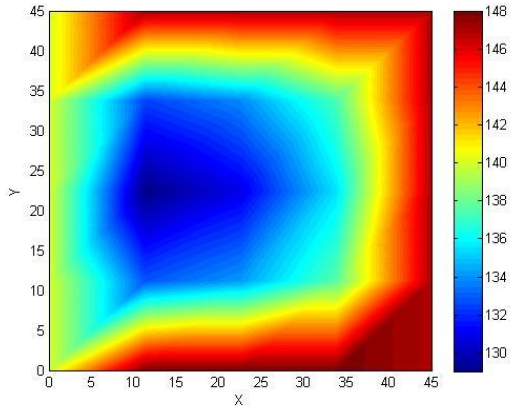

Figure 11. Simulation of temperature distribution for n=5

Figure 12 shows the temperature distribution on moulding of rubber press machine with higher number of nodes (n = 10) compared to that of previous result. However, the increasing number of nodes would decrease the temperature on the middle of moulding model. The average simulated temperature were 124.3 ^{o}C, 124.4 ^{o}C, 124.5 ^{o}C, 124.8 ^{o}C, 125.3 ^{o}C, 126.5 ^{o}C, 129.2 ^{o}C, and 134.8 ^{o}C from left to right position which were lower compared to previous results.

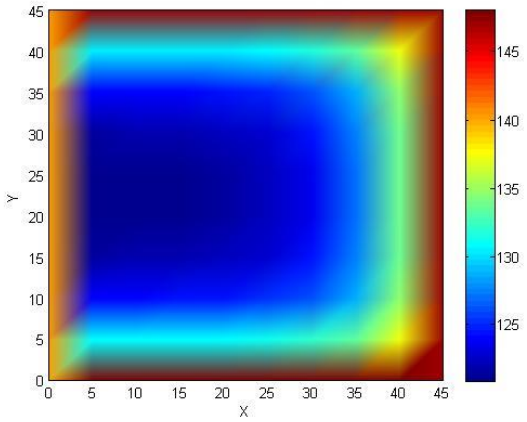

Figure 12. Simulation of temperature distribution for n=10

Figure 13 and Figure 14 shows average temperature distribution on moulding of rubber press machine with increasing of number of nodes (n = 45) for x and y-axis, respectively. The temperature on x-axis shows almost constant value from x =1 cm to x = 36 cm. While, the temperature increase from x = 36 cm to x = 45 cm. High temperatures were found almost all position of moulding model. Similar to those of temperature on x-axis, the temperature on y-axis shows higher near the boundary condition compared to those of on the middle of moulding model. The simulation shows that the conduction heat transfer across from boundary condition to the middle positon of moulding model by decreasing temperature.

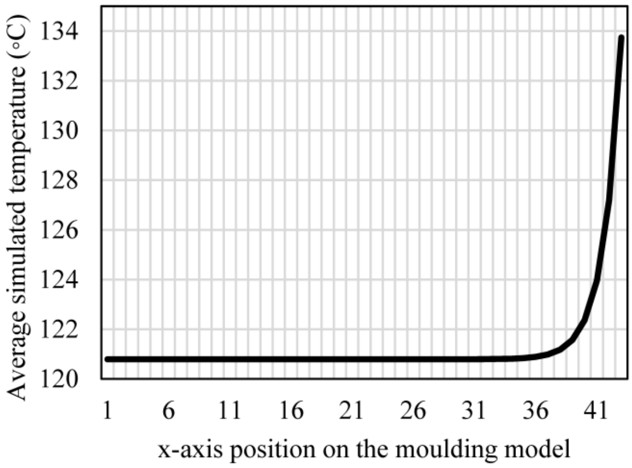

Figure 13. Simulation of temperature distribution on x-axis position for n=45

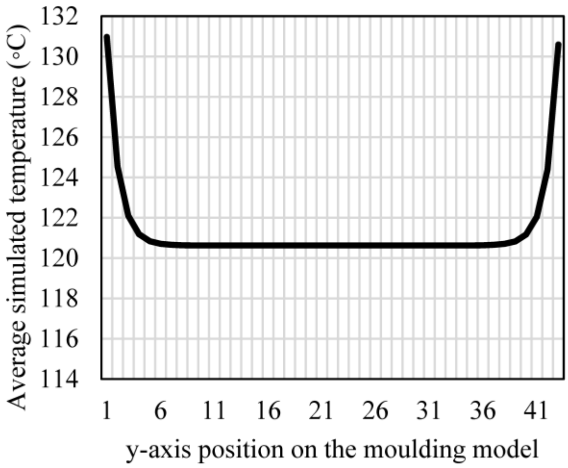

Figure 14. Simulation of temperature distribution on y-axis position for n=45

3.2. Calculation of convection and radiation

Figure 14 shows the convection heat transfer with three different positions such as horizontal, inclined and vertical. The results showed that the inclined and vertical had similar magnitude while horizontal position showed the lowest convection heat transfer. The natural convection would occur mostly on the inclined and vertical compared because the wind would easily hit those positions than that of horizontal position. Figure 15 shows the radiation heat transfer with three different positions of moulding. The results showed that the inclined positions showed higher radiation compared to those of horizontal and vertical positions. The inclined positions had higher radiation due to reflection among two surfaces of moulding. While, horizontal position showed lower radiation heat transfer due to the inability of thermal image to measure the moulding in this position. Therefore, the captured temperature in horizontal was lower than those of inclined and vertical. Convection heat transfer had higher magnitude than those of radiation heat transfer because the air medium increase the impact of heat transfer. While, radiation heat transfer occurs without intervention any medium.

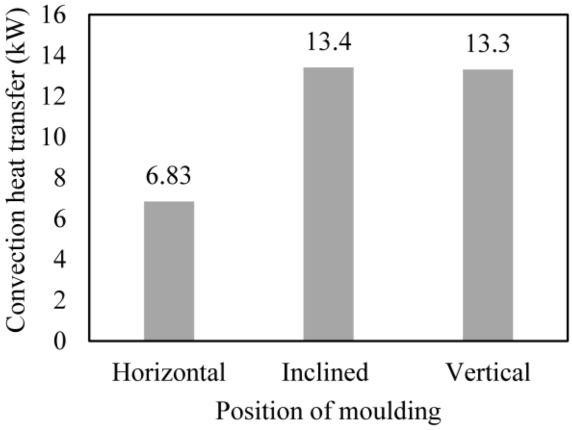

Figure 14. Calculation of convection heat transfer on moulding with three different positions of moulding

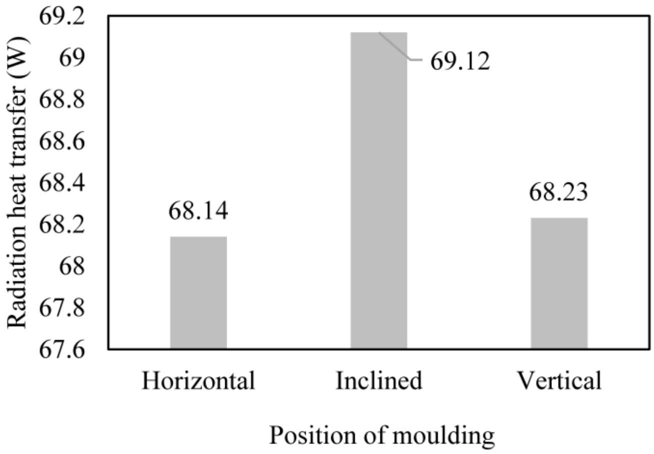

Figure 15. Calculation of radiation heat transfer on moulding with three different positions of moulding

3.3. Comparison with measurement and previous studies

Current study of temperature distribution using FEM showed similar results for the fundamental concept of finite element method and experiment of two dimensional heat transfer as confirmed by Blunt and Coldwell [14]. Similar results with current study also confirmed by Stewart [15] who simulated the temperature distribution of heated plate. Furthermore, current simulation in Figure 9 and 10 showed similar distribution of the average simulated temperature compared to that of thermal image in Figure 2. The slightly different temperatures on simulation and thermal image were caused by the different assumption of heat generation on the moulding model.

Previous studies did not consider the calculation of convection and radiation from the moulding. Most previous studies only focus on temperature distribution of conduction heat transfer. Current findings could give information to the users of rubber press machine so that they did not open the case of moulding for long time. The moulding of rubber press machine tended to give convection heat transfer to the surrounding of machine for 13.4 kW. It would give heat stress to the user of machine which could cause fatique. Furthermore, the inclined position of moulding could give 69.12 W of radiation heat transfer. If this phemonenon occured for long period time, it might affect on health of user which contradicted to the principle of health and safety in workplace.

3.4. Limitation of study

Current study had limitation which only considered two dimensional heat transfer and steady state condition. Future studies should consider the three dimensional and transient approach in order to improve the modelling and simulation of moulding on the machine. Furthermore, detail calculation of convection and radiation heat transfer did not consider in this study. Many parameter and view factors of convection and radiation heat transfer that should be investigated in the future studies.

4. Conclusion

Modelling and simulation of conduction heat transfer had been studied by considering the temperature distribution of moulding on rubber press machine. The current results showed similar results with previous studies and measurement using thermal image. The slightly different was caused by the different assumption on heat generation of the moulding. Current study contributed to the research in this field by considering convection and radiation heat transfer. The finding of current study could be used to improve the health and safety regulation in using rubber press machine by considering the heat comes from convection and radiation. Therefore, the user of machine could utilize the machine by minimizing the negative impact due to the convection and radiation heat transfer.

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