SEMARAK ILMU
PUBLISHING
202103268166(003316878-P)

Journal of Advanced Research in Applied Mechanics

Journal homepage:
https://semarakilmu.com.my/journals/index.php/appl_mech/index
ISSN: 2289-7895

An Application of Computer-aided Engineering on Heat Transfer in a Mold for Natural Rubber Boot Production

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ARTICLE INFO

Article history:
Received 30 June 2024
Received in revised form 6 August 2024
Accepted 14 August 2024
Available online 30 August 2024

Keywords:
Natural rubber boots; Rubber Injection Molding; Finite element analysis; Heat transfer in mold; rubber mold design

ABSTRACT

The production of natural rubber boots refers to the process of manufacturing boots using natural rubber as the primary material. The manufacturing process involves injecting natural rubber into a mold to shape and size the boot. The molded boots are then cured and finished with other materials, such as fabric linings, soles, and straps. Natural rubber boots are popular for outdoor activities, work, and fashion. The purpose of this research is to develop a computer-aided engineering analysis simulation tool for heat transfer in the injection mold of rubber boot products. In this study, a finite element model was created to reduce the preheating time of the mold during the injection molding process, thus increasing production capacity. The first step was to design the mold used in the current factory, followed by an analysis of the heat transfer in the rubber mold. Finally, the position of the heater cartridges was fixed based on the analysis results. FEA was performed to improve the rubber mold, and experiments were conducted to validate the FEA. The results showed that the FEA was in good agreement with the experimental results, specifically with the temperature analysis.The time required for the heater cartridge to preheat the rubber boot mold is 35 minutes, down from 120 minutes, representing a percentage improvement of 70.8. The heat transfer values obtained at each location have an error of less than 10%, which is a good result for the calculated model. We propose an optimal design method for arranging cartridge heaters in rubber boot injection mold to improve the mold design, specifically on the mold outer surface.

1. Introduction

Natural rubber boots are commonly exported and used by farmers, builders, factories, or other workers to protect their feet from water or mud. They are comfortable to wear, highly agile, lightweight, good for anti-slip, durable, and almost knee-high. Typically, rubber boot products are produced using injection molding. Improving the mold design by analyzing the heat distribution in the mold using computer-aided engineering analysis can reduce the mold preheating time for injection-molded rubber boot products and improve the dimensional accuracy of the natural rubber

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https://doi.org/10.37934/aram.124.1.113126

boots. Uniform temperature distribution on the mold cavity surface is crucial for preventing defects in the product.

Although, many methods have been developed to achieve uniform heating of the mold. Hammami M. *et al.,* [1] studied heat transfer during injection molding using a series of injection technologies that enable total temperature control in molds (Rapid Heat Cycle Molding (RHCM)) through numerical analysis. They proposed improvements in temperature distribution and heat dissipation compared to the original injection molding. The simulation results showed that the uneven temperature system in the mold can be controlled more efficiently, and heat energy consumption can be significantly reduced by 27 percent, as was also observed by Kanbur B. B. *et al.,* [2] who developed systems to reduce cooling time for injection molding processes by investigating the mechanical and thermal properties. Two mold designs, 3-mesh vents and 5-mesh vents were designed to compare cooling times and uniform temperature distribution. The results showed that the 3-mesh cooling vents had better cooling time and temperature distribution, resulting in improved injection molding process. Kim M.H. [3] studied the arrangement of the rubber sole mold heater cartridges using finite element analysis (FEA), and the experimental results and FEA were within acceptable limits, resulting in good product shape. Wang J. *et al.,* [4] studied four factors affecting the quality of injection molding, namely mold temperature, repeated injection pressure, temperature before injection, and cooling rate by testing the sample Acrylonitrile Butadiene Styrene (ABS). The results of the research showed that the mold temperature was consistent with the pre-injection temperature, and the cooling rate had a variable effect on the shrinkage of the part. High injection pressure has a significant influence on the amount of shrinkage during injection molding. Bex, G.-J. *et al.,* [5] studied the influence of different process parameters on the adhesion strength between thermoplastics and thermoset rubbers for injection molding. Factorial experimental design by controlling the parameters as follows. Mold temperature Injection temperature Injection speed holding pressure and initial roughness of thermoplastic parts. The results are the bonding strength depends on the mold temperature which determines the adhesion of the material. As for other parameters There was no significant effect on the adhesion strength. The injection temperature and speed did not cause a significant increase in the temperature of the rubber material. Therefore, does not increase the temperature The initial roughness will cement and dissolve. due to high temperature

Zhao J. *et al.,* [6] developed the physical and mechanical properties of silicone rubber by finite element modeling and used heat to measure the deformation of rubber. They compared the numerical calculation method to the actual test. The results showed that it was possible to predict the remaining life of the rubber material from the measured parameters. Additionally, Surindra, M.D. *et al.,* [7] Study the heat transfer of the heater of the injection molding machine before and after maintenance. The problem is that the heater malfunctions causing the production process to stop, such as the heat not reaching the set value. When the heat is not reached, the plastic does not melt, resulting in a blockage in the nozzle. As a result of the heater modification, after 25 minutes of use, the temperature increased by 24% from the original temperature. But the use of electrical energy has increased. and production efficiency increased by 95.4% in 8 hours.

However, there is also the use of computer-aided mold design that is used in a variety of mold thermal analysis software. They are presented in the following formats, Beheshtian Mesgaran S. *et al.,* [8] conducted research on mold design, using Finite Element Analysis (FEA) to analyze burn marks and shrinkage effects during injection molding. The researchers designed the mold using SOLIDWORKS software. Finite element analysis in MOLD FLOW was used to analyze the part's burn and shrinkage marks. As a result, the following parameters must be set: adjusting the ejection pin at some point, reducing injection speed and pressure. This prevents burns caused by vacuum gaps at the end of the filling process and optimizes the design process. As a result, cost reductions as well as surface quality improvements have been achieved. Arrilaga A. *et al.,* [9] studied the evaluation of injection molding simulation tools to simulate rubber curing kinetics. The variable to be measured is the exothermic value. The exothermic value can measure the degree of hardening of the rubber compared to the curing time of the rubber. To take into account the best software used to predict the percentage of hardening, the nature of the material must be determined. The tires used for the test were natural rubber and synthetic rubber. The parameters used were a mold temperature of 160°C and a nozzle temperature of 110°C. As a result, Mold flow software was able to predict rubber solidification better and faster than Cadmould, according to Matin I. *et al.,* [10] developed CAD/CAE software with built-in functions for injection mold design improvement that help define the parameters of the design control parameters, as well as being able to base material on a solid design model. In order to conveniently choose designs in the design process, the results proved that a targeted software tool was precise for plastic injection molding processes, as investigated by Traintinger M. *et al.,* [11] They developed test methods to improve the simulation of the rubber injection molding process and calculate rubber curing kinetics. The equipment used in the experiment includes a test stand and an injection molding machine with given parameters, such as an initial temperature of 80 °C and a mold temperature of 160 °C. The default software to be improved is SIGMA Gmbh. The parameters set include the same temperature greater than the actual value above. The value measured when verifying is the hardening of the rubber temperature in the mold. The results show good accuracy, with the obtained values consistent with the actual test.

Additionally, Barriere T. *et al*., [12] performed numerical experiments on specimens using the injection molding method. They formed one piece of work using two types of materials: liquid silicone rubber and polyamide plastic. The test results showed faster heating, resulting in more heat flow and an increased curing rate. Using the Cadmould3D software, the complex model was created in a single part molding process using different composite materials that were accurate and precise. The model predicted the curing time, which was faster than the data from the experiments at the same temperature, with less than 2% of the expected deviation. Therefore, for the manufacture of high-precision rubber products, research is needed on methods to efficiently control the temperature distribution of rubber boot molds by properly arranging the heaters. Zink, B. *et al.,* [13] studied cooling in molds. To examine the effects of various cooling cycles and mold materials. that affects the quality of injection molded parts Mold inserts and a total of four refrigeration circuits are designed from three materials. The numerical procedure used Autodesk Simulation Moldflow Insight software. The same parameters were used in the simulation. Using a designated cooling system Instead of the original cooling system It can improve the quality of the product. and reduce the cycle time and heat load of the mold. From the results obtained in the case of injection molded parts that are simpler and smaller than custom cooling systems, it can be specified that the mold material contains a high copper alloy. Able to extract more heat even with a simple cooling system The use of mold materials with good thermal conductivity is limited by wear. and increased deformation but the thermodynamic side Heat conduction is slower for different materials.

Due to its low thermal conductivity, Bartłomiej Burlaga *et al.,* [14] studied the heat transfer analysis of 3D printed photopolymer wax injection molds using various cooling media and different geometries. Protection of the cooling channel Using COMSOL software based on the finite element method. As a result, the model can be successfully used in thermal analysis. This makes planning the production process more convenient. Water at room temperature is best heated in 25 seconds, after which it is cooled with cold air with a maximum flow rate of 0.001 kg/s. It is considered the most efficient process. After 30 -35 seconds, air cooling is more effective than heat dissipation through aluminum materials. Leszek Chybowski *et al.,* [15] present the main methods used for coastal protection. It discusses the construction and operation of a multi-tube ocean wave damper. A simulation study of the behavior of the device's floating elements when floating on waves was performed using ANSYS AQWAWB and AQWA software. The results showed a wave damping of more than 70% and a high level of horizontal force compensation. The results of the experimental study were consistent with the results obtained from computer simulations. The horizontal force acting on a single pipe submerged vertically in water, the ripples that appear at the top end of the pipe, are stronger than the horizontal forces that appear at the bottom end of the pipe. and two pipes immersed in wavy water. which has a distance equal to half the wavelength. Gruber & De Miranda [16] studied the hardening efficiency of parts produced by the thermoplastic injection process. It examines the dimensions, images, and production behavior according to changes in the shape, temperature, and cooling system design of injection molds. SolidWorks Plastics software was used in the simulation. The simulation results were able to analyze the efficiency of the solidification process for various thermoplastic injection mold cooling systems, showing that helical shape cooling systems are more efficient when compared with other systems, Jozef Dobránsky *et al.,* [17] studied heat transfer in an injection mold destined for the production of plastic parts. There are two types of mold cooling systems: Simple cooling and uniform cooling The simulation method was performed in ANSYS simulation software. The heat transfer results between each part of the mold were evaluated using a point to analyze heat at each point. Optimizing cooling at the bottom of the mold may affect heat transfer. which directly affects production time.

It was noticed that the mold warm-up time and injection molding cycle time were too long, which was causing problems. To address this, we applied computer-aided heat distribution analysis to the mold and installed a set of heating equipment. This will help reduce the time needed for warming up and increase the factory's daily production capacity.

2. Methodology

An AISI P20 grade mold was used for manufacturing rubber boots. The mold consisted of four parts: upper mold, left mold, right mold, and inner mold, which were studied in this research. Figure 1 shows the procedure used for developing a prediction model of heat transfer in the mold for natural rubber boot production. Numerical simulations and experimental analyses were carried out to determine the position of heaters and the heat transfer in the mold.

At present, the factory in the case study requires 120 minutes to preheat the mold due to the time required for heat transfer from the injection molding machine to the mold. Additionally, the temperature needs to be set higher than the desired value. Meanwhile, the cycle time is 12 minutes, and the current production capacity can produce 80 sides per day or 40 pairs. The rubber boots injection molding process is shown in Table 1.

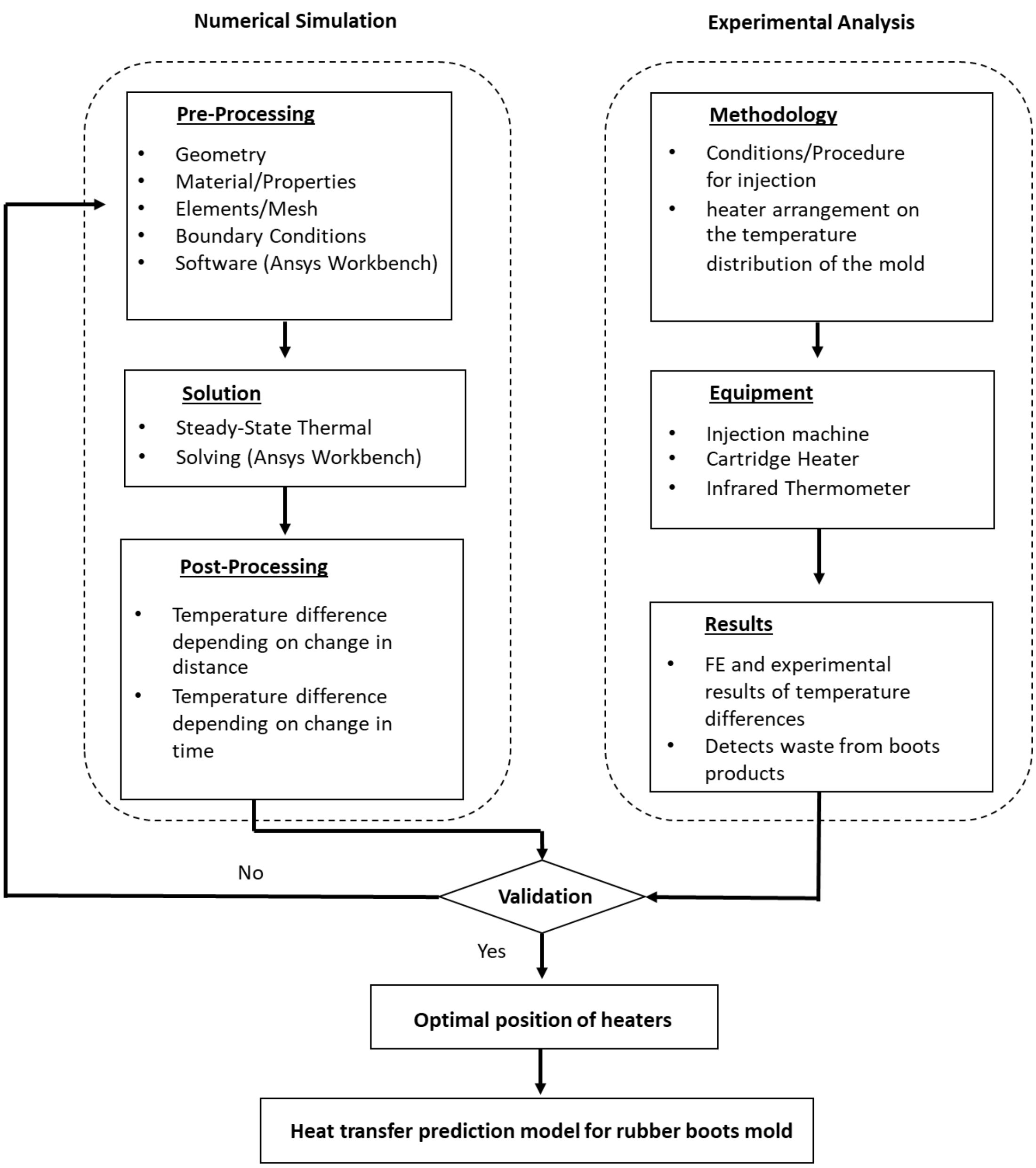

Fig. 1. Overall procedure of heat transfer in mold prediction model development for natural rubber boot product

Table 1
Rubber boots injection molding process

Injection molding process	Time (minutes)
1) Mold pre-heat; Set-up temperature at 190 ˚C. (Mold Temperature at 150 ˚C)	120
2) Feed the rubber compound into the barrel.	2
3) Clean the mold, assembly mold and load into the injection machine.	2
4) Injection the rubber compound into the mold	1
5) Curing the rubber to maintain its shape	5
6) Remove the mold from the injection machine. and release the product	2
Total	132

2.1 Modes of Heat Transfer

The field has been divided into three heat transfer modes: conduction, convection, and radiation. These three modes are briefly described next.

2.1.1 Conduction

Transfer of heat by conduction occurs in solids and in essentially nonmoving liquids and gases. It has been observed (through experimentation) that the rate of heat transfer per unit area is proportional to the temperature gradient in the material. For steady conduction heat transfer through a plane wall, Fourier's law can be integrated to give:

$$q_{cond}=\frac{KA}{L}(T_1 - T_2) \qquad (1)$$

where qcond is the conduction heat transfer rate, kt is the thermal conductivity of the material, A is the cross-sectional area normal to the heat transfer direction, and dT/dx is the temperature gradient in the direction of heat transfer. The algebraic sign of this equation is such that a positive q_{cond} always corresponds to heat transfer in the positive x direction, and a negative q_{cond} always corresponds to heat transfer in a negative x direction. Since this is not the same sign convention adopted earlier in this text, the sign of the values calculated from Fourier's law may have to be altered to produce a positive when it enters a system and a negative when it leaves a system.

2.1.2 Convection

Transfer of heat by convection typically occurs between a surface and an adjacent fluid. Convection is a phenomenon involving conduction in the fluid and fluid motion. however, occurs whenever an object is either hotter or colder than the surrounding fluid. The basic equation of convection heat transfer is Newton's law of cooling:

$$q_{conv}=hA(T_\infty - T_s) \qquad (2)$$

where Q_{conv} is the convection heat transfer rate, h is the convective heat transfer coefficient, A is the surface area of the object being cooled or heated, T_∞ is the bulk temperature of the surrounding fluid, and T_s is the surface temperature of the object. The algebraic sign of Newton's law of cooling has been chosen to be positive for $T_\infty > T_s$ (i.e., for heat transfer into the object). This corresponds to our thermodynamic sign convention for heat transfer when the object is the system. The convective heat transfer coefficient h is always a positive, empirically determined value.

2.1.3 Radiation

All electromagnetic radiation is classified as radiation heat transfer. Infrared, ultraviolet, visible light, radio and television waves, X rays, and so on are all forms of radiation heat transfer. The radiation heat transfer between two objects situated in a non-absorbing or emitting medium is given by the Stefan-Boltzmann law:

$$q_{rad}=F_{1\text{-}2}\epsilon_1 A_1 \sigma(T_2^4 - T_1^4) \qquad (3)$$

where q_{rad} is the radiation heat transfer rate, F_{1-2} is called the view factor between objects 1 and 2 (it describes how well object 1 "sees" object 2), ε_1 is the dimensionless emissivity or absorptivity (the hotter object is said to emit energy while the colder object absorbs energy) of object 1, A_1 is the surface area of object 1, σ is the Stefan Boltzmann constant (5.69×10^{-8} W/m^2 · K^4 or 0.1714×10^{-8} Btu/h · ft^2 · R^4), and T_1 and T_2 are the surface temperatures of the objects. A black object is defined to be any object whose emissivity is ε = 1.0 Also, if object 1 is completely enclosed by object 2, then F1–2 = 1.0. For a completely enclosed black object, the Stefan-Boltzmann law reduces to

$$q_{rad}=A_1\sigma(T_2^4 - T_1^4) \tag{4}$$

2.2 Numerical Simulation

A numerical simulation is a calculation that is run on a computer following a program that implements a mathematical model for a physical system. It can be divided into subtopics as follows:

2.2.1 Design of rubber boots molding model

The mold used for the drawing is a boots mold with a size of 10 US and has 4 parts: Inner mold, Right mold, Left mold, and Top mold. 3D drawings were performed and are shown in Figure 2, respectively, displaying dimensions of width, length, and height from 4 different perspectives. The flow channel of the natural rubber mold is 3 mm and Properties of a rubber boot mold in Table 2 shows the thermal properties of a rubber boots mold.

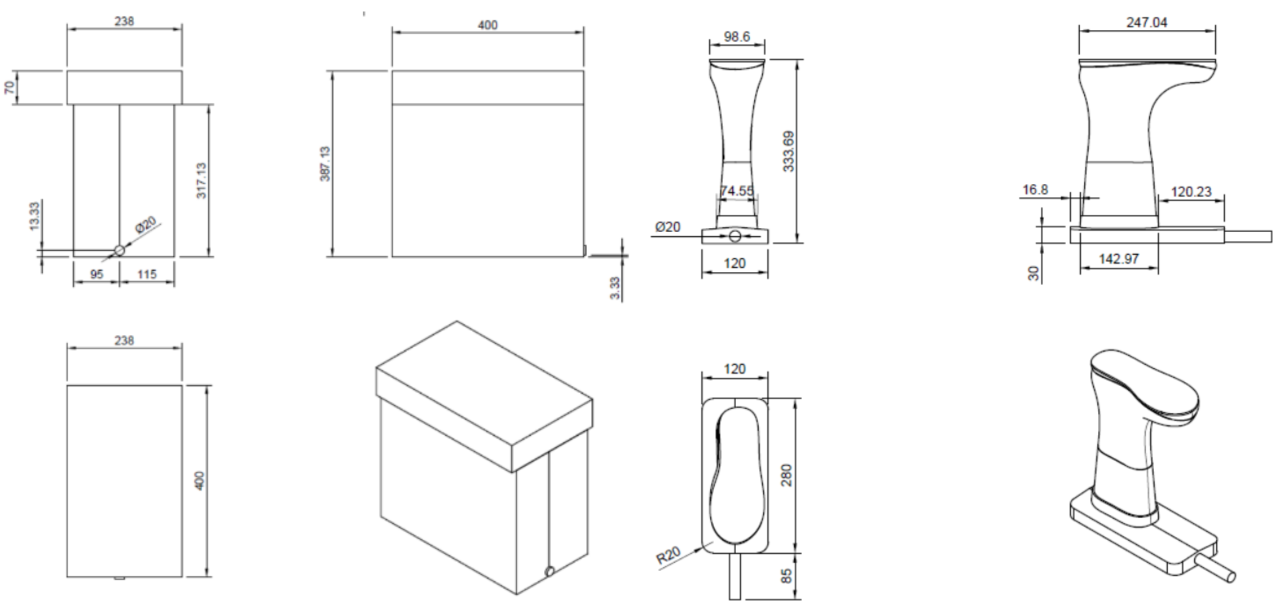

Fig. 2. Dimensions of rubber boots injection mold (present)

Table 2
Properties of a rubber boot mold [19]

Type	
Mold Material	SS400
Density (kg/m3)	7850
Conductivity (W/m·K)	60.5
Heat Capacity	434

2.2.2 Numerical simulation of rubber boots mold (3D model)

The rubber boot mold has been simulated, and two types of boundary conditions have been defined: a constant heat flux into the mold and a controlled heat flow that depends on the temperature of the injection molding machine heater. These boundary conditions have been defined in order to simulate a real rubber boots injection molding machine. Table 3 displays the boundary conditions used in the simulation.

Table 3
Boundary conditions of rubber boot mold

Type	Temperature controlled
Thermal of main heater	150°C
Convection air	10 W/m^2·k 30°C
Holes heater cartridge	150°C

2.2.3 Finite Element Analysis of rubber boots mold

The temperature control approach involves programming boundary conditions using ANSYS Workbench commands to simulate the actual temperature control of the injection machine. Heat is applied to a target temperature of 150°C and is then transferred through a mold on the upper and lower surfaces. The temperature is calculated at different intervals, every 10 millimeters, according to the heat transfer curve from top to bottom. Additionally, the temperature is measured at the heater installation location at various intervals. Heating will continue until a steady state is reached, and the temperature difference will be measured.

A finite element heat transfer analysis was performed to predict the temperature difference on the surface of the rubber boot mold. Heat was applied to reach the target temperature of 150°C, and the temperature was calculated at each time interval while the heater controlled the actual injection temperature. Figure 3 shows the finite element model used in the analysis.

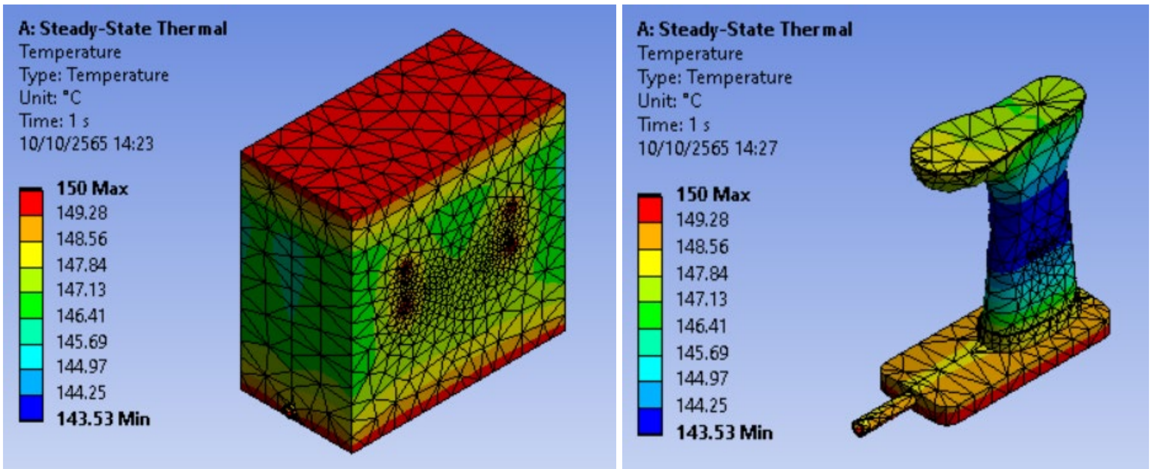

Fig. 3. FE model for rubber boots mold

2.3 Experiment Analysis

The machine type is a vertical injection molding machine, and the KM-300-3RT model comprises a compression unit, an injection unit, a temperature control unit, and so on. Figure 4 displays the rubber injection machine and the boots mold, while Table 4 describes the injection conditions.

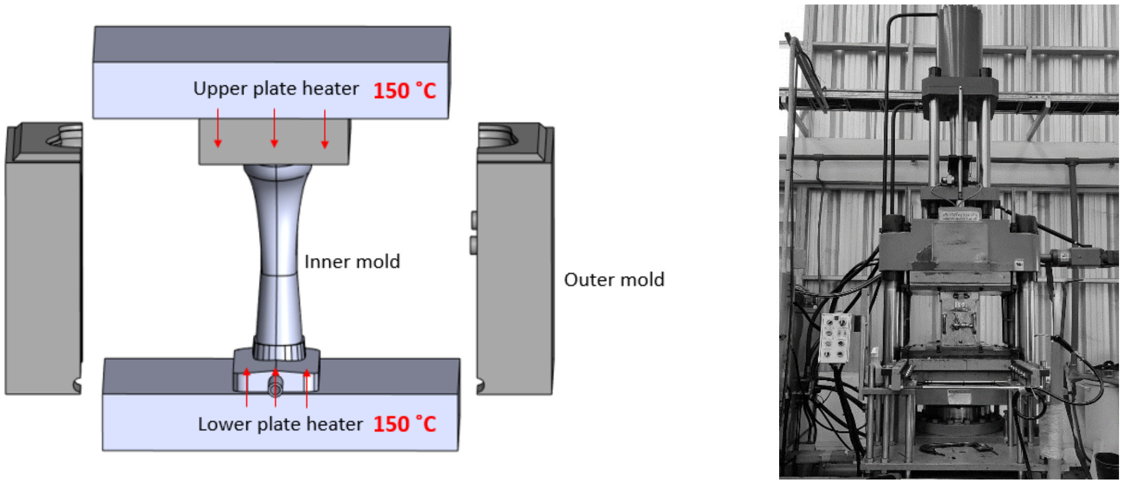

Fig. 4. Equipment and boots mold for rubber injection

Table 4
Experimental conditions for injection

Types	Condition	Note
Curing Temp.	150°C	Upper plate 150°C and lower plate 150°C
Screw and injection Temp.	60°C	Controller 60°C
Injection Time	1 min	Pressure 210 kgf/cm^2
Curing Time	5 min	

3. Results
3.1 Simulation Result
3.1.1 Locate the position to install the heater on the rubber boot mold

As a result of heating the upper and lower positions of the mold to 150°C at the upper edge of the model, the temperature in that area is the highest, as specified by the conditions, and the temperature value decreases with increasing distance into the mold. Over time, the temperature at different locations within the boots mold model kept increasing until it reached a constant value. Thereafter, no matter how much time is added, the temperature values at different locations within the model remain unchanged. The effect of this change is shown in Figure 5 and Figure 6.

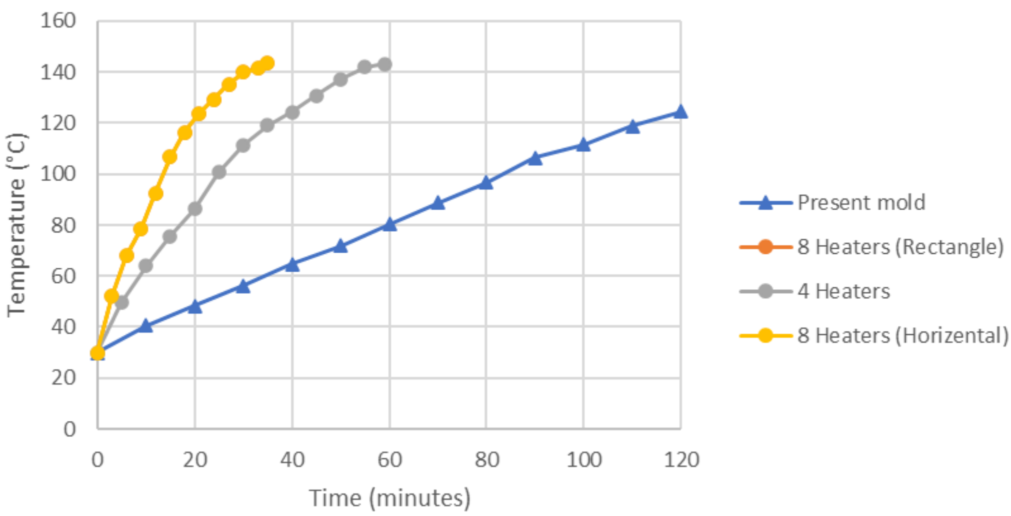

Fig. 5. Relationship of temperature and time of the inner mold

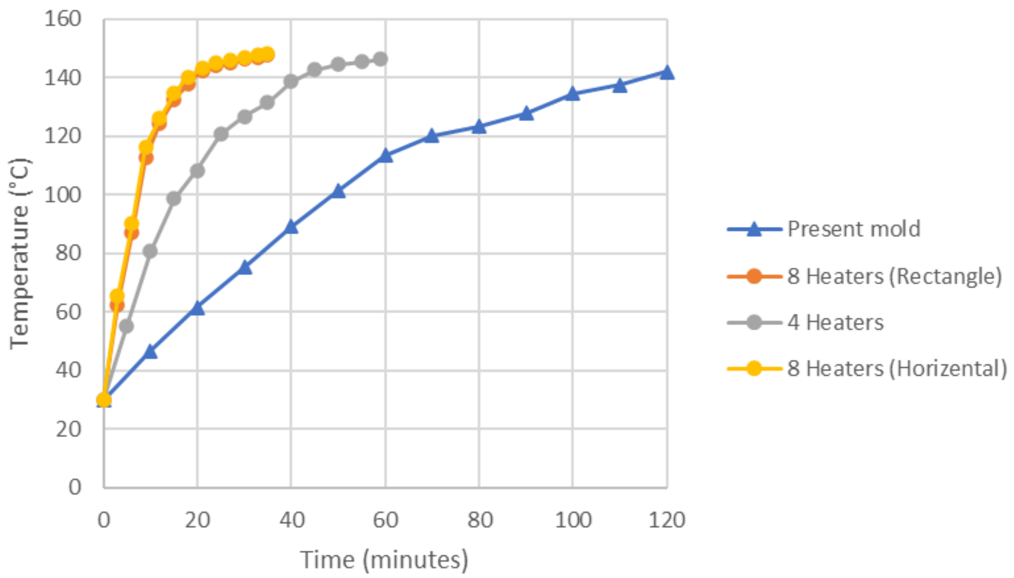

Fig. 6. A graph showing the relationship between temperature and time of the outer mold

Drill holes in the left and right molds with a diameter of 10 mm and a depth of 60 mm to insert the heater cartridge. Finite element analysis (FEA) and experiments were performed with the original mold, in which the heater arrangement was made based on field design dimensions, as well as with an improved mold as shown in Figure 7. A finite element heat transfer analysis was conducted to determine the effect of the heating element arrangement on mold temperature distribution. The recommendation of drilling holes for the injection mold is shown in Table 5.

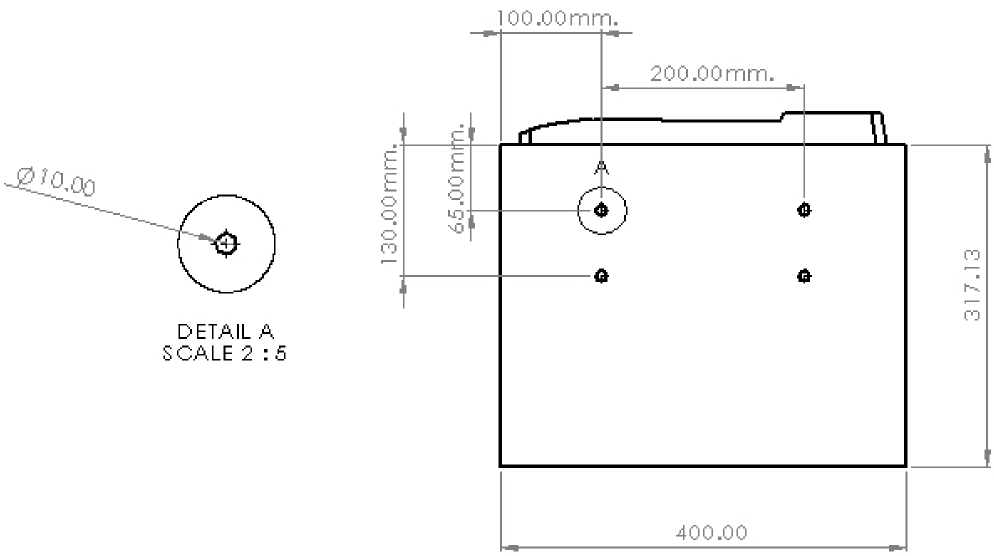

Fig. 7. Dimensions of Drill 8 holes in the left-right molds (Improve)

Table 5
Recommendation of drilling hole for injection mold

Conditions	Note	Position on mold
Drilled 4 holes	Insufficient temperature distribution Take a long time	Suitable position
Drilled 8 holes (Horizontal)	Good temperature distribution Take a little time	Unsuitable position
Drilled 8 holes (Rectangle)	Good temperature distribution Take a little time	Suitable position

3.1.2 Temperature affecting time for rubber boots mold

Figure 8 and Figure 9 depict the FE analysis and experimental results of the current temperature difference. It can be observed that the temperature of the inner mold increases linearly, and there is a slight temperature difference on the mold surface. therefore, the outer mold may have a slight deviation from the model due to weather conditions and the location of the infrared temperature measurement. A percentage of error of 7.76% and 4.97%, respectively, is expected.

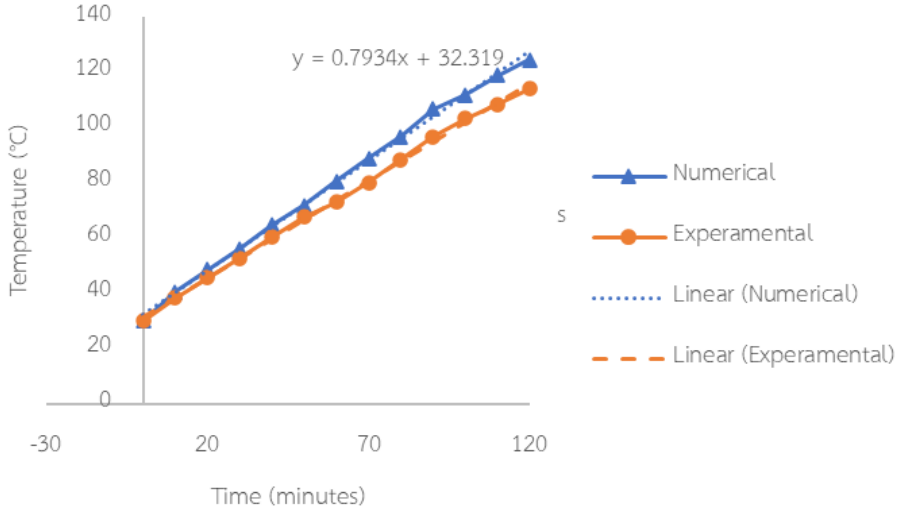

Fig. 8. Variation of rubber boots mold surface temperature for inner mold

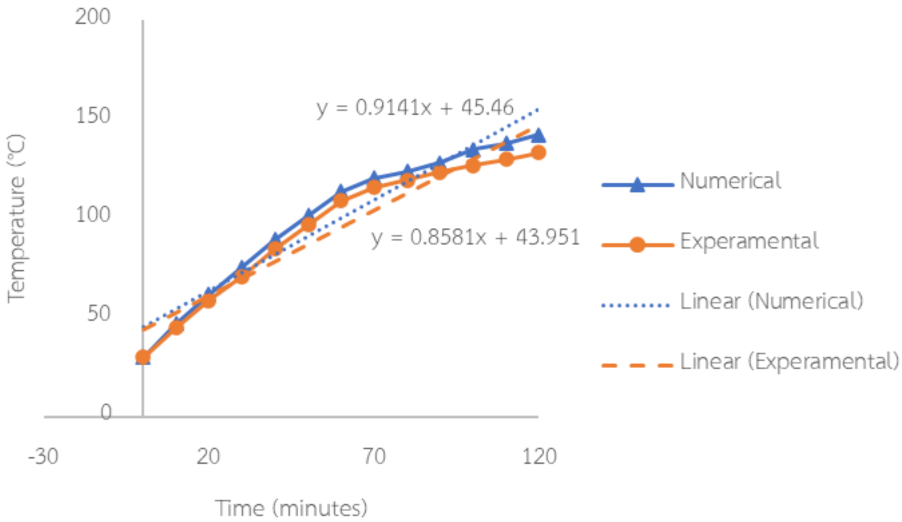

Fig. 9. Variation of rubber boots mold surface temperature for outer mold

3.1.3 Temperature affecting thermal conductivity distance for rubber boots mold.

Figure 10 and Figure 11 depict the FE analysis and experimental results of the current temperature difference of the inner and outer mold relative to the distance. It can be observed that the temperature trends of the two mold are in the same direction. therefore, there will be a percentage of error of 9.63% and 9.84%, respectively.

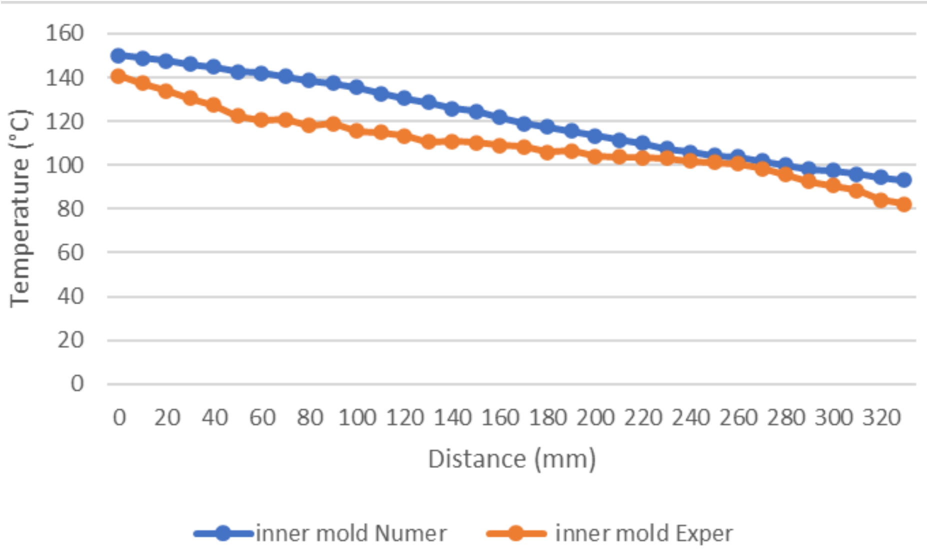

Fig. 10. Variation of rubber boots mold surface temperature for inner mold

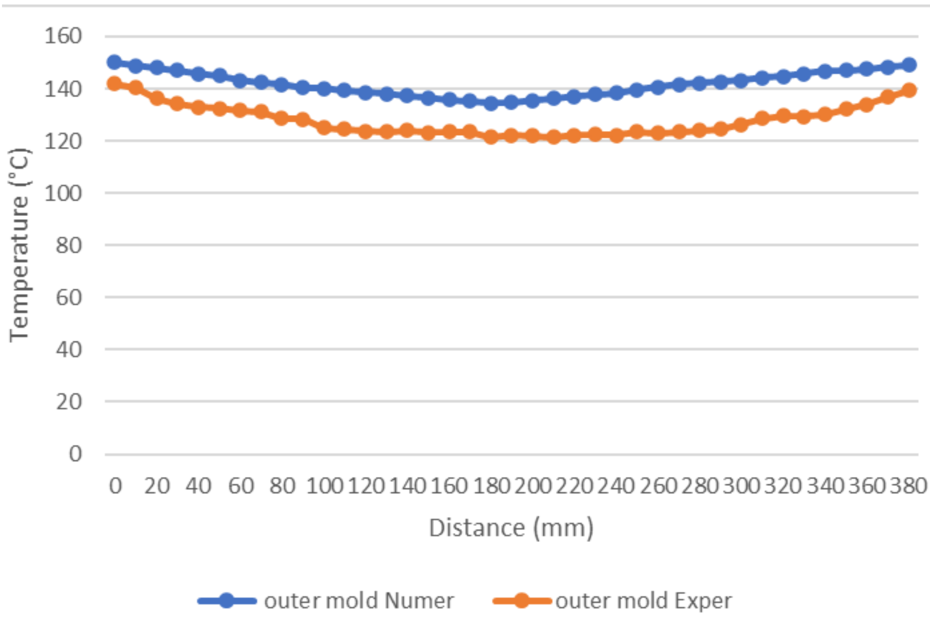

Fig. 11. Variation of rubber boots mold surface temperature for outer mold

4. Conclusions

The finite element analysis and rubber boot mold experiment revealed that the optimal heater position for 8 heaters of boot mold thermal parameters was identified. The position of the heater installation has an impact on the removal of the boot product from the mold, depending on the mold design. An important factor is the even distribution of heat at 150 °C throughout the mold. The heat transfer value obtained in each position has a tolerance of less than 10%. [20] Even if the heater is on the side surface of the mold, the heat conduction can efficiently heat the internal mold. Therefore, the rubber boot mold model can be utilized to validate the results of various parameters, such as fluid flow and thermal-electric. Furthermore, the rubber boot mold model can be a valuable tool for validating results related to various parameters, including fluid flow and thermal-electric considerations. The versatility of the model is emphasized, indicating its potential application in different fields beyond the specific context of rubber boot molds. This opens up possibilities for future research and applications in diverse industries where similar thermal considerations are relevant.

Acknowledgement
This research was not funded by any grant.

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