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Thermal Analysis of Infrared Heater as an Alternative Heat Source for Flexitank Application Using CFD

Mohamad Muzammil Mohamad Amin[1], Nofrizalidris Darlis[2,*], Abd Fathul Hakim Zulkifli[2], Md Norrizam Ja'at@Mohd Noh[2], Izuan Amin Ishak[2], Syabillah Sulaiman[3], Khairul Nizam Mustaffa[4], Asral[5]

1 Faculty of Engineering Technology, Universiti Tun Hussein Onn Malaysia, 84600 Pagoh, Johor, Malaysia
2 Centre of Automotive and Powertrain Technology, Faculty of Engineering Technology, Universiti Tun Hussein Onn Malaysia, 84600 Pagoh, Johor, Malaysia
3 Vehicle Dynamic and Sustainable Development Group, Faculty of Engineering Technology, Universiti Tun Hussein Onn Malaysia, 84600 Pagoh, Johor, Malaysia
4 My Flexitank Industries Sdn Bhd, Plot 3&4, Jalan PKNK 3, Kawasan Perindustrian LPK Fasa 3, 08000 Sungai Petani, Kedah, Malaysia
5 Department of Mechanical Engineering, Engineering Faculty, Universitas Riau, Kampus Bina Widya Jl. HR. Soebrantas, 28293 Pekanbaru, Riau, Indonesia

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ABSTRACT

The heating pad was a mechanism for heating elements using steam as a heat source and heating the liquid inside a flexitank to liquidise for easy discharge completely. Alternative heat sources such as infrared, electric, and exothermic reactions may improve thermal performance for the heating process. Infrared heating is chosen for this study due to its efficient radiation heat transfer compared to conduction and convection. This study aims to determine the optimal infrared heater configuration to improve the time to liquidify fluid on the flexitank for easier discharge. Nine flexitank and infrared heater geometries were made using SolidWorks with different heater positions and heating element thicknesses. Each geometry was simulated using Ansys Mechanical to study the thermal performance of radiation heat transfer with three different heating element materials. The heat output and energy input obtained from the simulation were used to calculate heating time and energy efficiency, respectively. The effects of each parameter were studied to determine the best configuration of the infrared heater in terms of heating time, energy consumption and both. The results showed that the position of the heater plays the most crucial role in determining the heating time and energy consumption, as a heater position that produces a larger heated surface area on the flexitank can reduce heating time. The thickness of the heating element and its material contributes a minor impact on heating time and energy consumption. Increasing thickness would lower the heating time and increase energy efficiency if the thickness improves heat retention capabilities. Increasing material emissivity will increase the heating time. Higher conductive materials would use more energy compared to lower conductive materials. The heating time was improved by about 30% compared to a steam heating pad. Energy consumption was reduced by about 85% compared to a small steam generator. In conclusion, the infrared heater was a promising alternative as a heat source for flexitank applications.

* *Corresponding author.*
E-mail address: nofrizal@uthm.edu.my (Nofrizalidris Darlis)

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1. Introduction

A flexitank serves as a liquid storage solution, commonly used for transporting various liquids safely, innovatively, and cost-effectively [1,2]. Heating pads are employed to liquefy the liquid inside flexitanks. Conventional heating pads, typically using steam, take around 48 hours to heat a liquid container, depending on the temperature and specific heat of the liquid [3]. The liquid may solidify in colder climates, complicating the discharge process [4]. Alternative heating methods are explored to expedite this, including electric, radiation, and exothermic reactions. Electric and exothermic methods, relying on conduction and convection, suffer from heat loss, unlike radiation heat transfer, which minimises such losses. A study found that the Net Frontal Radiant Efficiency (NFRE) of infrared heaters increased significantly compared to space heaters [5]. NFRE is a concept used to measure the effectiveness of a heating system, particularly radiant heating systems. It focuses on efficiency based on the amount of thermal energy the heating system delivers to the occupied space in the building, considering numerous factors that can affect the overall heating performance. This research aims to analyse the thermal performance of infrared heating using numerical methods, specifically employing ANSYS CFD for efficient and cost-effective analysis compared to experimental procedures. There is a limited study on alternative sources as a medium to transfer heat, especially in infrared. To reduce heating time, the optimum configuration for the infrared heater used to liquidise the liquid in Flexitank completely also leads to many parameters that need to be studied, such as heating element material, thickness, and infrared heater position.

This study aims to create an infrared heater as an alternative method for warming the contents of a flexitank, using 3-D simulation software, ANSYS Mechanical. The software helps analyse heat distribution and thermal efficiency. The study explores three configuration parameters: the material emitting the infrared waves, the heating element's thickness, and the infrared heater's placement. The material affects radiation emissivity, thickness influences energy needed to heat the flexitank, and heater placement impacts radiation view factor and heat distribution. Results are compared with thermal efficiency data from a previous study on steam heating pads.

The study primarily uses radiation for the CFD simulation model. The dimensions of the Flexitank and infrared heater follow specifications from MY Flexitank Industry Sdn. Bhd and Royal Infrared Heating. Heat distribution is analysed by varying the position of the infrared heater (45 degrees in front, 90 degrees on top, and 45 degrees at the side of the flexitank). Heating efficiency is examined using materials like tungsten, quartz, and carbon. Using SolidWorks, 3-D drawings of the heating pad are made with varying thicknesses of the infrared heating element (5 mm, 10 mm, and 15 mm). Additionally, 3-D drawings of the flexitank with a thin 2-layer LLDPE shell (0.4572 mm) are designed, incorporating infrared heaters of different thicknesses at various positions. The flexitank, holding 21,000 litres of crude palm oil, liquid latex, and water, is subject to analysis. The critical temperature output on the flexitank surface is aimed at being ten °C below the LLDPE melting point (122 °C) [6]. This is a safety precaution to prevent heater output from causing damage to the flexitank surface due to melting.

2. Methodology

2.1 Geometry Modelling

SolidWorks software modelled the heating pad's model geometry and simulated it using Ansys CFD simulation. A simplified heating pad with various thicknesses and materials was generated for the flow simulation. The details of the geometry of this simplified heating pad will be discussed in this section. This is a reference to successfully configuring the variable built into the infrared heater for efficient heat transfer from the heater to the flexitank. The dimensions of the heater were based on the Royal Infrared heater. The infrared heater length and width are 115 cm and 19 cm, respectively, and are designed to have an 8 to 25 m2 heating area suitable for shipping container size, as shown in Figure 1. Meanwhile, three types of heating elements were utilised in this study, and the heating element with different properties is tabulated in Table 1.

Fig. 1. Geometry of infrared heater

Table 1
Heating element with different material, emissivity, and thickness

Thickness (mm)	15		10		5	
Element	Carbon		Carbon		Carbon	
Emissivity	0.85		0.85		0.85	
Thickness (mm)	15		10		5	
Element	Quartz		Quartz		Quartz	
Emissivity	0.5		0.5		0.5	
Thickness (mm)	15		10		5	
Element	Tungsten		Tungsten		Tungsten	
Emissivity	0.45		0.45		0.45	

Emissivity measures a material's ability to emit thermal radiation compared to a perfect black body with an emissivity of 1. It varies due to atomic structure, surface roughness, and temperature. Different materials emit radiation differently based on their unique structures. For example, metals with free electrons have lower emissivity. Rough surfaces emit more radiation than smooth ones, and coatings or oxidation can change emissivity. Emissivity also changes with temperature and wavelength. Methods like thermal emission, reflectance, and comparison with known materials are used to determine emissivity. Spectrometers measure emissivity across different wavelengths, while indirect methods infer it from heat loss or cooling rates [7,8].

A flexitank 3D model with actual dimensions and size was created, as shown in Figure 2. The flexitank shape resembles the bag filled with 21000 litres of liquid. This was to simulate the real view factor of the flexitank surface shape with the heater for the radiation heat transfer model when the bag is filled. The thickness of the 2-layer LLDPE was set to 0.4572 mm according to MYFlexitank specification.

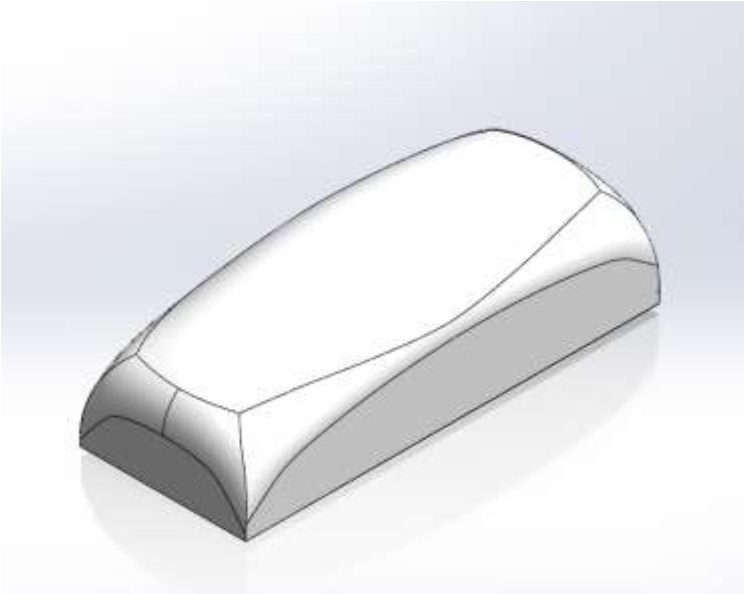

Fig. 2. Geometry of Flexitank

This flexitank is assembled with the heater at multiple positions to test the optimal view factor from the heater surface to the flexitank surface. Table 2 shows the positions of the heater when assembled with the flexitank inside a shipping container.

Table 2
Flexitank with different heater positions inside shipping containers

Position	45 degrees front	45 degrees side	90 degrees top
Model			

The combination of different thicknesses and different positions produced a total of nine unique 3D CAD assemblies that are ready to be imported to ANSYS Mechanical. The simulation aims to determine how much heat the infrared heater produces on the surface of the flexitank. The thermal conditions were measured in the Steady State Thermal process until they reached a stable state. This helps in finding the maximum heat output on the flexitank surface. Engineering data for materials like carbon, quartz, tungsten, and LLDPE was considered in the setup. The geometry from SolidWorks is imported to ANSYS and is used to create a mesh with a suitable size for accuracy. In the setup, the temperature of the infrared heater was specified, and radiation was set up for both the heater and flexitank surfaces. Emissivity values, dependent on material, are assigned. A temperature monitor on the flexitank measures its temperature at equilibrium. Two radiation probes measure the heat the heater releases and is absorbed by the flexitank. A reaction probe calculates the energy used to heat the heater. There were 27 different simulations for different heater materials.

2.2 Grid Independence Test

In simulations, a grid independence test is conducted to ensure that the results are not strongly influenced by the computer grid's size or resolution. This test is crucial for confirming and validating simulations, guaranteeing robust and precise results that are not excessively impacted by the grid. It verifies the simulation's ability to provide meaningful insights into the studied system. Five sizes were selected for this grid independence test, ranging from 0.2 to 0.6 mm, as illustrated in Figure 3. The geometry for this test involved placing the heater at the front at a 45-degree angle, with a heating element thickness of 15mm and carbon as the heating element material. This positioning aligns with Royal Infrared's advertised setup, and using carbon ensures consistency with the Royal Infrared heater specifications.

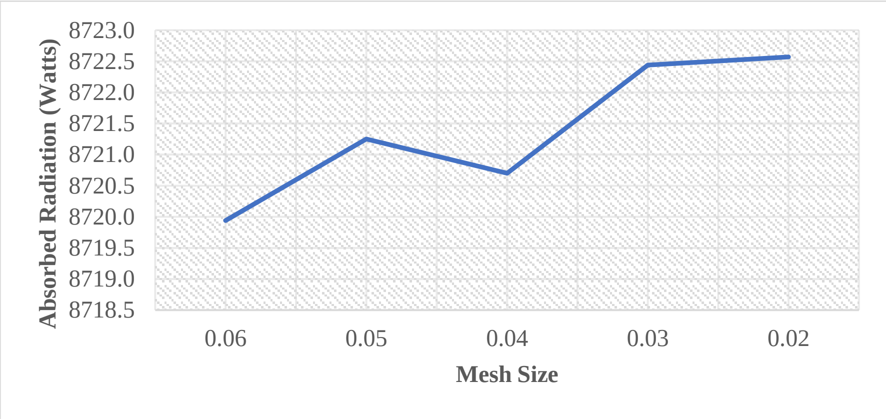

Fig. 3. Grid independence test graph

2.3 Heating Time Calculation

This research used simulations to find accurate heat values for the flexitank surface absorbing heat from an infrared heater. The simulations helped us model and understand how the system behaves under different conditions. Once the heat values were obtained, specific formulas were applied to determine how long it would take for the liquid to heat up. The formula requires the liquid-specific heat capacity and density. The specific heat capacity of water is 4186 $J \cdot kg^{-1} \cdot K^{-1}$ with a density of 1 kg/m^3. In comparison, the specific heat capacity of CPO is 1861 $J \cdot kg^{-1} \cdot K^{-1}$ with a density of 0.895 $kg/m^{3,}$ and the specific heat capacity of latex is 1720 $J \cdot kg^{-1} \cdot K^{-1}$ with a density of 0.94 kg/m^3. By combining simulation results with these formulas, our goal was to calculate precise estimates for the time required to achieve the desired level of heating [9-11].

$$Q = -k.A.\frac{\Delta T}{d} \tag{1}$$

where k is the thermal conductivity of the material in watts per meter-kelvin, A is the cross-sectional area perpendicular to the heat flow in square meters, ΔT is the temperature difference across the material in kelvin or degrees Celsius, d is the thickness of the material in meters [12].

$$Q = h.A(\mathrm{Ts} - \mathrm{T\infty}) \tag{2}$$

where h is the convective heat transfer coefficient in watts per square meter-kelvin, A is the surface area in square meters; Ts is the temperature of the solid surface in kelvin or degrees Celsius, T_∞ is the temperature of the surrounding fluid in kelvin or degrees Celsius.

2.4 Optimization

To optimise the setup of the infrared heater, we will compare its performance with a benchmark. Each parameter's impact on heating time and energy consumption will be ranked based on its significance percentage. Since each parameter affects absorbed radiation and heater energy, we calculate the average for each parameter value to isolate its effect from other parameters.

For instance, the average of all absorbed radiation values from heater configurations with the same thickness, regardless of position and material, was measured when examining the relationship between heating element thickness and absorbed radiation. This approach generates a general thickness performance unrelated to a specific position or material. This process is repeated for every parameter value to analyse their effects on heating time and energy consumption.

These calculations provide insights into which parameter contributes the most to improving the system's thermal performance. It also assesses the performance of each value within a parameter for heating time and energy consumption. Consequently, parameters and values can be ranked based on their significance in thermal performance. Multiplying the rank of the parameter by the rank of each parameter's value determines the weight of a single parameter value on heating time and energy consumption. The sum of each parameter's value for every heater configuration establishes the overall weight of the configuration on heating time and energy consumption. Balancing this weight with the lowest possible values for heating time and energy consumption will identify the optimal settings for the infrared heater that performs well in both aspects [13].

3. Results

The heat values found were recorded, and calculations using two formulae to find heating times were conducted based on those heat values. This part is the culmination of heat and gives a better understanding of how radiation heat transfer behaves in terms of heat, helping achieve our study's primary goal.

3.1 Mesh Quality Validation

Based on the GIT results in Figure 3, the graph gradience is the lowest between mesh sizes 0.03 and 0.02 m. The absorbed heat values between mesh sizes 0.03 and 0.02 m were near 0.1 Watts. This proves the simulation became less dependent on the number of grids at 0.03 m mesh size. Therefore, all simulations in the study will use 0.03 m for its mesh size because finer mesh was insignificant and reduced computational load. The aim was to obtain a mesh size that does not affect the simulation results, so at a mesh size of 0.03 m, it is inevitable that the simulation was stable and accurate while reducing the computational load compared to using a mesh size of 0.02 m.

3.2 Temperature Distribution

The study's findings show a clear pattern in how the tested heaters spread heat. In Figure 4, the discharge area was circled, ensuring a smoother discharge process as it has a higher temperature. The front-positioned heater at a 45-degree angle consistently covers the largest surface area with heat on the object, followed by the side-positioned heater at a 45-degree angle in second place. In contrast, the top-positioned heater at a 90-degree angle has the most negligible impact. This pattern is influenced by view factor radiation. These observations emphasise the importance of considering view factors when designing and placing heaters, as they directly affect how heat is distributed on the surface of the flexitank. Optimising view factor radiation orientation can lead to more effective and efficient heating strategies in real-world applications [14].

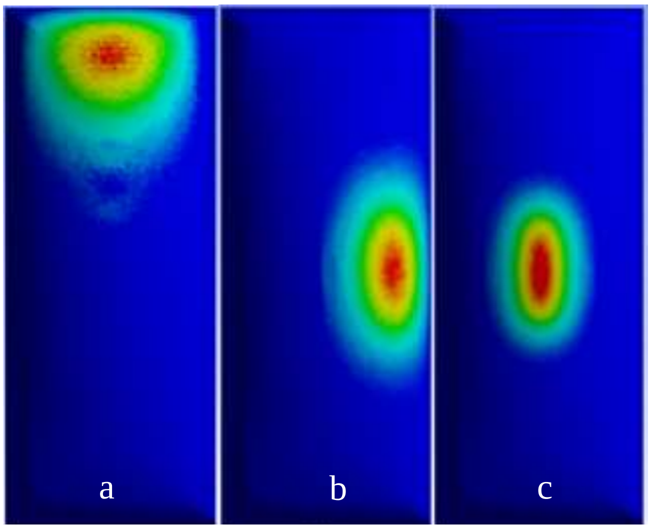

Fig. 4. (a) Front 45-degree angle. (b) Side 45-degree angle. (c) Top 90-degree angle

Based on Figure 5, as the thickness of the heating material increases, the average absorbed radiation increases. This result shows that the heating material thickness of the infrared heater does have some effect on the amount of radiation absorbed by the flexitank surface. Since thicker heating material stores more heat energy, it emits more heat radiation [15]. The slight change between the 10 mm and 15 mm is due to the limit of emissivity. The maximum heat that can be emitted is limited to the radiation wavelength produced by the material. The difference in average absorbed radiation between the highest heating material thickness (15mm) and the lowest heating material thickness (5mm) was 10.05 Watts.

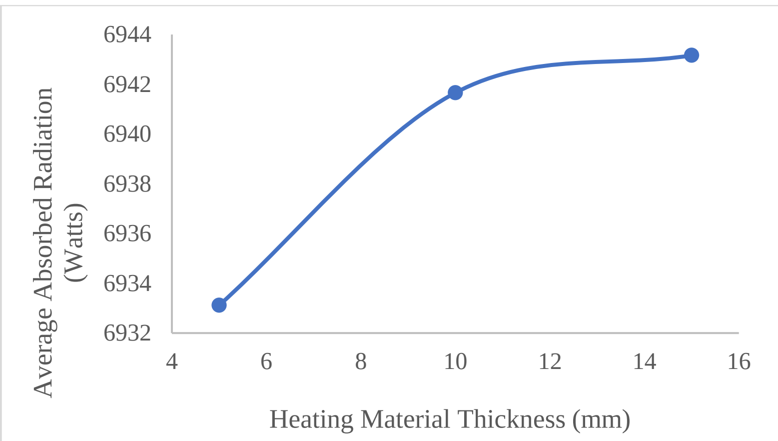

Fig. 5. Effect of heating material thickness on average absorbed radiation graph

It is shown in Figure 6 that the front position, on average, produces the most absorbed radiation compared to other positions of the heater. This confirms the relationship between heated surface area and the amount of absorbed radiation. This is because the larger surface area heated allows the heater to use higher temperature settings without reaching the flexitank melting point, as the temperature distribution was more dispersed than a heater that only covers the smaller surface area [16]. The difference in average absorbed radiation between the largest heated surface area and the smallest heated surface area was 3133.42 Watts.

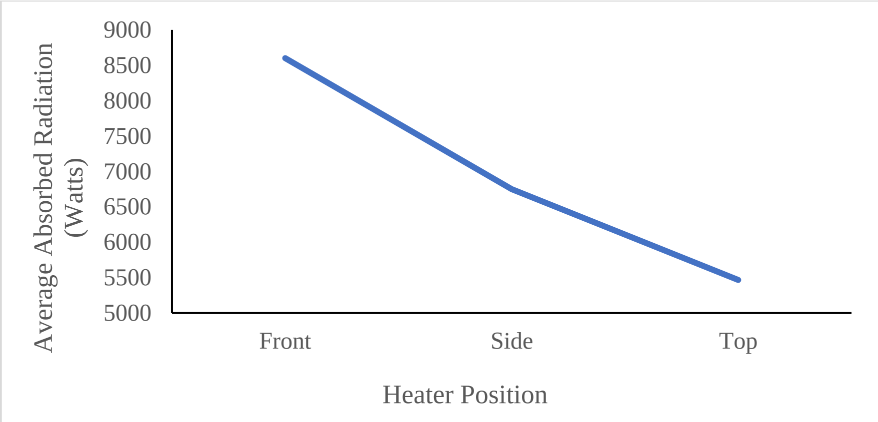

Fig. 6. Effect of heater position on average absorbed radiation graph

The difference in performance between low and high-emissivity heaters is due to how much the heating material emits and absorbs infrared radiation. Emissivity measures how well a surface gives off and takes in thermal radiation, ranging from 0, which reflects a lot of radiation, to 1, which emits and absorbs a lot of radiation. When a heater has low emissivity, it emits less radiation but might reflect more from its surroundings. On the other hand, a high emissivity heater emits more radiation and may absorb more. In the same conditions, a low emissivity heater could reflect more radiation onto the target surface, making the surface warmer than a high emissivity heater. The effectiveness also depends on the target's surface material properties [16]. When the target surface material is good at absorbing radiation, it will efficiently get heat from a low-emissivity heater. The effect of different material emissivity on average absorbed radiation is shown in Figure 7. The slight difference between quartz and carbon was due to having the same wavelength range, hence having roughly the same rate of radiation emitted based on Table 1. The difference in average absorbed radiation between the highest heating material emissivity (0.85) and lowest heating material emissivity (0.45) was 7.45 Watts.

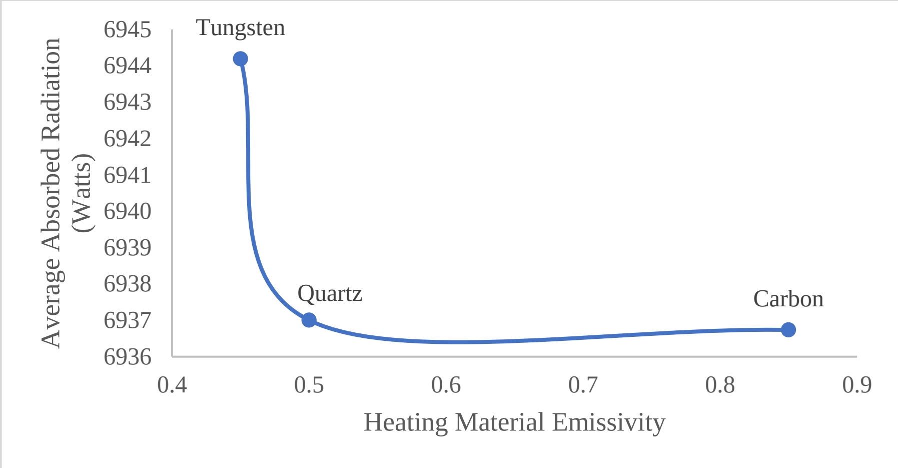

Fig. 7. Effect of heating material emissivity on average absorbed radiation graph

3.2 Effect of Different Types of Liquid on Heating Time

The heating time was calculated using Eq. (2), using the estimated amount of heat to increase the liquid temperature by 20 °C, as shown in Table 3, with the amount of absorbed heat on the flexitank surface obtained from the simulation results. Table 4 shows the results for average heating time with different liquid types.

Table 3
Liquid properties with required heat

Liquid	Density (kg/m)	Volume (l)	Mass (kg)	Specific heat capacity	Change in temperature (°C)	Required heat (Watts)
Water	1	21000	21000	4186	20	1758120000
CPO	0.895	21000	18795	1861	20	699549900
Latex	0.94	21000	19740	1720	20	679056000

Table 4
Average heating time of each liquid type

Liquid Type	Average heating time (hours)	Overall
Water	72.82	
CPO	28.97	43.31
Latex	28.13	

This calculation shows that the overall average heating time using an infrared heater was 43.31 hours, which is 9.77% lower than a traditional steam heating pad. This slight improvement in heating time reduction was based on the average performance of this study's infrared heater, which was not optimal. Hence, the heating time reduction can be further improved using the study's most optimal infrared heater configuration.

3.3 Energy Consumption for Heater Configuration

The average energy consumption of each liquid heating time can be then averaged to determine the general overall energy consumption for all liquid heating time. The benchmark for energy given by the Yuanda Boiler company was 9 kW minimum for a small portable steam generator, multiplied by the 48 hours of operating time, resulting in 432 kWh of energy consumption. The average overall energy needed to be calculated and compared to study the performance between infrared heaters and traditional steam heating pads. Note that the results from this calculation also do not describe the optimal infrared heater configuration performance. The calculated average energy consumption for each liquid type is shown in Table 5.

Table 5
Energy consumption of each liquid type

Liquid Type	Average energy consumption (kWh)	Overall
Water	101.33	
CPO	40.32	60.26
Latex	39.14	

This calculation shows that the average heater energy using an infrared heater was 1.39 kW (60.26 kW divided by 43.31 hours), which is 84.56% lower than a small steam generator at a minimum output of 9 kW. Other than that, the overall average energy consumption for this study's infrared heater performance was 60.26 kWh compared to 432 kWh (9kW times 48 hours) using a steam generator, which significantly reduced energy consumption. This significant improvement was from the average performance of this study's infrared heater, which again was not optimal. Hence, the energy consumption can be further improved using the study's most optimal infrared heater configuration.

Based on Figure 8, as the thickness of the heating material increases, the average absorbed radiation increases but decreases after exceeding 10 mm thickness. This is because thicker materials have higher thermal resistance, which can reduce the heat transfer rate and require more energy to heat up. Thicker materials also have a greater capacity to store heat (retention), requiring less energy to maintain the material temperature. The thickness increase from 5 mm to 10 mm only increases the thermal resistance and does not improve heat retention. Thickness increases from 10 mm to 15 mm, increases thermal resistance, and enhances heat retention, causing less energy required to maintain material temperature. The difference in average heater between the highest value (10mm thickness) and lowest value (15mm thickness) was 34.13 Watts.

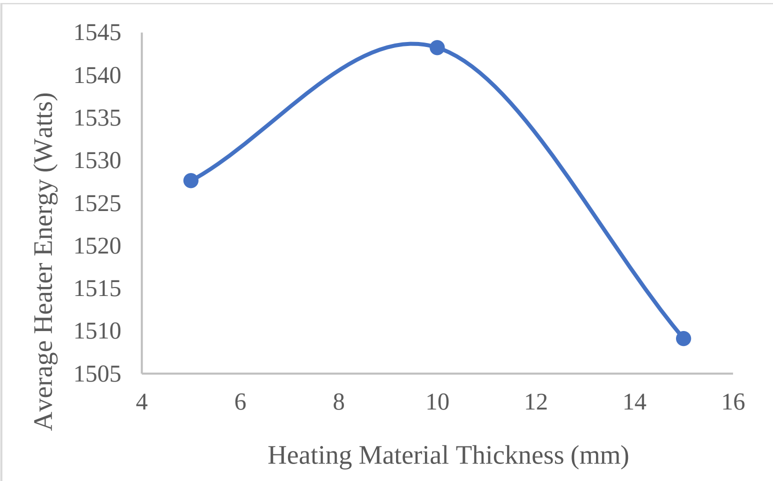

Fig. 8. Effect of heater position on average absorbed radiation graph

It is shown in Figure 9 that the front position, on average, produces the most heater energy compared to other positions of the heater. This confirms the relationship between the heated surface area and the amount of heater energy. This is because the larger surface area heated allows the heater to use higher temperature settings without reaching the flexitank melting point as the temperature distribution was more dispersed than a heater that only covers a smaller surface area. The difference in average heater energy between the largest heated surface area and the smallest heated surface area was 1820.67 Watts.

Fig. 9. Effect of heater position on average heater energy graph

The difference in performance between low and high-emissivity heaters is due to how much heat the material needs to emit and absorb infrared radiation. When a heater has low emissivity, it emits less radiation and requires more energy to reach the desired radiation emission. On the other hand, a high emissivity heater emits more radiation and may absorb more, requiring less energy for radiation emission. In the same conditions, a low emissivity heater could reflect more radiation onto the target surface, making the surface warmer than a high emissivity heater. The effectiveness also depends on the target's surface material properties. When the target surface material is good at absorbing radiation, it will efficiently get heat from a low-emissivity heater.

3.4 Optimization of Infrared Heater Configuration

From the previous analysis, the differences between the highest and lowest values of average absorbed radiation were calculated for every parameter to rank the significance of each parameter towards the amount of absorbed radiation, as shown in Table 6. The higher amount of absorbed radiation will reduce the heating time of the liquid. Hence, determining the best heater configuration for optimal heating time requires a configuration that outputs the highest absorbed radiation value on the flexitank surface.

Table 6
Parameter ranking according to difference of radiation

Parameter	Difference of absorbed radiation (Watts)	Rank
Thickness	10.05	3
Material	20.23	2
Position	1820.67	1

These comparisons show that the position of the infrared heater is the most important. Therefore, the infrared heater's best position will reduce the heating time compared to the best thickness and material. The rank of each parameter value also needs to be determined to choose the best configuration in terms of optimal heating time, as tabulated in Table 7.

Table 7
Parameter values ranking according to absorbed radiation

Position			Thickness			Material		
Front	Side	Top	15	10	5	0.85	0.5	0.45
Absorbed radiation (Watts)			Absorbed radiation (Watts)			Absorbed radiation (Watts)		
8600.55	6750.25	5467.13	6943.16	6941.66	6933.11	6936.74	6937.01	6944.19
Rank			Rank			Rank		
1	2	3	1	2	3	3	2	1

Choosing the minimum total of each parameter ranking will output the best configuration of the infrared heater regarding optimal heating time. The heater configuration is positioned in front, with a thickness of 15 mm, and tungsten as the heating material produces the highest absorbed radiation on the flexitank surface.

On the other hand, the lower amount of heater energy will reduce energy consumption. Hence, determining the best heater configuration for optimal energy consumption requires a configuration that outputs the lowest energy value. The parameter ranking according to the difference in heater energy is shown in Table 8.

Table 8
Parameter ranking according to difference of heater energy

Parameter	Difference of heater energy (Watts)	Rank
Thickness	34.13	2
Material	7.45	3
Position	3133.42	1

These comparisons show that the position of the infrared heater is the most important. Therefore, the best position of the infrared heater will reduce energy consumption compared to the best thickness and material. The rank of each parameter value also needs to be determined to choose the best configuration in terms of optimal energy consumption. The summary of parameter ranking value according to heater energy is tabulated in Table 9.

Table 9
Parameter values ranking according to heater energy

Position			Thickness			Material		
Front	Side	Top	15	10	5	0.85	0.5	0.45
Heater Energy (Watts)			Heater Energy (Watts)			Heater Energy (Watts)		
2524.76	1351.1	704.09	1509.1	1543.23	1527.62	1520.96	1519.38	1539.61
Rank			Rank			Rank		
3	2	1	1	3	2	2	1	3

Choosing the minimum total of each parameter ranking will output the best configuration of the infrared heater regarding optimal energy consumption. The heater configuration is positioned on top, with a thickness of 15 mm, and quartz as the heating material produces the lowest heater energy.

Analysing optimal heating time and energy consumption was crucial for achieving the best and affordable performance. To accomplish this analysis, the value of each parameter ranking needs to be multiplied by its parameter values rankings to obtain the weightage of each heater configuration for heating time and energy consumption.

Choosing from Figure 10, the heater configuration that has the lowest with an equal value of weightage for heating time and energy consumption was Q15F (Quartz heating material, 15 mm heating material thickness, and positioned at the front of the flexitank). The exact value indicates a balance in heating time and energy consumption efficiency. The lower value of weightage equals higher efficiency.

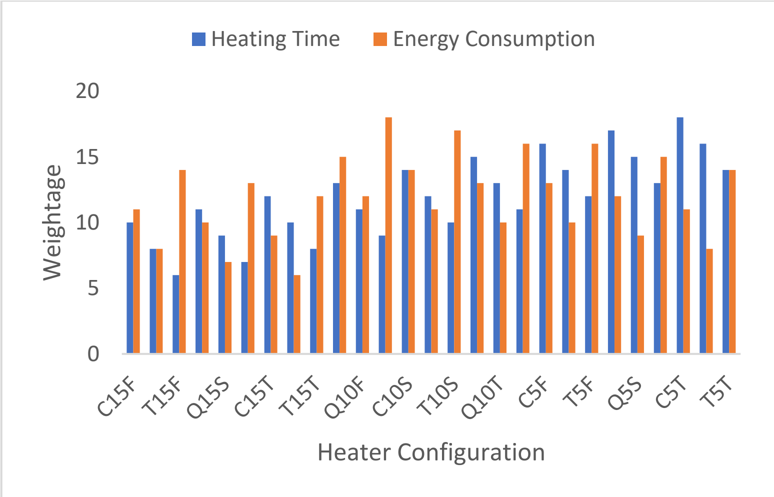

Fig. 10. Weightage of heating time and energy consumption of heater configurations

4. Conclusions

In summary, as an alternative to traditional heating, Computational Fluid Dynamics (CFD) analysis to evaluate how an infrared heater performs in different positions inside a shipping container looks promising for improving how efficiently things heat up. The study tested common liquids transported in a flexitank, like water, crude palm oil (CPO), and latex. The results show that placing the heater at the front at a 45-degree angle is best because it covers the heated surface the most. Specifically, this position resulted in the highest absorbed radiation value of 8600.55 Watts. As a heating material, Tungsten slightly increased the absorbed radiation value compared to other materials. Thicker heating elements generated more absorbed radiation and affected energy consumption. A smaller heated surface area led to less energy consumption, with the top position at a 90-degree angle requiring only 704.09 Watts. Quartz was the most efficient in terms of energy consumption. Considering both time and energy efficiency, the best configuration for the shortest heating time is T15F (Tungsten, 15mm thickness, and front position at a 45-degree angle). The Q15T configuration (quartz, 15mm thickness, and top position at a 90-degree angle) is the best for the lowest energy consumption. Balancing both time and energy efficiency, the optimal configuration is Q15F (quartz, 15mm thickness, and front position at a 45-degree angle). This configuration achieved a 29.6% reduction in heating time compared to a steam heating pad and an 84.56% reduction in energy consumption compared to a small steam generator. In conclusion, the research goals have been met successfully.

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