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Numerical Analysis of Thermal Distribution in a Solar-Powered Food Warming Prototype Utilizing PTC Heating Elements: A Comparative Study of Natural and Forced Convection in an Enclosed Chamber

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ABSTRACT

The need for efficient and low-carbon food warming systems in mobility applications continues to increase, particularly in maintaining food quality during the distribution process. However, conventional systems often experience uneven temperature distribution due to limitations in heat transfer mechanisms, leading to thermal stratification and reduced system efficiency. This study aims to numerically analyze the thermal distribution in a solar-powered food warmer prototype that utilizes a Positive Temperature Coefficient (PTC) heating element, by comparing the performance of natural convection and forced convection within an enclosed space. The analysis was conducted using a steady-state thermal method under steady-state conditions. The model considers heat transfer mechanisms including conduction, convection, and radiation. Two configurations were analyzed: without a fan (natural convection) and with a fan (forced convection), in order to evaluate temperature distribution, heat transfer characteristics, and system performance over time. The simulation results indicate that under natural convection conditions, the temperature distribution tends to be uneven, with the formation of thermal stratification where hot air accumulates in the upper part of the chamber. The average temperature gradually increases from 33.44°C to 50.48°C at 600 s, while the minimum temperature remains around 22°C, indicating the presence of a cold zone. In contrast, under forced convection conditions, the system shows a significant improvement in performance, with a more homogeneous temperature distribution and a faster heating process. The average temperature increases from 20.187°C to 61.552°C at 600 s, while the minimum temperature rises to 35.236°C, indicating a reduction in cold zones. Additionally, the temperature difference within the chamber is smaller, demonstrating improved thermal uniformity. Overall, the use of forced convection has been proven to enhance the effectiveness of heat transfer, accelerate the achievement of steady-state conditions, and produce a more uniform temperature distribution. Therefore, the integration of a fan becomes a crucial factor in optimizing the thermal performance of a solar-powered food warming system, making it more reliable and efficient for sustainable food distribution applications.

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1. Introduction

The need for heating systems that are efficient, environmentally friendly, and adaptable to mobility continues to increase along with the growth of the transportation and food distribution sectors [1,2]. In the context of operational vehicles such as MBG (Free Nutritious Meals), maintaining food quality during the distribution process becomes a major challenge, particularly in preserving optimal temperatures to ensure the food remains safe and suitable for consumption [3,4]. Conventional food warming systems generally still rely on energy sources based on fossil fuels or electricity from vehicle engines, which not only increase energy consumption but also contribute to carbon emissions [5]. In addition, conventional systems often produce uneven temperature distribution within the storage chamber, leading to the formation of hot and cold zones (thermal stratification), which can degrade food quality [7]. Therefore, an innovative heating system is required that is not only thermally efficient, but also capable of producing a homogeneous heat distribution while supporting a low-carbon concept through the utilization of renewable energy [8,9].

One promising approach is the integration of solar panels as the primary energy source with a heating element based on a Positive Temperature Coefficient (PTC) [10,11]. PTC elements have a unique characteristic in their ability to automatically regulate temperature without requiring a complex control system, making them highly suitable for heating applications that demand temperature stability [12,13]. In addition, this technology is known for its high level of safety due to its self-regulating properties, which prevent overheating [14,15]. In vehicle applications, the use of PTC heaters has been widely studied, particularly in electric vehicle cabin heating systems [16-18]. However, its application in solar-powered food warming systems within moving vehicle environments remains very limited and requires further investigation, particularly in terms of thermal performance and temperature distribution, including how different convection mechanisms—such as natural convection and forced convection—affect temperature homogeneity within an enclosed space [19,20].

The analysis of heating system performance cannot be separated from the study of heat transfer occurring within the heating chamber [21,22]. To understand temperature distribution, airflow, and the interaction between the heat source and the surrounding environment, the Computational Fluid Dynamics (CFD) method has become one of the most widely used approaches [23,24]. In this context, steady-state thermal-based simulation enables a detailed analysis of flow characteristics and heat transfer under steady-state conditions, where the system is assumed to have reached thermal equilibrium. The steady-state thermal analysis approach is essential for evaluating system performance under normal operating conditions, particularly in ensuring that the temperature within the food storage chamber is evenly distributed without the presence of hotspots or cold spots that could affect food quality. Furthermore, this approach also allows for a comparison of performance between conditions without forced flow (natural convection) and those assisted by forced flow (forced convection) in enhancing the effectiveness of heat distribution.

Table 1
State of the art

References	Method	Material / System	Key Results
[9]	CFD simulation (ANSYS Fluent), steady-state thermal analysis	Water tank (fluid + metal wall)	The temperature distribution is uneven, influenced by the position of the heat source and the fluid flow.
[25]	CFD using ANSYS Fluent with radiation analysis	PV/T solar panel with cooling fluid	The improvement in thermal efficiency is influenced by radiation intensity and the fluid flow rate.
[26]	CFD simulation using ANSYS Fluent	Electric motor with an air cooling system	Temperature distribution is influenced by flow velocity, and stagnant regions can lead to overheating.
[16]	CFD simulation with heat transfer analysis	Seawater tank (enclosed space with thermal radiation)	Temperature increases with radiation, and heat distribution occurs through convection and radiation.
[7]	3D CFD (ANSYS Fluent) simulation	Enclosed space with a ventilation/air conditioning (AC) system	Airflow patterns significantly influence temperature distribution and thermal comfort.

Several previous studies have shown that steady-state CFD approaches are capable of providing accurate results in analyzing thermal systems, such as heat exchangers, solar thermal collectors, and other heating devices [27,28]. However, most of these studies still focus on static systems and have not yet accommodated the requirements of mobile applications, such as those in food distribution vehicles [29,30]. Furthermore, the integration of renewable energy sources, PTC heating elements, and food storage systems into a single compact and efficient system has rarely been comprehensively studied, particularly in the context of comparing natural and forced convection mechanisms on temperature distribution. This indicates a significant research gap, especially in the development of clean energy-based food warming systems using in-depth thermal simulation approaches to achieve more homogeneous and efficient heat distribution [31,32].

2. Methodology

2.1 Research Flow Diagram

This study employs a numerical simulation approach based on steady-state thermal analysis to examine the thermal behavior of a solar-powered food warming system under steady-state conditions, considering a comparison between natural convection and forced convection mechanisms within an enclosed space. The simulation is conducted using a steady-state thermal model, taking into account heat transfer mechanisms including conduction, convection, and radiation. Under natural convection conditions, airflow occurs naturally due to density differences, whereas in forced convection conditions, a fan component is introduced to generate forced airflow, thereby influencing the temperature distribution within the system. A Positive Temperature Coefficient (PTC) heating element is modeled as an internal heat source that interacts with the air inside the food storage chamber, resulting in a dynamic temperature distribution until thermal equilibrium is achieved.

The physical model is assumed to be three-dimensional, with incompressible fluid flow, and heat transfer influenced by both natural and forced convection mechanisms depending on the system configuration being analyzed. Under no-fan conditions, heat transfer is dominated by natural convection, especially during the initial heating stage, whereas in the presence of a fan, heat transfer is dominated by forced convection, which accelerates the distribution of thermal energy. The system is analyzed within a closed domain representing the food storage compartment in MBG vehicles, with enclosure walls having thermal insulation properties to minimize heat loss to the surroundings. The interaction between the heat source, air, and enclosure walls generates temperature gradients that drive natural circulation as well as forced flow within the system.

Numerical validation is carried out by evaluating the consistency between the simulation results and the expected physical behavior, such as the gradual increase in temperature within the storage chamber until a stable condition is reached, as well as differences in heat distribution characteristics between natural and forced convection conditions.

Under no-fan conditions, validation is indicated by the formation of thermal stratification due to natural circulation, whereas in the presence of a fan, it is demonstrated by improved temperature homogeneity and faster attainment of steady-state conditions. This approach provides a comprehensive understanding of system performance in maintaining food temperature, as well as identifying potential heat losses and the effectiveness of heat distribution, which can be used as a basis for design optimization. The simulation workflow used in this study is illustrated in Figure 1 below.

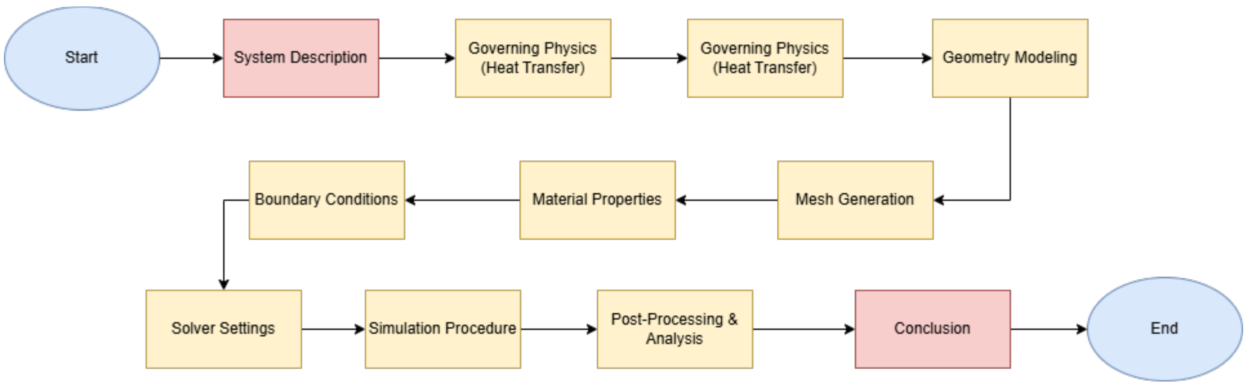


Fig. 2. Flowchart

2.2 System Description

The system analyzed is a solar-powered food warming system operating under enclosed conditions (enclosure system), considering two main configurations: without a fan (natural convection) and with a fan (forced convection). Solar energy is converted into electrical energy through photovoltaic panels, which is then used to operate a Positive Temperature Coefficient (PTC) heating element.

The heat generated by the PTC heater is subsequently transferred to the food storage chamber through conduction, convection, and radiation mechanisms. Under no-fan conditions, heat transfer is dominated by natural convection, whereas in the presence of a fan, airflow is forced to enhance heat distribution within the chamber. The system is designed as an enclosed space to minimize heat loss to the environment. The main components of the system include:

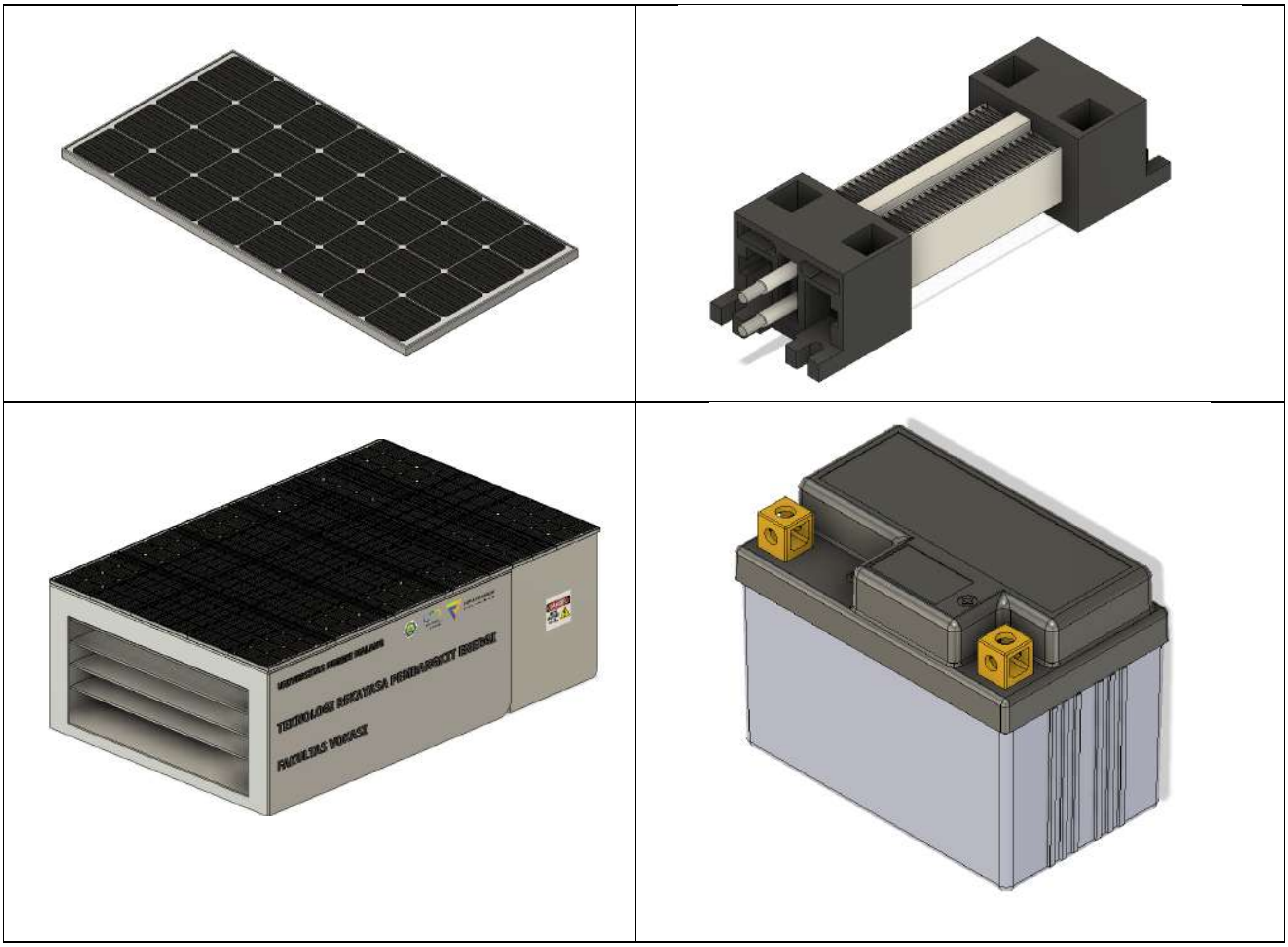


Fig. 3. Solar panel (a), PTC heater (b), food storage chamber (c), 3Ah battery (d)

Operationally, the solar energy received by the solar panel is converted into electrical energy through the photovoltaic effect. The generated electrical energy is then directly supplied to the PTC heating element without requiring a complex temperature control system. This is made possible by the unique characteristics of PTC materials, which exhibit self-regulating behavior, where electrical resistance increases as temperature rises. As a result, the electric current automatically decreases when the temperature approaches a certain limit, allowing the system temperature to remain stable without the risk of overheating. This mechanism makes PTC heaters a safe and efficient solution for heating applications in enclosed spaces, under both natural and forced convection conditions.

The heat generated by the PTC element is then distributed within the food storage chamber through three main heat transfer mechanisms: conduction, convection, and thermal radiation. Conduction occurs through solid materials such as the heater walls and the enclosure structure, while convection takes place under two conditions: natural convection due to air density differences caused by temperature gradients, and forced convection due to airflow generated by a fan. Under natural convection conditions, hot air with lower density rises, while cooler air descends, leading to the formation of temperature stratification. In contrast, under forced convection conditions, the induced airflow results in more intensive fluid mixing, producing a more uniform temperature distribution. Additionally, thermal radiation also contributes to heat transfer by directly exchanging thermal energy between surfaces within the enclosure.

The system is designed as an enclosed space (enclosure system) with the primary objective of minimizing heat loss to the surrounding environment. The enclosure walls are coated with thermal insulation materials with low thermal conductivity, enabling them to reduce the rate of heat transfer out of the system. Thus, the thermal energy generated by the PTC heater can be utilized optimally to maintain food temperature during the distribution process. This enclosure design also plays an important role in creating stable and homogeneous thermal conditions within the storage chamber, particularly in configurations with forced convection, which help reduce temperature gradients within the system.

The main components of the system consist of a solar panel as the energy source, a PTC heating element as the heat source, a food storage chamber as the primary analysis domain, a fan as an additional component to generate forced convection, and thermally insulated walls to reduce heat loss. The interaction among these components forms a complex integrated thermal system, in which the overall performance is highly influenced by temperature distribution and heat transfer efficiency within the system, under both natural and forced convection conditions.

2.2 Governing Physics

The heat transfer phenomena occurring in this solar-powered food warming system are governed by complex interactions between fluid flow and energy transfer within an enclosed space, under both natural and forced convection conditions. To accurately represent these phenomena, a Computational Fluid Dynamics (CFD) approach is employed, based on the numerical solution of the conservation equations of mass, momentum, and energy. These equations form the foundation for analyzing temperature distribution and airflow characteristics within the system, including differences in flow patterns between conditions without a fan and with a fan.

$$\nabla \cdot (\rho\vec{v}) = 0$$

This equation indicates that the mass flow rate entering and leaving a control volume must be balanced, so that no mass accumulation occurs within the system. In the context of a closed enclosure, this equation ensures that the resulting air circulation is driven by pressure and temperature distributions—either due to buoyancy forces in natural convection or due to forced flow generated by a fan—rather than by any sources or losses of mass.

In addition, the behavior of fluid flow within the enclosure is also influenced by forces acting on the fluid, such as pressure gradients, viscous forces, and gravitational forces. This is modeled using the momentum equation (Navier–Stokes), which describes the balance between these forces, including the effect of buoyancy in natural convection and the influence of external forces generated by a fan in forced convection.

$$\rho(\vec{v} \cdot \nabla)\vec{v} = -\nabla p + \mu\nabla^2\vec{v} + \rho\vec{g}$$

This equation shows that changes in thermal energy within the system are influenced by fluid flow (convection), heat transfer through materials (conduction), and internal heat sources (Q) originating from the PTC element. In the context of a food warming system, the value of Q becomes a key parameter that determines the amount of thermal energy available to increase the temperature inside the enclosure, while variations in convection mechanisms affect the effectiveness of heat distribution. Under natural convection conditions, heat transfer is strongly influenced by the Rayleigh number, which represents the strength of buoyancy forces, whereas in forced convection, it is influenced by an increase in the convective heat transfer coefficient associated with the Nusselt number.

In addition to the three main equations, heat transfer mechanisms also involve conduction through the enclosure walls and radiation between surfaces. Conduction is influenced by the thermal conductivity of the wall material, where materials with low thermal conductivity will slow down the rate of heat loss to the environment. Meanwhile, thermal radiation enables the transfer of heat energy without a medium through interactions between surfaces at different temperatures, which also contributes to energy distribution within the enclosed space.

In this simulation, the system is assumed to be in a steady-state condition, meaning there is no change in temperature with respect to time. Under this assumption, all thermal variables such as temperature, flow velocity, and energy distribution are considered constant once the system reaches equilibrium. The steady-state approach is highly relevant for evaluating system performance under normal operating conditions, particularly in determining whether the system is capable of maintaining food temperature in a stable and uniform manner under both natural and forced convection conditions.

2.3 Surveyors dan Mesh

Meshing is a crucial stage in Computational Fluid Dynamics (CFD) simulation because it directly affects the accuracy and stability of the numerical solution. In this study, the computational domain created during the geometric modeling stage is discretized into small elements using the ANSYS Meshing module. This discretization enables the numerical solution of the conservation equations of mass, momentum, and energy at each control volume within the system, under both natural and forced convection conditions. The specific geometric dimensions of the food warming system used in this study are shown in Figure 3.

Fig. 3. Food warming system geometry

The mesh type used is a tetrahedral unstructured mesh, which was selected due to its ability to handle complex geometries, particularly around the PTC heating element, fan, and enclosure corners. In addition, to improve accuracy in capturing heat transfer phenomena near the walls, an inflation layer feature is applied at the solid–fluid interface surfaces. This layer enables better resolution of temperature and velocity gradients within the boundary layer region, which is a critical area in both natural and forced convection analyses.

To ensure good mesh quality, several evaluation parameters were used, including:

- Skewness < 0.85 (ideal mendekati 0)
- Orthogonal Quality > 0.2
- Aspect ratio dijaga dalam batas wajar untuk menghindari distorsi elemen

In addition, local mesh refinement was applied in regions with high temperature gradients, particularly around the PTC heating element and heat distribution pathways. This aims to improve numerical resolution in areas with significant temperature variations. To ensure that the simulation results are not dependent on mesh size, a grid independence test was performed. In this test, simulations were carried out using several mesh densities (e.g., 100,000, 250,000, and 500,000 elements), and key parameters such as maximum temperature and average temperature distribution were compared for both convection conditions. The mesh is considered independent when the difference between the results of successive mesh refinements is less than 5%. This approach ensures that the simulation results have a high level of reliability in representing the heat transfer phenomena within the system.

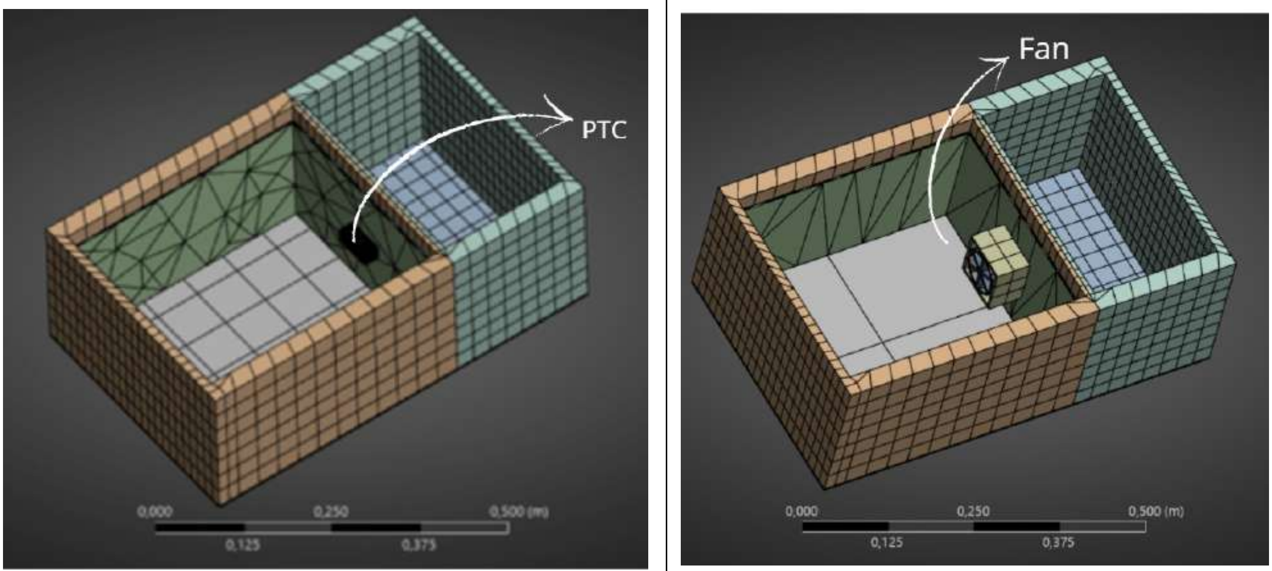


Fig. 4. Mesh box without fan (a) Mesh box with fan (b)

2.4 Material Properties

In this simulation, the materials used consist of air as the working fluid inside the enclosure and solid materials forming the system walls and the PTC heating element. Air is selected as the primary medium because it plays a direct role in heat distribution through natural and forced convection mechanisms within the enclosed space. Under no-fan conditions, air facilitates natural circulation driven by density differences, whereas under fan-assisted conditions, it serves as the main medium for forced convection, which enhances temperature uniformity. Meanwhile, solid materials such as the enclosure walls and the heating element are selected based on their thermal conductivity characteristics, which influence the rate of heat transfer. The combination of these material properties is crucial in analyzing temperature distribution and heat transfer efficiency in the food warming system. The material parameters used in the simulation, including physical properties such as density, thermal conductivity, specific heat capacity, and dynamic viscosity, are presented in Table 2.

Table 2
Material properties

No	Material	Density (kg/m³)	Thermal Conductivity (W/m·C)	Heat Capacity (J/kg·C)	Dynamic Viscosity (Pa·s)
1	Air	1.225	0.024	1006	1.789×10^{-5}
2	Steel	7850	60.5	434	-
3	Wood, Oak	935.7	0.45	1685	
4	PTC Copper	8300	401	385	-

The material properties used in this simulation are based on standard values from the literature to ensure accuracy in heat transfer modeling. Variations in thermal conductivity, heat capacity, and density of each material significantly influence the temperature distribution and overall system efficiency, both under natural convection conditions, which tend to produce thermal stratification, and under forced convection conditions, which enhance fluid mixing and temperature homogeneity.

2.5 Boundary Conditions

The boundary conditions used in this simulation are defined to represent the real operating conditions of the food warming system in an enclosed environment, considering the influence of internal heat sources, thermal interaction with the surroundings, and the effects of natural convection due to gravity as well as forced convection caused by airflow from the fan. Under no-fan conditions, the fluid flow is entirely driven by buoyancy forces, whereas under fan-assisted conditions, forced airflow is introduced, which enhances the heat transfer rate and temperature distribution within the system.

Table 3
Boundary conditions in the simulation

No	Component	Boundary Condition Type	Parameter	Value / Description
1	PTC Heater	Heat Source / Heat Flux	Heat Power (Q)	100 W
2	Enclosure Wall	Adiabatic / Convection	Convective Heat Transfer Coefficient (h)	5 – 10 W/m²K (if heat loss is considered)
3	External Environment	Ambient Temperature	Temperature (T)	22 °C
4	Gravity	Body Force	Gravitational Acceleration (g)	9.81 m/s²

The definition of these boundary conditions enables the simulation to consistently represent two different operating conditions. Under natural convection conditions, temperature distribution is influenced by temperature gradients and gravitational forces, whereas under forced convection conditions, temperature distribution is affected by increased flow velocity and the convective heat transfer coefficient. Thus, this approach enables a comprehensive analysis of the influence of heat transfer mechanisms on the thermal performance of the food warming system.

3. Result

3.1 Heat Distribution Analysis

A. No-Fan Condition

The simulation results of the temperature distribution in the food warming prototype without the use of a fan, as shown in **Figure 5**, indicate heat transfer characteristics dominated by the natural convection mechanism. At the initial condition (0 s), the temperature within the chamber is relatively uniform and close to the ambient temperature, indicating that no heat accumulation from the PTC heating element has yet occurred. As time progresses, particularly from 150 s to 300 s, a significant temperature gradient begins to appear around the heat source located at the center of the chamber. Theoretically, the heat transfer by conduction can be described using Fourier's law:

$$q = -kA\frac{dT}{dx}$$

where the rate of heat transfer is influenced by the material's thermal conductivity, cross-sectional area, and temperature gradient. In this case, aluminum as the wall material has a high thermal conductivity, which accelerates lateral heat spreading.

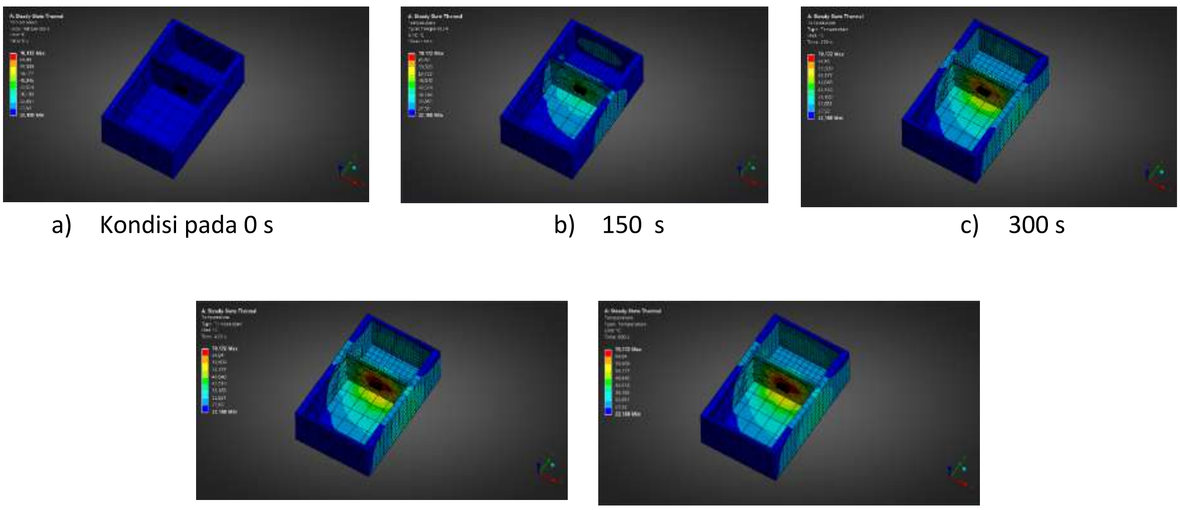
During the time interval of 300 s to 450 s, the temperature distribution becomes increasingly non-uniform, with higher temperatures tending to accumulate in the upper region of the chamber. This phenomenon is consistent with natural convection characteristics, where buoyancy forces caused by density differences act as the main driver of fluid motion. The tendency of natural convection can be analyzed using the Rayleigh number:

$$Ra = \frac{g\beta(T_s - T_\infty)L^3}{\nu\alpha}$$

A high Rayleigh number indicates the dominance of natural convection in the system. Hot air with lower density rises, while cooler air descends, resulting in temperature stratification within the enclosed space. At 600 s, the system begins to approach steady-state conditions, as indicated by relatively small changes in temperature distribution compared to previous time steps. However, temperature non-uniformity is still clearly observed, particularly between the upper and lower regions of the chamber. The convective heat transfer mechanism in the fluid can be expressed by Newton's law of cooling:

$$q = hA(T_s - T_\infty)$$

where the convective heat transfer coefficient (h) under natural convection conditions is generally lower than that under forced convection. This results in a slower and less uniform heat distribution rate, even though the aluminum walls assist in heat spreading through conduction. The detailed simulation results of the food warming prototype without fan usage can be seen in **Figure 5** below.



a) Kondisi pada 0 s b) 150 s c) 300 s

a) 450 s b) 600 s

Fig. 5. Simulation results of temperature distribution under no-fan condition

Overall, the simulation results indicate that the system without a fan produces a less homogeneous temperature distribution, with a tendency for hot zones to form in the upper region of the chamber. This non-uniformity can be explained by the interaction between conduction and natural convection, which is not strong enough to ensure complete air mixing.

Considering the low convective heat transfer coefficient and the dominance of the Rayleigh number in the closed system, the use of a fan to generate forced convection becomes a logical solution to improve temperature homogeneity. Therefore, this analysis provides an important basis for evaluating the effectiveness of fan integration in the heating system in future studies.

B. With Fan

The simulation results of the temperature distribution in the food warming prototype with the addition of a fan, as shown in Figure 6, indicate a significant change in heat transfer characteristics compared to the no-fan condition. At the initial stage (0 s), the temperature distribution is still relatively uniform and close to the ambient temperature, similar to the no-fan condition. However, during the time interval of 150 s to 300 s, the temperature increases more rapidly and its distribution appears more uniform throughout the chamber. This indicates that the presence of the fan is able to accelerate the heat transfer process through forced convection, where airflow is driven to move actively, thereby enhancing the distribution of thermal energy from the PTC heating element to the entire volume of the chamber.

Theoretically, the increase in heat transfer rate due to forced flow can be explained by Newton's law of cooling:

$$q = hA(T_s - T_\infty)$$

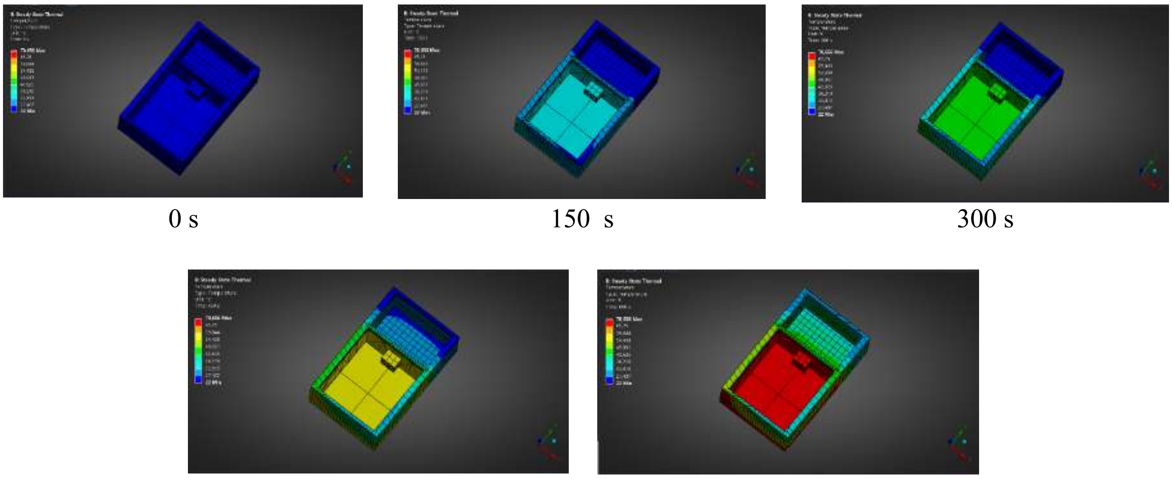
Under forced convection conditions, the convective heat transfer coefficient (h) increases significantly compared to natural convection. This increase in the value of h leads to a higher heat transfer rate, resulting in a faster and more uniform temperature distribution within the chamber. This is consistent with the simulation results, which show that the temperature gradient between points in the domain is smaller compared to the no-fan condition.

During the time interval of 300 s to 450 s, the temperature distribution becomes increasingly homogeneous without significant thermal stratification. Unlike natural convection, where hot air tends to accumulate in the upper region, the presence of a fan produces intensive air mixing, thereby reducing vertical temperature differences. This phenomenon can be analyzed using the Nusselt number, which represents the ratio of convective to conductive heat transfer:

$$Nu = \frac{hL}{k}$$

a higher Nusselt number under forced convection conditions indicates improved heat transfer effectiveness, which contributes to a more uniform temperature distribution within the enclosed space.

At 600 s, the system reaches steady-state conditions with a relatively homogeneous temperature distribution throughout the chamber. There is no significant temperature difference between the upper and lower regions, indicating that the fan successfully eliminates thermal stratification effects. In addition, the aluminum walls continue to play a role in enhancing heat spreading through conduction; however, under these conditions, forced convection becomes the dominant factor governing temperature distribution. The combination of wall conduction and forced convection within the fluid results in a more efficient and uniform heating system. The detailed simulation results of the food warming prototype using a fan can be seen in **Figure 6** below.



0 s 150 s 300 s

450 s 600 s

Fig. 6. Simulation results of temperature distribution under fan condition

Overall, the simulation results show that the use of a fan significantly improves the performance of the food warming system in terms of temperature distribution uniformity and the speed of reaching steady-state conditions. Compared to the no-fan condition, the fan-assisted system is able to reduce temperature gradients and enhance the effectiveness of heat transfer within the enclosed space. This confirms that the application of forced convection is an effective solution for improving heating quality in a solar-powered food warming system.

3.2 Thermal Performance Comparison of the System

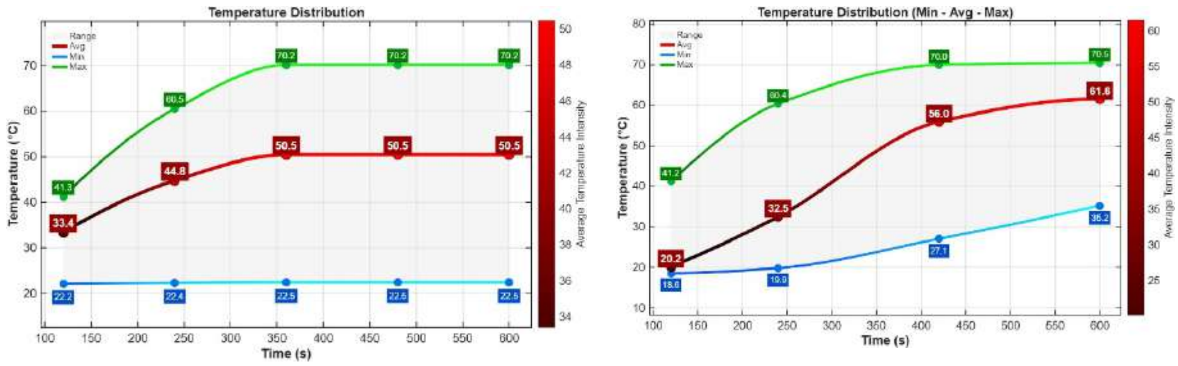
The thermal performance analysis of the system is carried out by comparing the minimum, maximum, and average temperature parameters under no-fan (natural convection) and fan-assisted (forced convection) conditions. Based on the obtained data, it can be observed that under the no-fan condition, the average temperature increases gradually from 33.44°C at 120 s to approximately 50.48°C at 600 s. This increase tends to slow down after 360 s, indicating that the system is approaching steady-state conditions. However, the minimum temperature remains relatively constant at around 22°C, indicating that there are regions within the chamber that are not significantly affected by the heat source, resulting in non-uniform temperature distribution.

In contrast, under the fan-assisted condition, the average temperature increases more significantly, from 20.187°C at 120 s to 61.552°C at 600 s. This indicates that the system with forced convection is able to enhance heat accumulation more effectively compared to natural convection. In addition, the minimum temperature also shows a considerable increase, from 18.631°C to 35.236°C, indicating that heat distribution reaches almost the entire chamber. Thus, it can be concluded that the fan plays an important role in reducing cold spots within the heating chamber.

In terms of maximum temperature, both systems show relatively similar values, approaching the PTC element temperature limit of 70°C. This indicates that the heat source operates consistently under both conditions, meaning that differences in thermal performance are more influenced by heat distribution mechanisms rather than heating capacity. In other words, the main difference lies in the effectiveness of heat transfer from the source to the surrounding environment. This phenomenon can be explained by the increase in the convective heat transfer coefficient under forced convection conditions, which is mathematically expressed as:

$$q = hA(T_s - T_\infty)$$

where an increase in the value of h leads to a higher heat transfer rate. A clearer comparison of the system's thermal performance in terms of minimum, maximum, and average temperatures under no-fan (natural convection) and fan-assisted (forced convection) conditions can be seen in **Figure 7** below.



a) No-Fan Condition b) Fan Condition

Fig. 7. Thermal performance of the system in terms of minimum, maximum, and average temperature under no-fan and fan conditions

In terms of temperature homogeneity, the fan-assisted system shows significantly better performance compared to the no-fan condition. This can be observed from the smaller difference between maximum and minimum temperatures in the fan condition over time. Under no-fan conditions, the temperature difference remains high, indicating a large temperature gradient within the chamber. In contrast, under fan-assisted conditions, the temperature difference tends to decrease, indicating a more uniform heat distribution. This phenomenon is associated with an increase in the Nusselt number, which reflects the effectiveness of convective heat transfer:

$$Nu = \frac{hL}{k}$$

which is higher under forced convection compared to natural convection.

Overall, the analysis results show that the use of a fan significantly improves the thermal performance of the system, in terms of heating rate, increase in average temperature, and heat distribution uniformity. The fan-assisted system is able to reach a higher average temperature within the same time period, while also reducing temperature differences between points within the chamber. Therefore, the implementation of forced convection is an effective solution to improve the efficiency and quality of heating in the solar-powered food warming prototype. These findings reinforce that system optimization depends not only on the heat source, but also on the mechanism of thermal energy distribution within the enclosure.

3.3 Physical Interpretation and Process Implications

The physical interpretation of the simulation results shows that the heat transfer mechanism in the system is strongly influenced by the interaction between the heat source, the air fluid inside the chamber, and the boundary conditions provided by the aluminum walls. Under no-fan conditions, heat transfer is dominated by natural convection, where fluid motion is driven by density differences caused by temperature gradients. This phenomenon causes hot air to rise and accumulate in the upper region of the chamber, while the lower region remains relatively cooler. As a result, thermal stratification is formed, indicating an uneven distribution of thermal energy within the system.

In contrast, under fan-assisted conditions, the heat transfer mechanism shifts to forced convection, where airflow is actively driven to circulate more uniformly throughout the chamber volume. Physically, this enhances fluid mixing, thereby minimizing temperature gradients. The increased flow intensity also contributes to a higher convective heat transfer coefficient, which directly improves the rate of thermal energy distribution. As a result, the system is able to transfer heat from the PTC element to all regions of the chamber more effectively compared to the no-fan condition.

The process implications of this phenomenon are very important in the context of food warming applications. In the no-fan system, the presence of low-temperature regions (cold spots) may lead to uneven heating, resulting in suboptimal thermal quality of the food. In addition, the time required to reach the desired temperature conditions becomes longer, which can reduce the overall efficiency of the system. This condition is less ideal, especially for applications that require temperature stability within a specific range.

In contrast, the use of a fan has positive implications for system performance, particularly in improving temperature homogeneity and accelerating the attainment of operating conditions. With more uniform heat distribution, the quality of food heating can be maintained consistently throughout the chamber. In addition, energy efficiency also has the potential to improve, as the generated heat can be utilized more effectively without accumulating in a single region. Therefore, the integration of forced convection mechanisms in the design of solar-powered food warming systems becomes a key factor in enhancing thermal performance and operational reliability.

Overall, the physical interpretation of these simulation results shows that system performance is not only determined by the heating capacity of the heat source, but also by the effectiveness of heat distribution within the chamber. The interaction between conduction through the aluminum walls and convection within the fluid is a crucial aspect that must be considered in system design.

By understanding these mechanisms, the development of food warming systems can be directed toward more efficient designs, both in terms of temperature distribution and energy consumption. These findings provide a strong scientific basis for optimizing system design in future research.

3.4 Limitations of the Study

This study has several limitations that should be considered when interpreting the simulation results. One of the main limitations is the use of a steady-state thermal analysis approach, which assumes that the system has reached a steady condition without fully representing transient heat transfer phenomena. Although time variations are included in the simulation results, this approach does not completely capture the continuous dynamics of temperature changes as they occur in real conditions. As a result, the initial heating characteristics and temperature fluctuations within the system cannot be analyzed comprehensively.

In addition, the simulation was carried out using several simplifying assumptions, particularly regarding material and fluid properties. The thermophysical properties of air were assumed to be constant, whereas in real conditions they may vary with temperature and influence both natural and forced convection flow patterns. The aluminum walls were also modeled as a homogeneous material without considering possible heat losses to the surrounding environment. Under fan-assisted conditions, the fluid flow modeling was still limited to certain boundary condition approaches, and therefore does not fully represent real flow characteristics, including velocity distribution and complex turbulence effects.

Another limitation of this study is the absence of experimental validation of the simulation results. Without comparison against direct measurement data, the accuracy of the numerical model used cannot be fully ensured. Therefore, future research is recommended to integrate an experimental approach as well as employ a more comprehensive transient analysis. In this way, the obtained results are expected to be more accurate and representative of the real operating conditions of a solar-powered food warming system.

4. Conclusions

This study presents a comprehensive numerical analysis of temperature distribution in a solar-powered food warming system using a PTC heating element within a closed enclosure. The Steady-State Thermal simulation results show that the heat transfer characteristics within the system are strongly influenced by the dominant convection mechanisms, which directly determine the temperature distribution patterns and thermal efficiency. The steady-state approach used is able to represent the system's operating conditions in a representative manner, particularly in evaluating temperature stability and the potential formation of non-uniform heat distribution.

Under natural convection conditions, the system shows limitations in distributing thermal energy uniformly. The occurrence of thermal stratification leads to the accumulation of hot air in the upper region of the enclosure, while the lower region tends to maintain a lower temperature. This is reflected in the significant difference between maximum and minimum temperatures, indicating a high temperature gradient and the formation of cold zones.
This condition results in low thermal homogeneity and may potentially affect the overall quality of food storage.

In contrast, the implementation of forced convection through the addition of a fan shows a significant improvement in thermal performance. The mechanically induced airflow enhances fluid mixing intensity, thereby accelerating heat distribution throughout the domain. This is indicated by an increase in the minimum temperature, a reduction in the temperature difference within the chamber, and a faster attainment of steady-state conditions. Thus, forced convection not only increases the rate of heat transfer but also plays a key role in reducing the temperature gradients that were previously dominant in the natural convection system.

Overall, the results of this study confirm that the integration of forced convection is an effective strategy for improving the thermal performance of solar-powered food warming systems. These findings provide an important contribution to the development of efficient, uniform, and sustainable heating systems for food distribution applications. Therefore, optimizing system design by considering the interaction between heat sources, flow characteristics, and enclosure configuration is a crucial aspect in enhancing energy efficiency and overall thermal performance.

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