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Numerical Analysis of Heat Transfer and Temperature Distribution in Molten Sodium Casting using ANSYS Fluent

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This study numerically investigates the heat transfer and temperature distribution of molten sodium during the casting process using Computational Fluid Dynamics (CFD). Unlike previous studies that focused on conventional metals such as aluminum and steel, this research addresses the limited understanding of high-conductivity fluids like molten sodium in complex mold geometries. A three-dimensional simulation of a T-junction mold reveals that heat transfer is initially dominated by convection and later by conduction as the system approaches equilibrium. Temperature uniformity is achieved after approximately 150 seconds, with a maximum temperature difference below 20 K, indicating high thermal stability. Comparison with aluminum-based studies (Yuwen et al.,) validates the numerical model and confirms molten sodium's superior heat transfer capability. The findings highlight molten sodium's potential as an efficient and stable heat transfer medium and underscore the importance of mold geometry and thermal control in achieving high thermal efficiency in casting systems..

1. Introduction

The casting process is one of the most commonly used manufacturing methods to produce liquid metal components into solids of a certain shape. In this process, molten metal is poured into the mold and then allowed to freeze and form components according to the mold geometry. During this process, the phenomenon of heat transfer and freezing is an important aspect because it affects the quality, microstructure, and mechanical strength of the casting results [1]. An imbalance of temperature distribution during cooling can lead to various defects such as cavity shrinkage, porosity, thermal cracking, and deformation due to residual stress [2]. Therefore, the analysis of temperature distribution in the casting process is one of the crucial aspects in the design of a metal casting system.

The development of computing technology allows for more accurate numerical analysis of the heat transfer and freezing processes of molten metals [3]. Some previous studies have shown that

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accurate temperature field prediction can be used to minimize casting parameters and reduce the risk of defects in the final product. Despite this, most previous studies have focused on metal materials such as aluminum and steel, while research on fluids with high thermal conductivity such as molten sodium is still relatively limited [4]. Further research is needed to understand the heat transfer and solidification characteristics of these types of fluids in order to be optimally applied in modern casting systems.

Molten sodium has unique thermophysical properties, namely high thermal conductivity, low viscosity, and a wide temperature operating range [5]. These characteristics make liquid sodium very potential as a working fluid in high-temperature heat transfer systems such as heat exchangers, fast reactors, and experimental metal casting systems [6]. However, the heat transfer characteristics at the interaction between liquid sodium and mold walls have not been studied in depth, especially in the context of metal casting[7]. The high thermal conductivity properties of sodium cause heat transfer to take place very quickly, so research on how sodium reacts to temperature changes is important to understand the dynamics of mold systems and the solidification phenomena that occur [8].

Based on this background, this study aims to analyze the temperature distribution during the casting process of molten metals in a pipe molding system using two types of molten materials, namely pure molten and molten sodium[9]. The analysis was carried out to compare the heat transfer characteristics of the two materials and evaluate their effect on temperature stability and freezing processes [10]. The results of the study are expected to provide a deeper understanding of the thermal behavior of molten metals during mold filling. In addition, the results of this simulation can also be used as a reference in determining the optimal design and operating conditions of the casting system with higher thermal efficiency [11].

Based on Table 1, most previous studies have primarily focused on conventional metallic materials such as aluminum, steel, and magnesium alloys, employing CFD or FEM-based simulations to predict temperature distribution, thermal gradients, and solidification zones. For instance, Anggono *et al.*, [12] and Liang *et al.*, [13] demonstrated high agreement between numerical and experimental results for aluminum alloys, but their analyses were limited to metals with moderate thermal conductivity (20–100 W/m·K) and relatively steady thermal conditions. Similarly, Yuwen *et al.*, (2012) provided valuable insight into the casting filling process of molten aluminum, revealing that temperature gradients decreased rapidly and reached thermal equilibrium within 5.5 seconds. However, these studies did not explore high-conductivity fluids such as molten sodium (71 W/m·K) or examine the influence of branched geometries (T-junction molds), which play a critical role in determining flow patterns and heat transfer performance in industrial casting systems.

Addressing these limitations, the present study aims to fill this research gap by conducting a three-dimensional numerical analysis of thermal behavior and temperature distribution in molten sodium using the Volume of Fluid (VOF) and Solidification–Melting models within ANSYS Fluent. This approach enables a more comprehensive examination of transient convection–conduction interactions and fluid–wall thermal coupling, aspects that have been insufficiently discussed in prior works. Furthermore, this study provides a critical comparison of heat transfer efficiency and thermal stability between molten sodium and other metallic fluids based on both simulation outcomes and existing literature. Through this contribution, the research seeks to establish a stronger theoretical foundation for developing high-thermal-efficiency casting systems with optimized channel geometries and improved temperature uniformity for high-temperature industrial applications.

Table 1
State of the art

Reference	Method	Research Materials/Objects	Key Results
[12]	ANSYS Fluent-based numerical simulation using enthalpy-porosity model for vertical solidification	Al–3wt.%Si alloy in water-cooled metal molds (unidirectional vertical solidification)	The temperature distribution of the simulation results showed a high conformity with the experimental data. The model is able to predict mushy zones and thermal gradients well.
[13]	Finite Element Method (FEM) using ProCAST software; Development of the Temperature Compensation Heat Capacity Method model	A356 Aluminum Alloy in low pressure casting process for vehicle wheels	The new method combines an equivalent heat capacity and temperature compensation approach. Provides the most accurate results on experimental data compared to other models
[14]	Element-based transient CFDs and thermal simulations up to	Carbon steel molds on molten metal castings	The simulation results show a non-uniform temperature distribution with a high gradient in the mold wall area; The model is able to predict cooling and potential thermal defects
[15]	Coupled thermomechanical simulation with conduction–convection models	Aluminum casting system with forced cooling	Temperature prediction and thermal deformation according to the results of the experiment. The thermomechanical coupling approach improves the accuracy of thermal crack estimation
[16]	Literature review and numerical validation of coupled thermomechanical models	Different types of metals (Al, Mg, Cu alloys) in the casting process	Confirms the importance of the interaction between thermal stress, temperature gradient, and deformation in the prediction of casting defects. Offers the direction of future development of integrated simulation models.

Addressing these limitations, the present study aims to fill this research gap by conducting a three-dimensional numerical analysis of thermal behavior and temperature distribution in molten sodium using the Volume of Fluid (VOF) and Solidification–Melting models within ANSYS Fluent. This approach enables a more comprehensive examination of transient convection–conduction interactions and fluid–wall thermal coupling, aspects that have been insufficiently discussed in prior works. Furthermore, this study provides a critical comparison of heat transfer efficiency and thermal stability between molten sodium and other metallic fluids based on both simulation outcomes and existing literature. Through this contribution, the research seeks to establish a stronger theoretical foundation for developing high-thermal-efficiency casting systems with optimized channel geometries and improved temperature uniformity for high-temperature industrial applications.

2. Methodology

2.1 Research Approach

This study uses numerical simulation based on Computational Fluid Dynamics (CFD) to analyze the thermal behavior of transient molten sodium during the casting process. Method Volume of Fluid (VOF) is used to capture the interface between liquid sodium and air, while the model Solidification–

Melting applied to predict heat transfer and phase changes within the mold. The simulation was carried out in a transient manner from 0 to 200 seconds to observe temperature distribution, thermal gradients, and heat transfer mechanisms [17]. This approach provides a comprehensive overview of the evolution of liquid sodium temperatures from an initial non-uniform state to a quasi-tuneous thermal state. The physical model is assumed to be three-dimensional, incompressible, and transient with the dominance of convection in the early stages and conduction in the advanced stages[18].

Branched mold-shaped computing domains (T-junction mold system) which consists of one main channel and two branches, is used to study the influence of geometry on the distribution of flow and heat. High-temperature liquid sodium is flowed through Inlet and interacts with a 300 K fixed-temperature mold wall, resulting in a significant thermal gradient that triggers convective circulation within the system [19]. Numerical validation is carried out by comparing the simulation results against the expected physical behavior, such as rapid cooling in the area Inlet and the achievement of temperature equilibrium at about 150 seconds. The integration between thermal fluid dynamics and solidification models allows for a thorough evaluation of the heat transfer capability of molten sodium, which contributes to the optimization of the system heat transfer and high-temperature industrial casting process [16]. As for the workflow of the simulation carried out, it is as follows: Figure 1 next.

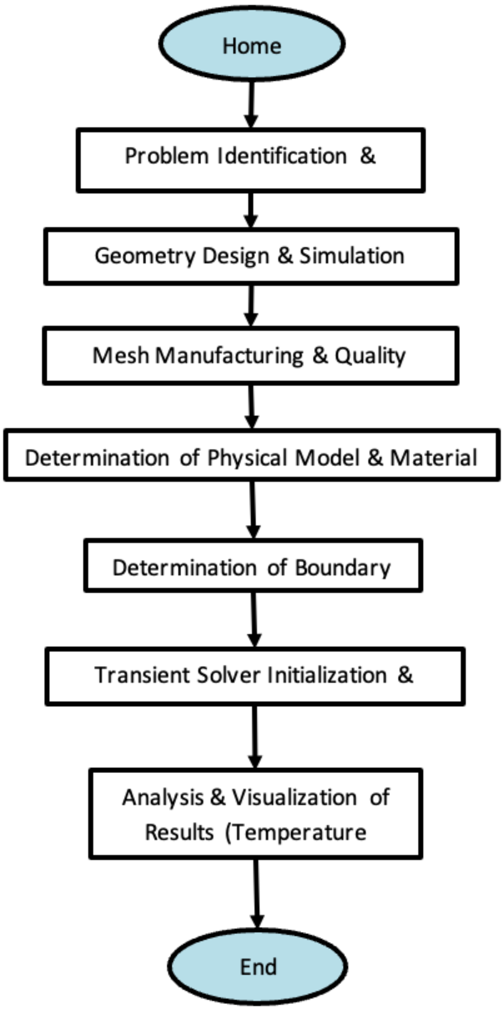


Fig. 1. Flowchart mechanism

2.2 Boundary Conditions

This simulation uses boundary conditions that represent the casting process in real life so that the prediction of heat flow and distribution has a high level of accuracy. Part Inlet designated as velocity inlet with a uniform flow speed of 0.2 m/s and a fluid initial temperature of 495 K, while Outlet defined as pressure outlet With a pressure of 1 ATM to allow outflow without the effect of back pressure. The mold walls are given a fixed temperature of 300 K to allow conductive and convective heat transfer between the fluid and the wall, while the outer surface of the mold is thermally insulated to minimize heat loss to the environment [20]. The gravitational effect is activated in the negative vertical direction with an acceleration of 9.81 m/s² to capture the natural convection phenomenon, while the rotational effect is negligible because the system has no rotating components or centrifugal effect [21].

The interface between phases is tracked using the model Volume of Fluid (VOF) which dynamically updates the boundary position between liquid sodium fluid and air [22]. The pressure is considered uniform in both phases, while the equation of energy and momentum is solved specifically for the liquid phase. Wall mold apply conditions No-slip to maintain realistic fluid-solids interactions and prevent artificial slip effects. The boundary condition setting was chosen to represent the physical condition of the casting process well while maintaining numerical stability during the transient simulation [23]. As for the boundary conditions, they are presented as shown in Figure 2 below.

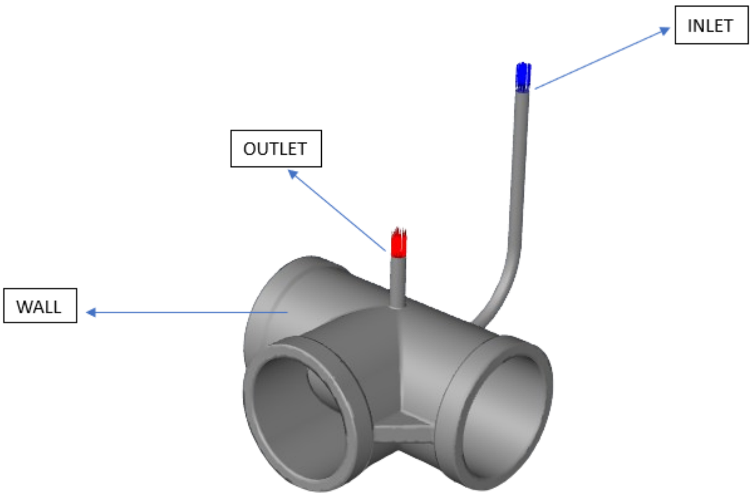


Fig. 2. Boundary conditions T-junction

2.3 Heat Transfer in the Metal Freezing Process

The process of heat transfer during freezing (solidification) occurs through three main mechanisms, namely heat conduction, heat convection, and thermal radiation. As the position of the heat source continues to change during freezing, latent heat release also changes nonlinearly as the freezing process progresses [24]. In this phenomenon there are two important interfaces, namely between the liquid and solid phases (liquid-solid interface) as well as between metal and mold (metal casting interface) [25].

On single-phase metal freezing (single-phase solidification), heat transfer macroscopically can be thought of as one-dimensional conduction, in which heat flows from the liquid to the solid phase perpendicular to the interface [26]. However, when there is an irregularity in the liquid-solid interface or dendritic growth, heat transfer becomes a three-dimensional phenomenon on a microscale because in addition to conduction there is also micro convection in the fluid [27]. At the interface of metals and molds, imperfect contact gives rise to thermal contact resistance as well as the contribution of microconvection and heat radiation [28].

Factors such as mold shape, material differences, and nonlinear changes in thermal properties make the freezing process very complex. Therefore, the calculation of temperature distribution and freezing rate is important because it has a direct effect on crystallization, cavitation shrinkage (shrinkage cavity), porosity, and residual stress of the casting. To analyze this phenomenon, two main approaches are used, namely analytical and numerical [17]. The analytical approach relies on a number of assumptions on changes in temperature and thickness of the solid layer as a function of time, while the numerical approach uses graph methods, electrical analogies, and numerical simulations based on the equation of inert heat conduction (transient heat conduction equation) [29,30].Both analytical and numerical methods are based on the following transient heat conduction equation

$$\frac{\partial}{\partial x}\left(\lambda\frac{\partial}{\partial x^2}\right) + \frac{\partial}{\partial y}\left(\lambda\frac{\partial}{\partial y}\right) + \frac{\partial}{\partial z}\left(\lambda\frac{\partial}{\partial z}\right) + q = c\rho\frac{\partial t}{\partial t} \quad (1)$$

If considered constant, then the above equation can be simplified to:λ

$$\lambda\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right) + q = c\rho\frac{\partial t}{\partial t} \quad (2)$$

2.4 Surveyors dan Mesh

The geometric model used in this study represents a casting pipeline with a T-junction type, where molten metal fluid enters from the upper vertical part and then flows horizontally towards the main channel. This design aims to simulate the mold filling process that is often used in industrial metal casting systems. As for the specific dimensions of the T-junction pipe used in this study, it is shown in Figure 3**.**

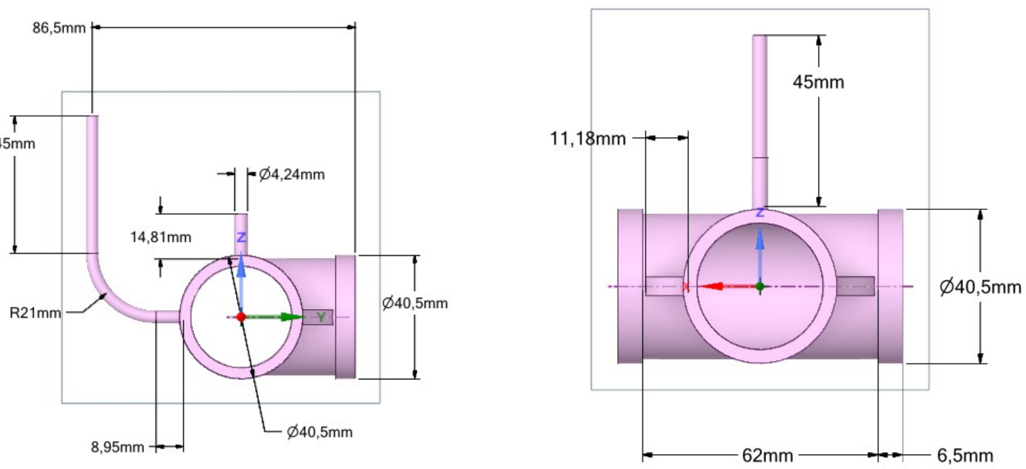


Fig. 3. T-junction geometry

The meshing process is carried out to discretize the geometric model into finite elements that will be used in numerical analysis on ANSYS Fluent. The type of mesh used is tetrahedral structured mesh because it is able to follow the complex shape of the channel and pipe branching well. The size of the element is made to be subtle enough in the intersection and inlet areas to capture significant temperature gradients and flows around the area. This approach aims to ensure that the simulation results obtained have a high level of accuracy in the critical areas where flow changes and heat transfer occur predominantly.

Overall, the resulting mesh shows a uniform distribution of elements with higher densities in the bend area and the connections between the pipes to improve the accuracy of the simulation results. The total number of mesh elements produced reached 273,529 elements and 60,987 nodes, with the element size set to 0.001 m. This arrangement was done to achieve a balance between the accuracy of the simulation results and the efficiency of the computational time. The visualization of the meshing results is shown in Figure 4.

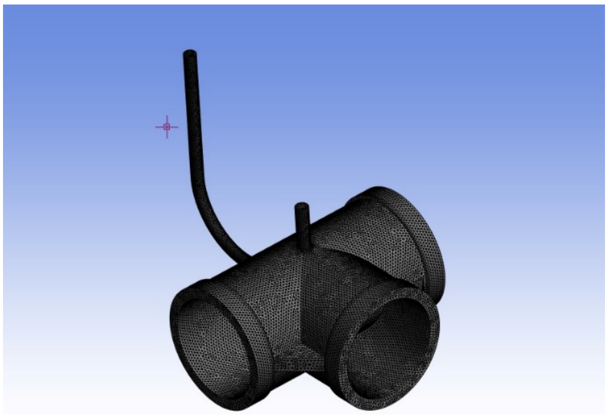


Fig. 4. Mesh T-junction

2.5 Property Parameters

In this simulation, the material used for the casting process is molten sodium. This material was chosen because it has high thermal conductivity, low viscosity, and excellent heat transfer ability. These characteristics make molten sodium suitable for use in the simulation of casting processes to analyze temperature distribution and heat transfer efficiency. The performance parameter values of molten sodium which include physical properties such as density, thermal conductivity, heat capacity, crystallization heat, solidus point, liquid point, and dynamic viscosity are shown in Table 2 below.

Table 2
Performance parameters of molten sodium

Material	Density (kg/m^3)	Thermal Conductivity ($W\cdot(m\cdot K)^{-1}$)	Heat Capacity ($J\cdot(kg\cdot K)^{-1}$)	Crystallization Heat ($J\cdot kg^{-1}$)	Solidus (°C)	Liquidus (°C)	Dynamic Viscosity ($N\cdot s\cdot m^{-2}$)
Molten Sodium	860	71	1275	113,000	97.8	97.8	0.00065

The molded material is 3Cr2W8V type hot molded steel. The thermo-physical performance parameters of the molded material are shown below. $\rho = 2710\ \mathrm{kg/m^3}$ Table 3 shows the value of thermal conductivity that increases with the increase in temperature, from 20.1 W/(m·K) at 100°C to 24.3 W/(m·K) at 700°C. This shows that the material's ability to conduct heat increases at higher temperatures. Meanwhile, the heat capacity of the type also experienced a significant increase, from 468.2 J/(kg· K) at 100°C to 685.5 J/(kg· K) at 700°C, which indicates that the material requires more energy to undergo temperature changes. Overall, the improvement of these two parameters indicates that the molded material has good thermal stability and is able to transfer heat efficiently during the casting process.

Table 3
Thermo-physical performance parameters of casting mould

Temperature (°C)	100	200	300	500	700
Thermal Conductivity (W·(m·K)$^{-1}$)	20.1	20.2	22.7	23.4	24.3
Heat Capacity (J·(kg· K)$^{-1}$)	468.2	525.5	564.0	612.3	685.5

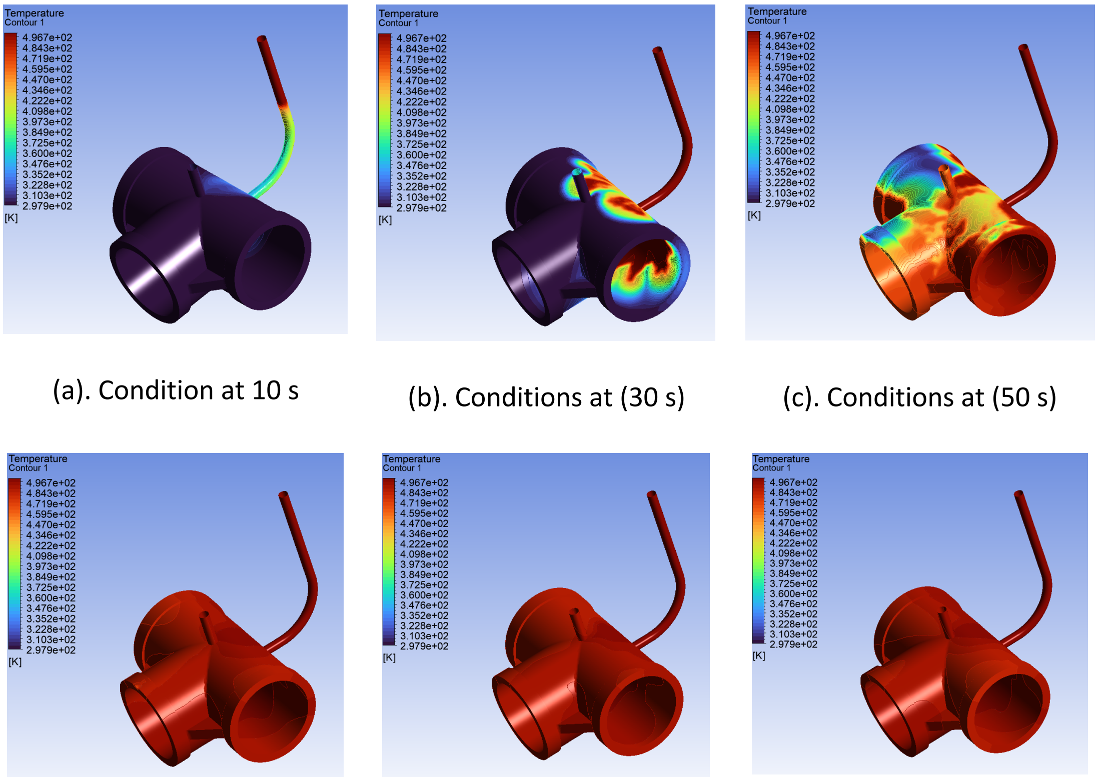
3. Simulation and Results
3.1 Molten Sodium Temperature Distribution to Time

In the simulation of the temperature distribution process in the mold, several important settings are used, namely the multiphase flow model (*VOF),* the energy model, the turbulence model, and the *solidification* model. The selection of these models aims to accurately represent the physical phenomena that occur during the *casting* process. In addition, appropriate numerical calculation methods are used to ensure that the simulation results are highly accurate. The surface tension of the fluid is also controlled so that the flow of molten metals can be well represented. The material properties of the molten and molded metals, as well as *the boundary conditions*, are determined before the simulation is run to ensure consistency in the calculation process. Once all parameters are set, the calculation domain is simulated, including all predefined flow and temperature initial conditions. The determination of this condition is important so that the simulation results can describe the actual state of the heat transfer process that occurs. Thus, accurate initial data is the main basis for obtaining representative numerical results.

Furthermore, the simulation was carried out in an integrated manner to calculate the interaction between the flow field (fluid movement) and the temperature field (heat transfer) during *the casting process*. This process is carried out repeatedly until the desired condition or simulation time is reached. The final results of the simulation were analyzed using ANSYS Fluent software, which is capable of displaying temperature distribution, flow patterns, and solidification times in detail. The results of the temperature distribution simulation are shown in Figure 5 to show the difference in heat distribution between molten and molded metals. The simulation results show the temperature distribution *of molten sodium* inside the mold system at simulation times of 10, 30, 50, 100, 150, and 200 seconds. At the beginning of the simulation (t = 10 s), the highest temperature was located at the inlet with a value of about 495 K, while the wall part of the mold showed a much lower temperature, about 300 K. This indicates that the heat transfer process took place predominantly in the initial phase, where *molten sodium* had just begun to fill the mold space and the liquid fluid was not evenly distributed throughout the channel. The large temperature difference between the liquid fluid and the mold wall causes a significant heat gradient around the pipe branching, as shown in Figure 5.

At time t = 30 to 50 seconds, it is seen that the high-temperature area begins to extend to the main part of the pipe branch. As time increases, the fluid reaches an initial state of tune, signifying that most of the mold area has been filled *with molten sodium*. The temperature distribution began to be more evenly distributed along the pipeline, but there was still a heat zone in the main flow path due to direct contact with the heat source in the initial simulation conditions. This shows that the heat transfer process is still active, especially in the area of joints and branches, where the thermal conductivity of the molded metal is lower than that of the flowing liquid fluid.

Entering the time *t* = 100 seconds, the temperature gradient between the fluid and the mold begins to decrease significantly. The temperature color in the simulation results shows a transition from bright red to orange and yellow, which signifies a gradual cooling of the *casting system*. This initially homogeneous distribution of heat indicates that thermal energy has been evenly distributed along the pipeline. At this stage, the conduction interaction between the mold wall and the liquid fluid becomes a major factor in stabilizing the system temperature before the solidification process takes place completely. In the final phase of the simulation, i.e. *t* = 150 and 200 seconds, most of the *molten sodium* volumes have reached conditions close to thermal equilibrium with a temperature value of about 490 K. Heating is still slight in the main pipeline zone, but overall the system shows a stable and controlled cooling process. This process illustrates that the *casting system* has reached a tuneous state, where the flow of heat from the molten metal to the mold takes place constantly without major fluctuations. Thus, the results of this simulation successfully show the transition of temperature distribution from the initial liquid state to the *steady-state thermal conduction* state, as visualized in Figure 5.



(a). Condition at 10 s (b). Conditions at (30 s) (c). Conditions at (50 s)

(d). Conditions at (100 s) (e). Conditions at (150 s) (f). Conditions at (200 s)

Fig. 5. Temperature distribution simulation results

As a model validation step, the temperature distribution results were compared with the study by Yuwen et al., which simulated mold filling using molten aluminum under similar conditions. In that study, the thermal conductivity of aluminum of 100 W/m·K resulted in temperature equalization during filling in approximately 5.5 seconds, with a similar cooling pattern high heat gradient at the beginning and thermal stability at the end. The results of this study show a similar thermal trend to the study by Yuwen et al., although molten sodium shows a longer stabilization time due to its greater specific heat capacity (1275 J/kg·K compared to 1090 J/kg·K for aluminum). This similarity in patterns indicates that the VOF-based CFD and solidification–melting models used in this study have good numerical validity and are capable of realistically describing physical phenomena.

The temperature distribution of molten sodium over time during the casting process can be seen in the graph in Figure 6. At the beginning of the process (0–50 seconds), there is a sharp increase in temperature from about 300 K to 430 K, with the average temperature in this phase being about 380 K. This increase is caused by the large temperature difference between molten sodium and the mold wall, so that the convection mechanism becomes dominant in the heat transfer process. Entering the 50–150 second time, the rate of temperature increase begins to decrease, and the average temperature increases from about 435 K to 470 K. In this phase, heat transfer begins to be dominated by conduction, where heat spreads evenly throughout the fluid volume. After 150 seconds to 200 seconds, the system begins to reach *a steady-state* state with an average temperature close to 480 K and very small temperature changes between observation times. Overall, the graph in Figure 6 shows an exponential temperature rise pattern that eventually flattens as molten sodium reaches thermal equilibrium. This shows that molten sodium has high thermal conductivity and good heat transfer efficiency, so the temperature equalization process takes place quickly and stable.

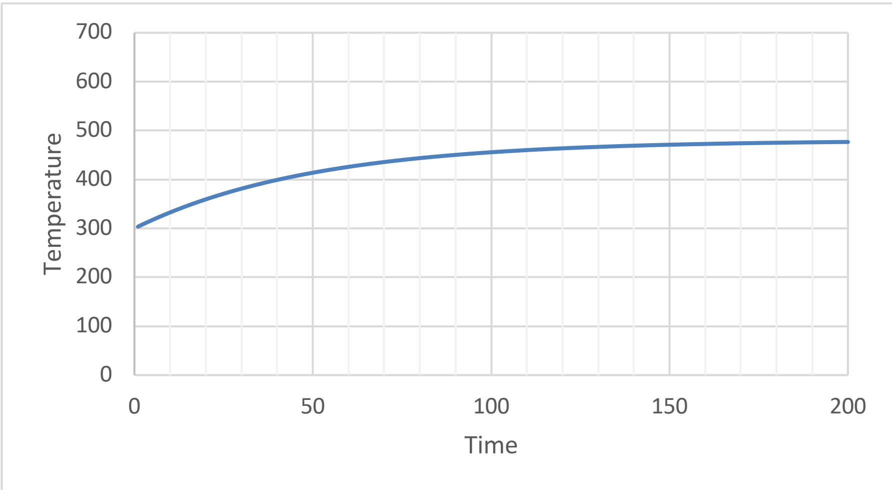


Fig. 6. Graph of the temperature distribution of molten sodium

3.2 Effect of Time on Temperature Change

To determine the effect of simulation time on changes in molten sodium temperature during the *casting* process, statistical analysis was carried out using the one-factor Anova (Analysis of Variance) test. This test aims to evaluate whether there is a significant difference between the temperature values at various time conditions observed in the simulation. Based on the results of Anova's calculations shown in Table 4, a Fcal value of 4163.33 with a Ftable of 3.8649 at the significance level of $\alpha = 0.05$. A P-value of 6.90×10^{-213} which is much smaller than 0.05 indicates that the differences between data groups are statistically significant. Thus, it can be said that there is a significant effect of the simulation time on the temperature change of molten sodium.

Physically, these results show that the heat transfer process in molten sodium undergoes a marked change over time. In the early stages of the simulation, the temperature increases sharply because the heat transfer is dominated by convection between the hot fluid and the still-cold mold wall. After about 150 seconds, the temperature rise begins to slow down and approaches *steady-state* conditions with an average temperature of about 480 K. High intergroup variance values also support a significant thermal gradient in the early phase, while variance in smaller groups indicates thermal stability in the late phase. Thus, the results of the Anova test strengthen the interpretation of numerical simulation results using Ansys Fluent, where the increase in molten sodium temperature is directly related to the length of the casting process time. These findings also confirm that the time duration and temperature control of the mold wall are important parameters in maintaining thermal stability and heat transfer efficiency in molten sodium-based casting systems as calculated in Table 4.

Table 4
Table Anova single factor

SUMMARY					
Groups	*Count*	*Sum*	*Average*	*Variance*	
Time	200	20100	100.5	3350	
Temperature	200	87252.83	436.2642	2065.74	
ANOVA					
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*
Between Groups	11273756	1	11273756	4163.33	6.902E-213
Within Groups	1077732	398	2707.87		

3.3 Physical Interpretation and Process Implications

The simulation results show that the heat transfer mechanism in molten sodium during the casting process is dominated by convection in the early stages and conduction in the later stages. The large temperature difference between the fluid and the mold wall produces a high heat gradient that causes intensive thermal circulation at the beginning of the process, which then decreases as thermal equilibrium is achieved. Molten sodium reaches temperature stability at around t = 150 seconds with a maximum temperature difference of less than 20 K, indicating high thermal conductivity (71 W/m·K) and good heat distribution efficiency throughout the fluid volume.

As a form of validation, the temperature distribution pattern was compared with the research by Yuwen et al. using molten aluminum. Both studies show similar trends, where a high heat gradient in the initial phase is followed by stable heat diffusion after a certain time. However, molten sodium exhibits a longer stabilization period due to its greater heat capacity (1275 J/kg·K compared to aluminum's 1090 J/kg·K), enabling it to store energy longer and maintain higher thermal stability. This reinforces the reliability of the VOF-based CFD and solidification–melting models used in this study.

Nevertheless, the use of molten sodium in industrial systems poses significant safety challenges due to its highly reactive nature with water and humid air. The exothermic reaction between sodium and moisture can trigger fires or explosions, so the process must be carried out in a closed system with an inert atmosphere such as argon or nitrogen. Additionally, the difference in thermal conductivity between sodium and the casting material can cause local thermal stresses, so the design of the flow path, pouring rate, and wall temperature control must be optimized to ensure operational efficiency and safety in high-temperature casting applications.

4. Conclusion

This study successfully modeled the temperature distribution and heat transfer mechanism in the casting process using molten sodium using the ANSYS Fluent-based CFD approach. The simulation results show that heat transfer is dominated by convection in the early stages and conduction in the later stages until a steady state is reached at around t = 150 seconds, with a maximum temperature difference of less than 20 K. This condition confirms that molten sodium has high thermal conductivity (71 W/m·K) and large heat capacity (1275 J/kg·K) which supports efficient heat distribution. Compared to the research by Yuwen et al. using molten aluminum, sodium shows a slower stabilization pattern but more even heat distribution, making it a potential efficient heat transfer medium in high-temperature industrial systems.

However, this simulation has limitations, such as not fully considering the 3D effect, mesh sensitivity, and simplification of material properties and boundary conditions that are assumed to be constant. For further research, it is recommended to conduct experimental validation of the numerical results with actual temperature measurements at several points in the mold and mesh sensitivity analysis to test the stability of the results. In addition, the use of nonlinear thermophysical models and simulations on complex geometries with dynamic pouring conditions is necessary to evaluate thermal stresses and deformations more realistically. This approach is expected to strengthen the accuracy of the model and support the safe and efficient application of liquid sodium in modern industrial casting systems.

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