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Analysis of Heat Distribution Processes and Casting Defects Supports 2D Direct Pouring Using CFDs

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ABSTRACT

Bolster and bogie frame of a train constitute a unified wheel system in both locomotives and non-locomotive cars. The bolster serves as the support for the bogie against the car body. Generally, both the bolster and bogie frame are made of steel construction with AAR Grade B+ cast material, which is categorized as medium carbon steel. In the casting of the bolster, despite hollow molds being made to the exact shape of the final product, often there are occurrences of hollow spots or imperfect shapes due to the challenging control of the cooling and solidification processes. This is caused by improper placement of mold venting channels. This study investigates the process of filling molten metal into the mold, the flow of molten metal, and the solidification process. The research utilizes ANSYS simulation software. The casting simulation method using ANSYS includes the following processes: Pre-Processing, Processing Stage, and Post-Processing. Pre-processing involves the creation of geometries, meshing, determination of parameters, and fluid property determination. The geometry model used is 2D. The Processing Stage includes setting general parameters, model determination, and defining material properties. Post-processing involves presenting and analyzing the obtained results. It can be concluded that the temperature distribution during the casting process to cooling generates a pattern where thicker sections have the highest temperature. Direct pouring gating systems tend to be vulnerable to porosity or hole defects in products because the molten metal comes into direct contact with the mold and it's difficult to control the solidification process.

1. Introduction

Bolster on the Bogie Frame of a train is a unified wheel system, both on locomotives and non-powered cars. The bolster functions as a support for the bogie against the body of the train. In general, the bolster is made of steel construction with AAR Grade B+ cast material, which includes medium carbon steel. In the industry, the production of a bolster is carried out using the casting method.

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The metal casting process is a long-established method widely applied in the industrial world. Metal casting is a manufacturing process conducted by melting metal in a melting furnace and then pouring it into a mold. In the mold, there are cavities that have the same shape as the planned original product [1]. The metal casting process involves several stages, namely: pattern making, sand mold making, melting process, pouring, mold disassembly, cleaning the casting from residual sand, until obtaining the planned product shape [2].

During the casting process, the cooling and solidification of the molten metal occur, influencing the microstructure and mechanical properties of the casting product [3]. There are several conventional methods to control the cooling of molten metal in the mold. Firstly, by using risers, internal and external chills. Secondly, by optimizing the structure of the sand mold. Thirdly, forced cooling is achieved by flowing air and/or water, etc. [4]. There is often difficulty in controlling the cooling of the casting in the production casting process of the bolster. This occurs because the molten metal is closely related to the thermal properties and microstructure of the metal and alloys used [5]. Other aspects that also influence the cooling of the metal casting include gas solubility, material, and molding shape [6]. During the cooling process of the casting, there is a temperature distribution in both the casting and the molding, thermal stress occurs, shrinkage takes place, ultimately influencing the solidification of the casting product [7].

The modernization of technical equipment and the reorganization of production processes in casting are necessary to achieve higher production volumes, manufacturing process flexibility, and product quality improvement. Considering the difficulty in controlling the casting quality related to the cooling process and its associated factors, simulation methods have been developed [8]. Simulation methods can be used to obtain an overview and verify whether the mold design and cooling process are capable of producing high-quality products. Simulation of casting cooling using software can provide insights into mold filling, distribution of metal liquid temperature, shrinkage, as well as defects in casting [9].

Numerical methods, today often used for computation analysis of dynamics and heat transfer, in solving engineering problems [10]. The ANSYS Fluent software features Computational Fluid Dynamics (CFD) analysis methods to simulate heat transfer and fluid dynamics [11]. This software has the potential to be used for simulating molten metal and its cooling in both two-dimensional and three-dimensional models. The simulation can be used for industrial optimization and material reduction in casting by understanding: 1) How the temperature distribution occurs during the casting process? 2) What factors influence the occurrence of casting defects in bolster mold with the direct pouring method?

The objectives of this research are: 1) Analyzing the occurrence of temperature distribution during the casting process. 2) Analyzing the influence of casting defects on the bolster during the casting process.

The benefits of this research are: providing guidelines and best practices for the implementation and utilization of casting simulation technology. Best practices in simulation can accurately predict outcomes before casting, saving time and costs. The results of this research can be used for industrial optimization, specifically in reducing the usage of materials in casting. This research also explains and examines various case studies.

2. Methodology

The space allows only a few examples taken from casting simulations, particularly from CFD simulations. To achieve accurate and unbiased research results, there is a need for limitations in this study. Namely, the product design layout is modified from 3D to 2D, reduced to 1:10 of its original size. The mold is assumed to be free from foreign inclusions, and both the casting material and the mold are assumed to be homogeneous. CFD simulation techniques are applied, and heat transfer phenomena are assumed to only occur in the riser and mold cavities.

In this research method, modeling is carried out gradually while still considering experimental findings, modeled according to the actual object. Figure 1 shows the detailed explanation of the research process.

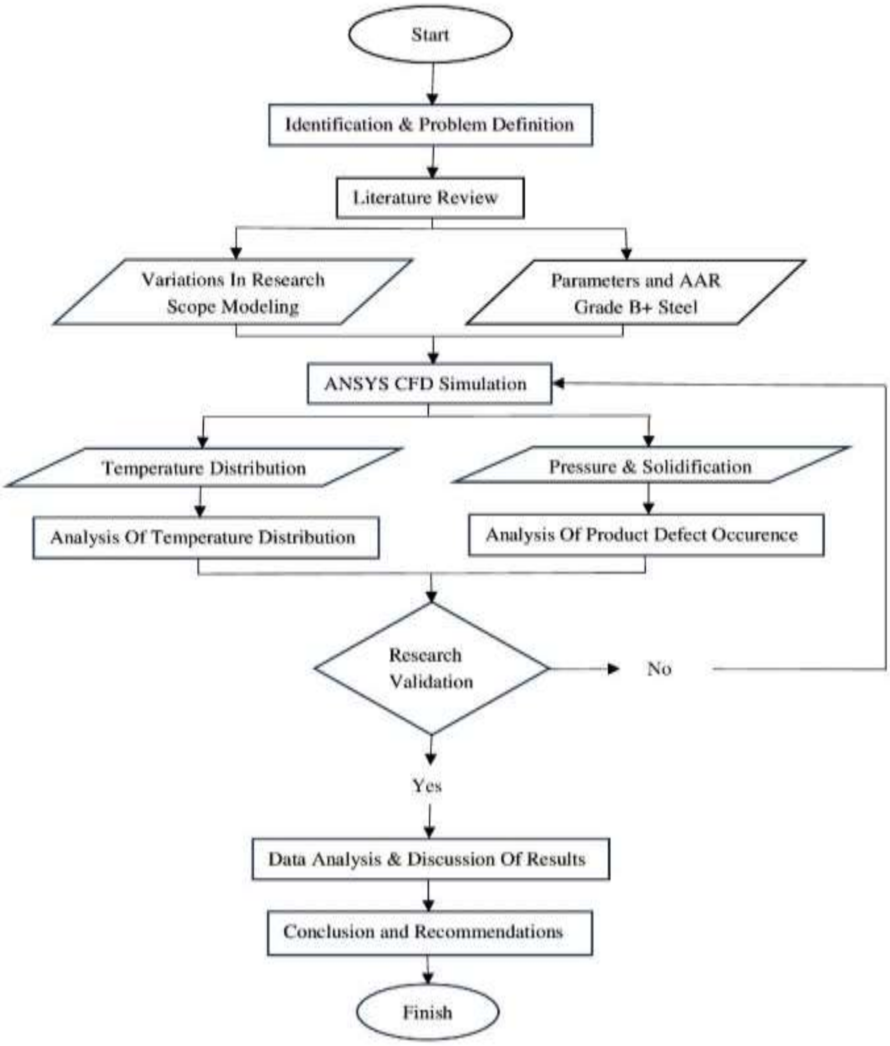


Fig. 1. Research flowchart

This research differs from conventional gating systems. This research utilizes a direct pouring gating system, which explores the temperature and pressure distribution during the casting process. And also, the solidification that occurs within it, as well as how the mold's gating system affects the casting defects that occur.

The simulation in this research is conducted in stages: Pre-Processing, Processing Stage, and Post-Processing.

2.1 Pre-processing Stage

The pre-processing stage consists of several sub-stages. Firstly, the creation of geometries using Geometry in SpaceClaim in ANSYS Mechanical Workbench 2022 R2. Secondly, meshing using ANSYS Mechanical Workbench 2022 R2. Thirdly, determination of the fluid and parameters used.

The function of Geometry in SpaceClaim in ANSYS is used for geometry creation. In this research, a 2D design is used to simplify the design to a scale of 1:10 of the original size, making it easier to conduct simulations.

Figure 2 represents the geometry used in this research. Using a 2D geometry, namely a bolster with the direct pouring gating system method through a riser that has 1 inlet and 3 outlets.

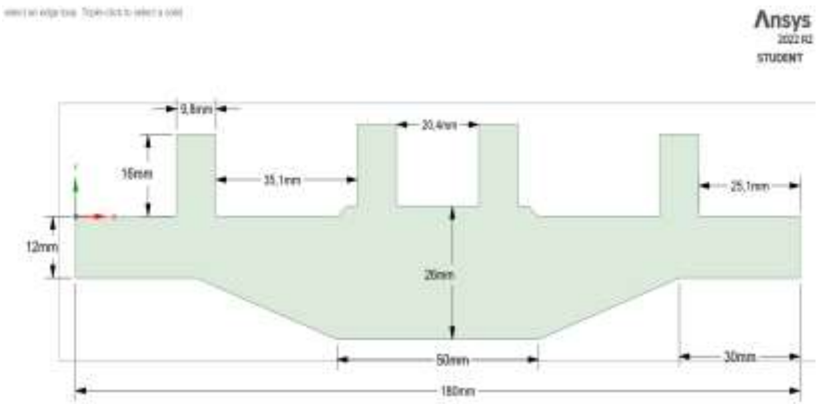


Fig. 2. 2D bolster geometry

In meshing, there are several types of meshes available for use in simulations, namely: triangle, quadrilateral, multizone Quad/Tri. In this research, a triangle mesh type with an element size of 5e-004 m is used. The accuracy and results of CFD analysis are influenced by the mesh size around the objects. A smaller or finer mesh provides more accurate results but requires greater processing power (Figure 3).

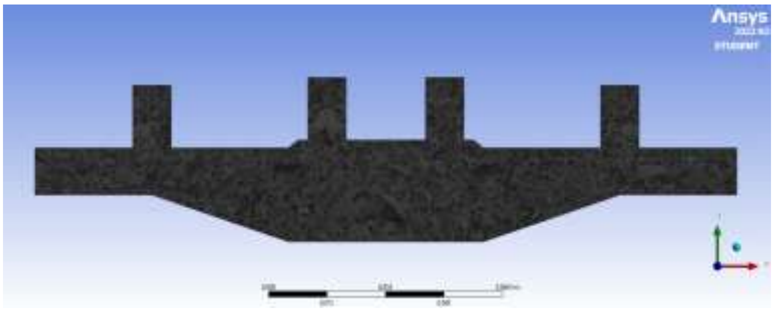


Fig. 3. Meshing of bolster

2.2 Processing Stage

Setting the general parameters, starting with a pressure-based solver type with steady time, absolute velocity formulation, and 2D space with Planar. Setting the gravity in one direction, specifically in the Y-axis direction, with a value of -9.81 m/s2.

The next stage is to determine the models. The simulation is carried out using energy and Solidification & Melting, and viscous with laminar flow.

Defining material properties is the next step. The material used is AAR Grade B+, which is a medium carbon steel that meets the specifications of the American Association of Railroads (AAR) for railway components. The detailed properties of AAR Grade B+ include a density of 7850 kg/m^3, specific heat of 1025 J/(kg K), thermal conductivity of 55 W/(m K). The viscosity is 0.001 kg/(m s), pure solvent melting heat is 245000 J/kg, solidus temperature is 1594 K, and liquidus temperature is 1924 K.

In the simulation, the pouring temperature is 1924 K, and the silica sand mold is given a temperature of 298 K. The pouring rate is set at 0.02 m/s. The boundary conditions are established as follows:

i) The riser inlet is set as a velocity-inlet with a velocity specification method using Magnitude, Normal to Boundary.
ii) The riser outlet is set as a pressure outlet.
iii) The sand mold wall is set as a wall with a convection heat transfer coefficient of 20 W/m^2K.

In solution methods, coupled is used as pressure-velocity coupling. Momentum and energy are considered as second-order upwind, while pressure is controlled at second order.

The entire state of the calculation domain is initialized using standard initialization, with initial values of 0 in the Y-axis direction. The velocity is -0.02 m/s, and the temperature is 1838 K. Then, the calculation is run with automatic time step.

After completing those steps, the adjusted upper boundary conditions based on the initial conditions are incorporated into the modeling during experimental casting. The convection currents employed outside the mold to dissipate heat during the casting process will alter the temperature distribution. When this occurs, it is assumed that the mold cavity is free from foreign material inclusions, the mold and casting material are homogeneous, and the mold base touches the ground to prevent convection. The phenomenon of risers and mold cavities becomes the focus of observation.

2.3 Post-Processing Stages

Post-processing is the final stage of simulation, involving the presentation of results and analysis of the obtained outcomes. The results from this stage can take the form of color plots, vectors, contours, and even animations. The graph is read based on its colors, where blue indicates the lowest temperature, and red signifies the highest temperature (Figure 4).

Fig. 4. Color post-processing graph

3. Results

3.1 Data Analysis

The analysis includes heat transfer, pressure, the cooling process, the solidification process, and factors influencing defects.

In the casting process, there are varying cooling rates at different points. In general, the fastest cooling rate occurs near the walls, while the slower cooling rate occurs at the central positions.

Furthermore, when the casting solidification process occurs at different points, variations in cooling rates also occur.

Thermal conductivity, density, and specific heat capacity are some of the crucial material characteristics for this research. The ability of a material to conduct heat is known as thermal conductivity [12]. Density is a measure of the mass density of an object per unit volume [13]. Meanwhile, specific heat capacity is the amount of heat required to raise the temperature of an object [14].

In this research, steady-state simulation settings were applied. The total simulation time is 223,400 seconds or 6.5 hours, with a total of 25,000 iterations. The initial temperature of the casting is 1924K, the initial temperature of the mold is 298K, and the convection coefficient is 20W/m2K.

This research also has limitations with conditions as stated in Tables 1 and 2.

Table 1
Properties of AAR Grade B+

Density	Specific heat	Thermal conductivity	Latent heat	Solidus Temperature	Liquidus Temperature
7850 kg/m^3	1025 J/kg K	55 W/m K	245000 J/kg	1594K	1924K

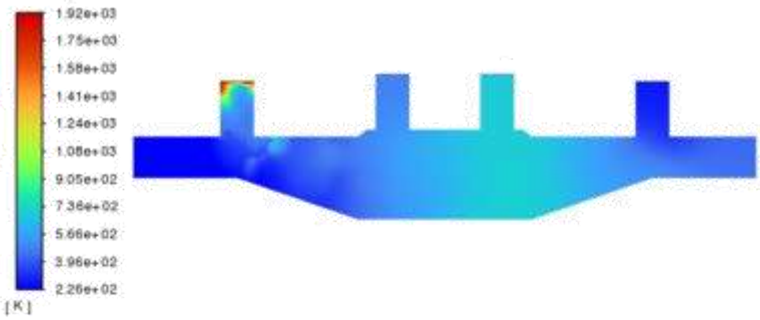
Table 2
Properties of mold

Temperature K	604	934	1264	1594	1924
Thermal Condition (W/mK)	13353.016	14412.225	18426.616	20465.614	22546.516
Specific Heat (J/kg K)	6.233	7.323	10.248	12.645	14.597

3.2 Heat Transfer Analysis

In this analysis, there are two temperature distribution phenomena occurring from the pouring stage to the cooling process of the casting.

In the temperature distribution during pouring, the initial temperature used in the casting process is 1924K for the casting object. The convection coefficient used is 20 W/m^{2}K. The simulation results of the casting show the temperature distribution process, as depicted in Figure 5.



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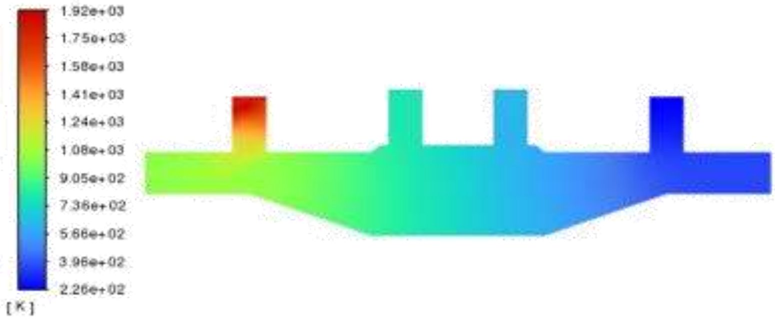
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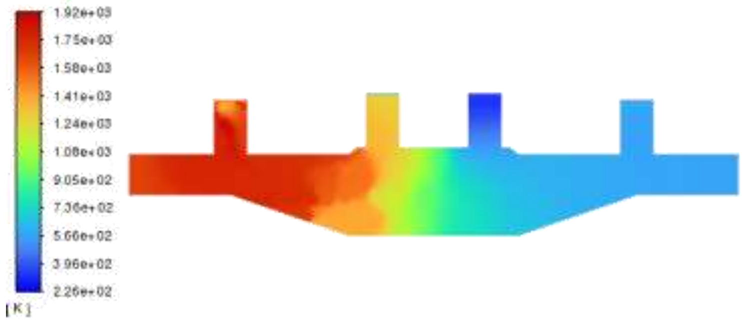
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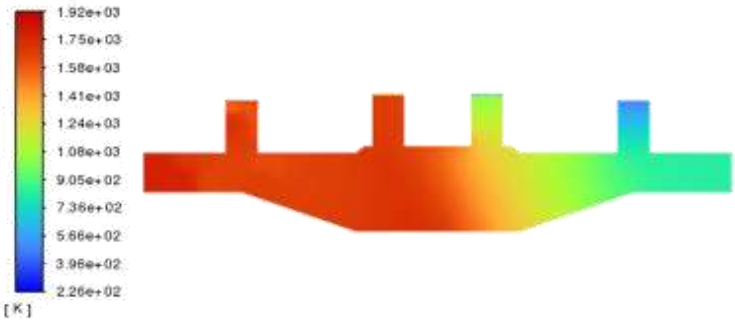
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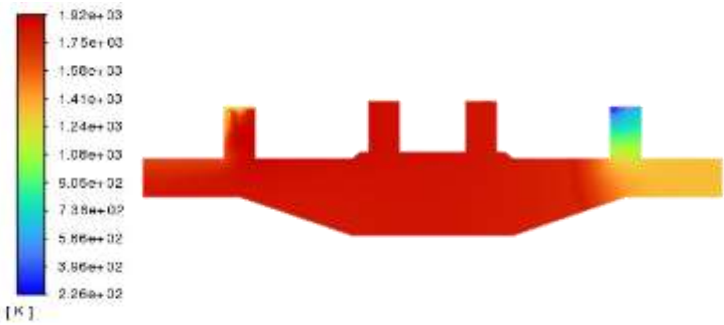
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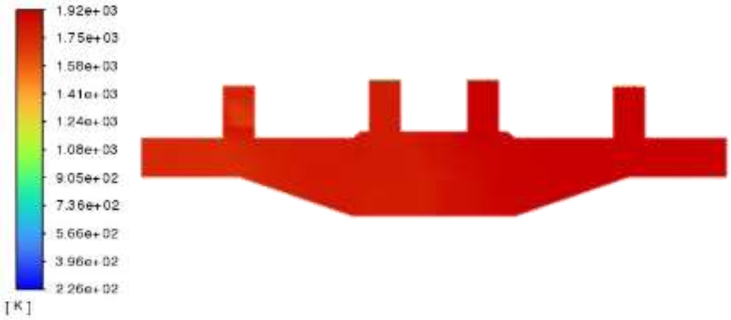


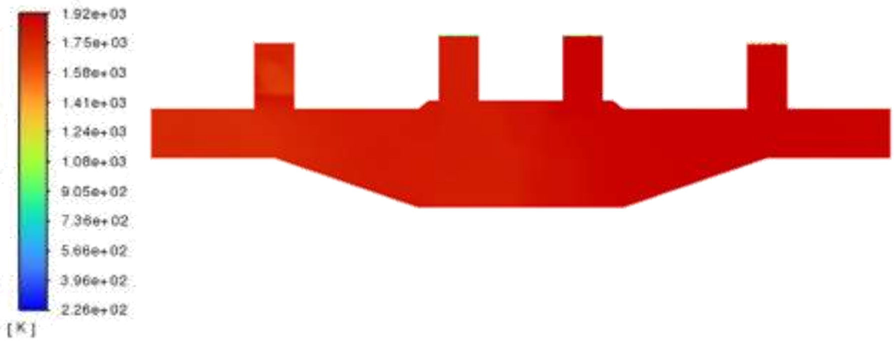
(f)

Fig. 5. Temperature distribution occurring during the pouring process at (a) 3,900 seconds, (b) 7,800 seconds, (c) 11,700 seconds, (d) 15,600 seconds, (e) 19,500 seconds, (f) 23,400 seconds

In general, during the casting process, there is a temperature distribution pattern where the highest temperature occurs at the inlet and gradually decreases towards the outlet [15]. This process occurs because the metal, considered molten at the inlet, continues to flow at the predetermined initial temperature. As heat is transferred from the metal towards the mold walls, the outlet area becomes cooler. The solubility of metals in air also depends on the temperature of the molten metal

This phenomenon is observed on the right side of the mold and casting, which has a lower temperature compared to the parts of the mold located in the center up to the left side. However, after the mold cavity is evenly filled with molten metal, temperature distribution occurs, causing the casting to become progressively cooler.

The temperature distribution during the cooling process can be seen in Figure 6.



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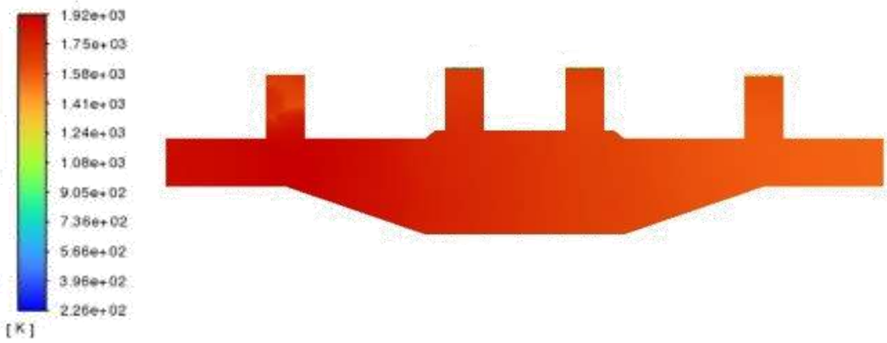

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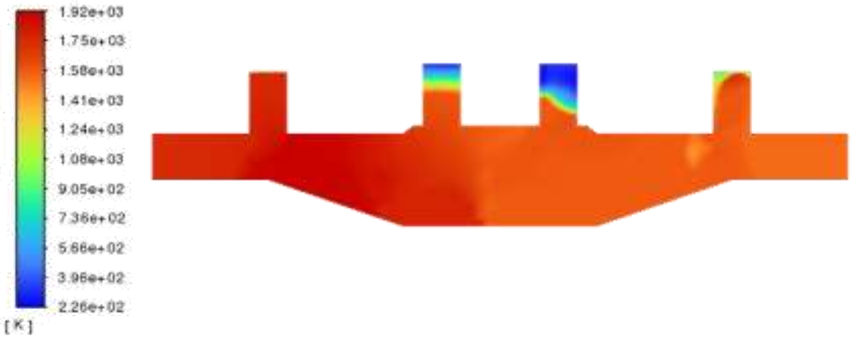

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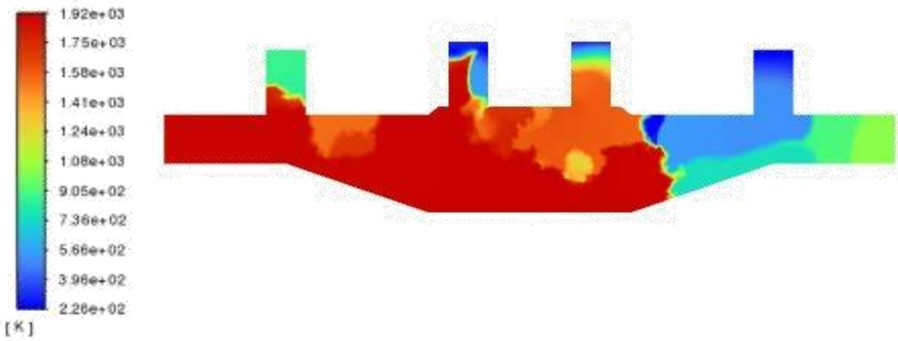

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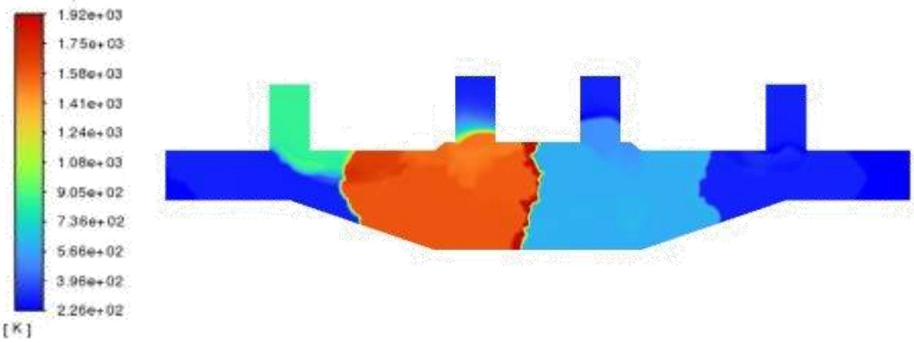

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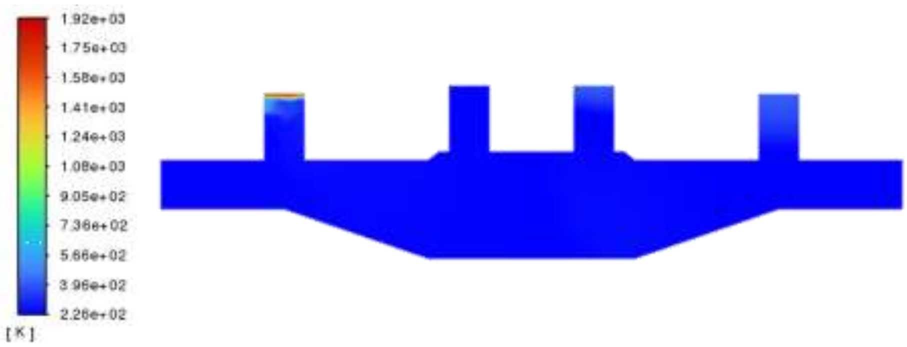

(f)

Fig. 6. Temperature distribution occurring during the cooling process at (a) 3,900 seconds, (b) 7,800 seconds, (c) 11,700 seconds, (d) 15,600 seconds, (e) 19,500 seconds, (f) 23,400 seconds

The phenomenon where the most interaction between the metal and the mold occurs is where the solidification begins in the casting process. As the mold absorbs heat from the molten metal, the portion of the metal in contact with the mold will experience cooling. If there is still additional heat from the casting, the mold will continue to experience an increase in temperature. However, when there is no longer heat absorbed from the casting, the temperature will begin to decrease. At this point, the heat inside the mold will be isolated from the surroundings, and the temperature will decrease after reaching equilibrium between the casting and the mold.

The heat inside the mold starts cooling after 7.800 seconds. The indication is that more heat is absorbed by the casting during this time period compared to the first 3.900 seconds. The casting then experiences further temperature decrease during the next 11.700 seconds of cooling.

Due to temperature distribution within the mold, the cooling process starts at 15.600 seconds. The temperature will gradually decrease across all components, including the casting and the mold, until it reaches a range between 226K to 396K within 23.400 seconds.

The edges of the casting cool more rapidly than the core due to lower convection at the outlet riser. The central part of the casting has thicker dimensions compared to the other sides. This results in the freezing of the outermost and upper parts of the casting more likely to be exposed to air or cooler temperatures outside the mold. Unlike the middle to bottom parts of the mold, which act as pathways for the casting material to spread throughout the mold cavity, the upper part or outlet riser is not directly exposed to the heat from the casting material.

3.3 Analysis of Factors Causing Product Defects

The first factor influencing product defects is pressure. Figure 7 illustrates the filling process conducted using an initial pressure of 0.0423 bar from the inlet riser.

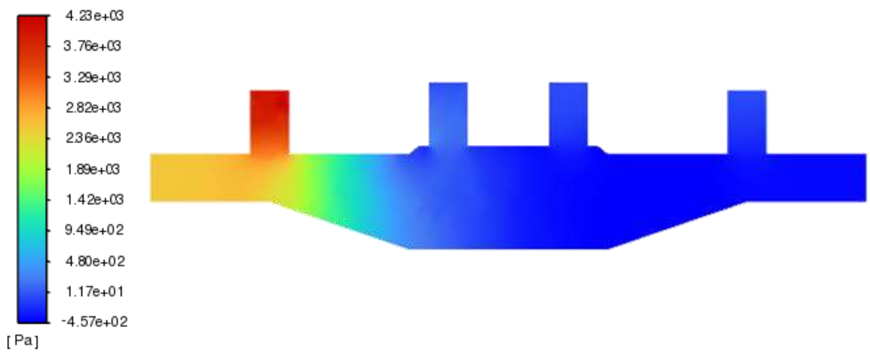

Fig. 7. Pressure during the filling of molten metal in direct pouring bolster

The molten metal is filled into the mold at a sufficiently slow speed to prevent turbulence. However, the pressure applied is not constant because the higher or further the filling of the molten metal, the more it opposes gravity. If the pressure remains constant, there is a possibility that the molten metal may not fully fill the mold or even fall out, thus requiring higher pressure. If the pressure applied is too high, the flow of molten metal may experience turbulence even though it can fill the entire mold. Therefore, it is necessary to apply linear pressure, where pressure is added as the distance traveled by the molten metal increases, measured in time (seconds).

The second factor influencing product defects is the solidification process. The solidification process depicted in Figure 8 shows differences in color, indicating areas that solidify first. At this stage, it is highly possible for defects such as holes or porosity to form because solidification occurs first in area "B". The part that should solidify first is area "C" because it is furthest from the riser inlet, has relatively thin dimensions, and is close to the mold's radii.

In Figure 8, the flow rate appears optimal because the consistent color in each part indicates temperature homogeneity. This success is attributed to well-arranged riser placement. Nevertheless, the possibility of differences in solidification time still exists. These differences can lead to the formation of pores or voids. If area "B" solidifies more quickly, area "A" may not be able to supply molten metal to the entire mold cavity during the shrinkage process. According to the law, all liquids that solidify will undergo shrinkage. Therefore, if this shrinkage is not compensated, pores or holes may occur.

The simulation results indicate defects in the bolster product, namely pores and holes. The cause is the uncontrolled solidification process, where the metal located furthest from the riser inlet tends to solidify first. Although riser outlets have been prepared at those locations to store more molten metal as reserves during shrinkage, defects still occur. The flow of molten metal must be laminar because most parts near the middle riser have thick dimensions. If the flow of molten metal is too fast, it can cause turbulence. As a result, the casting product will have fins, uneven surfaces, and the possibility of dirt particles being carried along and solidifying with the molten metal.

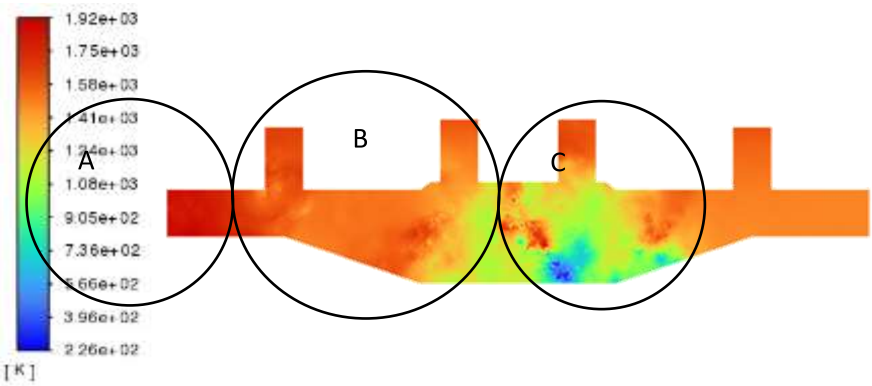

Fig. 8. Solidification process in direct pouring bolster

3.4 Prevention Solutions for Product Defects

The defects of porosity, holes, and shrinkage in casting products are caused by uneven solidification before the mold is completely filled by molten metal [16]. This condition arises due to non-convergent temperature distribution between molten metal and mold, slow pouring speed, and excessively high pouring temperature. To reduce the likelihood of defects in the product, solutions that can be applied include careful mold making, proper gating system planning, adjusting pouring temperature according to requirements, and optimizing parameters of molten metal and molds. With these steps, it is hoped that uniform temperature distribution can yield high-quality casting products without significant defects.

4. Conclusions

From this analysis, it can be concluded: 1. The temperature distribution that occurs from pouring to cooling; this pattern occurs when heat is distributed within the mold initially. The casting area in thick sections has the highest temperature, 2. The use of a direct pouring gating system is more prone to the occurrence of porosity or holes defects in the product. This is due to the direct pouring process, where the molten metal directly touches the mold, and the solidification process is difficult to control.

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