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Analysis of Sand Casting Method in Manufacturing Ship Water Jet Propulsion Impeller Based on Software Simulation

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ABSTRACT

This research aims to analyze the casting process of an impeller used in a marine water jet propulsion system using the sand casting method, assisted by ProCAST simulation software. Two gating system designs were compared: one without a riser and one with a riser, along with three pouring temperature variations (630°C, 660°C, and 680°C) to identify casting defects. Simulation results show that the design with a riser produced a total shrinkage porosity of 6.67%. The solidification time for the design without a riser was recorded at 225 seconds, while the design with a riser reached 282 seconds. The Niyama criterion for the design without a riser ranged from 3.70 to 7.40 (k.sec)^0.5/cm, while the design with a riser increased to 4.96 to 9.93 (k.sec)^0.5/cm. Among the three pouring temperature variations, 660°C provided the most optimal results. The combination of riser design and 660°C pouring temperature yielded the best casting quality.

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INTRODUCTION

Sandcasting is one of the most widely used and versatile metal casting methods in the industry, favored for its ability to produce complex components at a relatively low cost (Wahyudi et al., 2022). Its flexibility allows for the production of various industrial tools, ranging from simple consumer products like can openers to complex engine parts (Rosyidin, 2017). The foundation of this method relies heavily on an understanding of engineering materials and fundamental casting techniques (Sudjana, 2008; Samlawi & Siswanto, 2016).

However, a significant challenge persists, particularly in many industries in Indonesia, where the process often relies on conventional trial-and-error methods. This approach frequently leads to casting defects such as shrinkage porosity, misruns, and slag inclusions, resulting in increased production costs, material waste, and longer lead times (Muhammad & Putra, 2014).

The advancement of casting simulation software, presents a transformative solution to these challenges. This technology enables a virtual and accurate analysis of the mold filling, solidification, and cooling processes before any physical casting takes place. By predicting potential defects, simulation allows for the optimization of process parameters digitally, thereby minimizing the need for costly physical prototypes (Fachrie, 2015).

Previous research has demonstrated that simulation is highly effective for identifying shrinkage and casting defects in various automotive components, such as crankshafts and transmission housings (Fahrudin, 2015; Fachrie, 2015). The application of this technology is crucial for complex components like impellers, which have intricate geometries with varying thicknesses that are highly prone to defects.

In this study, the sand casting method is applied to manufacture a critical marine component: the impeller for a ship's water jet propulsion system. It is important to distinguish that an impeller is the rotating component housed within a pump that accelerates water flow for thrust, differing from a propeller which operates in open water (Arifin et al., 2019). The quality of the impeller is paramount to the efficiency and structural integrity of the propulsion system, especially in advanced applications such as Diesel Water Jet Propulsion (DWP) (Alfendry et al., 2018).

Recent studies underscore the importance of simulation-driven design. For instance, (Y. Li & H. Zhang, 2018) successfully used ProCAST to simulate and optimize the sand casting process for a pump impeller, effectively identifying and mitigating shrinkage defects. Furthermore, the design of the gating system, including the number of inlets, has been shown to significantly impact the performance of turbine impellers (Sugiarto, 2013).

The design of the gating and feeding system is a critical factor in achieving a defect-free casting. Research by (X. Chen, 2016) on a hydraulic turbine runner demonstrated that optimizing the gating system based on solidification simulation is an effective method to improve product quality.

Similar optimizations of gating systems and risers have been successfully implemented across various industrial products, including cylinder blocks, tractor wheel centers, and clamp saddles (Sidharta et al., 2022; Saputro, 2020; Laksono et al., 2022). These findings are supported by local research from (Wahyudi et al. 2022), who showed that modifying the gating system is an effective application for minimizing shrinkage defects in steel castings.

Building upon this foundation, this research focuses on a detailed analysis of the sand casting process for a ship's water jet propulsion impeller by utilizing ProCAST simulation software. The study will specifically investigate the effects of gating system design, including variations with and without a riser, and different pouring temperatures on the formation of defects.

This is consistent with previous findings which indicate that pouring temperature is a critical variable influencing porosity and the micro-structure of aluminum castings (Habibi, 2020). It is expected that this research will serve as a reliable reference for improving the quality, efficiency, and competitiveness of the casting process for high-value components within the Indonesian manufacturing industry.

METHOD

2.1 Data Collection

The design of the water jet propulsion impeller for the ship using SolidWorks software in this study is as shown in figure 1.

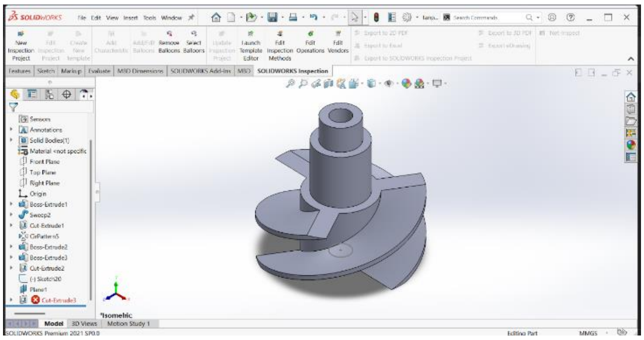


Figure 1. Impeller Design

The 3D design was created using SolidWorks software with the obtained data as follows:

- Based on SolidWorks software, the volume of the impeller is 236757.34 mm³.
- Based on SolidWorks software, the surface area of the impeller is 52862.35 mm².
- The center of mass is X = 250.00011, Y = 210.03667 and Z = 39.26433.
- The material used is aluminum-copper Al-Cu alloy lightweight, strong, seawater corrosion resistant, good castability, heat treatable for water jet impeller, alloy C355 with a density of ρ = 2.66 g/cm³.

2.2 Planning and Design

Based on these data, the values obtained from the design and modeling are as follows:

1. Total Volume Calculation

$$V_{total} = V_{impeller} + (N_s \times V_{impeller}) \quad ..(1)$$

$$= 236757.34 + (4.5\% \times 236757.34)$$

$$= 247411.42 \ mm^3$$

Given: $N_s = Shrinkage$ Value = 3.9%

2. Weight of the Casting (W)

$$W = \rho * V \ldots\ldots\ldots\ldots\ldots(2)$$

$$= 2.66 * 247.41$$

$$= 658.11 \ gr$$

$$= 0.66 \ kg$$

3. Pouring time (t)

$$t = 1.25 * \sqrt{2 * W} \ldots\ldots\ldots\ldots(3)$$

$$= 1.25 * \sqrt{2 * 0.66}$$

$$= 1.44 \ sec$$

4. *Effective Sprue Height* (ESH)

$$ESH = h - \frac{(p)^2}{2 \, .c} \ldots\ldots\ldots\ldots(4)$$

$$= 13 \ cm - \frac{(5)^2}{2 * 11.2}$$

$$= 12 \ cm$$

$$= 120 \ mm$$

5. Choke area (AB)

$$AB = \frac{W}{\rho * t * c\sqrt{2 * g * ESH}} \ldots\ldots\ldots\ldots(5)$$

$$= \frac{658.11}{2.7 * 2 * 0.47 \sqrt{2} * 9.8 * 12}$$

$$= 16.9 \ cm^2$$

$$= 1690 \ mm^2$$

6. Bottom Diameter of the Sprue:

$$AB = {}^{1}/_{4} \, . \pi \, . d^2 \ldots\ldots\ldots\ldots(6)$$

$$= \sqrt{\frac{4 * AB}{\pi}}$$

$$= \sqrt{\frac{4 * 16.9}{3.14}}$$

$= 4.6\ cm$
$= 46\ mm$

7. Calculating the Top Surface Area of the Sprue (AT):

$$A_r = A_B.* \sqrt{\frac{H}{b}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots(7)$$
$$= 16.9 * \sqrt{\frac{12}{2}}$$
$$= 41.3\ cm^2$$
$$= 4130\ mm^2$$

8. Top Diameter:

$$d = \sqrt{\frac{4\,.41{,}3}{\pi}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots(8)$$
$$= \sqrt{\frac{4\,.\,41{,}3}{3{,}14}}$$
$$= 7.2\ cm$$
$$= 72\ mm$$

9. Calculating the Runner Area

$$Runner\ Area = 4 \times AB \ldots\ldots\ldots\ldots(9)$$
$$= 4\ \times 16.9$$
$$= 67.6\ cm^2$$
$$= 6760\ \ mm^2$$

10. Calculating the Runner Width (Ar)

$$Ar = \frac{Runner\ area}{Workpiece\ Height} \ldots\ldots\ldots\ldots(10)$$
$$= \frac{67.6}{11.2}$$
$$= 6\ cm$$
$$= 60\ mm$$

11. Runner length are obtained:

$$Runner\ Length = \sqrt{A_r} \ldots\ldots\ldots\ldots(11)$$
$$= \sqrt{6}$$
$$= 2\ cm$$
$$= 20\ mm$$

12. Riser

The riser can be determined using the following equation:

$$M_c\ = \frac{V}{A} \ldots\ldots\ldots\ldots\ldots\ldots\ldots(12)$$
$$= \frac{236757.34}{52862.35}$$
$$= 4.47 cm$$
$$= 44.7 mm$$

13. Riser Volume Calculation

The riser volume is 1.2 times the casting volume to ensure proper filling and prevent shrinkage, as follows:

$$Volume\ riser = 1.2\ \times\ 236.7 \ldots\ldots(13)$$
$$= 284.04\ cm^3$$
$$= 284000\ mm^3$$

14. Diameter Calculation

$$V = 4\pi r^3 \ldots\ldots\ldots\ldots\ldots\ldots\ldots(14)$$
$$r = (\frac{V}{4 * \pi})^{\frac{1}{3}}$$
$$= (\frac{284000}{4 * 3.14})^{\frac{1}{3}}$$
$$= 28\ mm$$

Description of Calculation Parameters

In the calculation process, several parameters are used, including:

- AB : Choke area (cm²), the smallest cross-sectional area that controls the metal flow rate.
- H : Effective sprue height (cm), the vertical distance between the pouring basin and the choke point.
- V : Volume of the riser (cm³).
- r : Radius of the riser (cm).

These parameters are used to determine the gating and riser design dimensions according to standard sand casting equations. This research utilized a simulation-based experimental method. The impeller model was designed using SolidWorks and then imported into ProCAST in IGS format for casting simulation analysis shown at figure 2.

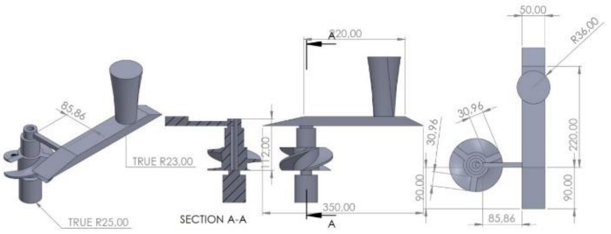


Figure 2. Design 3D Casting

Two distinct gating system designs were developed and tested:

Design 1: Gating System without a Riser

The initial gating system was designed based on established foundry engineering principles to ensure proper metal flow and minimize defects like turbulence and air entrainment. The dimensions for the sprue, runner, and ingates were determined according to the guidelines from the (ASM Handbook Vol. 15, 2008) and (Campbell, 2015). These references provide standardized calculations for gating ratios (the cross-sectional area relationship between sprue, runner, and gates) and channel dimensions that are adjusted based on the metal type (in this case, aluminum alloy) and the estimated casting volume. This approach ensures a pressurized and controlled fill, which is critical for reducing oxide formation. The specific tapered sprue design was implemented to maintain a choke at the base and prevent aspiration, as strongly recommended by both sources. Design 1 shown at figure 3.

Design 2: Gating System with a Riser

The second design incorporated a top riser to address shrinkage porosity in the impeller's hub, which is a critical thick section. The riser's dimensions (diameter and height) were not arbitrary but were calculated based on the geometric modulus method (also known as the Chvorinov's Rule-based method). This method, detailed in foundational texts like (Campbell, 2015) and applied in recent research such as dictates that the riser must have a larger modulus (Volume/Surface Area ratio) and solidify later than the casting section it is intended to feed. The initial riser dimensions were calculated using this modulus approach and then simulated in ProCAST. The design was further refined and verified against simulation data and design references from similar studies on marine components, including for feeding thick sections.

Each of the two gating designs was simulated at three different pouring temperatures for the aluminum alloy: 630°C, 660°C and 690°C. This temperature range was selected to analyze the interaction between feeding efficiency (handled by the riser) and thermal conditions, as the fluidity and solidification profile are highly temperature-dependent.

Although this study focuses on simulation-based validation, further experimental trials with dimensional variations are recommended to confirm the accuracy of the simulation results and optimize the designs for real-world production. Design 2 shown at figure 4.

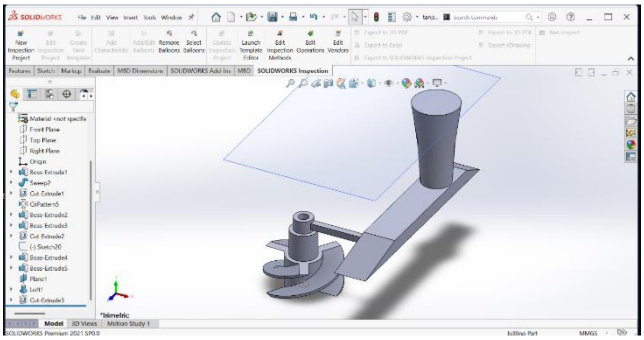


Figure 2. Design 1 Solidworks Software

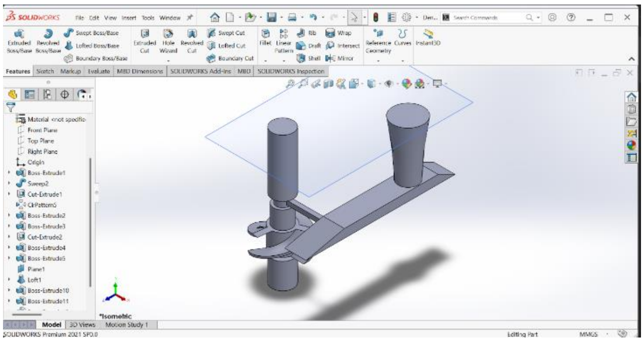
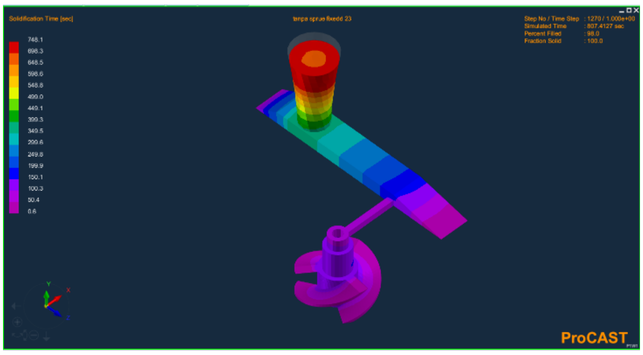


Figure 3. Design 2 Solidworks Software

RESULTS AND DISCUSSION

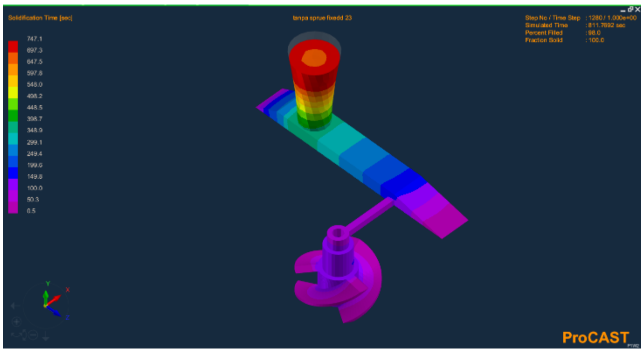
3.1 Simulation Design 1

The initial pouring temperature of 630°C in this study was established as the baseline, representing the lower practical limit for the Al-Cu alloy, just above its liquidus temperature, to define a reference point for "under-heated" conditions. The subsequent temperatures of 660°C and 680°C were selected in 20-30°C increments to systematically analyze the progressive effect of increased superheat on fluidity, mold filling and defect formation. This specific temperature range and variation were determined through preliminary trials and iterative simulation-based design rather than being derived from a single existing reference, following common best practices in casting process optimization where multiple levels are selected to capture the influence of the parameter on casting quality.



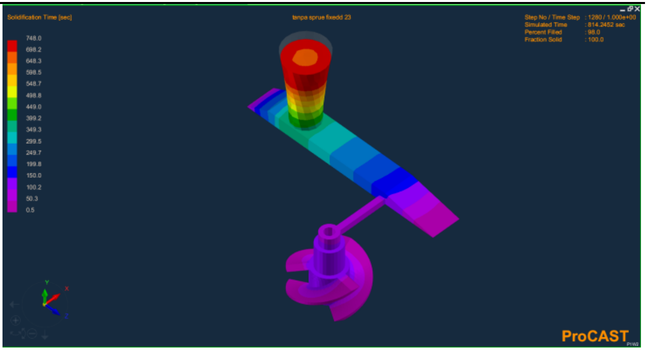
Step No / Time Step : 1270 / 1.000e+00
Simulated Time : 807.4127 sec
Percent Filled : 98.0
Fraction Solid : 100.0

Figure 4. Solidification Time Design 1 Temperature 630°C



Step No / Time Step : 1280 / 1.000e+00
Simulated Time : 811.7692 sec
Percent Filled : 98.0
Fraction Solid : 100.0

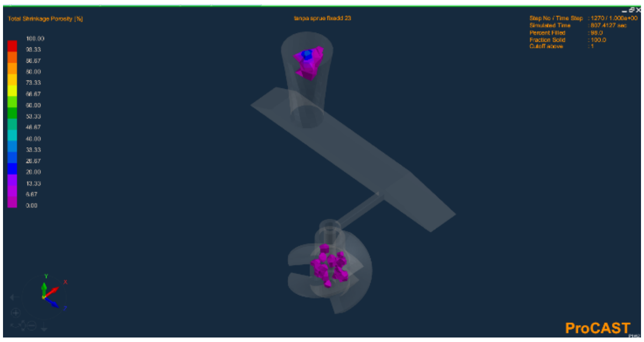
Figure 5. Solidification Time Design 1 Temperature 660°C



Step No / Time Step : 1280 / 1.000e+00
Simulated Time : 814.2452 sec
Percent Filled : 98.0
Fraction Solid : 100.0

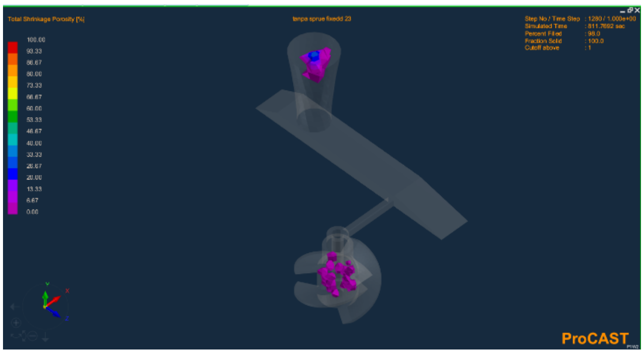
Figure 6. Solidification Time Design 1 Temperature 680°C

Shrinkage porosity is a casting defect caused by the reduction in metal volume during solidification due to insufficient molten metal supply. Simulation results for the impeller shown at figure 8, 9 and 10, show a shrinkage porosity value of 6.67% at pouring temperatures of 630°C, 660°C and 680°C. Although higher temperatures improve mold filling, the absence of a riser causes direct shrinkage in the impeller area, potentially reducing the mechanical strength of the casting. This condition contrasts with the findings of (Margono and Yusuf, 2017), where shrinkage was concentrated in the sprue and riser, thus not affecting the product quality.



Step No / Time Step : 1270 / 1.000e+00
Simulated Time : 807.4127 sec
Percent Filled : 98.0
Fraction Solid : 100.0
Cutoff above : 1

Figure 7. Shrinkage Porosity Design 1 Temperature 630°C



Step No / Time Step : 1280 / 1.000e+00
Simulated Time : 811.7692 sec
Percent Filled : 98.0
Fraction Solid : 100.0
Cutoff above : 1

Figure 8. Shrinkage Porosity Design 1 Temperature 660°C

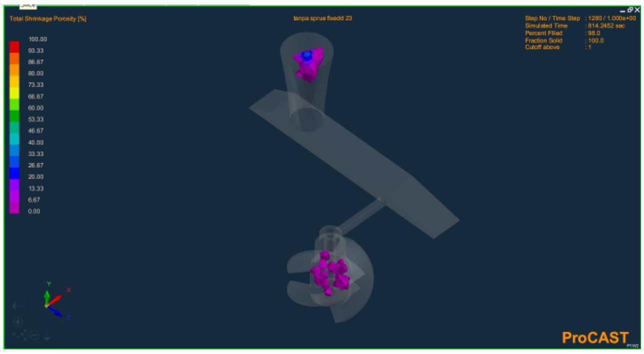


Figure 9. Shrinkage Porosity Design 1 Temperature 680°C

The Niyama Criterion is an important parameter for predicting porosity during solidification, obtained from the ratio of thermal gradient to cooling rate to identify areas prone to micro- or microporosity. Simulation results for design 1 show Niyama values shown at figure 11, 12 and 13, indicated that of 3.87–7.74 (k·s)^0.5/cm at 630°C, 3.82–7.63 (k·s)^0.5/cm at 660°C, and 3.42–6.83 (k·s)^0.5/cm at 680°C.

These relatively low values indicate regions on the impeller susceptible to microporosity due to unstable thermal gradients and high cooling rates, especially in the absence of a riser. Although higher pouring temperatures improve molten metal flow and extend solidification time, critical areas still show low Niyama values, increasing the risk of casting defects. This contrasts with (Vishwas Mehta, 2020), who stated that higher Niyama values correspond to better solidification quality and lower porosity risk.

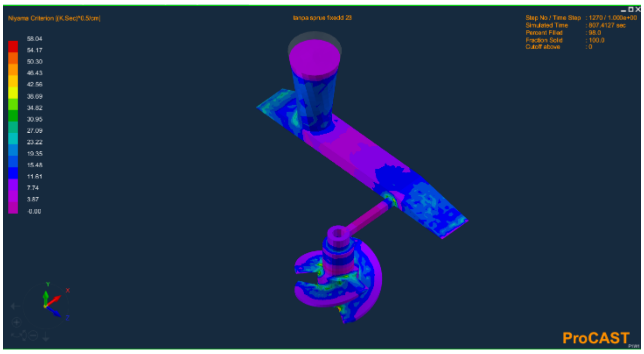


Figure 10. Niyama Criterion Design 1 Temperature 630°C

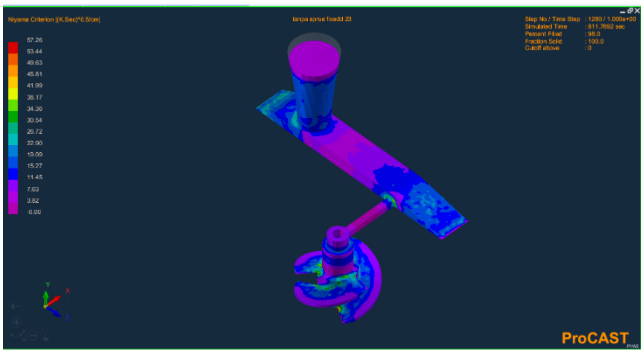


Figure 11. Niyama Criterion Design 1 Temperature 660°C

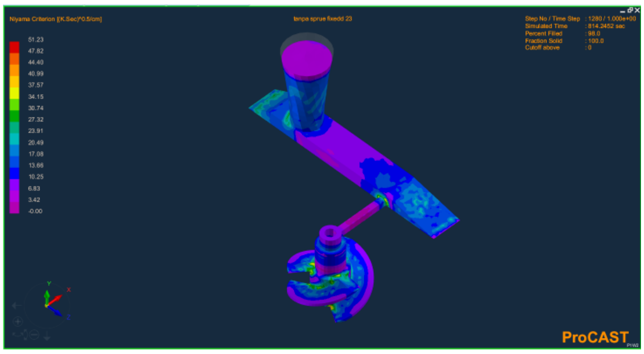


Figure 12. Niyama Criterion Design 1 Temperature 680°C

The Temperature at Fill Time simulation shows that at 630°C shown at figure 14, molten metal begins to lose heat before reaching the end of the mold, indicating early cooling and potential flow interruption. At 660°C shown at figure 15, the metal can still fill the mold, but temperature variations suggest localized early cooling, posing a risk of incomplete filling.

At 680°C shown at figure 16, the metal maintains a relatively high temperature during filling, ensuring smoother flow and more uniform mold filling. However, despite improved flow, shrinkage defects remain. These findings align with (Campbell, 2015), who emphasized that filling temperature critically influences metal flow, porosity formation, and final casting quality, where excessively low temperatures can halt flow and cause internal defects.

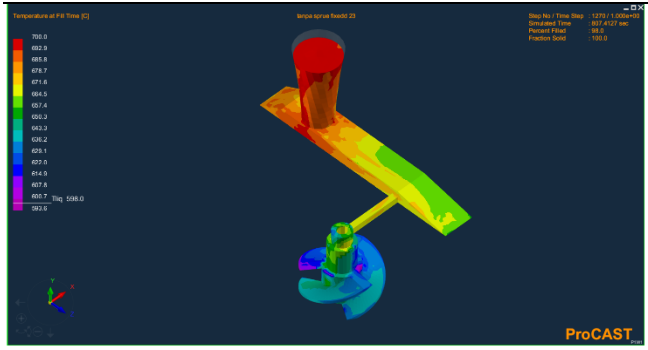


Figure 13. Temperature at Fill Time Design 1 Temperature 630°C

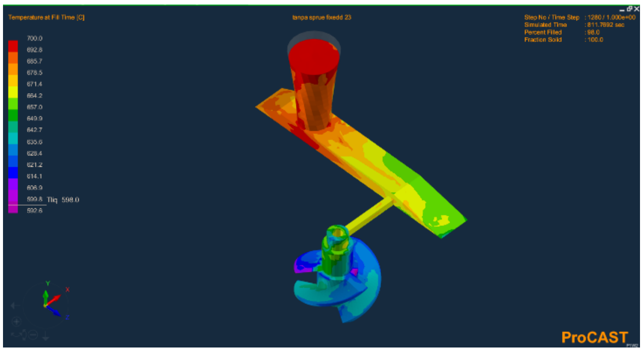


Figure 14. Temperature at Fill Time Design 1 Temperature 660°C

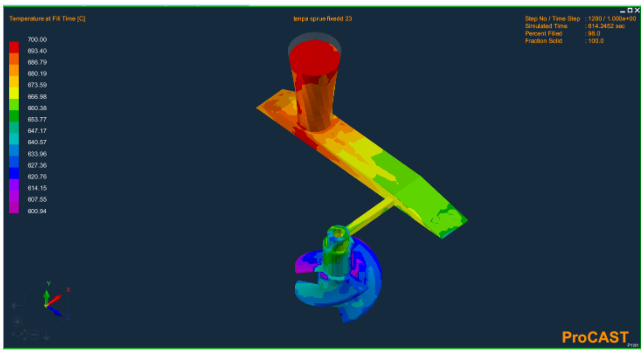


Figure 15. Temperature at Fill Time Design 1 Temperature 680°C

3.2 Simulation Design 2

The Solidification Time simulation for design 2 shown at for 630°C shown at figure 17, the impeller solidifies faster, while the riser solidifies last, consistent with (Parth Lakum, 2016), who stated that components with a higher volume-to-surface area ratio, such as risers, require longer solidification time. At 660°C shown at figure 18, the solidification pattern remains ideal, with the riser solidifying last, ensuring a gradual and controlled solidification process. This allows continuous metal feeding, reducing the risk of premature solidification in critical areas such as the ingate. At 680°C shown at figure 19, although the riser still solidifies last, the overall solidification becomes less stable, with uneven solidification observed in parts of the impeller. This instability, likely due to extended metal flow time, increases the risk of internal defects compared to the more controlled solidification at 660°C.

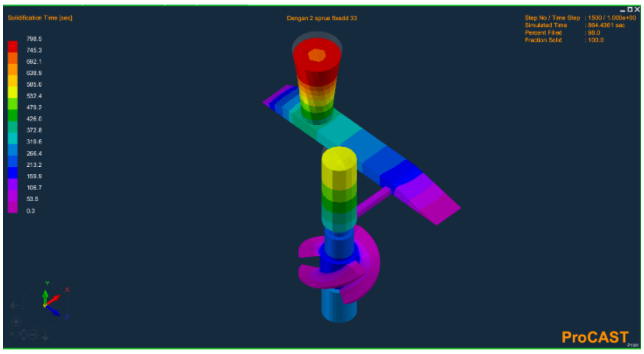


Figure 16. Solidification Time Design 2 Temperature 630°C

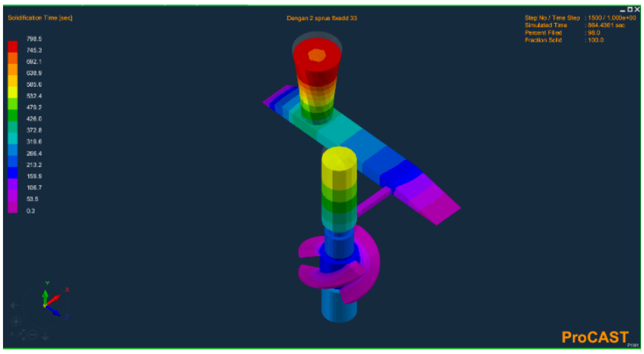


Figure 17. Solidification Time Design 2 Temperature 660°C

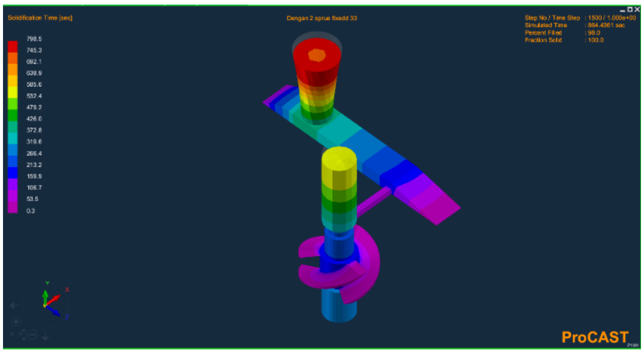


Figure 18. Solidification Time Design 2 Temperature 680°C

The shrinkage porosity simulation for design

2 shown at figure 20, 21 and 22, with a riser shows a porosity value of 6.67% at 630°C, with shrinkage concentrated in the sprue and riser, consistent with (Margono and Yusuf, 2017), who reported that shrinkage in these areas does not affect product quality. At 660°C, the shrinkage pattern remains similar, with porosity still localized in the sprue and riser, indicating the riser effectively accommodates volume shrinkage and maintains impeller quality. However, at 680°C, shrinkage distribution begins to shift closer to the impeller, likely due to prolonged metal flow and uneven cooling, which may reduce riser efficiency. Thus, 660°C is considered the most effective pouring temperature for controlling shrinkage within non-critical areas and ensuring better casting quality.

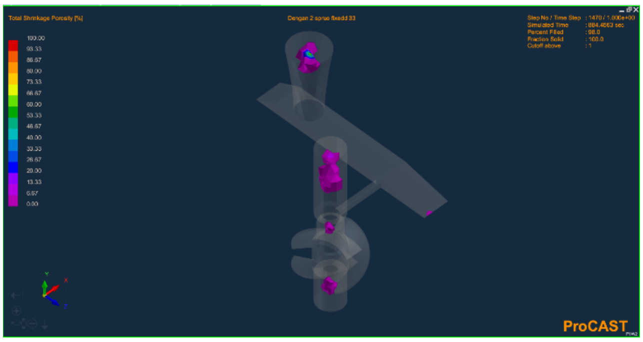


Figure 19. Shrinkage Porosity Design 2 Temperature 630°C

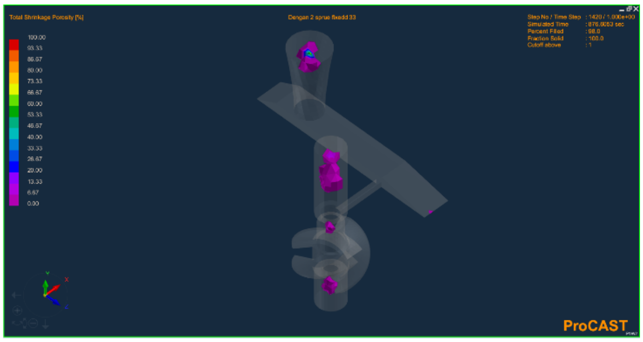


Figure 20. Shrinkage Porosity Design 2 Temperature 660°C

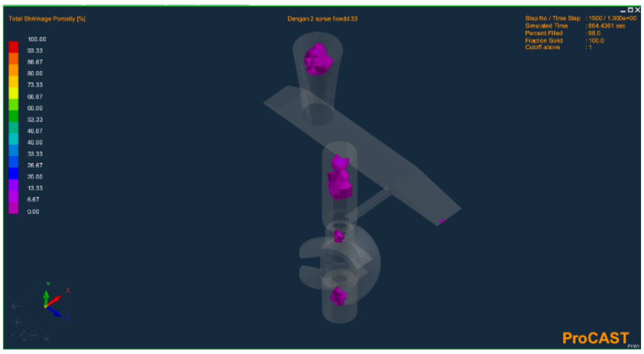


Figure 21. Shrinkage Porosity Design 2 Temperature 680°C

The Niyama Criterion simulation for design 2 shown at figure 23, 24 and 25 shows values of 4.18–8.35 (k·s)^0.5/cm at 630°C, indicating a relatively safe solidification with low porosity risk, consistent with Vishwas Mehta (2020), who stated that higher Niyama values indicate better solidification quality. At 660°C, the Niyama value increases to 5.42–10.84 (k·s)^0.5/cm, reflecting more stable solidification and lower microporosity risk, making this temperature optimal for maintaining casting quality. At 680°C, the value slightly decreases to 5.30–10.60 (k·s)^0.5/cm, with less uniform distribution, suggesting reduced solidification stability due to longer filling time and uneven heat distribution. Thus, while still within acceptable limits, 660°C provides the most stable solidification and lowest porosity risk among the tested temperatures.

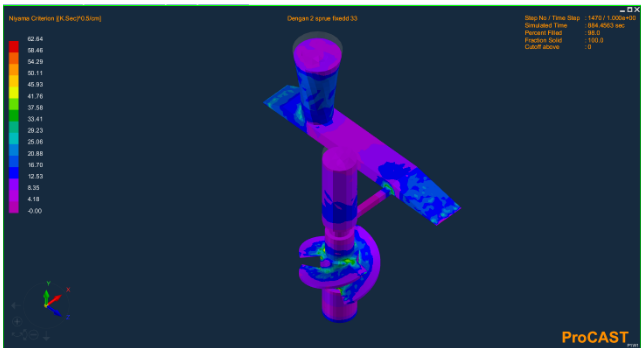


Figure 22. Niyama Criterion Design 2 Temperature 630°C

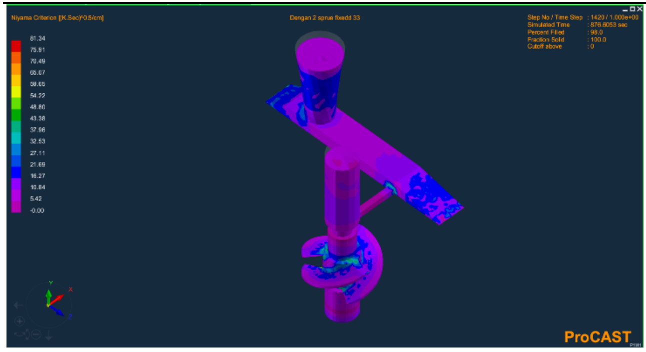


Figure 23. Niyama Criterion Design 2 Temperature 660°C

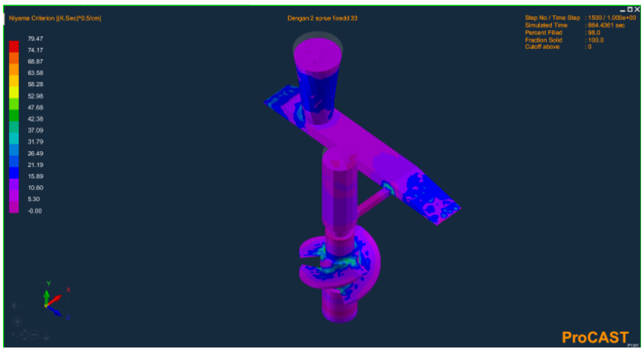


Figure 24. Niyama Criterion Design 2 Temperature 680°C

The Temperature at Fill Time simulation for design 2 shown at figure 26, 27 and 28 shows improved performance at 630°C, where the riser helps stabilize molten metal flow despite the relatively low pouring temperature. At 660°C, filling performance is optimal, with uniform flow and sufficient temperature maintained throughout the mold. The riser effectively stabilizes pressure and temperature, minimizing porosity risk, consistent with Campbell (2015), who emphasized the critical role of filling temperature in flow behavior, porosity formation, and final casting quality. At 680°C, although the molten metal fills the mold faster, delayed solidification and uneven cooling increase the risk of microporosity and structural instability. Thus, 660°C provides the best balance between filling efficiency and structural quality compared to other temperatures.

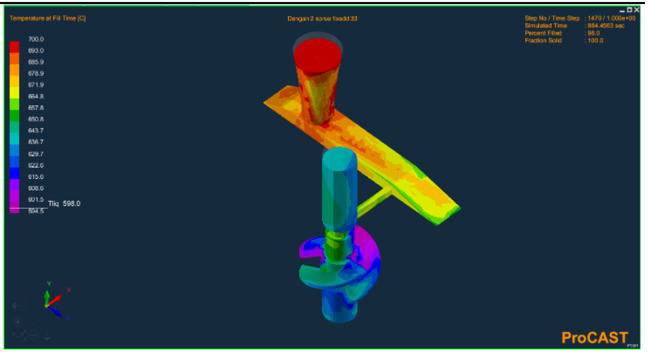


Figure 25. Temperature at Fill Time Design 2 Temperature 630°C

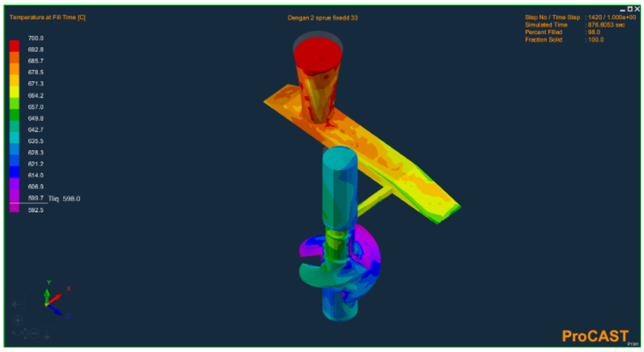


Figure 26. Temperature at Fill Time Design 2 Temperature 660°C

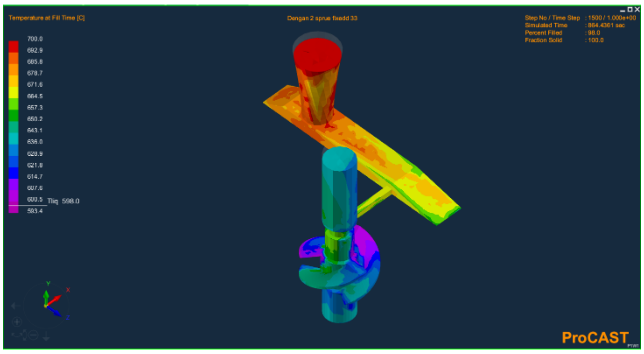


Figure 27. Temperature at Fill Time Design 2 Temperature 680°C

Based on the simulation results, the use of a riser in Design 2 proved more effective in reducing shrinkage porosity, consistent with the (ASM Handbook, Vol. 15), which states that risers compensate for solidification shrinkage by supplying additional molten metal. Increasing the pouring temperature to 680°C does not necessarily improve results; although higher temperatures enhance fluidity, they also increase the risk of gas entrapment and porosity, particularly near the riser.

The optimal pouring temperature was found to be 660°C, which balances metal fluidity and solidification stability. Thus, combining a riser design with a 660°C pouring temperature is most effective in minimizing casting defects. Table comparation for simulation results shown at table1.

Table 1. Comparison of Simulation Results

Aspect	Design 1 (Without Riser)	Design 2 (With Riser)
Design Purpose	Without molten metal reserve	Uses riser as molten metal reserve
Simulation Temperature	630 ℃ , 660 ℃ , 680℃	630 ℃ , 660 ℃ , 680℃
Shrinkage Porosity	6.67%, concentrated at the center of the impeller	*Concentrated in the sprue and riser*
Solidification Time	Average 225 seconds	Average 282 seconds
Niyama Criterion	Average 3.70-7.40 $(k.\sec)^{\wedge}0.5/cm$	Average 4.96-9.93 $(k.\sec)^{\wedge}0.5/cm$
Temperature at Fill Time	Uniform, smooth filling but unable to prevent porosity	Uniform, stable filling and not affected by the riser

CONCLUSION

Based on the simulation of the water jet propulsion impeller casting process using the sand casting method and ProCAST software, it can be concluded that the presence of a riser notably improves the solidification quality and reduces casting defects. The shrinkage porosity was found to be 6.67%, while the solidification time increased from 225 seconds without a riser to 282 seconds with a riser, reflecting better control over the solidification process.

The Niyama Criterion values also showed improvement, increasing from a range of 3.70–7.40 (k·s)^0.5/cm without a riser to 4.96–9.93 (k·s)^0.5/cm with the riser, which indicates enhanced solidification conditions. The optimal results were achieved with a pouring temperature of 660°C combined with the riser design, leading to uniform mold filling and effectively minimizing casting defects as validated by the simulation visualizations.

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