

Simulation And Analysis Of Investment Casting Process On Francis Turbine Runner

Prashil Raj Shrestha^{1, a, *)}, Smrit Dhimal^{1, b, *)}, Navin K.C^{1, c, *)},
Pratisthit Lal Shrestha^{1, d)}, Bhola Thapa^{1, e)}, Tejesh Man Shakya^{2, f)}

¹ Department of Mechanical Engineering, Kathmandu University, Dhulikhel, Kavre, Province-03, Nepal

² Foundry Foundation Nepal, Lalitpur, Province-03, Nepal

*These authors contributed equally to the work.

^{a)} Corresponding author: prashilrajshrestha@gmail.com

^{b)} Smritdhimal99@gmail.com

^{c)} Navinkc07@gmail.com

^{d)} pratisthit@ku.edu.np

^{e)} bhola@ku.edu.np

^{f)} sculpt.tejesh@gmail.com

Abstract. The investment and sand casting have always been a problematic case for complex shapes such as turbines, blades, and so on in Nepal, and due to which this has always been ineffective regarding functionality and financial aspects, because of multiple iterations of casting. The casting of turbines in a single iteration with few defects would be beneficial both in terms of cost and material use as well as the environment. Necessary expertise in this field can be gained from casting simulation. The paper is about the use of casting simulators like ProCAST with CAD software to understand the better method for investment casting. The single gating system was approached with Caine's method and Chvorinov's method in casting. Also, a section of the runner was cast at Metal Cast Pvt. Ltd, Butwal, using sand casting which was verified on ProCAST. Investment casting of 92kW and 14 kW Francis's runner turbine was simulated with minimum defects like shrinkage and porosity (under 4%) and CSF above 50%. Also, the Mass flowrate was around 2.23 kg/sec. Thus, the study deals with a better way to improve the investment casting of turbines through the help of simulation.

Keywords. Francis Turbine; Gating system Design; Investment Casting Simulation; Steel castings

INTRODUCTION

Casting deformation during solidification has made it much more difficult to perform casting. Various casting defects may occur due to temperature difference, shrinkage, flow, and so on, thus, various deviations occur in the final product as proposed according to the original design. So, simulation of the casting process has become an obligatory phase for high yield and high-performance cast components. Using these methods can lead to improved casting yield, reduced iterative trial, and error in the development of an optimized casting process. [1] Also, these tools are being used to reduce lead time, by the design engineer and the manufacturing plant, be economical, and to produce better castings. When it is economically feasible, Casting simulation should be used to predict and eliminate either internal or external defects like shrinkage, localized internal stress, air traps, porosity etc. to enhance the quality, yield optimization of the product. [2] It is used to imitate the real-life casting processes using a set of computer code or program. The program consists of a set of mathematical and thermal equations for mathematical modeling. Simulating casting phenomenon may include any of these aspects like mold filling, interface conditions, temperature distribution, solidification, shrinkage, grain structure, stresses and distortion, surface finishes, etc. Solid models of the product to be cast, gating system, temperature and flow properties of part and mold materials, and process parameters (mold

temperature, pouring temperature, pouring rate, fill limit, fill time, etc.). Then the defects can be substantially minimized by using specialized software for casting simulation. [3] However, the input parameters need extreme experience to be determined and may not be easily available to simulation engineers and may be identified by previous cases of casting. The foundry used can be minimized significantly and would be used for final testing of the simulation results.

The inputs necessary for casting simulation are:

- 3D model of the mold cavity (in this case 3D model of turbine runner with runner and gating system attached)
- Physical and thermal properties of the metal and mold material (such as melting points, boiling points, density, thermal conductivity etc.) □ Establish boundary conditions.
- Process parameters (such as pouring rate, time, fill limit, temperature, etc.). [4]

A simulation is an approximate imitation of the operation of a process or system that represents its operation over time. ProCAST was used as a simulation tool for this paper. ProCAST software is an advanced and complete casting process simulation tool that allows for easier engineering and manufacturing throughout the process. It is based on the Finite Element Method and is well equipped for predicting distortions and residual stresses. It allows modeling of Heat transfer, fluid flow, mold filling, microstructure modeling, porosity, fraction solid and stresses related to thermal expansion. [5]

THEORY

Fig. 1 shows the schematic diagram of casting which are explained below. Some terminology:

- Pattern: An approximated copy of the part to be cast is used to form cavity in the mold.
- Molding material: The materials like sands and clay are used to make molds. The pattern is pressed against the mold to create a cavity.
- Cope: Upper part of the mold.
- Drag: Lower part of the mold.
- Core: Made with fine silica, used to form the internal features of the casting.
- Core print: The part that is added to the mold which supports the core.
- Mold cavity: The holloware inside the cope and drag where molten metal is poured.
- Riser: Similar to gates which helps to compensate for the shrinkage that may occur.
- Gating system: Interconnected channels through which molten metal is delivered to the mold cavity.
- Pouring cup or pouring basin: Part where the molten metal is poured from the crucible.
- Sprue: Sprue are vertical channels that deliver molten metal to the runner. A pouring cup is attached to the top of sprue.
- Runners: Horizontal part connecting sprue to the gate.
- Gates: Entrance connecting runner to cavity.
- Gas Vents: Small channels made in the mold to release of trapped gases.
- Parting line or parting surface: The interface between the cope and drag halves of the mold.
- Core box: Dies used in the production of cores.

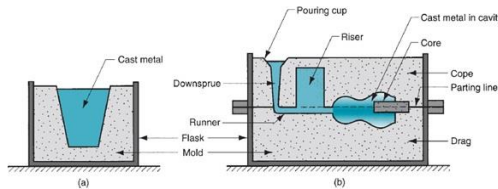


FIGURE 1. Schematic Diagram of Casting [13]

Casting Designs

Design Consideration in Castings:

- Parts having a low surface area to the volume will cool slower.

- Bulkier sections cool slower – lies more potential for hotspot resulting in void formation solidification, and large grains crystals of casted product.
- Uniform wall thicknesses should be maintained. If not possible using a progressive change in the section is suggested.
- Fillets are preferred where walls/section intersects.
- Risers should be located near heavy sections.
- To minimize wrap, avoid large, unsupported areas.

Sprue Design Consideration

Sprue:

Sprue design depends on the type and size of pattern, type of casting, type and size of pattern, and the dimension of the ring.

Sprue diameter:

It is required diameter of sprue for which the flow is adequate for obtaining minima errors in the cast.

Sprue Position:

Positioned so that it is attached to the thickest part of the mold or pattern to prevent early solidification of thinner parts.

Sprue Attachment:

As mentioned above, attached to the bulky part having large cross-sectional area for flow of molten metal from thicker to thinner parts of the mold or pattern minimizing chances of any turbulence.

Sprue direction:

Despite attaching to the bulky part there may be turbulence if the sprue is attached perpendicularly so, the sprue should be attached about 45° to the attached area.

Critical Fraction Solid

It can be described as a phase or point where the molten metal is sufficiently solid such that the molten metal can no longer flow. Critical Fraction Solid Time is the time taken for each segment to achieve the Critical Fraction Solid Point in minutes. That is why, in determining the solidification direction, and also any disconnected areas within the casting that cannot be supplied by risers. For solidification time, Critical Fraction of Solid provide a better measure. Plotting it offers a clear indicator as to whether any shrinkage that occurs could be fed by liquid feed metal within the risers or feeders. Generally, a value greater than 50% is regarded for good casting. Table 1 shows the material and their porosity at different CFS. Fig. 2 shows the shrinkage occurring at different CFS. [6]

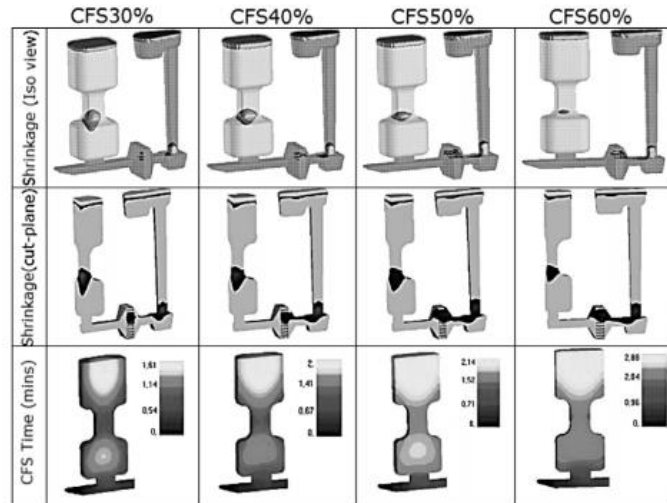


FIGURE 2. Representative results obtained with a casting simulation with four different CFS conditions [6]

TABLE 1. Comparison of measured porosity fraction of the castings with their CFS values [6]

Experimental Castings	Modeling	
	Measured Porosity (%)	CFS value (%)
As-cast	2.25	34
TiB modified	1.83	52
TiB + Sr modified	1.36	>57
Mild Steel	4.86	>50
Brass	2.73	>30%

Investment:

Investment selection mainly depends on the melting temperature of the metal and its reaction with the investment at that temperature. Once mixed, the pattern is dipped to form several layers of the liner material to obtain the required thickness and is left to set. When finished, the pattern is melted and removed.

Generally, two types of investments are used;

- Gypsum bonded with silica
- Phosphate bonded

Gypsum bonded with silica:

Gypsum has conventionally been used for casting inlays, crowns, and fixed partial dentures in gold alloy. Gypsum-based investment is constituted by quartz and α -hemihydrate. The α -hemihydrate in gypsum serves as binder and gives the investment strength. [7]

Setting time:

The investment time is usually between 5 and 25 minutes, with the modern investment time initially between 9 and 18 minutes.

Effects on setting expansion of the investment:

- Amount of silica in the investment determines its expansion.
- Expansion of investment is inversely proportional to size of the silica particles.
- Higher the water to powder ratio, lesser the hygroscopic setting expansion it will develop.
- Lesser the mixing time, lesser the hygroscopic expansion.
- Effect of the confinement offered by the casting ring.

Effects on thermal expansion of the investment:

- Amount of silica dictates the shrinkage of the investment. So, type and amount of silica should be well maintained.
- Water to powder ratio: amount of water determines thermal expansion: more water tends to lessen the thermal expansion.
- Chemical modifiers: the small amount of sodium, potassium or lithium chlorides help to prevent shrinkage.
- Thermal contraction once it starts to cool down.

Phosphate based Investment:

The use of phosphate-based investment is caused by a rise in the use of metal ceramic prosthesis, which allowed higher melting temperatures than gold alloys. Owing to temperature limits, the gypsum-based investments could not be properly casted.

Investment also consists of binders and refractory fillers, which are the same as for gypsum-based investments. In this case, however, the binder is magnesium oxide and mono-ammonium phosphate. The addition of carbon is made to the investment in the manufacture of a clean casting and in order to promote the decoupling of the mold casting. These investments in practice display signs of a small expansion that needed to be taken into account. [8]

METHODOLOGY

Study Design

This paper deals with the simulation of Francis Turbine runner using investment casting and solidification of alloy steel investment casting and suggesting a process to cast it. For the methodology of casting simulation, 3D Model and casting simulation software are used to enhance the gating system design of the casting as seen in the flowchart. First, the drawing of the part is converted into a 3D model using CAD software. The proper gating system is defined in the simulation software and simulation was then performed for defects like porosity, thermal, cold draw, rats and tail, flaking, and so on. And finally, casting simulation was performed in ProCAST. The First Simulation of 14kW turbine was carried out. The gating system was arranged as specified by the manufacturer of the turbine. This turbine was taken into consideration before proceeding to 92kW Francis Turbine as the Turbine Testing Lab (TTL) was caring out the process to manufacture this turbine by casting. Then the results were compared with the defective turbine. After verifying an appropriate gating system is proposed for 14kW Francis runner and casting simulation is carried out. The refinement was done to the gating system to optimize the casting process and the final design is proposed. With the help of the output result, we optimize the parameter required for the casting of 92kW Francis Runner.

Two gating systems designed was proposed. Option I included a bottom gating system which has the riser diameter and height of 85mm, sprue diameter of 22mm, height of 195mm, pouring basin of 55mm choke diameter of 18mm, sprue diameter of 40mm and height 45mm, in gate diameter of 18mm with pouring time varying from 18 to 20 second. Option II differs from Option I only in the orientation of the gating system and the riser height is 100mm. The defects were reduced in the cast as well as it was found to be in the gating system rather than the casted body, the optimization results were accepted as successful and the new design was finalized. This step usually takes many iterations in practice. The finalized design is then sent for manufacturing.

The following procedures were followed:

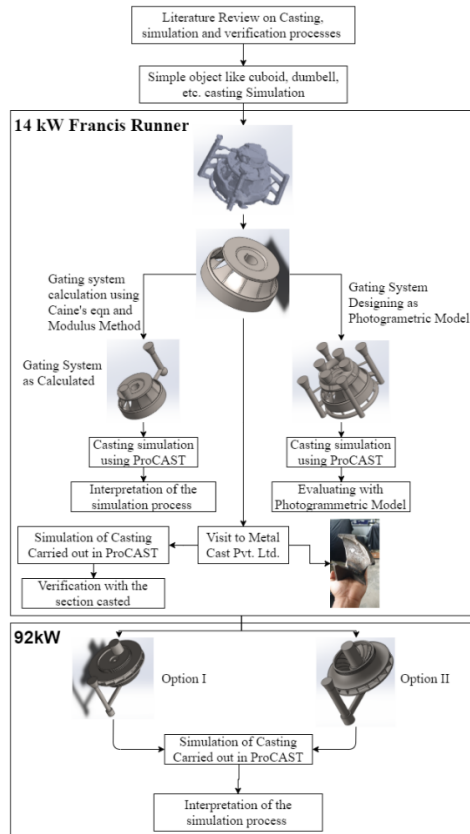


FIGURE 3. Study Design

The design objective of the Fig. 3 was followed. First, simpler object casting was done followed by components of the Francis turbine runner. The defects on the previously casted Francis turbine were studied.

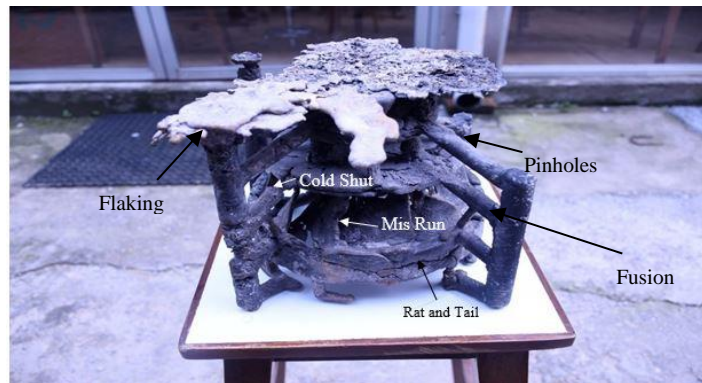


FIGURE 4. Failed Runner Casting

Computer aided modeling plays an important role for the foundry industry for the past several years. Not only with the new design components but also in the redesign of existing products. Simulation gives the observed porosity and it will give the possibility to reduce porosity by changing appropriate gating system, riser design & modification. [9] As you can see from the photogrammetric model and the Fig. 4, various errors and defects were present in the casting. Some of the major defects that are prominent in the turbine were identified as follow:

- Cold shut
- Misruns
- Slag inclusion (scab)

- Shrinkage [10]
- Flaking
- Pinholes
- Subsurface blowhole
- Fusion
- Rat tails, veins and buckles

Design and Calculations

Various methods of gating system can be followed but the system includes somewhat directional cooling, riser to compensate for shrinkage, and how molten metal can be poured in the most optimized way to prevent cold draw, porosity and shrinkage was chosen.

Specifications that influence the proper casting of the runner were considered and several preliminary design options were generated. The first specification is to remove cold draw as possible followed by porosity and shrinkage. Also, the Runner system design must minimize, the metal used in casting.

Gating System Design Equations

$$X = \frac{a}{Y - b} + c \quad 1$$

where,

$$(X) = \frac{\frac{\text{Surface area of Cast}}{\text{Volume of Cast}}}{\frac{\text{Surface area of riser}}{\text{Volume of riser}}} \quad 2$$

$$Y = \frac{\text{Volume of riser}}{\text{Volume of Cast}} \quad 3$$

a, b and c are constant.

$$A_s \times V_s = A_c \times V_c \quad 4$$

$$V_s = \sqrt{2 \times g \times h_p} \quad 5$$

where,

A_c = Choke area,

A_s = Sprue area,

V_s = Velocity at top of sprue,

V_c = Velocity at choke area,

h_p = Height of pouring basin.

$$A_c = \frac{W}{d \times t \times C \times \sqrt{2 \times g \times H}} \quad 6$$

$$V_c = \sqrt{2 \times g \times h} \quad 7$$

where,

W = Weight of the cast

d = Mass density of the metal

t = Pouring time of the molten metal

C = Efficiency factor which is a function of the gating system
 g = Acceleration due to gravity
 H = Acting metal head
 h = Height of cavity

$$A_w = 5 \times A_c \quad 8$$

$$D_w = \sqrt{A_w \times \frac{4}{\pi}} \quad 9$$

$$A_g = 1 \times A_c \quad 10$$

$$D_g = \sqrt{A_g \times \frac{4}{\pi}} \quad 11$$

$$t = K_2 \times \sqrt[3]{W} \text{ s} \quad 12$$

where,

K_2 = a constant

W = Weight of casting, Kg

These equations were used to model the gating system of Francis Turbine runner as well as the other simulations used for verification.

Validating Casting Results of 14kW Francis Runner

Casting at Butwal:

The mold was prepared using silica sand and green sand. Silica sand was used in the part surrounding the pattern and green sand was used to fill the rest of the cope and drag. The runner, riser, and gas vents were made to ensure the proper casting of the runner section.

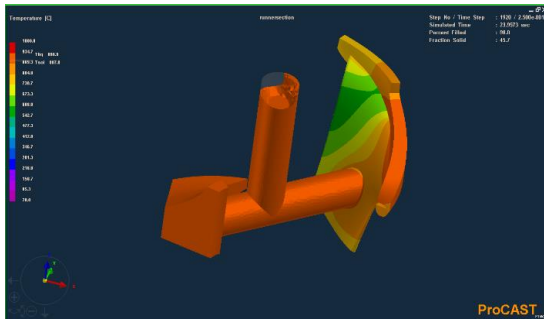
After preparing the mold, the patter was removed and the mold was baked using fire. Post baking, mold was assembled into one. Then melted mild steel was poured into the mold. The casted part was quickly retrieved and was water-cooled. After removal of the gating system, the cast was sandblasted and surface finishing was done by grinding the cast. The simple illustration is show in the Fig. 5.



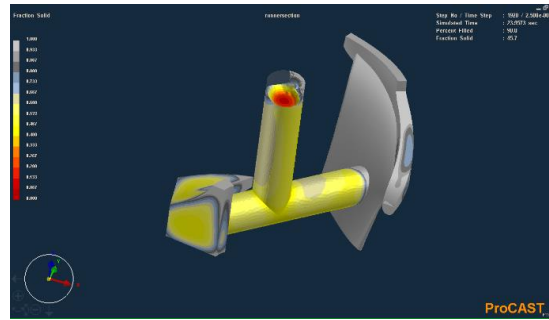
FIGURE 5. (A) Sand Casting Process at Metal Cast
FIGURE 5. (B) Finished Product (Casted Section of Francis Turbine Runner)

Simulation in ProCAST:

The solidification of casting began from the blade after the mold is nearly filled. This should be watched as blades are the thinnest section and lose heat rapidly compared to that of other parts.



(a)



(b)

FIGURE 6(A). TEMPERATURE DISTRIBUTION AND FRACTION OF SOLID OF RUNNER SECTION
FIGURE 6(B). FRACTION OF SOLID OF RUNNER SECTION

Figure 6 (a) shows the temperature distribution of the runner section. Here, the metal was still in the molten state while pouring. In Fig.6(b), the thin section of the blade solidified early as the other thicker section began solidifying. Upon discussion with experts at Metal Cast Pvt. Ltd, this section being relatively small didn't require any riser and also gas vent made by poking through the mold would act as a riser.

TABLE 2. COMPARING SIMULATION WITH THE CASTED SECTION

Parameter	Simulations	Casting at Butwal
Casting	Sand	Sand
Gating system	Top	Top
Metal	AISI 1040 Mild Steel	AISI 1040 Mild Steel
Mold	Silica Sand	Silica Sand
Metal Temperature	1560 °C	1560 °C
Baking Temperature	100 °C	100 °C cooled to Room Temperature
Interface condition	h = 400	h = 400
Radiation Enclosure	Not present	Not Present
Fill Time	2.5sec	2.5sec
Fill Limit	95%	>100%
Velocity	145.5986 mm/sec	Wasn't measured
Mass flowrate	0.493 kg/sec	Wasn't measured
Fraction Solid	84%	Wasn't measured
Mass	1.241 kgs	Around 1.2 kgs

Table 2 compares the result between the simulation that was performed using ProCAST and the casting of runner section that was done at Metal Cast Pvt. Ltd.

Gating System Design of 92kW Francis Turbine Runner

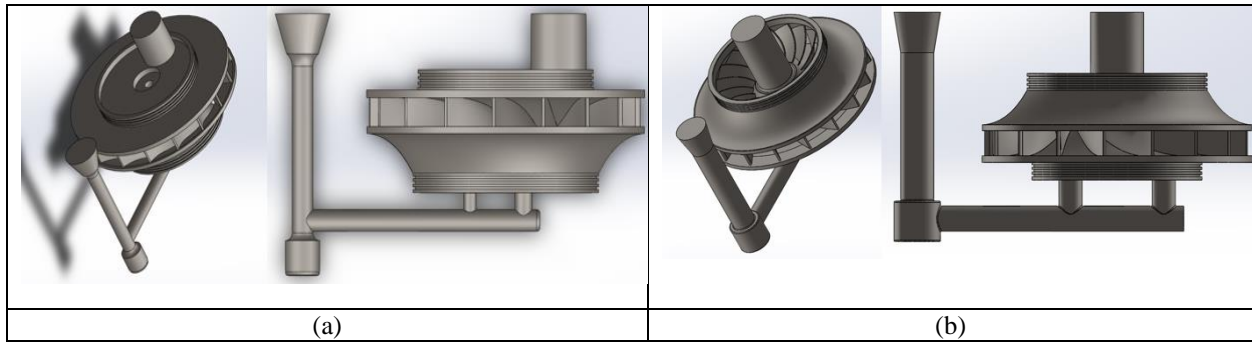


FIGURE 7(A). Isometric and Front View of Gating System and Francis Runner Option I

FIGURE 7(B). Isometric and Front View of Gating System and Francis Runner Option II

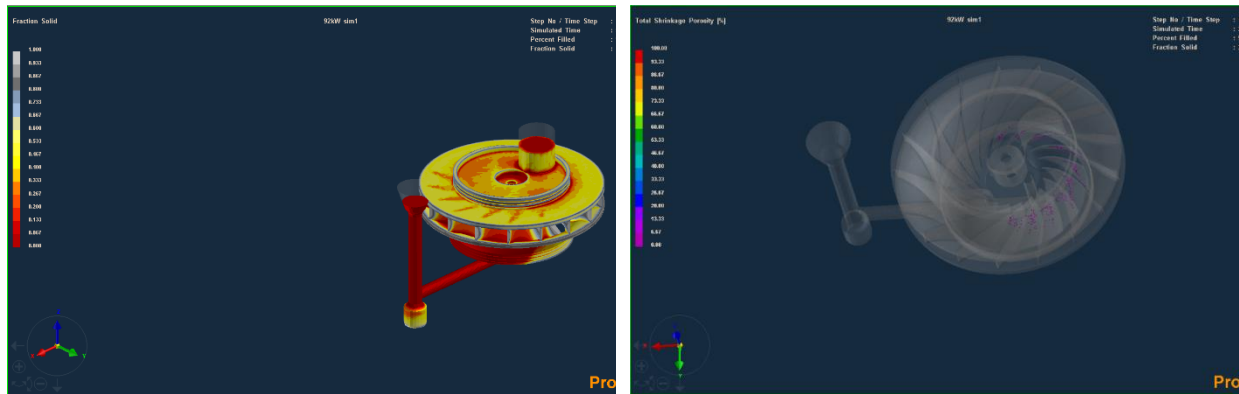
Figure 7 shows the designs of the gating system for simulation. Fig. 7 (a) represents the first design approach where the molten metal is fed through the bottom of the hub. Fig. 7 (b) represents the second design approach where the molten metal is fed through the top of the hub.

Simulations

Simulation 1:

Initial conditions for simulation:

1. A fine mesh was prepared first. A mesh of 2 in the critical reason and a mesh of 4 for the rest of the body and a mesh of 8mm for the in-gate system was prepared for this simulation.
2. A shell of 4mm was created and a similar mesh of the shell was prepared.
3. Tetra volume mesh was done.
4. The volume was computed as a finite element.
5. A 1560 °C melting point was given for metal and 1100 °C was given for the mold.
6. The interface condition was taken as IN738-Mullite which corresponds to the h value 340.
7. The velocity inlet was defined and also the pressure was taken as 1barr.
8. Adiabatic heat transfer to the surrounding was considered.
9. A filling of 95% of the total volume is done.



(a)

(b)

FIGURE 8(A). Fraction Solid of Calculated Gating System for 92kw Turbine Runner

FIGURE 8(B). Shrinkage Porosity of 92kw Francis Turbine Runner

Figure 8 (a) shows the fraction solid of the casting and Fig. 8 (b) shows the shrinkage porosity of the 92kW Francis turbine runner which is further explained on Results and Discussion

Simulation 2:

Initial conditions for simulation:

1. A fine mesh was prepared first. A mesh of 4 in the critical reason and a mesh of 6 for the rest of the body and a mesh of 8mm for the in-gate system was prepared for this simulation.
2. A shell of 4mm was created and a similar mesh of the shell was prepared.
3. A radiation enclosure was also developed around the shell to account for radiation.
4. Tetra volume mesh was done.
5. The volume was computed as a finite element.
6. A 1580 °C melting point was given for metal and 700 °C was given for the mold.
7. The interface condition was taken as IN738-Mullite which corresponds to the h value 340.
8. The velocity inlet was defined and also the pressure was taken as 1barr.
9. Adiabatic heat transfer to the surrounding was considered.
10. A filling of 98% of the total volume is done.

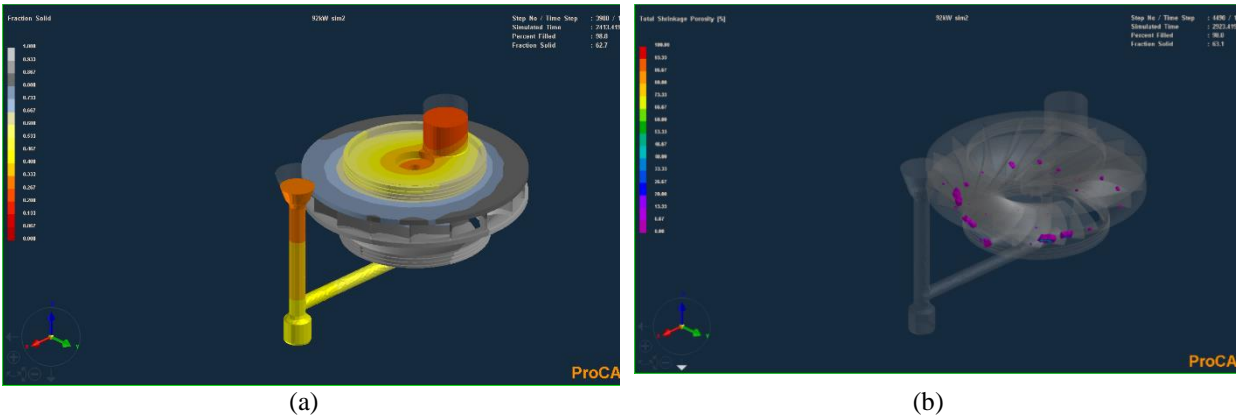


FIGURE 9(A). Fraction Solid of Calculated Gating System for 92kw Turbine Runner
FIGURE 9(B). Shrinkage Porosity of 92kw Francis Turbine Runner

Figure 9 (a) shows the fraction solid of the casting and Fig. 9 (b) shows the shrinkage porosity of the 92kW Francis turbine runner which is further explained on Results and Discussion

Simulation 3:

Initial conditions for simulation:

1. A new gating system was designed.
2. A fine mesh was prepared first. A mesh of 4 in the critical reason and a mesh of 6 for the rest of the body and a mesh of 8mm for the in-gate system was prepared for this simulation.
3. A shell of 4mm was created and a similar mesh of the shell was prepared.
4. Tetra volume mesh was done and the volume was computed as a finite element.
5. A 1580 °C melting point was given for metal and 1000 °C was given for the mold.
6. The interface condition was taken as IN738-Mullite which corresponds to the h value 340.
7. The velocity inlet was defined and also the pressure was taken as 1barr.
8. Adiabatic heat transfer to the surrounding was considered.
9. A filling of 98% of the total volume is done.

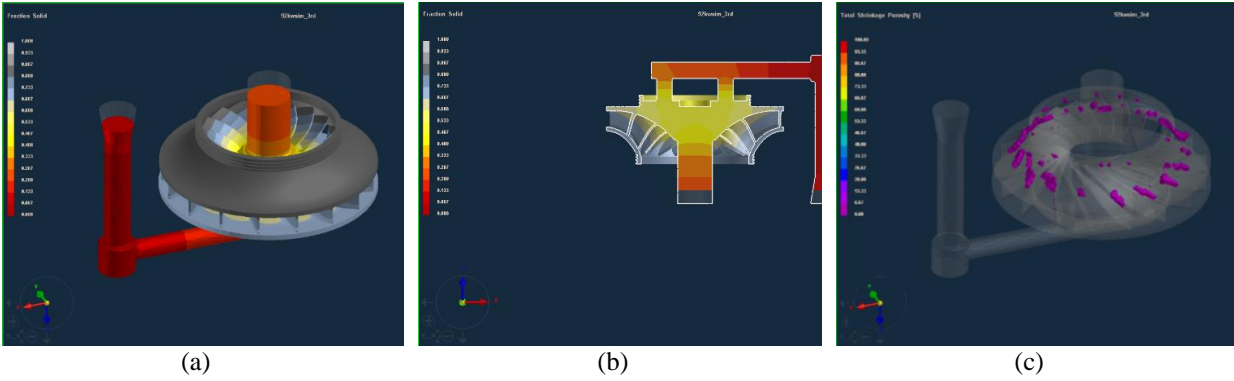


FIGURE 10(A). Fraction Solid of Calculated Gating System for 92kw Turbine Runner
FIGURE 10(B). Section of Fraction Solid of Calculated Gating System for 92kw Francis Turbine Runner
FIGURE 10(C). Shrinkage Porosity of 92kw Francis Turbine Runner

Figure 10 (a) shows the fraction solid of the casting, Fig. 10 (b) shows the section of the fraction solid, and Fig. 10 (c) shows the shrinkage porosity of the 92kW Francis turbine runner which is further explained on Results and Discussion

Analysis of Design

The turbine should have an acceptable surface finish with a tolerance for post-machining. Also, the error should be limited for efficient performance. Even a small defect or error would directly affect the performance. So, the investment casting for the turbine should be properly calculated with few chances of error. Hence, there are various conditions and parameters which affect the casting. Thus, various design challenges were thoroughly analyzed and concluded some design parameters for dimensional accuracy.

Pressurized Gating System

The gating system ratio for the modeled turbine was assumed 1.667:1:1 which provided pressure in the mold for smooth flowing of the melt in the pattern. This would in turn minimize the air aspiration effect. Also, the flow of liquid from every in the gate is almost equal, and hence casting yield is higher. However, due to high-velocity turbulence may occur at corners.

Mold

The mold for the 92-kW turbine was molochite. During the simulation, the molochite mold was baked in various temperature ranging from 700 to 1100 ° C. The main benefits that molochite offers are:

1. Consistency of the mold.
2. No reaction between mold and molten metal.
3. Binders' compatibility.
4. Tightly packed due grain having angular shape.
5. Low dust content resulting in fine surface finish.
6. Grading available in great variety.

Bottom Gating System

The bottom gating systems control the turbulence of molten metal. Less turbulence inflow into the mold cavity is best achieved when it is introduced form the bottom of the mold. In this method, the metal rises steadily through the mold, reducing the spatter of the molten metal, and dislodged molding material tends to be carried to the surface. In spite of its complexity this method is much used for heavy castings. [7]

Bottom gating systems allow the metal stream to enter the casting cavity with minimal turbulence and entrapment of air. The metal rises relatively without any turbulence through the casting cavity and the entire metal body can be

expected to be free of oxidation or other defects associated with air contact and oxygen reaction. Hence, reducing the turbulence effect caused by the pressurized gating system to a minimum.

Radiation Enclosure

The radiation enclosure was used in one of the simulations to note the change in the simulation it causes. Radiation was taken from the enclosure in all the directions and emissivity of 0.9 in the room temperature 20 ° C was taken for the simulation.

RESULTS AND CONCLUSION

Discussion and Results

Assumptions:

1. Steady-state heat conduction and convection.
2. Radiation Enclosure was included in one of the simulations only.
3. The ambience had no interaction in the enclosed mold.
4. The melt has uniform temperature until fully poured in the mold from crucible to pouring basin.
5. Adiabatic heat transfer occurs through the mold shell.

TABLE 3. Simulation Results

Parameters	Simulations		
	1	2	3
Shelling	4mm	4mm	4mm
Gating system	Bottom	Bottom	Bottom but designed changed
Metal	AISI 1040 Mild Steel	AISI 1040 Mild Steel	AISI 1040 Mild Steel
Mold	Molochite	Molochite	Molochite
Metal	1560 °C	1580 °C	1580 °C
Temperature			
Baking	1100 °C	700 °C	1000 °C
Temperature			
Interface condition	IN738-Mulite	IN738-Mulite	IN738-Mulite
Radiation Enclosure	Not present	Present	Not Present
Fill Time	20sec	15sec	20sec
Fill Limit	95%	98%	98%
Velocity	64.6990 mm/sec	129.5337 mm/sec	99.7146 mm/sec
Mass flowrate	2.23 kg/sec	2.47 kg/sec	2.62 kg/sec
Fraction Solid	56%	63.1%	51%
Mass	45.1 kg	45.08 kg	53.04 kg

From Table 3, Simulation 1 & 2 have represented a better-casted product than simulation 3. This is since simulation 3 has a slight modification on the way it is cast which results in the flow of metal from a thicker section to the thinner section than to thicker section. The later process caused some minor problems in the simulation which results in an increased in shrinkage porosity and decreased in Fraction solid (but above CFS).

Conclusion

This study has put forward an approach for the casting of 92kW Francis Turbine Runner with minimum defects. The objective of this project was to remove possible defects during casting like cold draw, shrinkage, porosity, early solidification, etc. and to propose a casting parameter for 92kW Francis Turbine Runner. The result was obtained from the casting were validated by the actual casting of a runner section at Metal Cast Pvt. Ltd, Butwal.

Casting Simulation is an effective tool that can be used to predict the growth as well as defects of the process without ever visiting the foundry. Solidification, shrinkage, porosity, miss run, flaking, rats, and tail simulation provides frequent means of redesigning or changing the gating system which in turn minimizes the economics of scale of developing the method for new casting by minimizing the time, scrap, cost as well as labor involved in it. An enormous number of preliminaries could be done rapidly on the computer and an optimal conclusion can be obtained.

A single bottom gating system was used for this study and the hub was used as the location of in-gate. With modifications like filling of shaft hole and filleting the gating system as well as making the gating system 20% of its original size, shrinkage, porosity, and flaking were avoided. The process defined by this study will be equally valid for other turbines as well as the availability of enough information.

Recommendations

Complexity increased while going with a multi-gating system in the calculation as well as in designing. Molochite, which is used as mold is very difficult to obtain so Silica-based mold was used in Metal Cast Pvt. Ltd. The main objective of the project, i.e., to propose the casting process for the fabrication of 92kw Francis turbine runner was completed. However, there was some aspects that that entail recommendations for further works on the subject.

1. Focus on Multi-gating system
2. Integration of Graphical User Interface (GUI) for gating system calculation
3. Using Exothermic Sleeves and Directional Solidification

REFERENCES

- [1] M. J. Marques, "CAE Techniques for Casting Optimization," Leça do Balio.
- [2] B. Ravi, "Selection and utilization of casting simulation system," in *Gravity Die Casting Technology*, Mumbai, 2013.
- [3] S. Sriram, "To believe or not to believe Results of casting simulation software," *ALUCAST*, pp. 62-67, 2012.
- [4] ESI Group, "ESI," ESI-Goup, [Online]. Available: <https://www.esi.com.au/software/procast/>. [Accessed 13 9 2019].
- [5] R. Kayikci, M. Çolak, S. Sirin and E. Kocaman, "Determination of the critical fraction of solid during the solidification of a PM-cast aluminium alloy," *Materiali in Tehnologije*, vol. 49, no. 5, pp. 797-800, 2015.
- [6] J. Campbell, *Complete Casting Handbook, Metal Casting Processes, Metallurgy, Techniques and Design*, Elsevier, 2015.
- [7] C. -. L. W. Process, "University of Babylon," [Online]. Available: http://www.uobabylon.edu.iq/eprints/publication_3_23426_70.pdf. [Accessed 15 9 2019].
- [8] V. M. Vasava1, "Identification of Casting Defects by Computer Simulation –A Review," *International Journal of Engineering Research & Technology (IJERT)*, vol. 2, no. 8, pp. 2550-2555, August - 2013.
- [9] S. Wong, "21 CASTING DEFECTS AND HOW TO PREVENT THEM IN YOUR PRODUCTS," 18 September 2018. [Online]. Available: https://www.intouch-quality.com/blog/21-casting-defects-and-how-to-prevent-them-in-your-products?fbclid=IwAR3MdIG9jsq-VI_UBnfoJ4pV4IfEjFjOOIGIK2vwFAxA9DH4nqLYW0paW6s.
- [10] A. A. Chalekar, S. A. Daphal, A. A. Somatkar and S. S. Chinchankar, "Minimization of Investment Casting Defects by Using Computer Simulation," *Journal of Mechanical Engineering and Automation*, 2015.