A review on casting technology with the prospects on its application for hydro turbines

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Abstract

Casting is one of the oldest manufacturing processes that has been in use since 3400 BC. Over the years, casting technology has evolved tremendously and is one of the most integral parts of ancient history as well as a modern society. The world produced a total of 109.8 million tons of casting in the year 2017, which is a clear indicator of the massive capacity of this industry. Most of it in the current scenario is being used by the automotive industries. Despite being the biggest and the richest industry in the field of energy, hydropower has never been a major market for the casting industry. This might be because the hydropower components are mostly manufactured using other techniques such as machining and rolling. Nevertheless, studies have proven that casting can be used for the manufacturing of several components of the hydropower, especially hydro turbines. Casting technology comes with its own sets of advantages and limitations. This study presents an overview of the status of the casting technology and challenges, the proper optimization in casting that needs to be considered, and the latest technological advancements in this area. This paper aims to develop a theoretical foundation for show-casing the beneficiary, challenges, and possibility of manufacturing hydro turbines through casting technology.

Keyword: Casting, Turbine Manufacturing, Hydro Turbines, Francis Turbine

1. Introduction

Casting is a manufacturing process in which a material is first heated to its melting point and then poured into a mold of desired shape and size that gives the metal a required definite form after solidification. Casting is done when a large quantity of complex structures is required. Metal casting is the oldest manufacturing processes. Casting has been in use since 3400 BC when it was first discovered in Mesopotamia. For many years since then, casting has been in use for making ornaments, weapons, tools, and utensils [1]. According to the world casting census 2014, Asia is by far the top continent in terms of foundry production with a share of over 70 percent in the world scenario [2]. In the year 2017, the global production of casting increased by 5.3% (109.8 million) [3]. Figure 1 shows the data of the
annual production of casting in million Tons of top 3 countries in the year 2017: the major two are India and China. The main recipient of this industry in the current scenario (as shown in Figure 1) is the automotive industry taking up over 50%, Engineering industry 30%, construction and Infrastructure 10% and other (Electronics, medicine, and aviation) 10% [4,5]. However, if proper methods and methodologies are developed, hydropower could be the next big market for the casting industries. Data shows that the annual consumption of electricity in Nepal is about 100 kWh per person, and in India, China, and the US it is 1,181 kWh, 2,674 kWh, and 12,071 kWh per person respectively [6]. With the increasing demand for energy, there has been constant pressure on the supply side to match the power requirements. Hydropower is the major source of renewable energy worldwide. As the world is moving more towards the direction of sustainable energy, hydropower seems to be the most appropriate option [7]. The total worldwide install capacity of the turbine in 2018 was 4.2 TWh and the global market for the hydro turbines in 2018 was 1 billion USD [8,9]. As the market size is large and increasing, the manufacturing industry should also be at the same pace to capture the market for which an efficient and economical manufacturing process is required.

1.1 Manufacturing of hydro turbines and the role of casting

The major manufacturing techniques used for the fabrication of hydro turbines are Investment casting, Sand casting, CNC machining, and forging. Currently, most of the major turbine manufacturers around the world use the CNC machining process to manufacture hydro turbines. The process includes CNC milling, grinding, polishing, and static and dynamic balancing of the turbines. The CNC machining is done either of the whole body of the runner at once or the blade/bucked of the runner is manufactured independently which is welded together with the other components of the runner. The remaining components like spiral casing, head cover, guide vanes, draft tube is manufactured by other manufacturing processes like turning, forging, rolling, bending, etc. and the joining is done by welding. The table 1 summarizes the list of turbines along with the per-unit cost based on head and discharge with reference to the price of for turbines in Nigeria on the basis of the report published by ministry of energy of Georgia and Norwegian Water Resources and Energy Directorate in the year 2016 [10]. The table clearly specifies that the cost for any hydro turbine is not very specific and parameters such as head and discharge should be known to know the per unit cost of the turbine. As the cost and size of the turbine depending on the specifics of the parameters in the hydropower plants, the manufacturing of these turbines should also be done based on these parameters. For that, every possible manufacturing technique can be considered and the various required parameters such as surface finish, tool cost, unit cost, manufacturing size should be compared with the desired output to come up with the best possible method for manufacturing under a given condition.
Table 1 Price of hydro turbines based on head and discharge[10]

| S.N. | Turbine       | Head (m) | Discharge (m$^3$/s) | Cost (USD/kW) |
|------|---------------|----------|---------------------|---------------|
| 1    | Pelton Turbine| 600      | 0.2-2.6             | 360-80        |
| 2    |               | 400      | 0.2-3               | 485-105       |
| 3    |               | 250      | 0.2-6               | 600-100       |
| 4    | Francis Turbine| 200      | 2-8                 | 200-85        |
| 5    |               | 100      | 2-15                | 325-100       |
| 6    |               | 80       | 2-18                | 380-110       |
| 7    |               | 60       | 2-24                | 460-120       |
| 8    | Kaplan Turbine| 20       | 10-75               | 860-175       |
| 9    |               | 10       | 10-140              | 1230-190      |
| 10   |               | 5        | 15-150              | 1190-325      |

Table 2 Parametric comparison of the different manufacturing process[11]

| Parameter               | Investment Casting | Sand Casting | CNC Machining | Forging |
|-------------------------|--------------------|--------------|---------------|---------|
| Design Freedom          | Most               | Average      | High          | Least   |
| Tolerance Control       | Best               | Average      | Best          | Poor    |
| Surface Finish          | Good               | Poor         | Best          | Average |
| Metal Selection         | Most               | Average      | Most          | Average |
| Size Range              | Average            | Large        | Average       | Average |
| Tool Cost               | Average            | Low          | High          | Average |
| Unit Cost               | Average            | High         | High          | Average |

The selection of the manufacturing process can be done by comparing the desired requirements with table 1 and table 2. Hydro turbines have unique designs and depending upon the site-specific head and flow specifically in the case of reaction turbines, the shape of the runner blades changes [12]. The hydraulic performance of especially the reaction turbines depends mainly on the shape of the runner.
The geometry of these turbines is more complex than others, so the manufacturing becomes even more complex and challenging in this type of turbine.

![Graph showing comparative production costs of casting technology vs mechanical treatment technology](image)

**Figure 3** Comparative Production costs of the casting technology Vs mechanical treatment technology[5]

The graph in Figure 3 shows comparative production costs between the metalworking and casting process. Larger hydropower means the demand for larger hydro-mechanical/electromechanical components, and especially the larger hydro turbines. Manufacturing hydro turbines of larger sizes is a challenge to manufacturers in terms of scale and complexity. Hence the manufacturing of hydro turbines using casting technology can be considered as a suitable option and local casting industries should be upscaled to cope up with the latest advancements in this technology. This paper reviews the casting technologies applied in various sectors including hydro-turbines presents the challenges of some of the common casting techniques and some optimization techniques used to improve the quality of the cast products.

2. **Studies in casting Technology**

Multiple research works can be found that explains the development of activities in casting technology. Relevant and recent works and findings are mentioned and explained in this section. A detailed study by R.G. Craig on the property of Natural waxes suggests that the material for investment casting should have a lowest possible thermal expansion, it should have sufficient strength such that it does not break easily and can be handled easily, the surface of the pattern should be smooth such that the model will have a smooth surface finish [13,14]. Some relevant studies can be found in the manufacturing of gas turbine blades. S.A.M. Rezavand carried out an experimental study to investigate the dimensional stability of injected wax patterns of gas turbine blades [15]. The study identifies the significance of various parameters including temperature and holding time on the final dimensions of the injected wax model. The paper also shows the deviation of the airfoil to be more towards the convex side affected by the temperature. I. Nawi studied about the auto pour technique in the sand casting processes [16]. The auto pouring process is operated by a PLC (Programmable logic controller) and the parameter such as temperature, position, and time are controlled. The laser sensor senses the depth of the molten metal and when the mold is filled it is moved away to the cooler area by the conveyer belt. After some time, it is taken to the vibrator where the sand is removed and the product is taken for sandblasting. Auto pouring leads to a higher production rate of about 70.2% and a lower rejection rate of more than 43%. H.M. Lus proposed a new approach of metal casting called swage casting. Swage casting has been one of the most recent developments in semi-solid metal processing technologies. It was developed in the Balkan center for Advanced casting technologies (RCACT) for manufacturing near-net shape...
components form lightweight metals. This process has the advantage of producing smooth surfaces that not only has less defect and high quality but also have sound and fine-grained microstructures [17].

![Figure 4 Sand Mold of Francis turbine developed by Binder jetting [18]](image)

The rise of the additive manufacturing process has had an impact on the advancement of casting processes. Binder jetting of the foundry sands has brought a revolutionary change in sand casting allowing the whole-body casting of a variety of complex structures (shown in Figure 4). These molds are produced by layer by layer bounding of the sand molds which is binder jetted at the required positions controlled by a moveable head. The binder jetting has brought a huge scope on the manufacturing of the complex structures leaving behind the complication limitations only to the imagination of the designer [19]. This technology may also be used to manufacture the turbine runners.

Fused filament fabrication also known as Fused deposition modeling is the process of heating the polymer plastics such as ABS and PLA to a temperature slightly higher than its melting temperature and the layer by fusing this material layer by layer until the final desired model of producing. Andrew L. studied about new and improved techniques that could replace lost wax castings [20]. He proposed about the Ice casting methods. Ice casting is one of the latest forms of casting in which the ice molds are used for casting and so all the materials during the molding process is kept below 0°C which requires a larger freezer that is capable of keeping all the supplies refrigerated.

3. Challenges in casting processes
Multiple challenges may be overcome during casting processes every time a new product is to be cast. The major obstacles could be the design of casting and pattern, molding sand, melting and pouring temperature, gating system, etc. M. R. Latte has presented a study on the blowhole defect analysis of the MHI-VST 4-Cylinder block (a central component of a vehicle) using quality control tools [21]. For the holes due to trapped air, the study suggests the use of air vents, and similarly, for the holes on the head, face drains connections are provided. R. Hardin studied the effect of shrinkage on the service performance of steel casting [22]. The research proposes a new set of engineering guidelines based on radiographic inspection standards with the help of the data on the effect of shrinkage discontinuities on mechanical properties and performance of steel casting. FLOW-3D CAST is one of the popular software to predict the shrinkage during the investment casting processes [23].

![Figure 5 Fracture seen in the Pelton turbine[24]](image)
D. Ferreno researched the failure analysis in Pelton turbine manufactured in soft martensitic stainless casting [24]. Several experiments were carried out including inspection of fractured surfaces, chemical composition, and metallurgical examination to figure out the probable mode of failure. The metallurgical observation through optical microscopy showed the presence of sharp crack following the path of a ferrite island. The SEM inspection of fracture surfaces showed the presence of discontinuities in the surface and interpreted it as shrinkage cavities or hot tears. The paper concludes the inadequate manufacturing process to be the major reason behind the cause of the defect.

4. Casting of Hydro Turbines

Turbine Testing Lab at Kathmandu University used the traditional investment bronze casting technology to cast a 14 kW Francis runner [25,26]. Two attempts were made to manufacture the turbine. In the first attempt, the runner had many defects including blowholes, shrinkage, misrun, fusion. Through a detailed study that was not done a preliminary hypothesis was made suggesting the lower temperature, improper gating system, to be the major reason behind the failure of the casting process. The second attempt to manufacture the runner was done taking into consideration the learnings from first attempt and adding in the modifications. The results improved drastically although many defects could be seen in the second turbine as well (shown in Figure 6).

![Figure 6](image_url)

Figure 6 Francis Turbine runner manufactured by investment casting [25,26]

A 92 KW Francis runner designed by the Turbine Testing Lab (TTL) was manufactured by Nepal Hydro and Electric Company Pvt. Ltd. (NHE) [27]. The blades of this turbine were manufactured in Metals Cast Pvt. Ltd. In the manufacturing of this runner, two different technologies were used. The hub and shroud were manufactured by machining while the blades of the runner were cast. Ei Ei Mon used sand casting for the manufacturing of a Pelton turbine [28]. The sand mold was machined to give the shape of the bucket using CNC machining. Then the buckets of the turbine were sand cast and assembled. S. H. Desai has proposed a design for the centrifugal casting of turbine bearings with Length= 0.7m, diameter=1.2m, and good mechanical properties like strength, stress, wear, rigidity, etc. which is mainly obtained due to the centrifugal force generated in this process. The Francis turbine runners of the three gorges dams were manufactured by casting and assembled by welding. These runners are 10m in diameter, 450 tons in weight, and generated 700 MW of power. The material used in the runners is 410 NiMo type martensitic stainless steel (13% Cr, 4% Ni, 0.5% Mo). Welding is used for the assembly and repair of casting defects. These runners for the Three Gorges project produced by the Harbin Electrical Machinery Company Ltd in China are welded partly with metal-cored wires and partly with the SAW two-wire process with a solid wire as described above. FILARC PZ6166 was introduced after a test program was completed, showing that requirements relating to mechanical properties and hydrogen levels could be fulfilled. However, other important aspects included weldability features, such as good penetration, excellent wetting, and low spatter, ensuring a minimum of post-weld cleaning, grinding, and repair. The consumption of the metal-cored wire is estimated at roughly 7-10 tones per runner [29].
5. Optimizations in processes developed for better heavy steel metal casting

5.1. Efficient cooling

J W Kang proposed a method to improve production efficiency and reduce residual stress and deformation [30]. He proposed the Post Solidification Intensive Riser Cooling (PSIRI) method, a new method for heavy steel castings. In this process, after the solidification of casting is finished, risers are cooled by forcing air from its top. Here, the risers act as cooling passage increasing the cooling efficiency by 40% and also decreasing the residual stress. The hot spot was also pushed to the casting bottom. In this procedure, in the beginning, the casting is suddenly cooled by the sand mold. Hence, in Figure 7(a), it can be seen that the heat flux pointing towards the molding surface. As seen in Figure 7(b), after the progression of cooling, the majority of the heat transfer takes place from the top of the riser to the bottom of the casting. After the use of PSIRI, heat flows from hot spots towards the top surface and after 30 hours of cooling, the heat leaves the riser.

![Figure 7](a) 0.25 hrs (b) 17.8 hrs before adding PSIRI (c) 30 hrs with PSIRI[31]

Hai-Liang Yu studied the distortion behavior of a heavy hydro turbine blade casting during forced-air cooling in the normalizing treatment process to determine the geometrical accuracy [31]. He carried out real-time measurements of distortion and temperature field of a heavy hydro turbine blade casting weighted 17 ton during forced-air cooling in normalizing treatment process by using deformation measurement instruments and an infrared thermal imaging camera. He found a large distortion at the blade corner in the outlet side cooling from 220 to 510 min for the non-uniform cooling and phase transformation. Thus, he proposed this period as a critical period to control the distortion behavior and necessity of controlling the cooling speed and phase transformation in the period for the same.

5.2. Optimization of Sand Mold

More than 80% of the total casted product is produced by the casting process [32]. Optimizing the sand mold composition before the casting process is essential for high-quality casting with better casting. C. Saikaew worked on the optimization of molding sand composition for quality improvement of iron castings [33]. This research focused on the investigation on properties of the molding sand with the variation in bentonite and water added to the sand mold. The statistical analysis showed the mean hardness of the iron casting made with the optimized mixture to be significantly higher than those made with the conventional mixture. Hardness data sets of two different data sets of casting made in the research.
The research concluded the optimal proportion of the components to be at 93.3 mass% of one-time recycled molding sand, 5 mass% of bentonite, and 1.7 mass% of water [33].

Table 3. Hardness data of sand mold

| S.N. | Optimized mixture | Conventional mixture |
|------|-------------------|----------------------|
| 1    | 18.90             | 17.80                |
| 2    | 18.30             | 16.63                |
| 3    | 18.53             | 16.57                |
| 4    | 17.57             | 17.00                |

5.3. Simulation in Casting Technology

Simulation in the casting technology has become one of the most integrated tools for the larger casting industries for visualizing and designing the casting processes. It is also being used for troubleshooting the existing problems in the casting. B. Ravi in his paper highlights the importance of the three major applications of casting simulation which are casting troubleshooting, method optimization, and part design improvements [34]. For the casting troubleshooting, the exact parameters of the existing foundry are replicated and the simulation results are calibrated. This indicates the problems that caused the defects in the first place. For method optimization, the iterative process is carried out before obtaining results with high quality and yield. Similarly, the part design improvements are done based on its ease of manufacturing without losing the functionality. One of the major bottlenecks in casting technology is its lack of use. Looking at the casting industry of Nepal, none of the traditional casting manufacturers use the computer simulation for the process and product design. The process is planned based on traditional approaches and experiences. Optimal riser design is one of the most important parameters of the casting process design that can be achieved through the casting simulation process. An optimal riser is necessary for any system to establish a controlled progressive directional solidification and minimize the volume shrinkage. The riser design also affects the cooling rate, hence in the mechanical properties of the system. So proper sized and positioned riser is necessary for high quality and sound casting. T.E. Morthland researched optimizing the riser design for metal casting [35]. He combined the approaches of finite element analysis, data-sensitive analysis, and numerical optimization to systematically improve the casting design and present the methods for performing the sensitivity analysis of the parameters such as freezing time, temperature gradient, and cooling rate. R. Tavakoli has presented his work on the optimization of riser design using Poisson approximation of nonlinear heat transfer equation [32].

Following is the list of available casting simulation software along with the related vendor list and country.
Table 4. List of casting Simulation Software [34,36]

| Software Name | Vendor and country |
|---------------|--------------------|
| AutoCast      | Advanced Reasoning Technologies P. Ltd., India |
| CAP CAST      | EKK, Inc., USA     |
| Cast CAE      | CT-Castech Inc., Oy, Finland |
| MAGMA Soft    | MAGMA GmbH., Germany |
| Pro Cast      | ESI Group, France  |
| FLOW-3D Cast  | Flow Sci, Inc., USA |
| SOLID Cast    | Flow Science., USA |
| JSCAST        | Komatsu Soft Ltd., Japan |
| SIMTEC        | RWP GmbH., Germany |

6. Conclusion and way forward

Looking back from the current scenario, the casting technology has come a long way with a range of applications in the manufacturing industries. Development of casting simulation and rapid prototyping have been the major boon for the further enhancement of this technology. There are a few challenges in terms of various defects that could come with this technology, but proper process planning and computer simulation of this process can help to improve the quality of the product. With all these developments the manufacturing of hydro turbines using casting technology seems more efficient are a few optimization processes such as efficient cooling, optimal riser design, use of the optimal sand mold, etc. that was found to be tested in the reviewed papers which should be considered. Also, with the rapid technological development, a strong collaboration between the industry and academia is necessary to boost this process and bring a major change in the casting industry for heavy steel hydro turbine casting.

Many small hydropower projects are under development in Nepal. Francis Turbines are most suitable in those projects both technically and economically. The knowledge of casting technology acquired in this research will be used to motivate Nepalese industry to carry out stainless-steel casting of Francis Turbine in Nepal itself. This will also increase new load for electricity in Nepal and make electricity industry sustainable.

7. Scope and Limitations

The study presented in this paper is based on the literature survey available on the internet. For this review around 80 papers that were found over the internet were selected based on the title and abstract. Out of these 50 papers were read in detail by the authors and 32 of them have been used in this paper. Since the information and data presented in this paper are based on the research works that are available in the public domain so the manufacturing advancements that have may have been achieved especially by the major industries have not been taken into consideration. This paper mainly discusses the status of the casting technology in the world scenario, present developments, challenges, and optimizations in casting.

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