

VIABILITY STUDY OF PRODUCTION OF ENCLOSED IMPELLERS FOR CENTRIFUGAL PUMPS BY INVESTMENT CASTING PROCESS

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Abstract. Centrifugal pumps are used to transport fluids and can operate continuously for long periods. Thereby, the increase of efficiency can generate significant reduction in energy consumption. The motivation of this work was the development of better alternatives (manufacturing processes, design and materials) for the production of hydraulic centrifugal pumps aiming to increase the hydraulic efficiency and reduce the operation costs due to the improvement of the standard quality of its components. This work describes the design, production and testing of enclosed impellers manufactured by investment casting process from ASTM A216 Grade WCB carbon steel and a comparison concerning quality and efficiency with enclosed impellers manufactured by conventional sand casting process from ASTM A48 CL30 gray cast iron. To establish benchmarks, the following tests were performed: roughness, weighing, dynamic balancing, centrifugal pump performance, wear and hardness. Investment casting process could allow the development of a new enclosed impeller design with small fluid passages and the switch to higher mechanical properties materials (i.e., steel versus cast iron) that supported the structural changes imposed by the new design. Impellers manufactured by investment casting presented better surface finishing, more microstructure homogeneity, less initial imbalance and higher hydraulic performance when compared to impellers made by conventional casting. Despite the higher production operating costs, the impellers manufactured by investment casting presented final manufacturing costs practically equals that of conventional casting when the finishing operations are considered. Thus, the increasing of hydraulic pump efficiency and consequently the savings in pump power consumption during operation demonstrated the viability, in terms of cost-benefit, of production of enclosed impellers for centrifugal pumps manufactured by investment casting process from carbon steel.

Keywords: investment casting, conventional sand casting, ferrous alloys, centrifugal pump impeller, hydraulic efficiency.

1. INTRODUCTION

Impellers for centrifugal pumps are normally manufactured in conventional foundries by molding processes in cold set sand or green sand. The materials used in the construction of these kinds of parts vary according to the characteristics of the fluid to be pumped and according to the work to which they are submitted. The no-bake cores are manufactured by cold curing or shell molding process. However many limitations can be observed in these processes, such as minimum thickness of the vane, difficulty in reproducing small radius, faithful reproduction of the hydraulic project, the need to include draft angles to facilitate shakeout, roughness and surface finishing. For impellers with narrow passages, where the area to volume ratio is high, the effects of process limitations in the conventional manufacturing can be highly perceived.

According to Bidwell (1997) the investment casting process present minor dimensional variations as well as deformations and it needs reduced output angles (used to facilitate removal from the mold). The cycle time is considered high, and the overall cost of the steel cast manufacturing and the surface roughness presents more than three times better values. The investment casting allows a high fidelity to detail, especially the small dimension one, which cannot be reached at the same level using the conventional casting process. Tab. 1 presents a comparison among the most common characteristics of the conventional casting and investment casting processes.

Twarog (1993) states that the precision casting market has great prospects for growth, particularly in high-tech industry. The number of precision casting is still small compared to conventional foundry and the major use of this technique is for the aerospace and the automotive markets. The excellent flexibility, accuracy and surface finishing that the investment casting process provides can be a competitive advantage if used in other markets. For the hydraulic

market, specifically for the pumping segment, the impeller is the main component for which it can obtain a significant gain by using this technique.

This work describes the design, production and testing of enclosed impellers manufactured by investment casting process from ASTM A216 Grade WCB carbon steel and a comparison concerning quality and efficiency with enclosed impellers manufactured by conventional sand casting process from ASTM A48 CL30 gray cast iron. The aim of this study is to compare both processes in terms of construction and operating characteristics of the obtained products as well as to evaluate their commercial viability.

Table 1. General characteristics of the conventional casting and investment casting processes (Bidwell, 1997).

Characteristic	Conventional casting	Investment casting
Dimensional variation	> 1.5 mm	> 0.3 mm
Form / position deviation	> 1.5 mm	> 0.3 mm
Roughness (Ra)	> 10 μm	> 3 μm
Fidelity to detail	Low	High
Remove angle (tool)	Min 1.5°	0 to 0.5°
Cycle time	Low	High
General costs	Low	High

2. EXPERIMENTAL PROCEDURES

The project of the enclosed impeller was designed, simulated and validated prior to manufacturing the metal die for assembling the investment casting system. The pump rotation (n) equals to 3500 rpm and the flow rate (Q) equals to 30 m^3/h were the parameters entered into the software ANSYS® to perform the mathematical calculations. In a conventional foundry sand process the smallest thickness obtained for the impeller vane is 3 mm and by the core box project design it is not possible to place rays between the vane final and the wall profile of the suction side of the impeller. The casting design applied in this research was prepared with the aid of filling and solidification simulation by the QUICKCAST® software, which established the downsprue and the risering. The hot spots were studied and shrinkage cavities caused mainly by the solidification contraction were shifted out of the piece. Fig. 1 presents the drawing of the designed enclosed impeller.

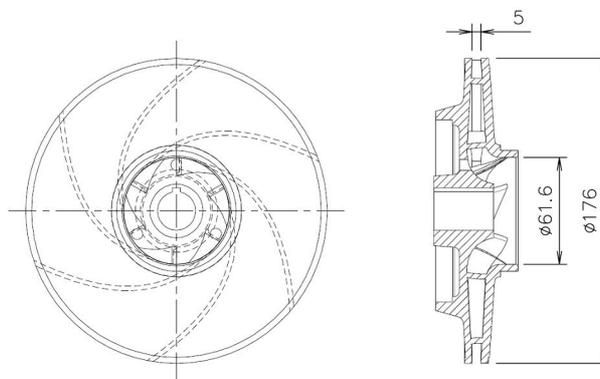


Figure 1. Drawing of the enclosed impeller showing the main dimensions.

Investment casting processes allow to reproduce fidelity to details, short radius and complex curvatures, which is not possible using conventional casting. The vanes became less thick, adjusting the minimum thickness with the smaller dimension of 1.6 mm. Unlike conventional casting where a sand mold at room temperature is filled with metal, in the investment casting process, the ceramic shell mold is heated to 1000 °C and afterwards receives the liquid metal. This condition provides a better fluidity in filling and a lower thermal gradient between metal and mold, which favors the obtaining of parts with thinner walls and without glitches or discontinuities.

Fig. 2 presents a schematic drawing of the manufacturing of the impellers by sand casting and investment casting. The main steps of the investment casting, briefly showed in Fig. 2b, consist in: injection the vane in soluble wax, injection the impeller in recyclable wax, removing the soluble wax with impeller, assemble cluster, investing (thermal protection and mechanical resistance), dewaxing from the ceramic mold, fire the shell mold, pouring the liquid metal (casting), knockout the metallic peace, cutting the gates and risers, cleaning the impeller interior and final finishing.

For the conventional casting molds and casting cores there was employed a quartz sand with 50 to 60 AFS grain size containing 99% of SiO_2 + lower contents and 0.1 % clay; this sand was mixed with phenolic urethane resin in a ratio of 1.2 % mass. For the investment casting part there was employed a zircon sand coating with 140 AFS grain size

containing 65 % of $ZrO_2 + HfO_2$ and 35% of SiO_2 . Zircon sand is thinner and more resistant at high temperatures and the difference in particle size is necessary like in the conventional process that uses the mold at room temperature during the metal casting. High generation of gas occurs and the mold must have good permeability, so that there is time enough for the gases to dissipate and not be trapped inside the part, so the sand used is thicker. In the investment casting process, the mold is heated to a temperature of 1000 °C to receive the metal, which minimizes the gas generation, differing from the conventional process. Moreover, the ceramic shell is thinner (around 8 mm), whereas, the conventional mold has walls over 50 mm, due to the resistance to heat. Since the ceramic shell has less thickness, it will have a lower barrier and thus it is easier to dissipate the gases.

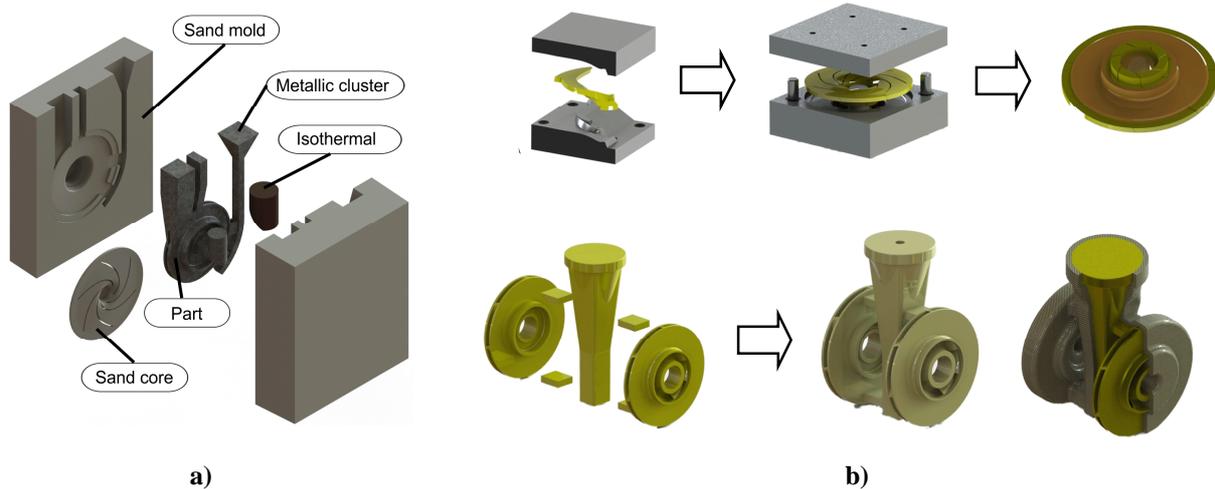


Figure 2. Schematic manufacturing of the impeller by: a) cold set sand molding and b) investment casting.

The material used to produce the impeller by sand casting was a gray cast iron according to the ASTM A48 CL30 standard (ASTM A48, 2012). To support the manufacturing of the impeller with optimized hydraulic geometry and to endure the work, a carbon steel according to ASTM A216 Grade WCB standard (ASTM A216, 2016) was applied in the investment casting. With this alteration the restricted thickness of 3 mm by the conventional casting process could be adjusted to 1.6mm as discussed above. The use of carbon steel instead of gray cast iron for investment casting occurred mainly for the following reasons:

- The manufacturing cost of the ceramic shell and the metal is the same regardless of merging carbon steel or cast iron and the part made of carbon steel favors the cleaning process precisely because of its higher ductility. The vibratory hammer using during the ceramic shell removal could cause cracks in the internal vanes of the cast iron impeller once this material does not have a yield point;
- As the carbon steel has a higher tensile strength, it was possible to optimize the hydraulic profile and to work with smaller thicknesses, which directly influenced the pumping efficiency, one of the objectives of this study;
- Carbon steel has higher resistance to abrasive wear than cast iron, as demonstrated in the tests forward discussed and with that, in situations where there is particulate matter in mixture, there will be a longer life cycle for the impeller made of this material.

Thus, the viability study of production of enclosed impellers for centrifugal pumps by investment casting process was evaluated by means of the following tests performed: roughness, weighing, dynamic balancing, centrifugal pump performance, wear and hardness. All the results presented were established from three replicas obtained from three different pouring which defined the standard deviation. The average of five measurements for each one of the replicas evaluated was calculated.

3. RESULTS AND DISCUSSION

When comparing the parts obtained from each of the casting processes it was noticed that the impeller obtained by the investment casting process had a better visual aspect and less dimensional deformation as can be seen in Fig. 3.

Apart from the different applied procedures in the manufacturing compared impellers, the materials used were also different. Parts conventionally casted were produced with gray cast iron while the investment casted parts were produced with carbon steel as discussed above. Tab. 2 presents the chemical composition of the alloys used to produce the impellers. Measurements were obtained using optical emission spectrometry technique.

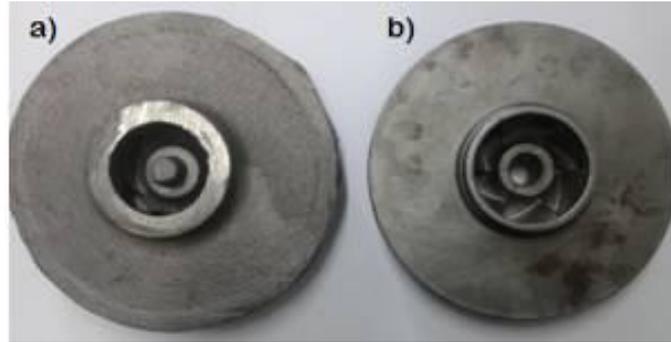


Figure 3. Enclosed impellers produced by: a) conventional casting and b) investment casting.

Table 2. Chemical composition of the alloys used in this work (in wt %).

Alloy	C	Si	Mn	P	S	Cr	Cu	Fe
ASTM A48 CL30	3.47	1.71	0.44	0.05	0.12	0.19	0.32	balance
ASTM A216 Grade WCB	0.25	0.27	0.55	0.03	0.01	0.21	0.06	balance

Specimens polished up to 1µm and etched with nital 3 % reagent were characterized by light microscopy. Fig. 4 presents the microstructure of the alloys. Fig. 4a shows lamellae graphite for the conventional impeller manufactured with the gray cast iron according to ASTM A48 CL30 standard. It is observed that the cast iron is composed by a pearlite matrix and graphite flakes. It can be classified as type VII and graphite with type A distribution according to ASTM A247 standard (ASTM A247-10, 2010), as expected for this material.

Fig. 4b shows the investment casting material, hypoeutectic carbon steel already in a normalized condition, presenting ferrite and pearlite grains homogenously distributed due the heat treatment. The normalization heat treatment is essential for the good mechanical behavior of the final part. In the normalized condition the material exhibited a more refined structure due to the austenitizing (around 920 °C) followed by air cooling which promotes the nucleation and the growth of new grains (Novikov, 1994). By controlling the temperature and cooling time the new grains presented smaller sizes compared to the as-cast condition.

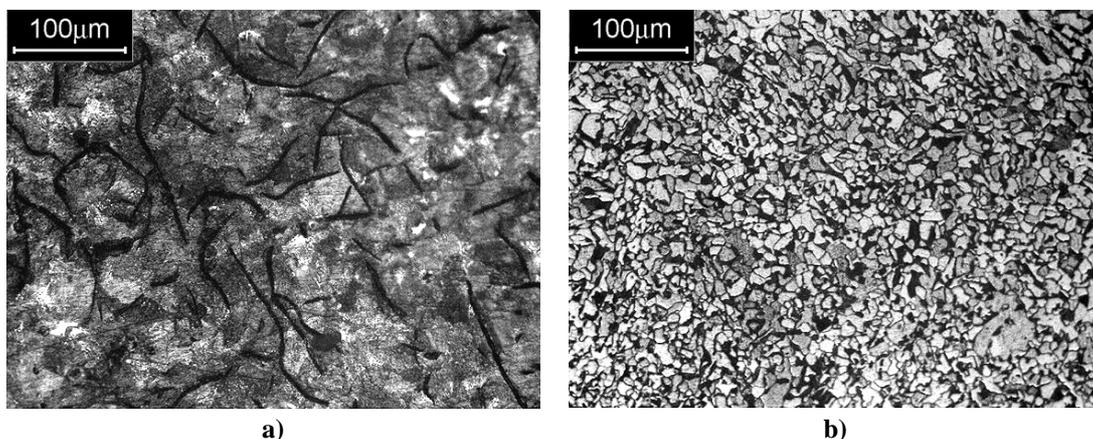


Figure 4. Microstructures of the alloys used in this work: a) ASTM A48 CL30 gray cast iron and b) normalized ASTM A216 Grade WCB carbon steel. Nital 3 %.

In addition, taking into account the low carbon content of the carbon steel, the investment casting impeller has a higher weldability when compared to the conventional impeller manufactured with cast iron. This condition provides welding repair performance during the manufacturing process or on possible future interventions during corrective maintenance operations.

The hardness measurements in the cast samples are shown in Tab. 3. The cast iron presented the highest hardness, 184 HB. The carbon steel in the normalized condition showed a hardness of 147 HB, higher than the hardness found in the as-cast condition.

Table 3. Brinell hardness of the alloys used in this work.

Alloy	Hardness (HB)	Standard deviation
As-cast ASTM A48 CL30	184	12.5
As-cast ASTM A216 Grade WCB	134	4.2
Normalized ASTM A216 Grade WCB	147	5.5

In addition to the tests carried out to compare the impeller construction materials, the abrasiveness test was performed according to ASTM G65 practice B standard (ASTM G65-04, 2010). The abrasion test consists in applying a 130 N load on a sample (machined and grinded with 12.7 x 25.4 x 70 mm) against a rubber wheel for a period of 10 min at a constant speed of 200 rpm and maintaining between them a sand flow of 300 to 400 g/min. The initial mass and the final mass of the sample were measured with a scale of 0.0001 g resolution. Weight loss (the missing mass in mg) was determined and the volume loss (mm³) was calculated considering the density measured by the Archimedes method. The less the weight and volume are removed, the greater will be the resistance of the tested material to abrasion. Tab. 4 presents the abrasive wear resistance of the alloys according to ASTM G65 practice B.

Table 4. Abrasive wear resistance of the alloys used in this work according to ASTM G65 practice B standard.

Alloy	Weight loss (mg)	Standard deviation	Volume loss (mm ³)	Standard deviation
ASTM A48 CL30	4103	319	578	48
ASTM A216 Grade WCB	2078	102	271	10

The carbon steel presented a better resistance to abrasive wear once the weight and volume lost during the practice B were 2078 mg and 271 mm³ respectively while the cast iron lost 4103 mg and 578 mm³, more than twice material. These results means that during the operation the steel impeller will behave better pumping fluids with solids in suspension and its useful lifetime will be greater than the impeller manufactured with cast iron.

The roughness evaluation shows a substantial difference on the part surface quality as can be seen in Tab. 5. While the investment casting part reached an average of 3.98 µm Ra, equivalent to a machined surface, the part obtained by conventional casting showed an average of 12.43 µm Ra, more than three times higher. Thus, the investment casting part will provide a lower friction to the fluid during the pumping than the conventional casting one.

Table 5. Roughness of the parts manufactured in this work.

Part	Roughness (µm Ra)	Standard deviation
Conventional casting	12.43	1.85
Investment casting	3.98	0.37

Due to the high dimensional and form stability provided by the investment casting process, the necessary machining allowance can be drastically reduced herewith the casting weight was significantly reduced. Tab. 6 presents the weight measurements for the casting and machined parts. In addition, as discussed above, investment casting and the consequent adoption of the carbon steel allowed working with smaller vanes and walls thicknesses reducing the final weight of the part. The weight reduction will influence the pump power consumption and will raise its performance; the slightest work on the shaft will provide a longer life cycle to the pump bearings.

Table 6. Weight of the conventional casting and investment casting parts.

Part	As-cast (kg)	Standard deviation	Machined (kg)	Standard deviation	Removed material (kg)	Standard deviation
Conventional casting	3.80	0.11	2.77	0.16	1.03	0.10
Investment casting	2.61	0.08	2.40	0.05	0.21	0.05

Although the impellers come out with some residual imbalance, according to ISO 1940-1 standard (ISO 1940-1, 2003) the grade 2.5 is acceptable. Before any intervention, the initial imbalance helps to show the cast quality. If the initial imbalance is low, it will require little adjustments and consequently less time and low cost for mass removal and for the framing in its acceptable limits. The results presented in Tab. 7 show that the investment casting impeller demanded a removal of 7.28 g for its adjustment, while the impeller obtained by conventional casting demanded a removal of 26.60 g.

Table 7. Dynamic balance process of the conventional casting and investment casting parts.

Part	Initial imbalance (g)	Standard deviation	Removed material (g)	Standard deviation	Finish imbalance (g)
Conventional casting	26.75	4.57	26.60	4.57	0.15
Investment casting	7.43	2.36	7.28	2.36	0.15

Another aspect to consider is that there is a relationship between the vanes equidistance with the initial imbalance. A better equidistance is recommended if the value found is low; this will provide a better hydraulic stability during pumping and lower vibration transmission on the equipment. The impeller has six vanes and thus six fluid inputs and six discharge areas. In the event of equidistance failure between the vanes, it will certainly have a volume difference among the six fluid parts within the impeller. In operation, the 3500 rpm rotation will have a total of 58.3 cycles of loading and unloading the six volumes within the impeller per second and with the difference between these volumes, there will be a higher vibration than if we take this process with equal volumes.

As discussed, manufacturing costs are higher for the investment casting when compared to conventional casting. However, when considering the machining and the dynamic balancing operations, the subsequent total costs were practically equal for both processes in this work once the machining and dynamic balancing operations costs are higher for the conventional casting while the machining allowance and balancing time are less for the investment casting.

Performance tests were performed according ANSI/HI 14.6 standard (ANSI/HI 14.6, 2011) substituting only the impellers and maintaining the same diametric clearances between wear rings. The test rotation was of 3500 rpm and impellers manufactured with the both processes and alloys were tested. According to the experimental data presented in the Fig. 5, it can be seen that a higher discharge pressure was achieved by using the investment casting impeller. Note that as the flow rate increases, higher is the pressure difference. Comparing the yield shown in Fig. 5b, the pump tested with the investment casting impeller exceeded the pump tested with a conventional casting impeller.

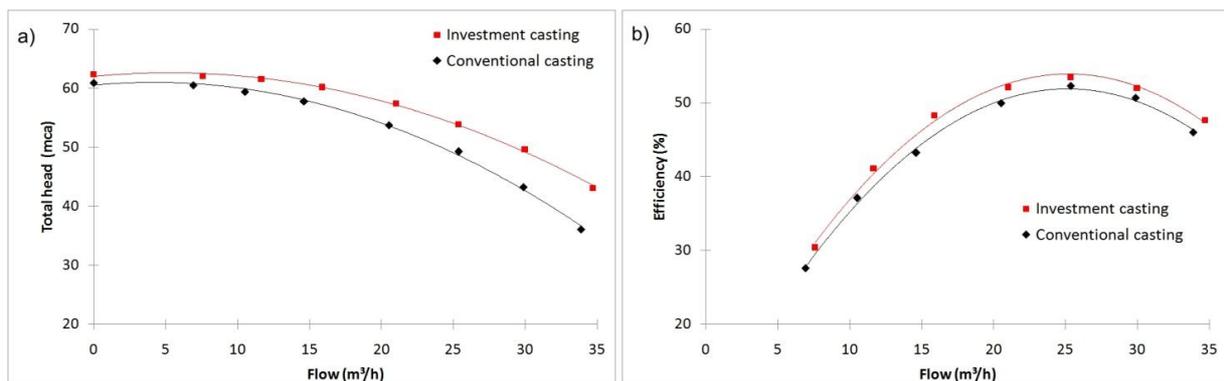


Figure 5. Centrifugal pump performance: a) flow versus total head and b) flow versus efficiency.

For centrifugal pumps the performance test is the most important among all the tests performed during the product manufacturing process. A complete performance test foresees the pump evaluation throughout its operating range from zero flow to maximum flow design. The flow rate chosen for the tests is between zero-flow up to thirty-five cubic meters per hour. The higher efficiency point of the investment casting impeller is obtained at the 25 m³/h flow.

The hydraulic efficiency is the ratio between the hydraulic power and the mechanical power measured at the tip of the pump shaft in operation. Due to the hydraulic performance difference for a pumping flow of 25 m³/h, considering a 8 hours a day operation year-round (365 days), the energy savings can reach 1406 kWh and considering a 24 hours a day operation year-round, the energy savings can reach 4218 kWh.

The reduction in power consumption is significant when using the carbon steel impeller instead of the conventional gray cast iron impeller, as is evidenced in the pump performance test. The viability is evident in a market where the pumps and impellers are manufactured mostly by the conventional casting process, so there are many opportunities for the use of the investment casting process. For impellers with other dimensions, diameters and passages further studies should be performed.

4. CONCLUSIONS

A viability study of production of enclosed impellers for centrifugal pumps by investment casting process was proposed. The following conclusions can be drawn from the study:

- Through the flexibility provided by the investment casting process it is possible to improve the hydraulic models aiming for a greater efficiency in the operation;

- The initial imbalance of the conventional cast is considered high, when compared to the investment casting;
- The surface roughness obtained for the investment casting impeller is less than that one observed for the conventional casting impeller, which impacts directly on the pumping hydraulic efficiency since there is lower friction to the fluid during the pumping;
- Using the ASTM A216 Grade WCB carbon steel as construction material for the impeller instead of the ASTM A48 CL30 gray cast iron provides to the part a greater resistance to abrasive wear;
- The cast part manufacturing cost is higher for the investment casting. However when considering the machining and the dynamic balancing operations, the subsequent total costs are practically equal;
- The hydraulic performance of the investment casting impeller is undoubtedly higher and as the hydraulic efficiency is better, the power consumption is lower to meet the same pump operating point;
- The viability of investment casting process is evident for manufacturing impellers for centrifugal pumps.

5. ACKNOWLEDGEMENTS

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