BEHAVIOUR OF 3D PRINTED IMPELLERS IN PERFORMANCE TESTS OF HYDRODYNAMIC PUMP

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Abstract
The paper summarizes the results of testing the performance characteristics of various types of radial centrifugal pump impellers manufactured by Rapid Prototyping method. Experimental performance characteristics were compared to those of conventional impellers manufactured by sand moulds casting. The operational testing had shown that all tested variants of impellers were able to withstand the maximum load at the highest power output without any damage. In terms of performance, the impellers manufactured by 3D printing had higher efficiency at higher flow rates than conventional casted impellers by a few percentage points. The main advantage of this method is the rapid manufacturing of the prototype – in this case, the production time of one impeller did not exceed 33 hours.

Key words: *Rapid Prototyping; pump; turbine; power characteristics.*

INTRODUCTION
Contemporary Czech, but also Central European landscape is facing increasingly a lack of rainfalls. The rainfall deficiency is particularly noticeable in the soil management sectors - agriculture and forestry.
Lack of irrigation water is also a serious problem in dry-climate areas and underdeveloped countries (*Kazim, 2003*). Micro-irrigation systems (MIS) are ever more frequently being introduced in areas with limited water supplies. The size of such irrigated areas is gradually growing – from 1.1 million hectares in 1986 to approximately 3 million in 2000. Nowadays more than 70 countries use micro-irrigation on a total area exceeding 6 million hectares as mentioned in (*Zamaniyan, Fatahi, Boroomand-Nasab, 2014*). On the other hand, (*Ebrahimian, & Liaghat, 2011*) pointed out that there are many cases of inefficient water utilisation – such as the case of Iran which has a dry climate (average annual rainfall of 240 mm) but uses efficiently only 35% of the total amount of water designated for agriculture.
Due to the lack of rainfall water, our farmers are nowadays also considering increasingly the possibility of using controlled artificial irrigation systems. These systems, consisting usually of a set of storage tanks, water distribution pipes and pumps, are often considerable energy consumers. Some sources, for example (*Melichar, 2009*), indicated that up to 30% of all electricity generated is consumed for pumping liquids. Efforts to save energy lead to the development of technical innovations in the most energy-demanding parts of these systems – pumps, as described in (*Fontana, Giugni, & Portolano, 2011*) and (*Venturini, Alvisi, Simani, & Manservigi, 2017*).
One major driving force for innovations is the effort to improve the efficiency of machines in operation, a trend which in recent time has been supported by EU legislation (*Directive 2009/125/EC*). Nevěřil indicated in his publication (*Nevěřil, 2012)* that Regulations focused specifically on hydraulic machines (*Commission regulation (EU) No 547/2012*) specified a so called minimum energy efficiency index (MEI) of at least 0.1 which meant in practice that 10% of pumps with the lowest efficiency had to be withdrawn from the EU market. From 1st January, 2015, this index has to be at least 0.4, which means it is necessary to replace 40% of the pumps on the European market.
Today, the experimental, research and production activities in engineering cannot do without using 3D-CAD powerful graphics systems. The basis is a parametric graphical three-dimensional model in CAD software. The most widely used software in practice are INVENTOR, SOLIDWORKS, CATIA, CREO, SOLID EDGE, AUTOCAD and others. 3D models can be used not only for various analysis, but also as a basis for production of components by Rapid Prototyping.
As mentioned in (*Mohan, Senthil, Vinodh, & Jayanth, 2017*) and (*Jayanth, Senthil, & Prakash, 2018*), fused deposition modelling (FDM) is the most significant technique in additive manufacturing that refers to the process where successive layers of material are deposited in a computer-controlled environment

to create a three-dimensional object. This technology was also chosen for our experimental verification of properties of the impellers for radial centrifugal pump.
The aim of the testing was to verify the hydraulic parameters of those impellers and to compare them with the parameters of cast iron or cast steel impellers manufactured by conventional casting.

MATERIALS AND METHODS

Impellers manufactured by 3D printing were tested on a hydraulic test circuit where pump and reverse turbine operation was examined in a similar way as in (*Pugliese, De Paola, Fontana, Giugni, & Marini, 2016*).
The META Plus 5 pump, manufactured by ISH Pumps Olomouc, was selected for experimental verification. From a design point of view, this is a one-stage centrifugal pump with a spiral box and impeller with outer diameter D_1 = 132 mm (Fig. 1).

Fig. 1 Variants of impellers

Five different impeller variants were created for testing in total, all having the same flow section geometry. The impellers were made using Stratasys Dimension Elite 3D Printer 180-00105 from material ABS-P430 (Acrylonitrile Butadiene Styrene, density: ρ_{ABS} = 1,050 kg.m^{-3}). The impellers parameters and printer settings are summarized in Tab. 1. Temperature settings of printer were the same in all cases – model head: 280°C, support head: 150 °C, chamber environment 75 °C.

Tab. 1 Overview of variants of tested impellers

Variant	Description	Slice height [mm]	Print time [h:min:s]	Used ABS [cm^3]	Weight [g]
1 - Cast iron	Grey cast iron, sand mould				1,400
2 - Steel	Stainless cast steel, sand mould				1,810
3 - Composite	Rear shroud, cast iron + ABS blades	0.18	30:57:01	159.4	710
4 - Shell	Shell ABS - 3D print	0.18	23:21:52	87.9	80
5 - Full	Compound impeller, ABS - 3D print	0.18	32:29:10	187.5	185

Fig. 2 shows the internal structure of the impeller construction used in 3D printing. The lines indicate the paths of the printing head nozzle in one of the printed layer. The structure on the left was used for printing the full and the composite impeller (variant 5 and 3, respectively). The structure in the middle was used to print the shell impeller (variant 4). The structure on the right is another possibility of inner construction; it was not used in our research.

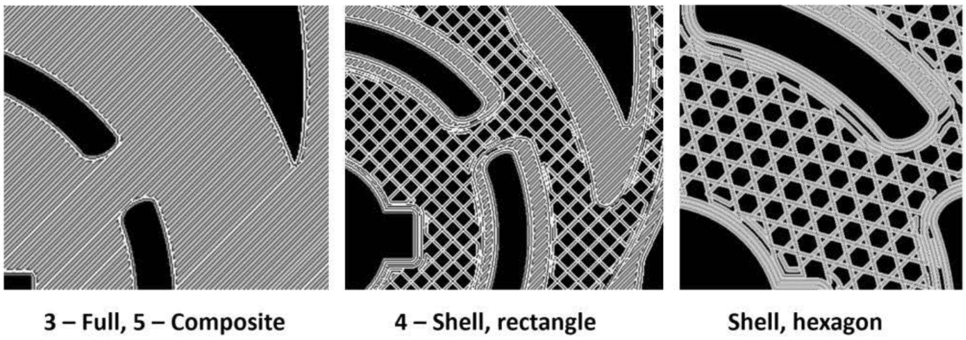

Fig. 2 Detail of inner structure of the impeller, ABS – 3D printing

Verification tests were conducted on a hydraulic circuit in the Fluid Mechanics Laboratory at the Faculty of Engineering, Czech University of Life Sciences Prague. The circuit diagram is shown in Fig. 3.

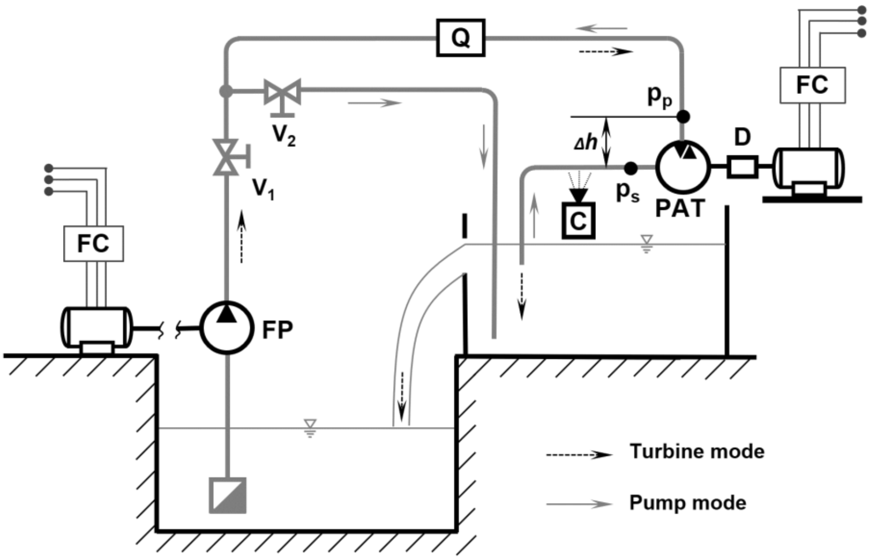

Fig. 3 Hydraulic circuit scheme for testing turbines/pumps. Q – flowmeter, FP – feed pump, PAT – tested pump, V1, V2 – control valves, D – dynamometer, FC – frequency inverter, C – camcoder. (*Polák, 2019*)

The testing circuit consisted of a set of two reservoirs with pipes and control and measuring elements. With this setting, the tested machine was measured in pump and turbine mode – by closing valve V_2 while regulating valve V_1, the water flows in the direction of dashed arrows, while the feeding pump (FP) creates the hydropower potential for the turbine. The dynamometer (D) with momentum sensor Magtrol TMB 307/41 (accuracy 0.1%) allows continuous regulation of shaft speed by frequency inverter LSLV0055s100-4EOFNS. This device enables operation in motor and braking mode. The water flow was measured using an electromagnetic flowmeter (Q) SITRANS F M MAG 5100 W (accuracy 0.5%). Pressures at (p_p) and (p_s) were measured by pressure sensor HEIM 3340 (accuracy 0.5%) installed according to 1st class accuracy requirement (*ČSN EN ISO 9906*).

The mechanical input of the pump, or the output of the turbine is given by:

$$P_m = M_T \frac{\pi \cdot n}{30} \tag{1}$$

where, M_T is the torque on the pump/turbine shaft (Nm) and n, the pump/turbine speed (min^{-1}). The hydraulic potential is determined by:

$$P_w = Q \cdot \rho \cdot \left[\frac{p_p - p_s}{\rho} + \frac{8 \cdot Q^2}{\pi^2}\left(\frac{1}{d_p^4} - \frac{1}{d_s^4}\right) + g \cdot \Delta h\right] \tag{2}$$

where Q is flow rate (m$^3 \cdot$s^{-1}), p_p and p_s are pressures (Pa) in pressure and suction pipe respectively, d_p and d_s are inner diameters (m) of pressure and suction pipe, respectively, Δh is the vertical distance (m)

between p_p and p_s, and ρ is the specific weight of water (kg·m^{-3}). The element in brackets of equation (2) expresses the specific energy Y (J·kg^{-1}). Detailed investigation of related functions and relations can be found in (*Gülich, 2014*) and (*Kramer, Terheiden, & Wieprecht, 2018*).
The overall efficiency of the pump η_p or turbine η_T is:

$$\eta_p = \frac{P_w}{P_m}, \quad \eta_T = \frac{P_m}{P_w} \qquad (3)$$

RESULTS AND DISCUSSION

Based on the measured values, the performance characteristics of all five impeller variants were stated according to (*Pugliese, De Paola, Fontana, Giugni, & Marini, 2016*) and (*Polák, 2019*). Fig. 4 shows the pump operational characteristics, in particular the efficiency courses and the total heads related to flow rates. The characteristics were measured at 1,450 rpm, which corresponds to a pump driven by a four-pole asynchronous motor as indicated in (*Gülich, 2014*). The measurement was carried out at a constant pump rotational speed, where the flow was controlled by the throttle valve V_2 at the pump discharge.

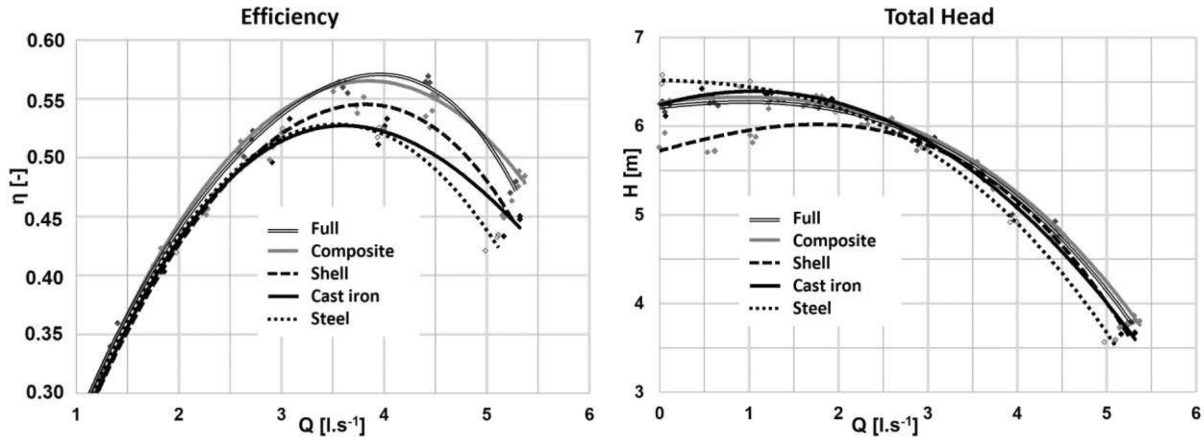

Fig. 4 Performance parameters in pump mode at 1,450 rpm

Fig. 5 presents pump characteristics measured at 2,950 rpm, corresponding to a two-pole asynchronous motor drive. The measurement procedure was the same as in the previous case.

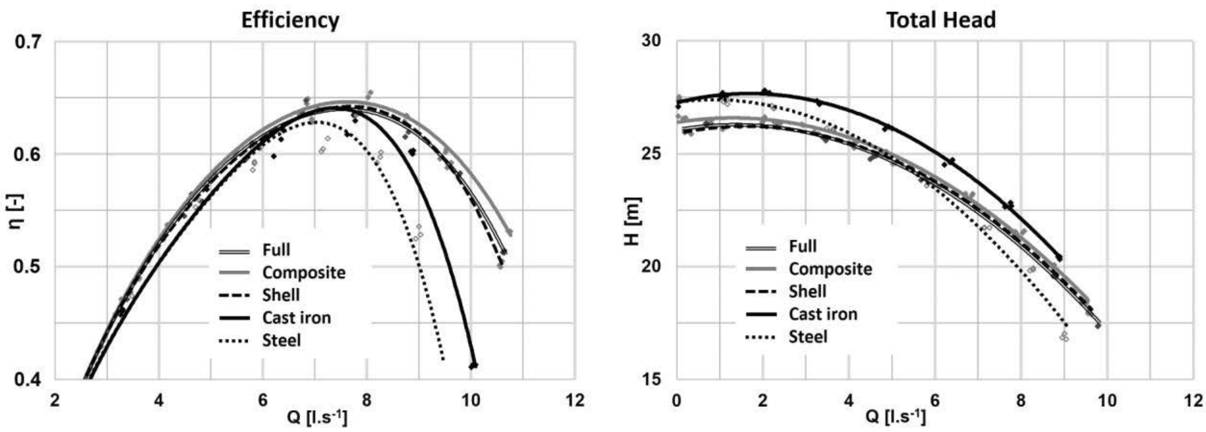

Fig. 5 Performance parameters in pump mode at 2,950 rpm

Fig. 6 below describes the characteristics of reverse turbine operation. The measurement was carried out at constant hydraulic potential (constant speed of feeding pump FP). At this setting, the turbine was gradually loaded from idle speed to 500 rpm.

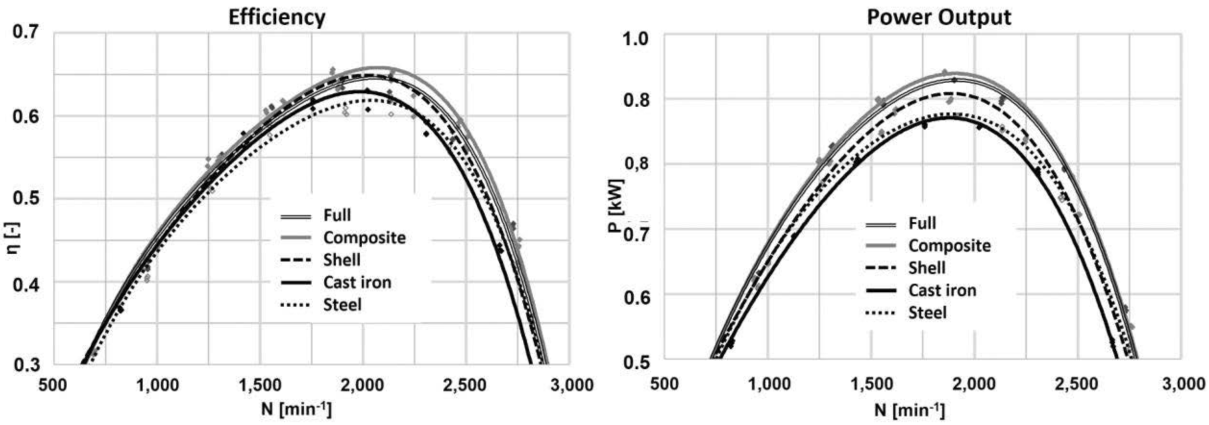

Fig. 6 Performance parameters in turbine mode

The operational tests have proved that all tested impeller variants are able to withstand the maximum load even at the highest output without damage (here pump mode at n_T = 2,950 rpm, P_m = 3kW, M_T = 9.8 Nm).

CONCLUSIONS

As far as the pump operation is concerned, the graphs showed that at 1,450 rpm, the total heads of the individual variants were almost the same, with the exception of the Shell variant, which showed a reduction of about 4.8% at the lowest flow rates. Conversely, at 2,950 rpm, all 3D variants showed on average 15% reduction in the total heads compared to the cast iron variant.

Pump operation efficiency courses at the low flower rates were the same for all variants. At higher flow rates, the efficiency of the 3D impellers increased gradually. This is particularly noticeable at 1,450 rpm, where the Composite and Full variants achieved higher overall efficiency (by 5% in absolute value) at optimum operation (= maximum efficiency) compared to a conventional cast iron impeller. Besides, at 2.950 rpm, ABS impellers presented flatter, thus more favourable efficiency courses and higher flow rates. This is due to the lower surface roughness of the flow parts. The roughness (Ra) of the internal coarse flow surfaces at the metal sand mould casted impellers ranged from 50 to 100 μm. The roughness of the impellers produced by 3D printing depended on the surface position. Vertical surfaces had a roughness of 3.2 μm, inclined and horizontal surfaces 6.3 and 12.5 μm, respectively. The metal rear shroud of the composite impeller had a roughness of 0.8 μm. Lower surface roughness results in lower hydraulic losses and higher impeller flow rate, which is also reflected in their performance characteristics.

In terms of turbine operation, the steel and cast iron impellers again presented lower overall efficiency compared to the impellers produced by 3D printing. The difference is particularly noticeable at the Composite variant, which had higher efficiency and especially output compared to cast iron impeller (on average by 4 to 6%). Again, the cause can be found in lower roughness and therefore lower hydraulic losses. This fact is confirmed by the increased machine flow rate when using impellers made with 3D printing.

Based on the results described above, the FDM Rapid Prototyping method can be recommended for testing hydrodynamic pumps. Indisputable advantage of this way of manufacturing is the speed of prototype production - in this case the production time of one impeller did not exceed 33 hours.

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REFERENCES

1. Commission regulation (EU) No 547/2012. Retrieved from http://ex-twprlegs1.fao.org/docs/pdf/eur113548.pdf.
2. ČSN EN ISO 9906. (2013). Rotodynamic pumps - Hydraulic performance acceptance tests - Grades 1, 2 and 3 (in Czech). ČSNI.
3. Directive 2009/125/EC. Retrieved from https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1556369519391&uri=CELEX:32009L0125.
4. Ebrahimian, H., & Liaghat, A. (2011). Field evaluation of various mathematical models for furrow and border irrigation systems. *Soil and water research, 6*(2), 91-101.
5. Fontana, N., Giugni, M., & Portolano, D. (2011). Losses reduction and energy production in water-distribution networks. *Journal of Water Resources Planning and Management*, *138*(3), 237-244
6. Gülich, J. F. (2014). *Centrifugal pumps* (3rd edition). Berlin: Springer.
7. Jayanth, N., Senthil, P., & Prakash, C. (2018). Effect of chemical treatment on tensile strength and surface roughness of 3D-printed ABS using the FDM process. *Virtual and Physical Prototyping*, *13(*3), 155-163.
8. Kazim, A. M. (2003). Thermal and water management in irrigating lands in the arid and semi-arid regions. *Applied thermal engineering*, *23*(7), 807-820
9. Kramer, M., Terheiden, K., & Wieprecht, S. (2018). Pumps as turbines for efficient energy recovery in water supply networks. *Renewable energy*, *122*, 17-25.
10. Melichar, J. (2009). *Hydraulic and pneumatic machines – Part pumps* (in Czech). ČVUT in Prague ISBN 978-80-01-04383-7.
11. Mohan, N., Senthil, P., Vinodh, S., & Jayanth, N. (2017). A review on composite materials and process parameters optimisation for the fused deposition modelling process. *Virtual and Physical Prototyping, 12*(1), 47-59.
12. Nevěřil, J. (2012). Limits of energy demands (in Czech). *Sigmaprofil, 20(4), 10*.
13. Polák, M. (2019). The influence of changing hydrotechnical potential on performance parameters of pump in turbine mode. *Energies 2019, 12(11), 2103.*
14. Pugliese, F., De Paola, F., Fontana, N., Giugni, M., & Marini, G. (2016). Experimental characterization of two Pumps As Turbines for hydropower generation. *Renewable energy*, *99*, 180-187.
15. Venturini, M., Alvisi, S., Simani, S., & Manservigi, L. (2017). Energy production by means of pumps as turbines in water distribution networks. *Energies*, *10*(10), 1666.
16. Zamaniyan, M., Fatahi, R., & Boroomand-Nasab, S. (2014). Field performance evaluation of micro irrigation systems in Iran. *Soil and Water Research*, 9(3), 135-142.

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