Rapid Manufacturing Technique used in the Development of a Regenerative Pump Impeller

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Abstract – **This paper presents a method of rapid manufacture used in the development of a regenerative pump impeller. Rapid manufacturing technology was used to create complex impeller blade profiles for testing as part of a regenerative pump optimisation process. Regenerative pumps are the subject of increased interest in industry. Ten modified impeller blade profiles, from the standard radial configuration, were evaluated with the use of computational fluid dynamics and experimental testing. Prototype impellers were needed for experimental validation of the CFD results. The manufacture of the complex blade profiles using conventional milling techniques is a considerable challenge for skilled machinists. The complexity of the modified blade profiles would normally necessitate the use of expensive CNC machining with 5 axis capability. With an impeller less than 75 mm in diameter and a maximum blade thickness of 1.3mm, a rapid manufacturing technique enabled production of complex blade profiles that were dimensionally accurate and structurally robust enough for testing.**

As more advanced rapid prototyping machines become available in the study in the future, e.g. 3D photopolymer jetting machine, the quality of the parts particularly in terms of surface finish will improve and the amount of post processing operations will reduce. This technique offers the possibility to produce components of increased complexity whilst ensuring quality, strength, performance and speed of manufacture. The ability to manufacture complex blade profiles that are robust enough for testing, in a rapid and cost effective manner is proving essential in the overall design optimisation process for the pump.

Keywords: **rapid manufacturing, rapid prototyping, rapid tooling,**

NOMENCLATURE

A	Cross sectional area	(m^2)
ABS	Acrylonitrile-Butadiene-Styrene	$(C_8H_8 \bullet C_4H_6 \bullet C_3H_3N)_n$
CO_2	Carbon Dioxide	
CFD	Computational Fluid Dynamics	
CNC	Computer Numerically Controlled	
D	Impeller diameter	(m)
FDM	Fused Deposition Modelling	
HPC	High Performance Computer	
MTON	Metric Ton	
P	Power	(kW)
Q	Volume Flowrate	(m^3/s)
RM	Rapid Manufacturing	
RP	Rapid Prototyphing	
RT	Rapid Tooling	
TWh	Terawatt Hour	
η	Efficiency	
ϕ	Flow coefficient	$\frac{Q}{\omega\ D^3}$
ω	Rotational speed	(Rev/min)

INTRODUCTION

Pumps are the single largest user of electricity in industry in the European Union and energy savings of 3% would result in a 1.1TWH p.a. reduction in consumption or a saving of 0.54 Mton of CO_2 production [1]. As industry attempts to make energy savings and reduce environmental impact, this paper considers the manufacture of impellers to compare the computational predictions with experimental results of a regenerative pump with a view to improving pump performance. The complex flow-field within a regenerative pump represents a significant challenge to detailed mathematical modelling as there is considerable flow separation in the impeller blading [2]-[4]. Analytical models do not describe the flow characteristics fully as they are based on simplified assumptions and experimental correction factors [5]-[7]. The previous theories rely on assumptions not based on detailed measurements or rigorous CFD calculations. The main characteristic of such pumps is the ability to generate high discharge pressures at low flowrates. Although the pump has other advantages the main limitation is its inherent lack of hydraulic efficiency, typically 35-50%. [8],[11].

Notwithstanding CFD being recognised as a good design tool in the initial design stage, the computational results must be validated with experimental data. It is therefore critical to have access to manufacturing methods that can produce dimensionally accurate, small and complex impellers that are robust enough for testing. Prototypes this complex would normally be machined using computer numerical control (CNC) machining techniques.

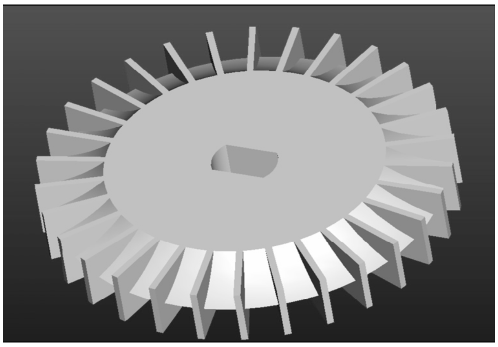

Fig. 1: **Regenerative Pump Impeller**

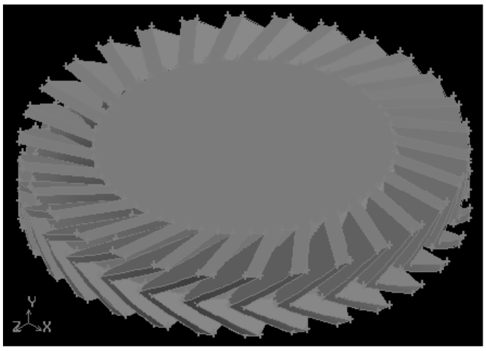

Fig. 2: **Chevron Profile Regenerative Pump Impeller**

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Having produced the standard radial impeller using conventional milling techniques, Fig. 1, to modify the blade profiles presents a considerable challenge even for the most skilled operators. The complexity of the modified blade profiles, shown in Fig. 2, would normally necessitate the use of expensive CNC machines with 5-axis capability. This paper investigates an accurate alternative manufacturing technique to create suitable impeller prototypes rapidly and cost effectively for use in experiments during the CFD evaluation process.

The key technologies of rapid manufacturing (RM) are rapid prototyping (RP) and rapid tooling (RT). RP is a technology for quick fabrication of physical models or functional prototypes directly from computer aided design (CAD) data. RT involves the production of moulds and tooling inserts using RP.

EXPERIMENTAL PROCEDURE

The experimental rig was a closed loop arrangement where a head tank contains the working fluid which in this case was water. The pump itself was driven by a 3kW induction motor to operate at a constant speed of 3000 rpm. The motor was connected to a dynamometer containing a load cell to accurately measure the input torque to the impeller for calculating the pump efficiency. The fluid flowrate was determined by a flow control valve metering the flow to a degree necessary to produce a running characteristic. This allowed a range of possible flows to be measured using a hall effect turbine flowmeter at a constant running speed (Fig. 3).

The test procedure was to measure input power, suction pressure and discharge pressure over a range of flowrates. The test impeller was a 30 bladed impeller of width 1.3 mm and diameter 74.5mm. The impeller was a double suction shape designed with alignment of the blades to balance axial thrust (Fig. 4). In this design the impeller had radial teeth or vanes machined into each side at its periphery.

The fluid entered both sides of the impeller through a suction port making the unit a double suction unit. The casing had a barrier wall "stripper" through which the impeller passes with close clearance (Fig. 4). The stripper seperates flow between suction and discharge and the length of this barrier was equal to at least two blade pitches. The angle between the inlet and outlet ports, known as the "stripper angle", was 30° in the test case.

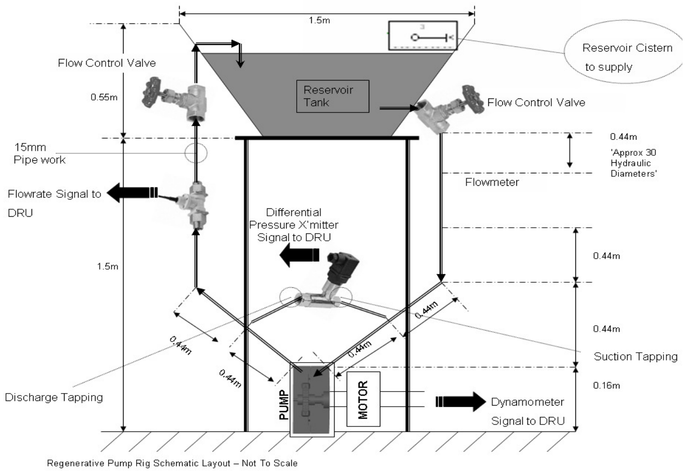


Fig. 3: **Regenerative Pump Rig Schematic**

DESIGN OF THE REGENERATIVE PUMP IMPELLER

The regenerative pump uses an impeller with Turbine-type blades mounted on the periphery running in an annular channel surrounding the periphery of the wheel. In the design, the impeller has radial teeth machined into the impeller periphery and the fluid passes through an open annular channel and circulates repeatedly through the impeller vanes. (Figs. 1, 4)

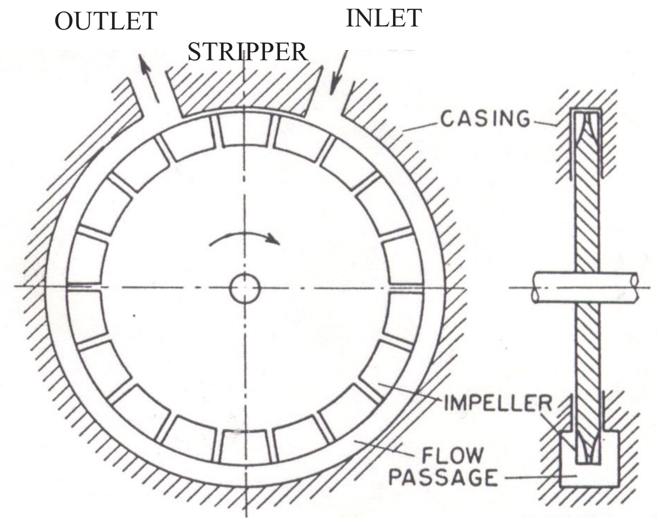


Fig. 4: **Regenerative Pump**

The regenerative pump is sometimes also referred to as a peripheral pump, turbulence pump, friction pump, turbine pump, drag pump, side channel pump, traction pump or vortex pump. The repeated fluid circulation during the flow process or 'multistaging' principally allows regenerative pumps to generate high heads at relatively low specific speeds.

It is essential to have access to manufacturing methods that can produce dimensionally accurate, small and complex parts. Having determined that the baseline radial impeller (Fig. 1), with parallel blade surfaces, was the limit of operator controlled milling techniques, an alternative approach was required to facilitate the production of increased complexity variants of this standard. (Fig. 2) The need is to consider a faster and cheaper process to produce prototypes. An answer to this need is rapid prototyping.

Previous means of producing a prototype typically took man-hours, many tools, and skilled labour. For example, drawings were sent to skilled craftsmen where the design on paper was followed and a three-dimensional prototype was produced in wood. This typically was not a speedy process with high skilled labour costs. The complexity of the blade profiles, need for strength, accuracy/surface finish, quality whilst considering the relative size present problems in this approach.

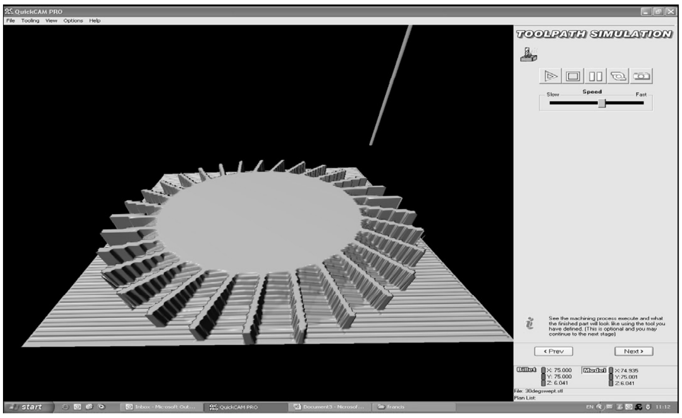
MANUFACTURING

Fabrication with rapid prototyping methods may be divided broadly into those involving the addition or the removal of material.

In this paper, RP systems are considered to build prototypes for the regenerative pump impeller using 4 axis milling machine, 3D printing, fused deposition modelling (FDM) and FDM in conjunction with RTV process (vacuum forming).

RP is an acronym for Rapid Prototyping while SRP is an acronym for Subtractive Rapid Prototyping. Subtractive Rapid Prototyping is used to describe traditional CNC cutting where generally material is removed from a solid block with a rotating cutter. In the strictest sense Rapid Prototyping applies to both additive and subtractive processes since both create prototypes in a relatively rapid fashion. In recent years, Rapid Prototyping has generally referred to the innovative additive processes which build a model up one layer at a time. This additive process allows the creation of extremely complex parts that cannot be produced by traditional Subtractive Rapid Prototyping machines.RP parts are generally created as conceptual models for designers and manufacturers to evaluate at the product development stage RM parts are usually made for inclusion in a finished product.

The first method considered producing the blades was with 4 axis CNC. CNC machines can exist in virtually any of the forms of manual machinery, like horizontal mills. A 4th axis allows rotation of machine parts. The part can be machined and then rotated, or continuously spun as it is machined. The most advanced CNC milling-machines, the 5-axis machines, add two more axes in addition to the three normal axes (XYZ). The fifth axis (B axis) controls the tilt of the tool itself. (Fig. 5). In the case of the regenerative pump impeller the set-up and fixture difficulties particularly for 10 or more blade configurations was considered.

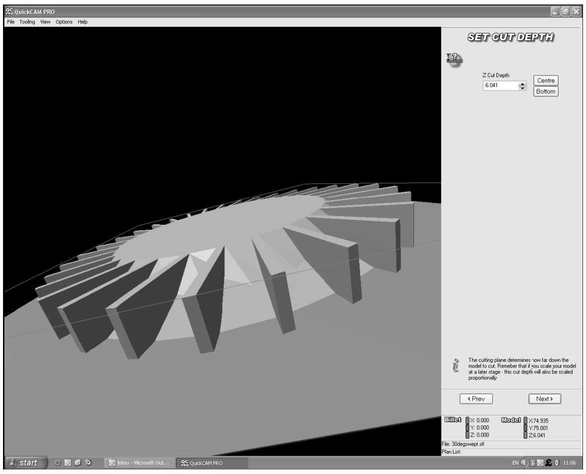


See the machining process execute and what the finished part will look like using the tool you have defined. (This is optional and you may continue to the next stage)

Billet X: 75.000 Y: 75.000 Z: 6.041
Model X:74.935 Y:75.001 Z:6.041
File: 30degswept.stl
Plan List:

Fig. 5: **CAM tool path plot of Impeller**

As seen in Fig 6, the Impeller would have to be turned and refixed to allow symmetric machining. The geometry of the impellers that were assessed contained difficult overhangs and interior volumes (between blades), that proved problematic for the four axis machines. The need to machine along a split line then, turn the component and continue machining would introduce repeatability and allignment issues for the operator. This would increase manufacturing time and be a source of possible error and was hence discounted as a production method. [Fig 6]



Z Cut Depth: -6.041

The cutting plane determines now far down the model to cut. Remeber that if you scale your model at a later stage - this cut depth will also be scaled proportionally

Billet X: 0.000 Y: 0.000 Z: 0.000
Model X:74.935 Y:75.001 Z:6.041
File: 30degswept.stl
Plan List:

Fig 6: **CAM tool split line plot of Impeller**

The next category to be considered was 3D printing rapid prototyping technology. A three dimensional object is created by layering and connecting successive cross sections of material. 3D printers are generally faster, more affordable and easier to use than other additive fabrication technologies. Layers of a fine powder (plaster, corn starch, or resins) are selectively bonded by "printing" an adhesive from the inkjet printhead in the shape of each cross-section as determined by a CAD file. (figs. 7, 8)

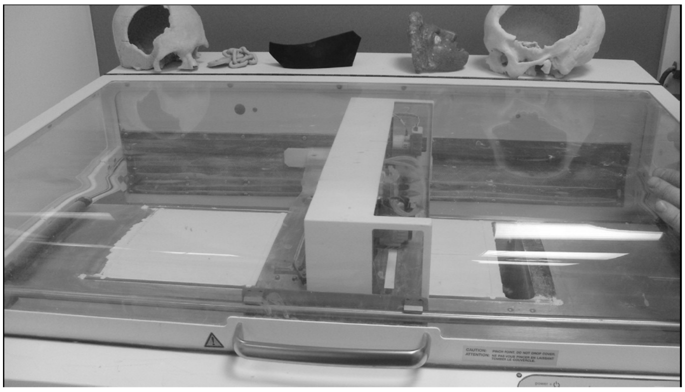


Fig 7 : **3D -Printer**

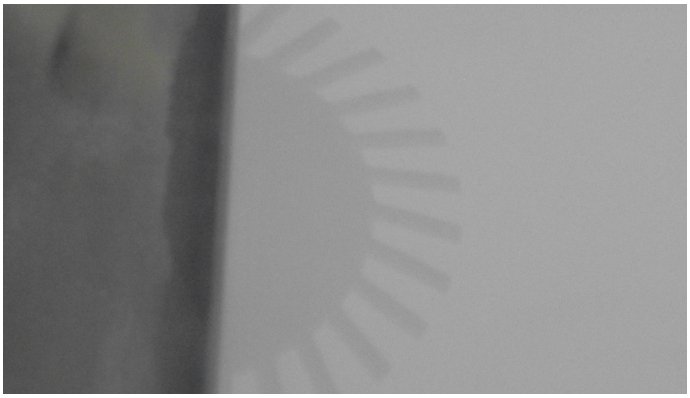


Fig 8: **Bonded Shape Impeller Lay down**

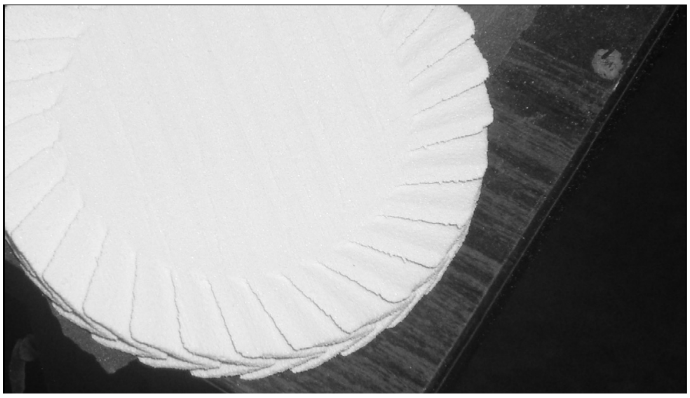


Fig 9: **3D Impeller**

The finished printed impeller is then coated with an infiltration material to prevent the fragile structure from crumbling. (Fig 9). Even after coating the specimen proved too fragile to test in the experimental rig.

The next process to be considered was fused deposition modelling. (FDM) systems consist of two movable heads (one for building the part and one for the supports) which deposit threads of molten material onto a substrate (Fig 11). The material is heated just above its melting point so that it solidifies immediately after extrusion and cold-welds to the previous layers. When the first layer is complete, the platform lowers by one layer thickness and the process begins again. The part is easily removed from the platform, supports are removed and the specimen is ready. (Fig 10)

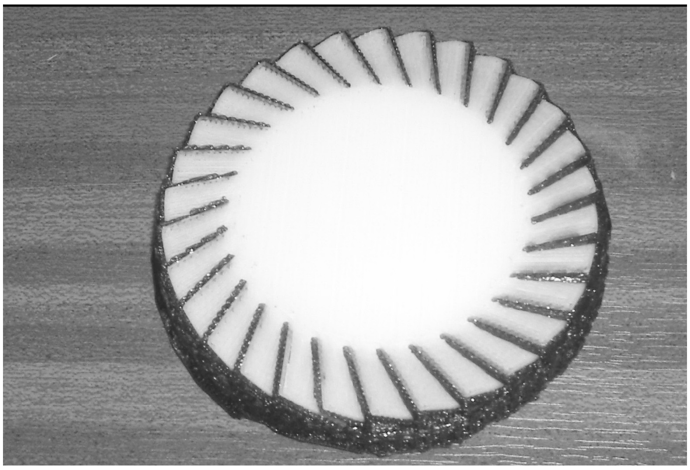


Fig 10: **FDM Completed Impeller**

The technology was developed by S. Scott Crump in the late 1980s and was commercialised in 1990. The FDM technology is marketed commercially by Stratasys, which also holds a trademark on the term. [9]

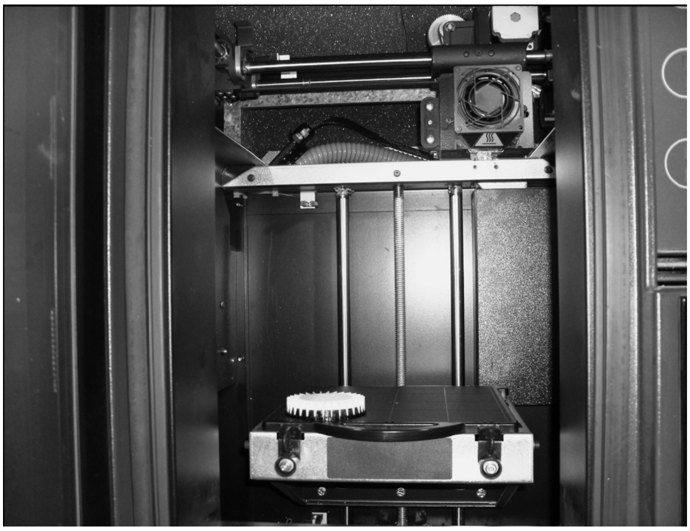


Fig 11: **FDM Machine and completed Impeller**

Several materials are available with varying trade-offs between strength and temperature. As well as acrylonitrile butadiene styrene (ABS) polymer, the FDM technology can also be used with polycarbonates, polycaprolactone, polyphenylsulfones and waxes. A “water-soluble” material can be used for making temporary supports while manufacturing is in progress. Marketed under the name WaterWorks by Stratasys this soluble support material is actually dissolved in a heated sodium hydroxide solution with the assistance of ultrasonic agitation [9].

ABS, $(C_8H_8 \cdot C_4H_6 \cdot C_3H_3N)_n$, is a common thermoplastic used to make light, rigid, molded products such golf club heads, (due its good shock absorbance). It is a copolymer made by polymerizing styrene and acrylonitrile in the presence of polybutadiene. The proportions can vary from 15 to 35% acrylonitrile, 5 to 30% butadiene and 40 to 60% styrene. The advantage of ABS is that this material combines the strength and rigidity of the acrylonitrile and styrene polymers with the toughness of the polybutadiene rubber. The most important mechanical properties of ABS are resistance and toughness. A variety of modifications can be made to improve impact resistance, toughness, and heat resistance. The impact resistance can be amplified by increasing the proportions of polybutadiene in relation to styrene and also acrylonitrile although this causes changes in other properties.

The FDM part was produced and run on test. However the impeller blades broke apart and after close inspection it was observed that the extruded material had small voids across the blade thickness. This was due to insufficient material lay down as a result of the relative blade size. (Fig 12)

Of the processes described, only the FDM process was able to produce a specimen for direct use.

Fig 12: **Failed FDM Impeller**

To produce a mechanically stronger impeller FDM in conjunction with RTV was considered. RT as previously mentioned involves the production of moulds and tooling inserts using RP. Room temperature vulcanizing (RTV) is a relatively inexpensive and fast way to fabricate prototype or pre-production tools. RTV tools are also known as silicone rubber moulds. The most widely used form of RTV moulding is vacuum casting. (Fig 13)

The range of materials with improved strength characteristics and the ability of better filling of the impelller profile to prevent voids increases with RTV. A porous or vented mold is used and is placed on a table or container where vacuum is applied. The liquid to be cast will be driven into the mold by atmospheric pressure, while the vacuum will also remove trapped air that would otherwise impede the free flow of the liquid casting material.

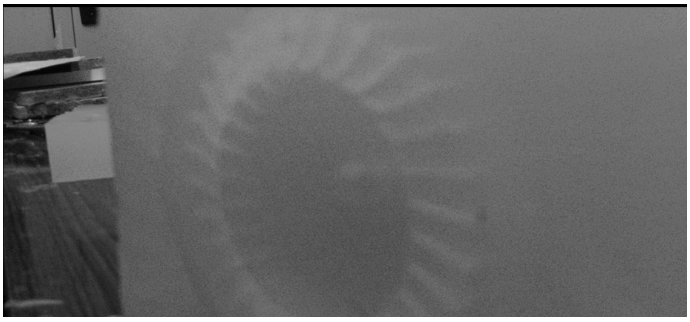


Fig 13: **RTV mould containing Impeller**

Vacuum Casting is widely used for producing accurate silicone tools for casting parts with fine details and very thin walls. Vacuum castings are precise replicas of the patterns, dimensionally accurate without blemishes with all profiles and textures faithfully reproduced.

The main difficulty till this point had been producing impellers with such small dimensions that could be produced mechanically strong enough to survive the fluid loading within the running pump.

The vacuum casting process includes the following main steps:

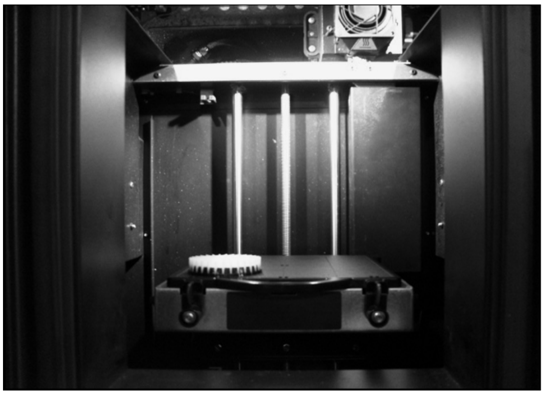


Fig 14: **FDM pattern**

The first step is to produce a pattern using any of the available RP processes (FDM in this case) (Fig 14)

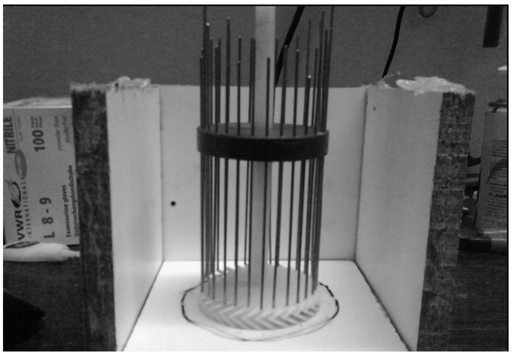


Fig 15: **Gated / vented blade.**

The impeller blade with a chevron profile shown here, is prepared by adding venting and gating to the pattern; this is needed as the vacuum is imposed during casting to allow air to escape (Fig 15).

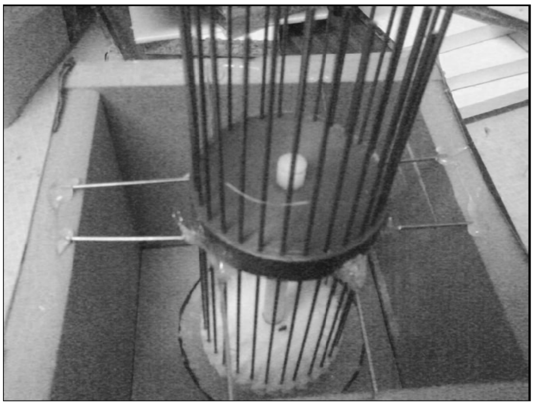


Fig 16: **Suspension and parting**

The pattern is fit with a casting gate and set up on the parting line, and then suspended in a mould casting frame. The pattern needs to have adequate mould material on all sides and still have the parting line identified to facilitate removal (Fig 16).

Fig 17: **Mould pouring**

Once the two-part silicone-rubber is de-aerated and then mixed, it is poured into the mould casting frame around the pattern. (Fig 17)

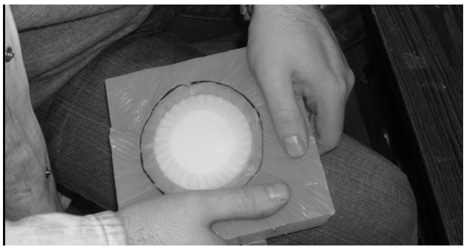


Fig 18: **Pattern removal**

After curing the mould inside a heating chamber; the next stage is the removal of the pattern from the silicone mould by cutting along the parting line and then closing and sealing the mould; (Fig 18)

The computer-controlled equipment mixes and pours the resin inside the vacuum chamber. As this takes place in a vacuum, the mould is filled completely without leaving any airpockets or voids. The MCP vacuum casting requires initial investment in a vacuum chamber with two sections.

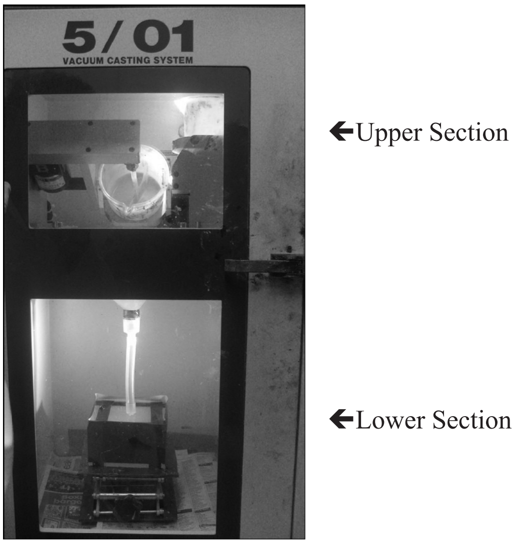


Fig 19: **Vacuum casting Impeller**

The upper section is for mixing the resin and the lower is for casting the resin into the mould. (Fig 19)

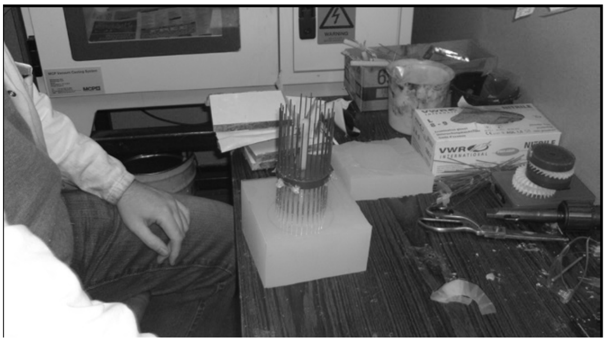


Fig 20: **Impeller mould**

After curing the part in a heating chamber for 2–4 hours and then removing it from the mould. After casting the resin, the mould is moved to the heating chamber for between two to four hours to cure the urethane part. (Fig 20).

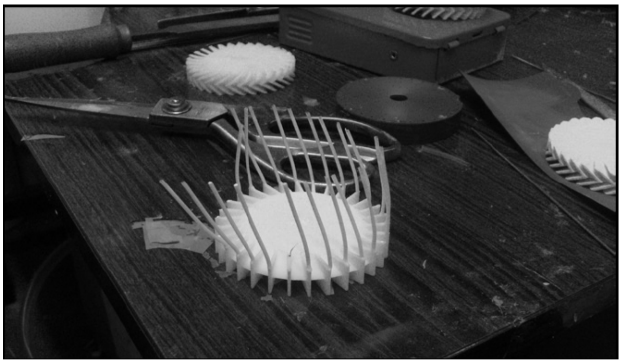


Fig 21: **Removing gate risers**

The gate and risers are removed from the casting to make an exact copy of the pattern. After hardening, the casting is removed from the silicone mould. (Fig 21)

The introduction of RT technology enabled prototype, pre-production and in some cases full production tooling to be fabricated with significantly reduced time frames.

RESULTS

Ten FDM/RTV manufactured blade profiles were tested and all completed the testing without any failures. The success of the methodology has lead to further more complex blade profiles being assessed in the experimental test procedure.

Rapid prototyping techniques are extremely useful in helping the pump designer to conduct preliminary testing on a low-cost prototype. Based on the results obtained, the ability to modify or improve the designs before resorting to more costly fabricating methods has proved extremely beneficial in this current research.

The results have shown that FDM/RTV is a viable and feasible method of producing prototypes for testing. Further refinements of the technique are currently being pursued so that the surface finish, is enhanced whilst maintaining the accuracy of the parts produced.

Preliminary results demonstrate that the impellers have the potential to improve the pump efficiency [13].

Whilst the process has demonstrated reasonable success in producing viable test samples, the FDM/RTV method several disadvantages. Surface finish and the need for a two stage manufacturing process (FDM then RTV). Limited range of materials available meant that a new method of photopolymer setting will be considered in the future. This will increase the range of materials for selection, improve surface finish and delete the need to use RTV. However the results achieved using the FDM/RTV methodology have successfully lead to the optimisation of the pump in an effective manner. [13]

CONCLUSIONS

As the capabilities of CFD continue to develop, it is to be expected that the uncertainties associated with CFD prediction should also reduce. At the very least it is to be expected that there will be a continuing growth in processing power for the foreseeable future, which will reduce and perhaps remove the geometric simplifications which have to currently be made. The ability to test and validate the models is only possible through detailed experiments. The remarkable increase in the number of commercially available RP and RT solutions since the 1990s by advances in three-dimensional CAD modelling, computer aided manufacturing, computer numerical control and the development of new materials, are the reason this work proceeds. The sucess of the performace and CFD modelling has carroborated [130, the successfull flow visualisation studies on the pump [10], [12].

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