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Experimental and Computational Fluid Dynamics (CFD) Analysis of Additively Manufactured Vanes

Dr. Fayyaz Rehman[1], Robert Benham[2]

[1]Associate Professor, Faculty of Creative Industries, Architecture and Engineering, Solent University, Southampton, UK
[2]Senior Lecturer, Faculty of Creative Industries, Architecture and Engineering, Solent University, Southampton, UK

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Abstract - *Additive Manufacturing is emerging as a cost-effective alternative to conventional manufacturing techniques for applications requiring: components with complex geometries, assemblies comprising a large number of parts or small productions runs. Cost savings can be realized through reduction in raw material required, reduced manufacture times and removing the need for expensive tooling. AM can offer both an economical alternative to the existing aluminum alloy vanes. The current designs of available vanes are limited to flat/angled or hemispherical profiles. Much more sophisticated vane profiles are possible by using 3D CAD designs that can be tested by means of manufacturing vanes through AM techniques. The paper will analyze experimental and CFD simulation results of identical vanes made from AM materials to existing aluminum alloy vanes. New vane designs will also be tested, which will allow for comparisons to theoretical models for simple geometries as well as experimentation to produce more complex designs to reduce weight and increase the performance. In addition, other significant factors will also be reviewed, such as cost, build-time, finish and fitness for purpose related to AM manufactured vanes.*

Key Words: Additive Manufacturing, Photopolymer Resin, Experimental Methods, CFD Analysis

1. INTRODUCTION

Additive Manufacturing is relatively a new material addition technology to design and manufacture production ready polymeric and metallic components as compared to the classical manufacturing processes such as machining, casting or moulding. They allow new innovative design to be produced with regards to material, shape and complexity of the part because these manufacturing processes eliminate the need of tooling.

A lot of current restrictions of design for manufacturing and assembly are removed due to the use of these AM processes. However, AM processes have their own characteristics and requirements which needs to be considered during the design stage to ensure the manufactured parts conform the quality requirements. Additive manufacturing (AM) printed parts offer a number of distinct advantages over conventionally machined components, in terms of production time, cost, and the possibilities of achieving complex geometries. The current experiment used at the University for undergraduate students studying Mechanical Engineering includes two vanes, manufactured from 6063 aluminium alloy. These existing vanes are flat plate and hemispherical (Figure 1). Obtaining other shape vanes from the supplier is limited to only two other types of vanes (30° flat plate and 120° conical); the lead time for the supply is around 6 weeks, and the cost is around double that of the existing AM specimens. Given these constraints the applications of AM are clearly warranted. Multiple vanes can be created with differing geometries at a low cost and within two days. In addition, computational fluid dynamic (CFD) modelling can be used to simulate the flow and predict parameters that cannot be estimated accurately from the experiment. During the experiment students record a range of volumetric flow rates and determine the force on the vane.

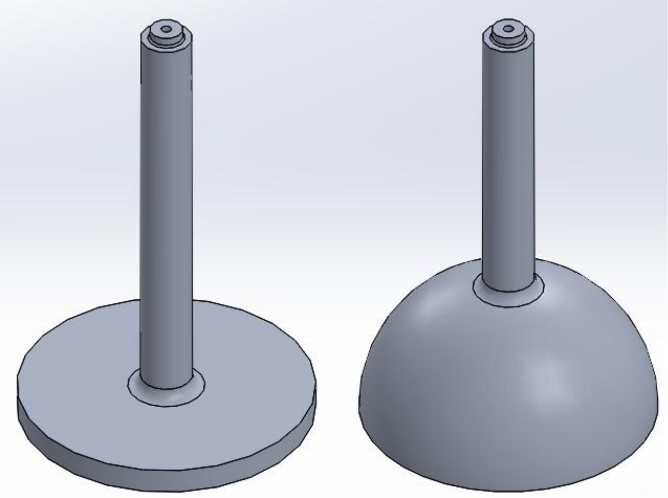


Figure 1: Existing Aluminium 6063 (Flat & Hemispherical) Vanes

2. RESEARCH METHDOLOGY

Vanes are made from the Visijet M3 crystal material [1], a tough translucent plastic type commercially available photopolymer created using an AM material jetting machine. Vanes were printed with 16 microns print resolution. Due to the limited time and scope of testing, the number of vanes was restricted to a duplicated hemispherical vane (for direct comparison to the aluminum alloy type), a domed vane based on the top half of an egg (generated by computer-aided design), a hemispherical vane with 1.5 mm dimples and one with 4.5 mm diameter dimples (Figure 2) on the inside surface of hemispherical profile. The flat vane was not produced since the design yields a low force in comparison to curved profiles.

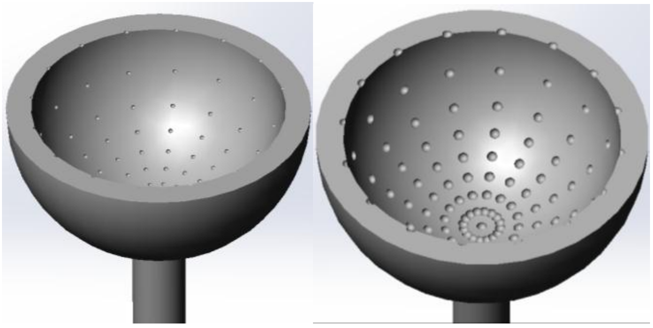


Figure 2: 1.5 mm and 4.5 mm dimpled Hemispherical Vanes

The experimental set-up is shown in Figure 3. A number of flow rates are created and are measured by setting the jockey weight to achieve equilibrium and timing the flow to an attached hydraulic tank. The procedure for performing the experiment is outlined below:

- A vane is selected and secured to the weigh-beam by means of the retaining screw.
- With the jockey weight set to the "zero" position the adjusting nut is moved to set the weigh-beam horizontal.
- The pump is switched on and set to maximum flow.
- The jockey weight is adjusted so that the weigh-beam returns to the horizontal position.
- The hydraulic tank is then filled by closing a valve. A capacity of 35 liters is measured. The time it takes for this capacity to fill is recorded.
- The timing procedure is repeated twice at maximum flow.
- The flow rate is reduced so that the weigh-beam is no longer horizontal. Repositioning of the jockey weight is carried out as per step 4 and then the remaining steps are repeated until results for 8-12 flow rates are recorded.

The vanes were tested over a range of 10 different jockey weight positions, timed for three runs and then checked again. An ultrasonic motion sensor was also used to monitor the amplitude of vibration at the end of the weigh beam. The vane was photographed and video recordings were taken of it operating in situ. Finite Element Analysis (FEA) based flow simulation was carried out using the actual flow rates, so that the variation in velocity profile could be seen and the exit velocity of the water at the outer edge of the vanes can be computed and verified.

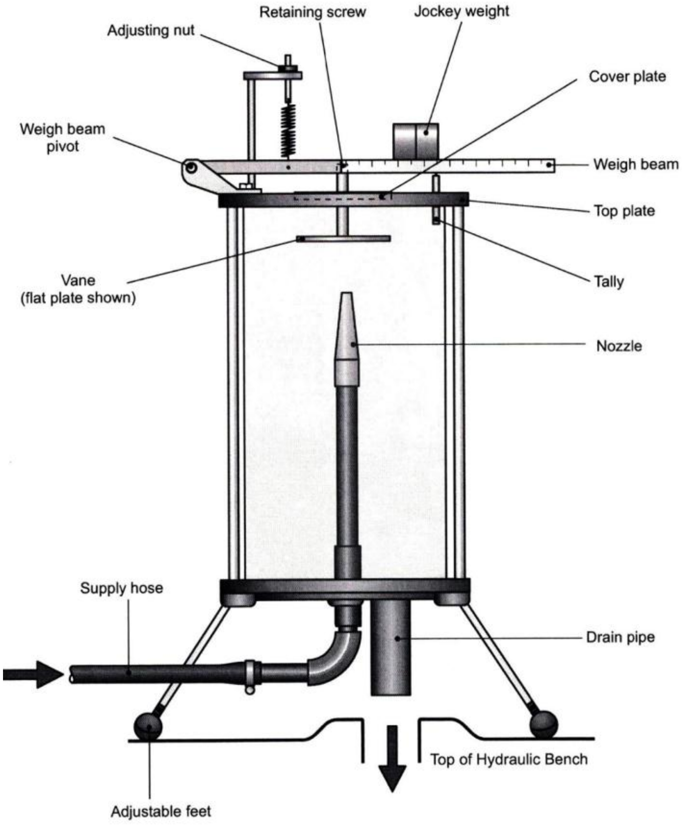
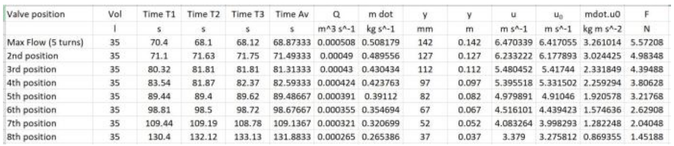


Figure 3: Experiment set-up (courtesy of TecQuipment Ltd.).

A spreadsheet (Table 1) was used to compute the flow rates and forces on the vane. The thrust force was then plotted against the rate of change in momentum for each vane, and the thrust force was also plotted against the volumetric flow rate. In addition, a data logger was used in conjunction with an ultrasonic motion sensor to monitor vibration of the weigh-beam. Trend lines were generated to predict the forces for higher flow rates, and CPD simulation was reviewed and utilized in comparisons between the vanes. It should be noted that for economy reasons, a dimple profile set to one size can be changed to a larger dimple size using a bullnose cutter. However, the depth cannot be controlled or the angle of the tool piece so requires a high level of workmanship to obtain accurate/consistent dimples.

Table 1: Data Collection for different flow rates



Valve position	Vol	Time T1	Time T2	Time T3	Time Av	Q	m dot	y	y	u	u_0	mdot.u0	F
	l	s	s	s	s	m^3 s^-1	kg s^-1	mm	m	m s^-1	m s^-1	kg m s^-2	N
Max Flow (5 turns)	35	70.4	68.1	68.12	68.87333	0.000508	0.508179	142	0.142	6.470339	6.417055	3.261014	5.57208
2nd position	35	71.1	71.63	71.75	71.49333	0.00049	0.489556	127	0.127	6.233222	6.177893	3.024425	4.98348
3rd position	35	80.32	81.81	81.81	81.31333	0.00043	0.430434	112	0.112	5.480452	5.41744	2.331849	4.39488
4th position	35	83.54	81.87	82.37	82.59333	0.000424	0.423763	97	0.097	5.395518	5.331502	2.259294	3.80628
5th position	35	89.44	89.4	89.62	89.48667	0.000391	0.39112	82	0.082	4.979891	4.91046	1.920578	3.21768
6th position	35	98.81	98.5	98.72	98.67667	0.000355	0.354694	67	0.067	4.516101	4.439423	1.574636	2.62908
7th position	35	109.44	109.19	108.78	109.1367	0.000321	0.320699	52	0.052	4.083264	3.998293	1.282248	2.04048
8th position	35	130.4	132.12	133.13	131.8833	0.000265	0.265386	37	0.037	3.379	3.275812	0.869355	1.45188

3. ANALYSIS OF RESULTS

3.1 Force on Vanes

Due to the jet of water impinging on the vane, it is possible to calculate the force of impact of water (Figure 4) on vane which results a slight difference between inlet and exit velocities of water.

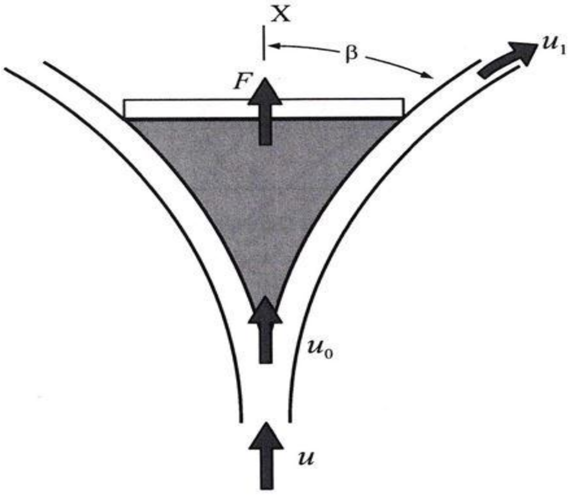


Figure 4: Vertical Jet of a Fluid Striking a Symmetrical Flat Vane.

This gives a relationship between mass flow rate and force impact on vanes through the following formula.

$$F = \dot{m}\,(u_0 - u_1 \cos\beta) \qquad (1)$$

The plot of force for two aluminum alloy vanes is shown in figure 5.

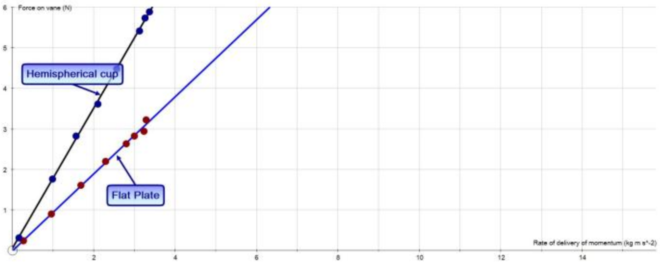


Figure 5: Force-Momentum Relationship for Existing Vanes

Using the actual lab data, the volumetric flow rates (or mass flow rates) can be compared against the force on the vane, which are plotted as shown in Figure 6 for all 4 different types of vanes.

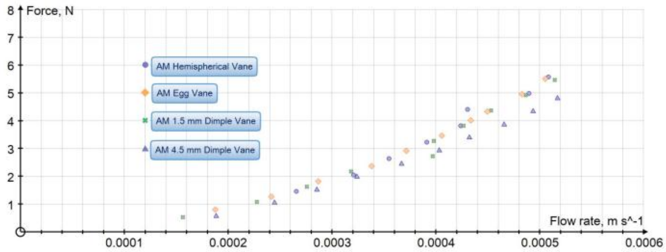


Figure 6: Force- Flow Rate Plot for all AM manufactured Vanes.

The plotted values were used to predict the trends of four vanes for higher flow rate as shown in Figure 7.

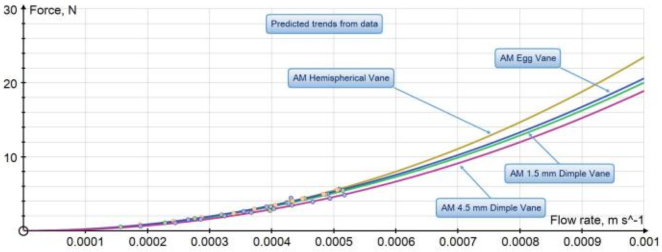


Figure 7: Predicted Trends of Force Plots against Higher Flow Rates for all AM manufactured Vanes.

3.2 Velocities at the Vanes

Plots were also created by calculating the exit velocities from the actual data for given volumetric flow rates, shown in Figure 8.

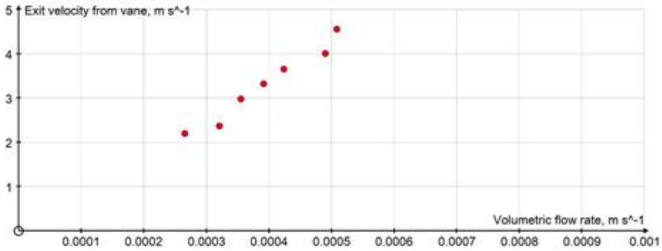


Figure 8: Exit Velocity Vs Flow Rate Plot.

In the experiment students plot the force on the vane against the product of momentum and work on the assumption that u0 ≈ u1. A graph can be plotted and the gradients can be compared. The vane striking velocity is determined by the exit velocity of the fluid from the nozzle. Figure 9 shows the different velocities. Clearly there is a difference between the exit velocity of the jet to the striking velocity, although for vanes without dimples the values are close. Comparisons can be made between the hemispherical AM vane and the egg-shaped AM vane show gradients of 1.73 and 1.67 respectively. Losses due to turbulence, friction, variations in pump efficiency/parameters at different flow rates and other factors will have a significant effect on the readings. The accumulation of losses across the variation of flow rates is particularly of importance here, as reviewed by Stoffel [2]. The CPD simulation carried out for maximum and minimum velocities showed consistently higher velocities, which is to be expected with the losses mentioned.

The results show a close correlation between the 1.5 mm dimpled surface and the egg vane profile. The 4.5 mm diameter dimpled vane shows the lowest forces, due to the losses around the dimples. Since the nozzle remained unchanged, the potential effects of the dimples could not be realized. Dimple experimentation has been evaluated in other contexts by Zhang et al [3] albeit in thermodynamic modelling context. Many research papers on vane design concentrate on spacer grids.

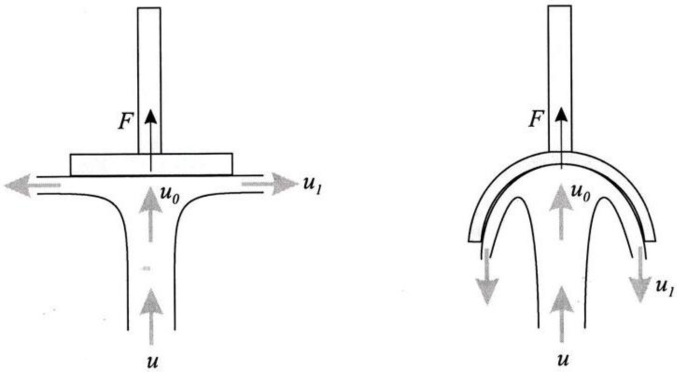


Figure 9: Velocities direction of the fluid for a flat plate vane (left) and hemispherical vane (right).

3.3 Vibrational Displacement

The ultrasonic motion sensor data shows the lowest difference of vibrational amplitude displacement was on the 1.5 mm dimpled AM vane at full flow rate as shown in Table 2. Mean values and standard deviations were recorded over a 90 second interval. The egg shape vane was consistent with the hemispherical vane; although the standard deviation for the egg profile was the lowest of all of the vanes. Runs were timed over 90 seconds and were repeated to check the ranked order of standard deviations. The results (Table 2) show that the hemisphere profile had the least vibrational displacement at low flow rate and the egg profile had the most. This was visually noticeable in addition to the recorded data.

Table 2: Vibrational Displacement for Different Vane Profiles

AM Egg	Max	Min	Δh	Mean	S.D.	Mode
	m	m	m	m	m	
	0.137	0.125	0.012	0.131	0.00125	FULL
	0.141	0.131	0.01	0.13	0.00094	LOW
AM 1.5 mm dimples	Max	Min	Δh	Mean	S.D.	Mode
	m	m	m	m	m	
	0.134	0.128	0.006	0.131	0.00125	FULL
	0.133	0.126	0.007	0.13	0.00114	LOW
AM 4.5 mm dimples	Max	Min	Δh	Mean	S.D.	Mode
	m	m	m	m	m	
	0.134	0.126	0.008	0.129	0.00158	FULL
	0.134	0.125	0.009	0.128	0.00166	LOW
AM Hemisphere	Max	Min	Δh	Mean	S.D.	Mode
	m	m	m	m	m	
	0.135	0.125	0.01	0.131	0.00305	FULL
	0.137	0.123	0.014	0.132	0.00241	LOW

3.4 Flow Dynamics

Finite Element Analysis based flow simulations were done to evaluate and compare the flow dynamics results obtained from experimental data for all four different types of vanes to. Flow simulations accurately predicted the pattern of flow of exit velocities vertically downward as shown for hemispherical AM vane in Figure 10 for actual flow to CFD based simulated flow in Figure 11.

Figure 10: Exit Flow Direction for Hemispherical Vane

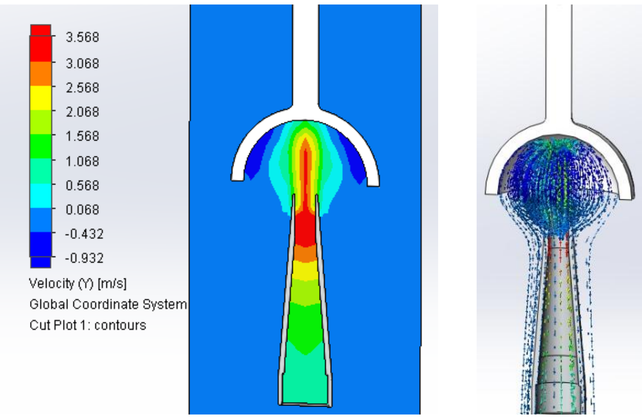


Figure 11: Flow simulation velocity trajectories for hemispherical AM vane for 0.000265 m^3/sec volumetric flow rate

Similarly flow simulations accurately predicted the pattern of flow of exit velocities downwards and sideways for egg shaped AM vane in Figure 12 for actual flow versus simulated flow in Figure 13.

Figure 12: Exit Flow Direction for Egg Shaped Vane

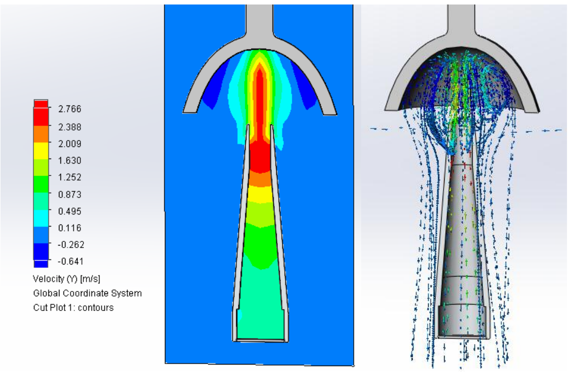


Figure 13: Flow simulation velocity trajectories for Egg shaped AM vane for 0.000188 m^3/sec volumetric flow rate

Flow simulations also accurately predicted the pattern of flow of exit velocities vertically downward as shown for hemispherical 4.5 dimpled AM vane in Figure 14.

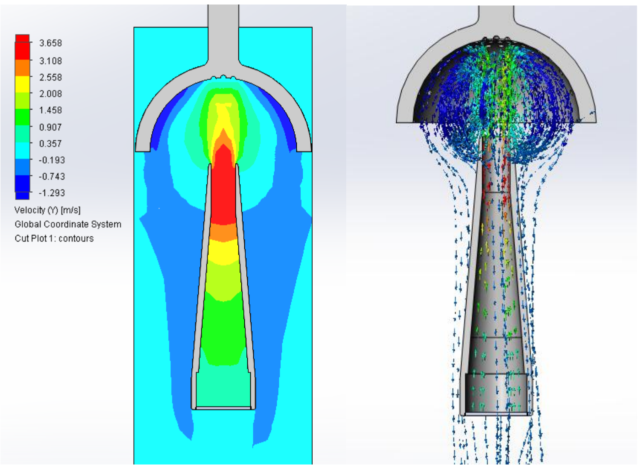


Figure 14: Flow simulation velocity trajectories for hemispherical 4.5mm dimpled AM vane for 0.000265 m^3/sec volumetric flow rate

Simulation results also verified the impact and exit velocities obtained from experimental data for both hemispherical and egg shaped AM vanes as shown in Table 3. Change in shape from hemispherical to egg shaped clearly shows reduction in exit velocities.

Table 3: Comparison of Impact and Exit Velocities through Experiment and Simulation

Hemispherical AM Vane				Egg Shaped AM Vane			
Parameter	Experimental	Simulation	% difference	Parameter	Experimental	Simulation	% difference
Impact Velocity (U0)	3.28 m/sec	3.32 m/sec	1.20%	Impact Velocity (U0)	2.24 m/sec	2.36 m/sec	5%
Exit Velocity (U1)	2.2 m/sec	3.29 m/sec	33%	Exit Velocity (U1)	Not Possible to Measure due to different flow directions	2.3 m/sec	N/A

4. CONCLUSIONS

The anticipated cost reduction that results from using Additive Manufacturing instead of machined aluminum alloy (appropriate conventional manufacturing technique for a vane) has been estimated. The benefits of AM in the production of these low-force vanes are clear: low-relative cost per unit, complexity in design and short lead-times (48 hours in extreme ultra high definition for multiple vanes). There was no difference in the performance between the original 6063 aluminum alloy and the AM hemispherical vane. Investigation through experimental setup and comparison through CFD results provided interesting results. In addition to the top half of an egg profile, other profiles are possible, by means of 3D hand-scanning other objects, natural or man-made. Structures can be analyzed by spline interpolation (as covered by Kreyszig [4]) and adapted profiles are possible. Clearly results are going to be limited unless the nozzle can be redesigned so that the interaction of the jet is optimized. Nozzle design is crucial in optimization of the flow in turbines, studies by Pereira et al [5] have researched into finding the optimum efficiency conditions and flow analysis in the nozzle. To overcome the pump irregularities a new experimental set-up utilizing a gravitational feed could be considered, which would allow a large head and much higher flow rates than the current experiment. A wider range of flow rates is required so that evaluation at realistic operating conditions of hydropower applications can be applied. Scale factors of both size and flow rate need to be evaluated, which requires the construction of new experimental apparatus.

This study could be developed further, once optimization of the nozzle and vane combination has been established for the experimental set-up. Vane design could be applied to help in turbine models such as in Pelton buckets. Zoope et. al [6] explore flow analysis in this context. Currently the experiment analyses single vanes and a fixed nozzle orientation, so the potential of applications in Pelton or Turgo turbines would require a completely new experimental set up. This however does warrant further investigation once more work has been carried out with the existing experiment. Multiple vanes using AM show many distinct advantages. Material toughness and strength need to be considered though as forces will be much higher than in the experiment carried out in this study.

Acknowledgements

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BIOGRAPHIES

"**Dr. Fayyaz Rehman** is an Associate Professor at Warsash School of Maritime Science and Engineering, Solent University, UK. He is a Fellow of Higher Education Academy, a Chartered Engineer from the Engineering Council and a Fellow of the Institution of Engineering Designers, UK. He is also vice chair and committee member of the Consortium of UK Manufacturing Engineering Heads (COMEH), a UK-based body responsible for promoting manufacturing engineering education and research, as well as organizing the International Conference on Manufacturing Research (ICMR) conference series annually. His research interests are CAD/CAM/CAE, Material Testing and Additive Manufacturing Technologies."

"**Rob Benham** is a senior lecturer in engineering science and currently course leader for the HNC Engineering and Foundation Year Engineering. He has been teaching on engineering courses at Solent University for over 15 years. Prior to the introduction of individual course leaders, he was programme leader on the old engineering programme. In 2003 Rob completed his PGCE (post-compulsory education) at Oxford Brookes University. He then taught in further education for one additional year. He continued some FE teaching and also supply teaching when working part-time. In addition to this, in more recent times, Rob has delivered many taster days at Solent. He has strong research interests in manufacturing and materials. As a result, he brings a wide range of experience of educational settings with a diverse scope of learners."