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

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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 an economical alternative to the existing alloy weir design to perform fluid mechanics experiment in our lab. An existing 2.5 m open channel fluid flow experiment contains a set of standard weirs which is limited to sharp crested flat profile in design. This paper will compare experimental AM weirs (e.g., labyrinth, piano, catenary), that would not be possible on some laser-cut polymer or machined aluminum weirs. Due to the bespoke complex nature of weirs' design other manufacturing methods would be too expensive and impossible to use. AM technology allows a cost-effective solution for progressive design modifications to be implemented throughout investigations. This paper will highlight comparisons made between a range of AM produced weirs in terms of flow rate, fluid velocity profile, water level height and discharge coefficient. Computation fluid dynamic modelling (CFD) will also be used to verify, analyze, and compare results. Based on the experimental results and verification, the paper will also discuss the suitability of application of AM techniques in fluid flow analysis experiments.*

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 need 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. Weir improvements in their designs have historically required a substantial amount of empirical testing. The existing experiment used at the University for undergraduate students studying Mechanical Engineering uses a 2.5 m long flow channel (Figure 1) which allows for many different experiments to observe the behaviour of open channel flow with various components. The existing apparatus is supplied with machined parts, including simple weirs which are limited to one sharp crested flat weir design (Figure 2), sluice gates and a flat Venturi channel. Most parts are machined; some polymeric parts are injection moulded. The flow channel can be used to test more complex geometry parts. Multiple weirs can be created using AM technology with differing geometries at a much lower cost than the machined alloy parts. Leadtime is around 6 - 8 hours for the components in this study. During the experiment students record a range of volumetric flow rates and determine key fluid parameters. 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. Therefore, computation fluid dynamic modelling (CFD) will also be used to verify, analyse, and compare results. Based on the experimental results and verification, the paper will also discuss the suitability of application of AM techniques in weir design and analysis.

Figure 1: A 2.5 m long flow channel along with hydraulic tank

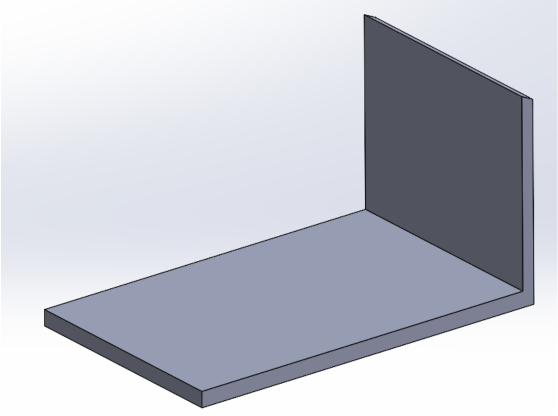

Figure 2: Existing sharp crested flat weir design

2. RESEARCH METHDOLOGY

Due to the limited time and preliminary testing, the number of weirs was restricted to four design models that could be compared to the supplied machined sharp-crested weir. The weirs selected for this study include two with a catenary crest (one empty and one ramped in Figure 3), a labyrinth weir and a piano key type weir (Figure 4). New weirs (Figure 5) are made from tough additive manufacturing polymer, like ABS, a translucent plastic type commercially available photopolymer resin using a Stereolithography (SLA) AM machine.

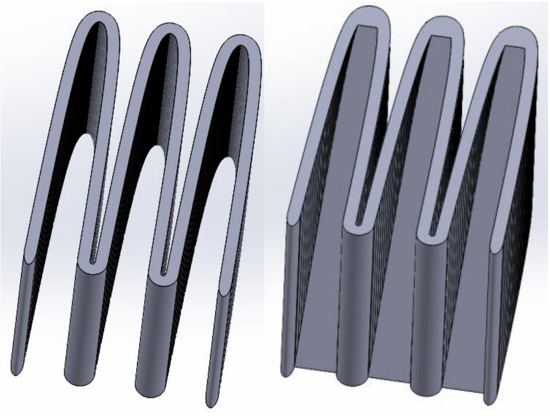

Figure 3: Empty and Ranked Catenary Weirs

Two flow rates were used: maximum flow (to mimic flood conditions) and minimum flow (ensuring full coverage of the weir wall). The datum for taking height measurements was the top of the flow channel and depth to the water level was measured by a depth gauge. Points were measured at 200 mm intervals close to the weir upstream and 600 mm from the weir downstream. A pitot tube connected to a data logger was used to measure the velocity and a representative value was recorded at each of the measuring points using the statistics tool over 20-second time periods.

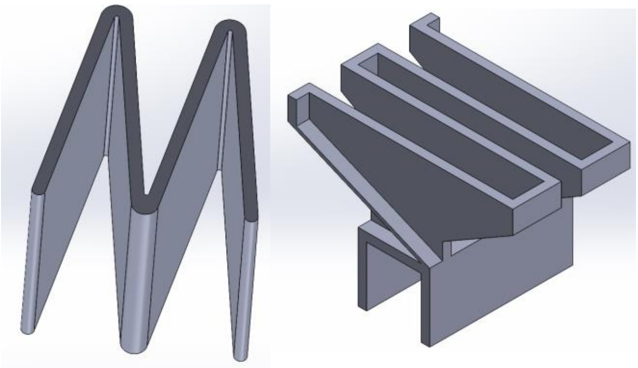

Figure 4: Labyrinth and Piano Weirs

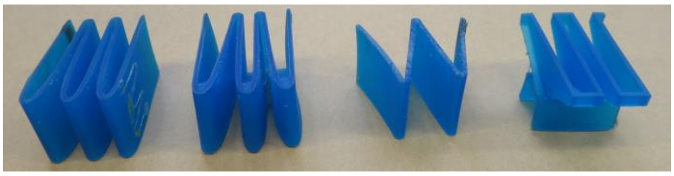

Figure 5: AM weirs (from left to right: empty catenary, ramped catenary, labyrinth, piano key).

The procedure for performing the experiment is outlined below:

- The flow channel is connected to the hydraulic tank and an angle of 0.5° (entry level higher than exit level). The internal dimensions of the channel were recorded (53 mm wide x 120 mm deep).
- The pump is switched on and set to maximum flow.
- The height of the water level is recorded at designated positions along the channel, 200 mm apart. These positions remain constant once the weirs are inserted.
- A pitot tube connected to a data logger is used to measure the velocity of the fluid over 20-second intervals. Statistics tools give the mean, maximum and minimum values. The process is repeated twice to check consistency of readings.
- The volumetric flow rate was recorded by timing the tank to fill to 35 litre capacity. From the data, the velocity is calculated (and compared), the Reynolds number, Froude number as well as flow rates.
- Each weir independently is then inserted 1800 mm from the entry end, and stages 2 – 5 repeated.
- The experiment procedure is repeated for minimal flow (ensuring water coverage on the walls of the weir).

Each weir had a flat crest; further research will look at variations in crest profile. The flow channel was run empty and recorded when set at 0.5° at full flow. A number of parameters were calculated, such as volumetric flow rate, average velocity, the Reynolds number, Froude number. The weirs were then tested at maximum flow rate and then a reduced flow rate so that the range in upstream height could be calculated and the weirs could be compared under different flow conditions. Computational Fluid Dynamic (CFD) modelling based on flow simulation was carried out

using the actual flow rates, so that the variations in velocity profile could be seen and regions of interest established.
A spreadsheet was used to compute the flow rates, Froude and Reynolds numbers as well as carry out comparisons to the supplied (machined) sharp-crested weir. The main comparison factors used are the average height of the water marks upstream; the differences in water heights between the maximum and minimum flow rates; the discharge enhancement ratio, referred to here as the "r" value (see equation 1); the mass-flow rate ratio of discharge between the upstream and downstream and the mass flow rate downstream. CFD modelling was used to compare the calculated the parameters and in addition observe the velocity profiles at regions in the channel such as the weir approach, the crest, nappe, and other sections of the channel far away from the weir.

A spreadsheet (Table 1) was used to compute important results parameters for different flow rates.

Table 1: Data Collection for different flow rates

Sharp Crested								
Position			800	1000	1200	1400	1600	2400
(mm)								
Measured depth from datum	*d*	(mm)	48.5	46.75	44	42	40.25	108
Height of weir	*a*	(mm)	49	49	49	49	49	0
Height of water	*a+h*	(mm)	71.5	73.25	76	78	79.75	12
Height of water above crest	*h*	(mm)	22.5	24.25	27	29	30.75	12
Depth of channel	*a+h+d*	(mm)	120	120	120	120	120	120
Wetted Area - Measured points	*A(points)*	(mm^2)	3789.5	3882.25	4028	4134	4226.75	636
Wetted Area - Weir approach+Weir downstream	*A (wi)/(wo)*	(mm^2)					1629.75	636
Volumetric flow - Measured points	*Q (points)*	(m^3 s^-1)	0.001478	0.001685	0.0017	0.002125	0.002075	0.000671
Volumetric flow - Weir approach+Weir downstream	*Q (wi)/(wo)*	(m^3 s^-1)					0.0008	0.000671
Theoretical discharge	*Q (wi theory)*	(m^3 s^-1)					0.000844	
Coefficient of discharge							0.948202	
Velocity	*v (points)*	(m s^-1)	0.39	0.434	0.422	0.514	0.491	1.055
Hydraulic Depth - points	*D (points)*	(mm)	71.5	73.25	76	78	79.75	12
Hydraulic Depth - weir approach+weir downstream	*D (wi/wo)*	(mm)					30.75	12
Hydraulic radius - points	*R (points)*	(mm)	19.33418	19.4599	19.64878	19.7799	19.89059	8.25974
Hydraulic radius - Weir approach+Weir downstream	*R (wi/wo)*	(mm)					14.23362	8.25974
Froude Number - points	*f (points)*	-	0.465669	0.511978	0.488732	0.587599	0.555113	3.074874
Froude Number - Weir approach+weir downstream	*f (wi/wo)*	-					0.893973	3.074874
Reynolds Number - points	*Re (points)*	-	7502.818	8403.579	8250.533	10116.29	9717.69	8670.673
Reynolds Number - Weir approach+weir downstream	*Re (wi/wo)*	-					6953.94	8670.673
r value = Q(AM weir)/Q(sharp-crested weir)	*r*						1	

3. ANALYSIS OF RESULTS

3.1 Weir Theory

For a sharp crested weir (Figure 6), the computation of discharge is calculated

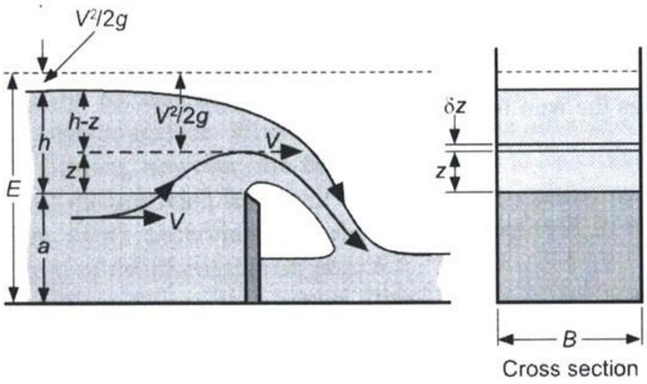

Figure 6: Sharp Crested Flat Weir Flow Parameters

Ignoring the velocity head $\left(\frac{V^2}{2g}\right)$ and assuming horizontal flow:

$$Q=\int_0^h \sqrt{2g(h-z)}B.dz$$

Which gives: $Q=\frac{2}{3}\sqrt{2g}B\sqrt{h^3}$ (theoretical discharge)

and $Q=C_d\frac{2}{3}\sqrt{2g}B\sqrt{h^3}$ (actual discharge)

3.2 Testing of Weirs

One factor that limits the testing of weirs is the relatively narrow width of the available flow channel (53 mm). A lot of research employs wider channels, although the results overall show that the AM weirs had good consistency for the upstream water height a maximum flow. One problem with geometry of the weirs coupled with the parameters was to try and determine the coefficient of discharge accurately. As mentioned by several authors, notably Kumar et al (2020) the determination of these parameters is complicated often requires different modelling approaches. Unlike the sharp-crested weir that has a relatively straight forward formula to calculate the coefficient of discharge, Cd, the other weirs could be compared instead by the discharge enhancement ratio:

$$r=\frac{Q_{AM\ weir}}{Q_{Sharp-crested\ weir}}=\frac{C_d L_{effective}\sqrt{2g}H^{\frac{3}{2}}}{C_d W\sqrt{2g}H^{\frac{3}{2}}}=\frac{L_{effective}}{W} \qquad (1)$$

3.3. Comparison of Maximum and Minimum Flow Rates

Initial testing of the weirs showed very clearly that variation in upstream height between the maximum and minimum flow rates was much lower than the sharp-crested weir. For maximum flow rate, the simple catenary weir exhibits the best combined properties. The comparisons (Table 2) are relatively simple. The labyrinth weir scored the lowest in all parameters apart from average height of water upstream.

Table 2: Maximum Flow Rate Comparisons for Weirs

Max Flow		🟥	🟨	🟩	🟦
		C1	C2	L	P
Average height of water upstream	(mm)	63.7	64.4	64.4	64.9
Difference in height (max-min flow)	(mm)	16.8	17.15	17.8	15.9
"r" value	-	0.828	0.467	0.465	0.584
Cd based on mass flow rate	-	1.12	1.01	0.414	1.08
Mass flow rate down stream	(kg s^-1)	0.802	0.723	0.296	0.771
		Best	2nd	3rd	Worst
Average height of water upstream		🟥	🟩🟨	🟩🟨	🟦
Difference in height (max-min flow)		🟦	🟥	🟨	🟩
"r" value		🟥	🟦	🟨	🟩
Cd based on mass flow rate		🟥	🟦	🟨	🟩
Mass flow rate down stream		🟥	🟦	🟨	🟩

For minimum (reduced) flow rate, again the catenary remains the better model however the comparisons (Table

3) are more complicated. The piano key weir does not perform in majority of parameters such as average height of water upstream, Coefficient of discharge and maximum flow rate.

Table 3: Minimum (Reduced) Flow Rate Comparisons for Weirs

Reduced Flow		🟥	🟨	🟩	🟦
		C1	C2	L	P
Average height of water upstream	(mm)	46.9	47.25	46.6	49
Difference in height (max-min flow)	(mm)	16.8	17.15	17.8	15.9
"r" value	-	0.455	0.496	0.428	0.883
Cd based on mass flow rate	-	1.672	1.443	1.408	1.35
Mass flow rate down stream	(kg s^-1)	0.222	0.191	0.187	0.179

		Best	2nd	3rd	Worst
Average height of water upstream		🟩	🟥	🟨	🟦
Difference in height (max-min flow)		🟦	🟥	🟨	🟩
"r" value		🟦	🟨	🟥	🟩
Cd based on mass flow rate		🟥	🟨	🟩	🟦
Mass flow rate down stream		🟥	🟨	🟩	🟦

Another aspect that can be easily compared is the gradient of the water line over the side length of the weir, and the difference in forms of nappes at the flow rates for both empty (Figure 7) and ramped (Figure 8) catenary type of weirs at full flow rate.

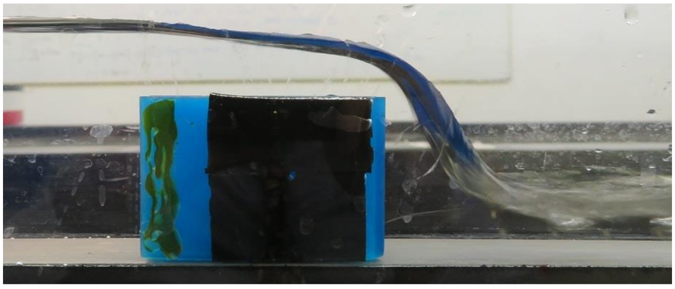

Figure 7: Side-on view of the empty catenary weir at full flow rate.

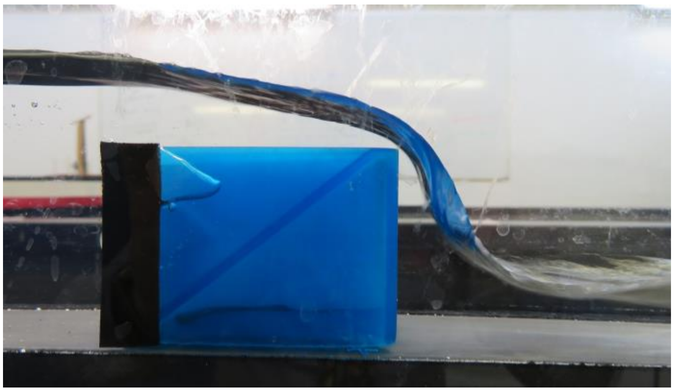

Figure 8: Side-on view of the ramped catenary weir at full flow rate.

The labyrinth (Figure 9) weir did not compare well in on most of the comparison criteria for both flow rates, however the major limitation of only having two cycles meant that weir characteristics are unlikely to be similar for much wider channels. Labyrinth weirs are attracted a lot of interest due to their relatively long existence and widespread use; studies by Crookston, Paxson and Campbell (2013) do compare several geometrical factors and include a 2-cycle labyrinth weir to others.

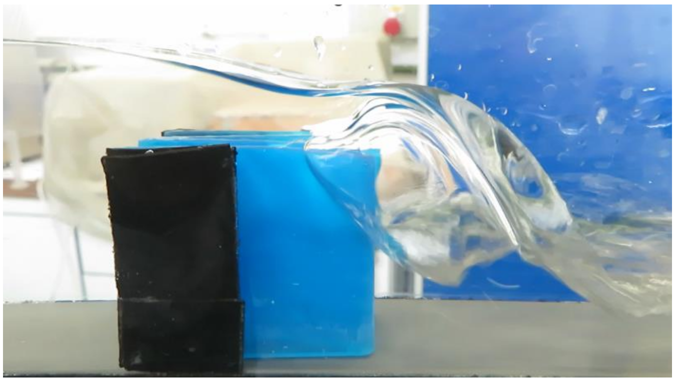

Figure 9: Side-on view of the labyrinth weir at full flow rate.

A logical next step in this research would be compare different crest profiles (e.g., sharp, flat, quarter-round, half-round, ogee). The catenary shape derived from the hyperbolic cosine function (cosh x) was chosen by authors due to the relatively long crest that can be achieved in a relatively narrow channel.

One issue that could be improved in terms of design for testing AM parts is reducing the side wall and under some weirs, this was most noticeable with the piano key weir (Figure 10). The most effective weir preventing this was the ramped catenary weir, due to the increased rigidity of the model.

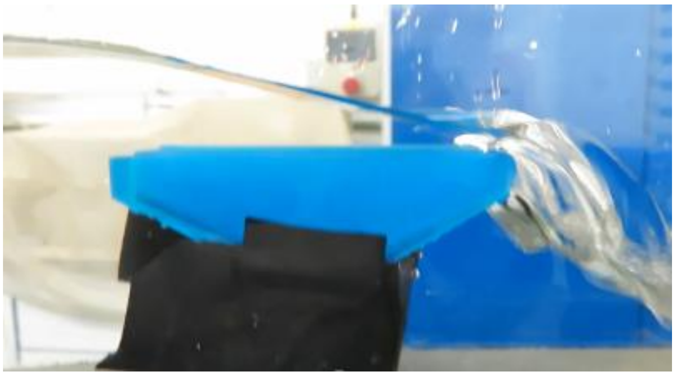

Figure 10: Side-on view of the piano key weir at full flow rate.

The piano key weir (figure 10) design was based on similar design ratio parameters from other research (Erpicum et al), and at high flow rates scored well. The most consistent in terms of ranking over all comparators is the ramped catenary, in third place at maximum flow but second at lowest flow. The error of the pitot tube was evaluated in the empty channel, where velocity was calculated from the volumetric flow rate. It was found to be 96% accurate, from the readings taken.

3.4 Experimental Issues.

Although results show consistency, however following experimental issues were encountered:

- The channel is relatively narrow, limiting the number of repeating sections of the weir.
- The ramped catenary weir had the optimum rigidity and required the least rubber mount support. The piano key was the least stable.
- Side leakage and floor leakage were observed on all weirs; the piano key showed considerable side leakage.
- The pitot tube position had to be securely fixed, otherwise considerable variation was probable.
- Limited time only allowed for a few weirs to be tested for this research.
- Only flat crest profiles were tested for the initial research. This profile is not optimum.
- The coefficient of discharge is easy to calculate for the sharp-crested weir but more complicated for other weirs. The narrow channel problem means that the coefficient is likely to be very different for a much wider channel with more repeating sections.
- As an alternative the “r” value was measured (Q test weir/Q sharp-crested weir).

3.5 Finite Element Analysis Flow Simulation

Finite Element Analysis based CFD flow simulations were done to evaluate and compare the flow dynamics results obtained from experimental data for all four different types of weirs. The fluid flow pattern observed through CFD analysis of empty (Figure 11) catenary, ramped (Figure 12) catenary, labyrinth (Figure 13) and piano key (Figure 14) weirs is almost like experimental flow pattern.

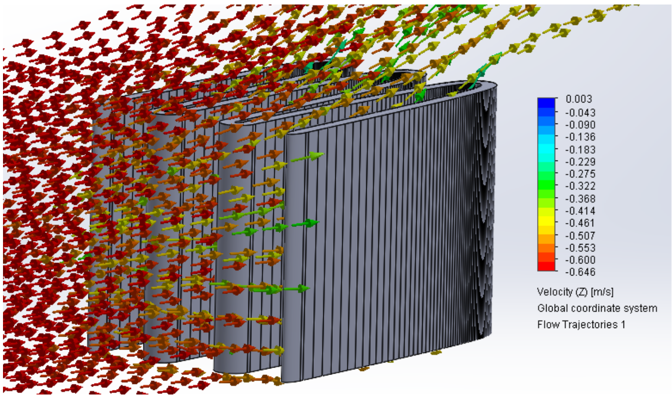

Figure 11: Flow simulation of empty catenary weir at maximum flow rate

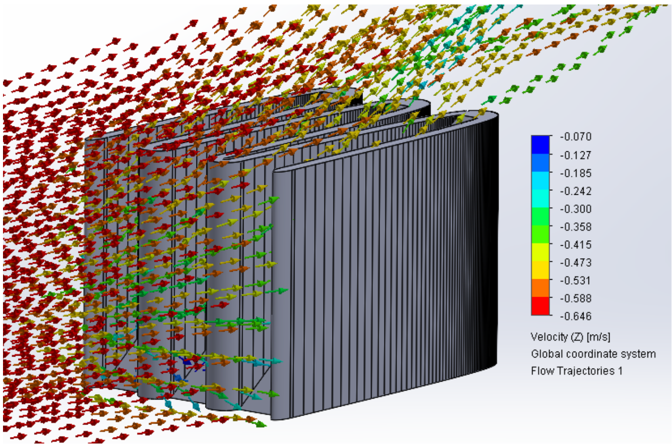

Figure 12: Flow simulation of ramped catenary weir at maximum flow rate

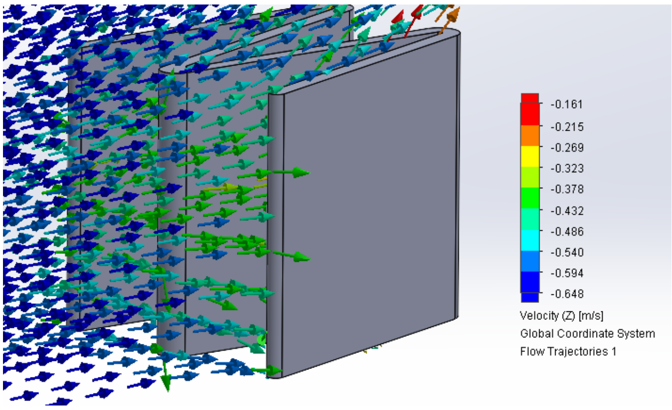

Figure 13: Flow simulation of labyrinth weir at maximum flow rate

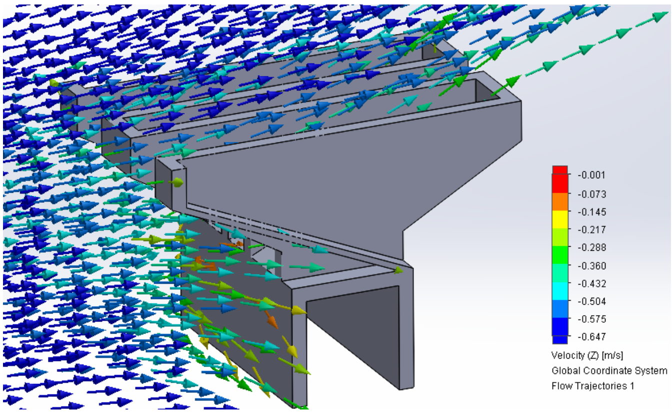

Figure 14: Flow simulation of piano key weir at maximum flow rate

Simulation results also verified and compared the average velocities obtained from experimental data for both empty and ramped catenary weirs shown in Table 4. Change in shape from empty to ramped shaped weir results in negligible reduction in average velocities from CFD analysis. Simulation analysis was also very useful for regions that are difficult to measure with the pitot tube and boundaries within the system.

Table 4: Comparison of Experimental/Simulation Data for average velocities in both catenary weirs.

Type of Catenary Weir	Experimental Average Velocity (m/sec)	CFD Average Velocity (m/sec)
Empty	0.650	0.628
Ramped	0.650	0.627

Overall results yield following key points:

- The scope for further testing is great. The results in this small study show the potential of a catenary shaped weirs, however other characteristics need to be considered, such as coefficient of discharge.
- AM weirs are lighter than the supplied metallic ones and do need supporting mounts. The side and bottom leakage could not be measured. Reducing this is important before further work can commence.
- AM parts took around 6 - 8 hours to produce and cost around £12 each. By introducing complex profiles, this does not alter these values very much. Several parts can be produced in one period.
- Some AM profiles could not be produced by conventional methods on aluminum alloys or Perspex models. The tough AM SLA resin is well suited to this application.
- Durability for some AM polymers could be an issue, however none of those tested raised any concerns and these will be used again.

4. CONCLUSIONS

The research shows that effective weir designs can be implemented and compared using suitable AM technologies. The tough AM SLA resin performs well although the flexibility in some designs requires further structural rigidity around the base to prevent the deformation of the shape when held in the channel. The catenary weirs show promising results however the regions of interference need to be studied further, and extra features could be added to try and reduce the detrimental factors on performance. For example, nappe breakers have been experimented with in several studies, Bilan et al (2018), and AM can allow for more complex geometries to be investigated. Further investigation is required prior to this to compare different forms of crest, as the flat crest is not optimal. In conjunction with this, coefficients of discharge need to be mathematically determined and compared to the measured flow rates over the weir. The volumetric flow rates can then be compared against the changes in height upstream to give a better comparison. The relatively narrow channel does limit the amount of work that can be carried out; however, the results show that even with flat crested weirs the variation in weir design can be effectively compared by using AM technology, which can give a good advantage over other construction methods of model weirs for open channel flow studies.
Overall, from this study, we can conclude that

- The advantages of AM are clear in this study: huge reductions in lead-times and very economical parts can be produced.
- Results are consistent and repeatability was good.
- A limited number of weirs were tested. There is a huge scope of weirs that could be experimented with, but the next step is to vary the crest profile (e.g., rounded, ogee).
- To achieve optimization, weirs in wider test flow channels should be tested. AM models can be made in sections and slotted together to accommodate larger widths.
- The next stages are to look at flow induced design optimisation

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BIOGRAPHIES

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"**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 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."