Experimental and CFD Analysis Based Design of Additively Manufactured Drum Gate for Open Channel Flow Experiments

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Abstract – *Additive Manufacturing (AM) is emerging as a cost-effective alternative to conventional manufacturing techniques for applications requiring components with complex geometries. Cost savings are achieved through reduced raw material usage, shorter manufacturing times, and the elimination of expensive tooling. AM serves as a valuable tool for designing and developing complex shapes in fluid flow research. This study examines the limitations of existing components in a 2.5 m open channel fluid flow experiment, characterized by their basic standard shapes. Specifically, it focuses on enhancing flow control in hydraulic systems by introducing gates with intricate geometries, which are typically expensive and time-consuming to acquire from equipment suppliers. AM technology provides a cost-effective solution for implementing progressive design modifications. This paper presents a comparative analysis of various positions of an AM-produced curved drum gate in terms of flow rate, fluid velocity profile, water level height, and related fluid flow parameters. Computational Fluid Dynamics (CFD) modelling, analysis, and simulation techniques are used to analyse and validate the results. Based on the experimental findings and their verification, this paper discusses the suitability and applicability of AM techniques in fluid flow analysis. The ability to manufacture customized components through AM offers a promising avenue for enhancing fluid flow research, enabling cost-effective and time-efficient design modifications. This study emphasizes the importance of utilizing AM and specific materials to advance fluid flow analysis.*

Key Words: CFD Analysis, Additive Manufacturing, Experimental Methods

1. INTRODUCTION

Additive Manufacturing (AM) is a relatively modern and innovative technology for designing and producing polymeric and metallic components, offering advantages over traditional manufacturing methods such as machining, casting, or moulding. AM enables the creation of innovative designs concerning material, shape, and complexity by eliminating the need for tooling. This removes many current design-for-manufacturing and assembly restrictions. However, AM processes have unique characteristics and requirements that must be considered during the design stage to ensure the manufactured parts meet quality standards. AM printed parts providing distinct advantages over conventionally machined components, including reduced production time, lower costs, and the ability to achieve complex geometries. Historically, improvements in weir designs have required extensive empirical testing.

Additive Manufacturing (AM) has emerged as a promising technology for conducting fluid mechanics experiments, offering numerous possibilities. Gated spillways have attracted significant interest due to their control capabilities and reduced footprint. However, crest gates face challenges such as gate failure, support member buckling, and friction-related issues. Alternatively, radial or Tainter gates have been historically used, though they present downstream complications from high-velocity movement, cavitation probability, and aeration. Mousavimehr et al. [1] investigated shockwave effects and proposed experimental methods to mitigate them, recognizing AM's potential in fluid flow research. Musa et al. [2] reviewed AM's established role in experimental fluid flow research, highlighting its significance and potential advancements in various areas.

The existing experiment at the university for undergraduate Mechanical Engineering students uses a 2.5 m long flow channel (Figure 1), enabling various experiments to observe open channel flow behaviour with different components. This experiment currently involves only a standard round aluminium-based drum gate component. However, this standard round configuration is insufficient to fully understand the complexities of practical drum gate use with different shapes.

The case study presented in this paper extends previously published research [3] by the authors, providing detailed experimental and computational fluid dynamics (CFD) analysis of the effects of changing the drum gate shape for various open channel experiments using additive manufacturing technology.

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

2. RESEARCH METHDOLOGY

In this study/research, the poor discharge profile downstream of the existing standard drum gate (Figure 2) used as a roller gate within a flow channel is investigated (Figure 3).

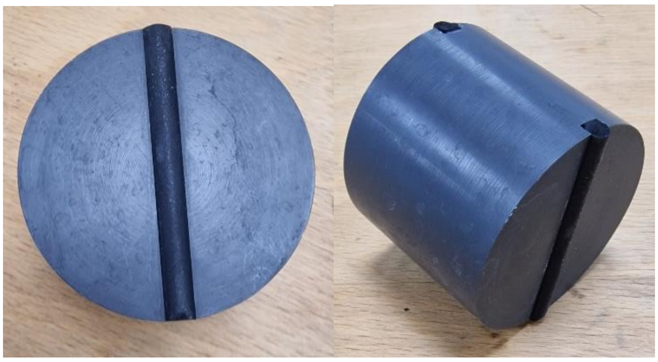

Figure 2. Standard Round Drum Gate

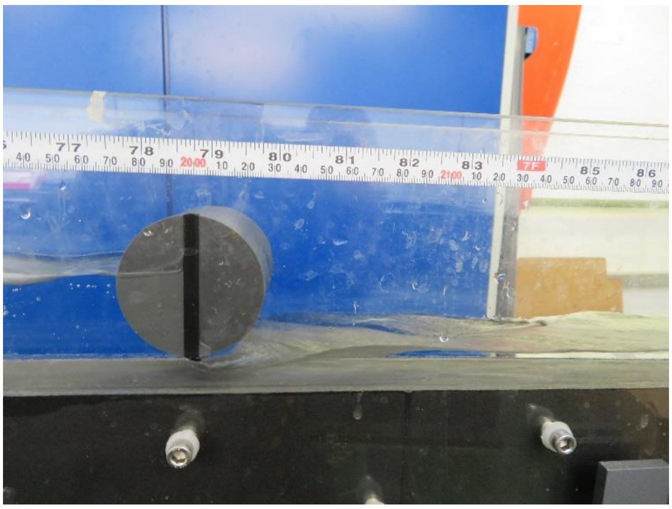

Figure 3. Standard Drum Gate Open Flow Experiment

Previous roller gates with rudimentary sector designs have proven ineffective. Therefore, this research aims to enhance roller gate design by incorporating mathematical curve profiles. Specifically, the study explores the utilization of a logarithmic curve profile based on the Golden ratio (ϕ), a phenomenon widely observed in nature and man-made structures [4]. This approach combines biomimicry principles with engineering disciplines. Extensive literature by Passino et al. [5] has reviewed the advantages and scope of utilizing biomimicry in engineering. Figure 4 depicts the Golden spiral, generated through mathematical software. The polar equation (1) and its components (2) and (3) are used to plot the curve:

$$r(\theta) = ae^{b\theta} \quad (1) \qquad |b| = \frac{\ln\varphi}{\frac{\pi}{2}} \quad (2) \qquad \varphi = \frac{1+\sqrt{5}}{2} \quad (3)$$

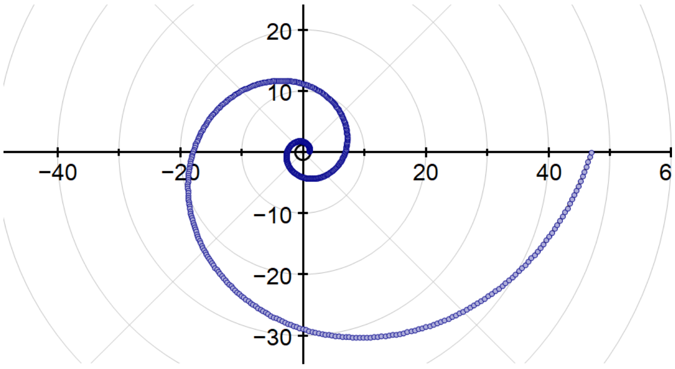

Figure 4. The Golden spiral was produced using mathematical software.

Figure 5 shows the drum profiles, featuring a logarithmic curve on one side and a standard drum on the other. For physical integration, the variable "a" was assigned a value of 1, and the Computer Aided Design (CAD) model was scaled to fit the dimensions of the existing drum enclosure. Data points were imported into CAD software and extruded to generate an STL file for producing an AM-based drum gate design (Figure 6).

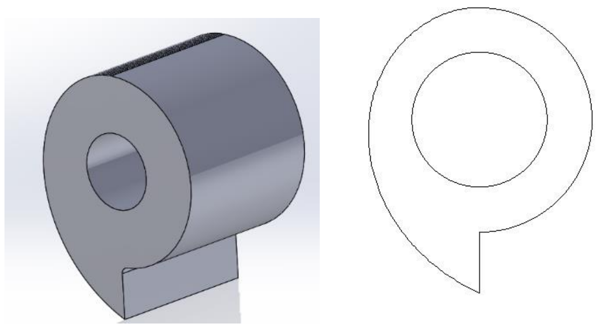

Figure 5. Golden Spiral Drum Gate Design

Figure 6. AM Based Golden Spiral Drum Gate Design

The provided standard drum was tested using the AM model to enable a comparative analysis. To minimize side wall leakage, the AM model was equipped with rubber mounts and sealant paper. Experimental investigations were conducted by introducing a 15 mm displacement between the channel bed and the gate's lowest point. This displacement ensured testing across a wide range of flow rates while maintaining a sufficient water height to interact with the gate without causing overflow. Although various displacements were feasible, the initial readings focused on examining the complete spectrum of flow rates.

For a comprehensive evaluation, the newly designed AM drum gate model with a golden spiral was tested in multiple positions, including upright and tilted 45 degrees to the left and right of the centreline (Figure 7).

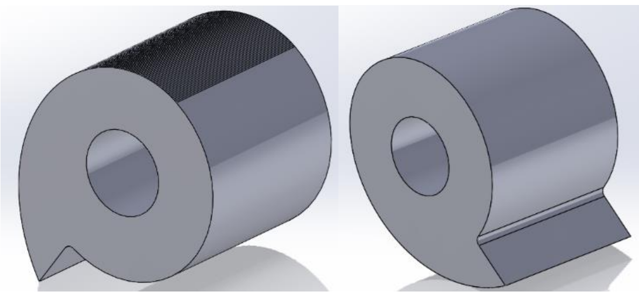

Figure 7. Up right tilted at 45 degrees to left and right of centreline.

It was crucial to assess both upstream sides of the AM model. Therefore, after testing the rounded side (right-hand side of Figure 5), the model was reversed to test the logarithmic curved side (left-hand side of Figure 5). This included testing in both the upright reverse position and tilted 45 degrees to the left and right of the centreline (Figure 8).

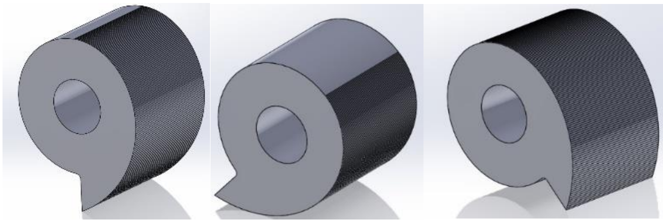

Figure 8. Up right reversed and tilted at 45 degrees to left and right of centreline.

The experimental setup of upright and tilted right is shown in figure 9 and reverse configurations in figure 10.

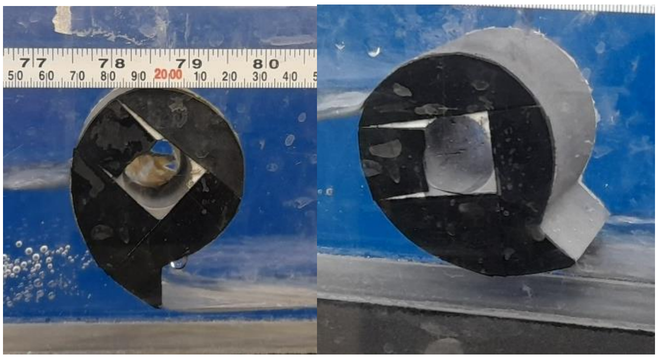

Figure 9. Up right tilted at 45 degrees to right of centreline experimental setup in flow channel

Figure 10. Up right reversed configurations of experimental setup in flow channel

3. ANALYSIS OF RESULTS

The results were comprehensively analysed using a spreadsheet, supplemented by observations, as findings were not immediately apparent from the spreadsheet alone. Significant variations in water height were observed upstream, with the largest disparities attributed to the occurrence of a hydraulic jump, particularly pronounced at lower flow rates. Notably, when comparing the curved drum to the standard drum, the height difference caused by the hydraulic jump was less pronounced for the curved drum. Additionally, the hydraulic jump position occurred much farther downstream with the curved drum, although it shifted closer as the flow rate increased. The hydraulic jump can be concerning due to the increased hydrostatic pressure it exerts on the upstream gate, but it can also be advantageous downstream by reducing erosion rates. Visual observations indicated that fluctuations with the standard drum were substantially greater than those with the curved drum in both orientations.

The analysis of Froude numbers downstream revealed relatively low values across most cases (0.59 to 2.57), which was expected given the limited flow rate of the experimental setup. However, this serves as a limitation of the research, necessitating further investigation with larger channels and higher flow rates to evaluate Froude numbers for full-scale applications. Singh et al. [6] noted that the optimal Froude number range lies between 4.5 and 9.0. Upstream, supercritical flow (Fr > 1) was only observed at the lowest flow rates, as anticipated. Lower Froude numbers can lead to various downstream issues, but since the curved drum could be opened almost fully, additional investigation is warranted. The velocity of the fluid 'V' and the channel size also influence Froude numbers due to hydraulic depth 'D'.

A comparative analysis of discharges was conducted, examining the performance of the original drum and the curved drum at different flow rates. Results indicated that the original drum exhibited higher values (ranging from 1.53 to 1.55) at lower flow rates compared to other findings. Interestingly, rotating the curved drum 45 degrees to the right on its curved side yielded the highest value of 2.56, whereas the highest value at full flow was 1.07. However, caution is advised as these measurements were pitot tube-based, albeit separately calibrated for accuracy.

The specific energy 'E' can serve as an alternative comparator, considering its dependency on fluid velocity and gravitational acceleration. It also affects the volumetric flow rate 'Q', where the breadth of the sluice gate 'B' and the displacement of the lowest point of the sluice gate from the channel bed 'd' come into play. However, this relationship is not linear due to the variable coefficient of discharge 'C' with flow rate. To compare the performance of various positions, an alternative approach involves plotting flow rates based on specific energies. Figures 11 and 12 depict the obtained results. This plotting method involves taking the root of the factor related to the specific energy term and plotting it against the volumetric flow rate, as per the overall equation. This technique allows for a comprehensive evaluation of the tested positions.

$$Q = CBd\sqrt{2g\left(E - \frac{d}{2}\right)} \quad (5)$$

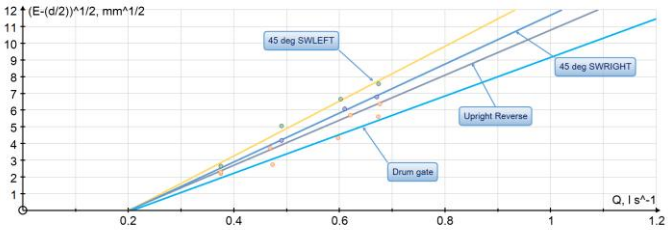

Figure 11. Linear comparison of the standard drum gate to the rounded side of the AM model gate.

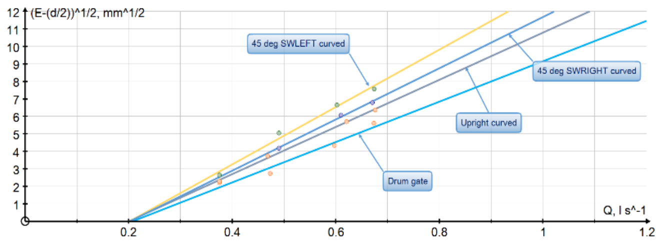

Figure 12. Linear comparison of the standard drum gate to the logarithmic curved side of the AM model gate.

For both orientations, the drum gate exhibits the lowest value gradient, indicating superior performance despite the absence of the coefficient of discharge. Tilting the model to the left in both orientations resulted in the highest gradient. Previous studies, such as those by Daneshfaraz et al. [7], have also focused on the impact of sluice gate geometry on performance, investigating various parameters including gate widths and different geometries. However, the current research has limitations, such as the channel width. Future studies could explore other factors, including the angle of tilt of the AM model, displacement of the AM model from the channel bed, and testing different size sectors.

The paper acknowledges that certain aspects have not been thoroughly examined. For example, comparing hydrostatic pressure when the gate is closed and the stresses during different flow rates would provide valuable insights. Additionally, further investigation is warranted to study visual observations in greater detail, such as the position and sizes of hydraulic jumps and the oscillatory behaviour of the fluid upstream at different flow rates.

While the paper focuses on the effects of geometry on flow parameters, it suggests that testing a standard drum gate with a fitted sector would be a logical step in future research. It is important to maintain focus on the most significant findings of this initial research, given the broad scope of potential testing. Furthermore, vibration problems in full-scale versions of these gates should be considered, as they can pose significant challenges. This highlights the findings related to sluice gate geometry and flow parameters, identifies limitations in the current research, and proposes potential avenues for further investigation. The section emphasizes the need to remain focused on the most significant outcomes of the initial study.

3.1 FEA simulation-based results evaluation

Finite Element Analysis (FEA) based Computational Fluid Dynamics (CFD) flow simulations were conducted to assess and compare the findings obtained from experimental data for four distinct types of drum gates. The flow simulations accurately predicted the fluid flow patterns and provided precise calculations of maximum velocities. The CFD analysis of the standard, rounded side, and logarithmic curved side drum gates (illustrated in Figures 13, 14, and 15, respectively) demonstrated fluid flow patterns that closely matched the experimental observations.

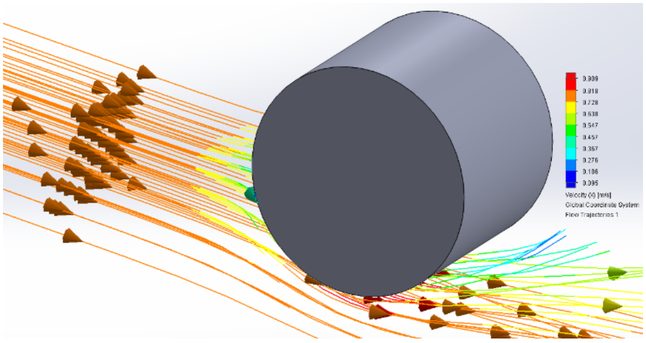

Figure 13. Flow Simulation through Standard Drum Gate

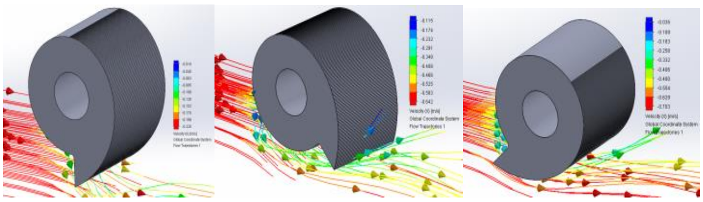

Figure 14. Flow Simulation through Rounded (Upright, Right, Left) Drum Gate

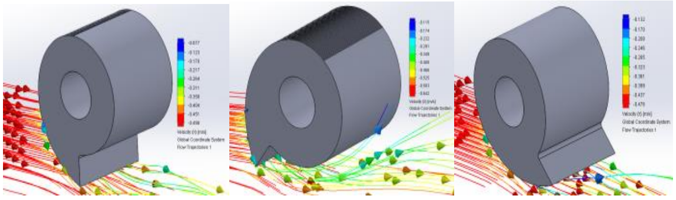

Figure 15. Flow Simulation through Logarithmic (Upright, Right, Left) Curved Drum Gate

The simulation results were also used to verify and compare the maximum velocities obtained from experimental data for standard, logarithmic side curved, and rounded drum gates (Figure 16) under full flow conditions. Although there were slight variations between the experimental and CFD analysis velocities, the CFD velocities were slightly higher, albeit with a negligible difference.

Type of Drum Gate	Experimental Maximum Velocity (m/sec)	CFD Maximum Velocity (m/sec)
Standard	0.775	0.909
Rounded Upright	0.205	0.220
Rounded Right	0.459	0.642
Rounded Left	0.682	0.703
Logarithmic Upright Curved	0.493	0.498
Logarithmic Right Curved	0.636	0.642
Logarithmic Left Curved	0.448	0.476

Figure 16. Comparison of Experimental/CFD data for maximum velocities in different drum configurations

4. CONCLUSIONS

In conclusion, the initial investigation has revealed several intriguing findings that highlight the necessity for additional research in this field. Additive Manufacturing (AM) has played a crucial role in creating cost-effective models with intricate geometries and durable designs for drum gate applications in flow channels. Although the authors aim to undertake a more extensive testing regime, this preliminary work primarily concentrated on three key gate positions for both orientations. The adoption of a curved gate presents several advantages, including the flexibility to accommodate various opening positions and tilt angles. The rounded side upstream of the gate has proven effective in minimizing hydraulic jumps, reducing vibrations, and improving the flow profile. Research by Yousif et al. [8] has explored and modelled the damage caused by scouring. The correctly oriented logarithmic curved side of the gate significantly enhances the flow profile. It is notable that the specific energies for the AM models are higher, which also includes greater hydraulic depths. This prompts questions about the pressures exerted on the gates at elevated flow rates. However, similar engineering design challenges have been faced by modern radial gates and other rounded gates. The full-scale implementation of a curved gate requires careful consideration. While curved gates may not always be justifiable in contemporary spillways and reservoirs, they are valuable for measurement applications, and are particularly useful in channels and spillways where it is critical to address vibration and scouring issues immediately upstream of the sluice gate. The findings from this research have the potential to resolve some existing issues in flow systems and contribute to improvements in these areas. Future research should build on these initial findings to further refine our understanding and application of curved gates in flow channels.

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BIOGRAPHIES

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"**Rob Benham** is a senior lecturer at Department of Science and Engineering, Solent University, UK. and currently a course leader for the HNC Engineering and Foundation Year Engineering. He has been teaching 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."