Analysis of Performance of Child Bicycle Helmet in CFD

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1 Introduction

A key topic of discussion surrounding youth involvement in recreational forms of cycling is in regard to regulated and self-prescribed safety equipment. Several leading nations as well as international organizations have aggressively pushed for further legislation requiring the use of safety equipment, especially for riders of younger ages. These movements claim that helmets may reduce the risk of critical head and brain injuries by 85-88% (Thompson Rivara, 1989). However, introducing mandatory wearing of helmets can act counter-productivity in users preferring to take up alternate forms of transportation. The most common piece of gear is helmets, which support safety by reducing crash impacts and reducing impacts of falling. Kid helmets can often be uncomfortable and bothersome to their users. Therefore, it is the goal of this project to further the development of a child's bicycle helmet that not only satisfies the safety needs presented by leading certification standards, but that as well limits the dissatisfaction of the younger audience in response to uncomfortable and ill-fitting helmets. The helmet will encourage children to wear helmets as well as provide a more enjoyable experience for families to cycle together. The following study will further outline the current standing design of the aforementioned helmet, and describe the approach used to analyze the design using a computational fluid dynamics (CFD) analysis to investigate drag forces and overall aerodynamic efficiency.

1.1 Design Process

The helmet was designed via an iterated and consumer focused design loop where the key pillars of literature review, consumer interviews, and market research were consolidated to inform an updated design. Priorities were placed on the aspects of fit, safety, cost, and awareness. It was determined that fit would be a primary focus as research indicates it to be a leading factor in refusal to wear helmets for youths. Additionally, the wide range of youth helmets are based on national averages and present limited opportunities to have a unique fit for youths who do not meet the head dimensions of these generalized fits. Aerodynamic efficiency was not considered a priority as this helmet is catered to those developing their skills as cyclists and not for market segments of elite athletes where speed is a primary concern. The following CFD analysis is representative of such low speeds and resultant low expectancy of turbulence via a representative free stream. Selected CFD models and turbulence models further represent this fact.

1.2 CAD Design

As seen in figure 1, the model geometry consists of a helmet mounted on top of an anatomical head surface. The helmet was designed for a 7-year-old boy at the 50% percentile mark as according to the World Health Organization (WHO, 2019). All dimensions and modelling were also based off this reporting. Features include a solid body with outlets alongside the front and top, along with an additional posterior hole meant for protruding hairstyles. Pierce et. al. (2013) found that obstructed hairstyles was amongst the top reported reasons for refusal to wear protective helmets amongst youths. Internal inflatable air padding allows for a unique customization of fit as it can be inflated or deflated based on preference as well to increase its potential lifespan for the user to allow additional room for the young user to continue usage while they grow. The helmet complies with size designation 495 (A) of BS EN 1080:2013 testing protocol released by British Standard Issuer for Impact protection helmets for young children. The Helmet also follows specifications outlined by the following governing organizations:

Organization	Standard
British Standard Issuer; BS EN	1080:2013
American Standards Organization	ASTM F1952-15
Snell Memorial Foundation	B-90A and B-95

2 Methods

Similar to the studies of Bixler et. al. (2007) and Defraeye et. al. (2010) this study will primarily focus on a qualitative analysis of pressure distributions and flow separations patterns via a comparison of the bare head geometry and its helmet inclusive assembly. Modelled as a bluff body with a low Reynolds number. The two simulations will attempt to model the scenario of a youth cyclist at a leisurely speed of 5 m/s during forward moving recreational activity (yaw = 0).

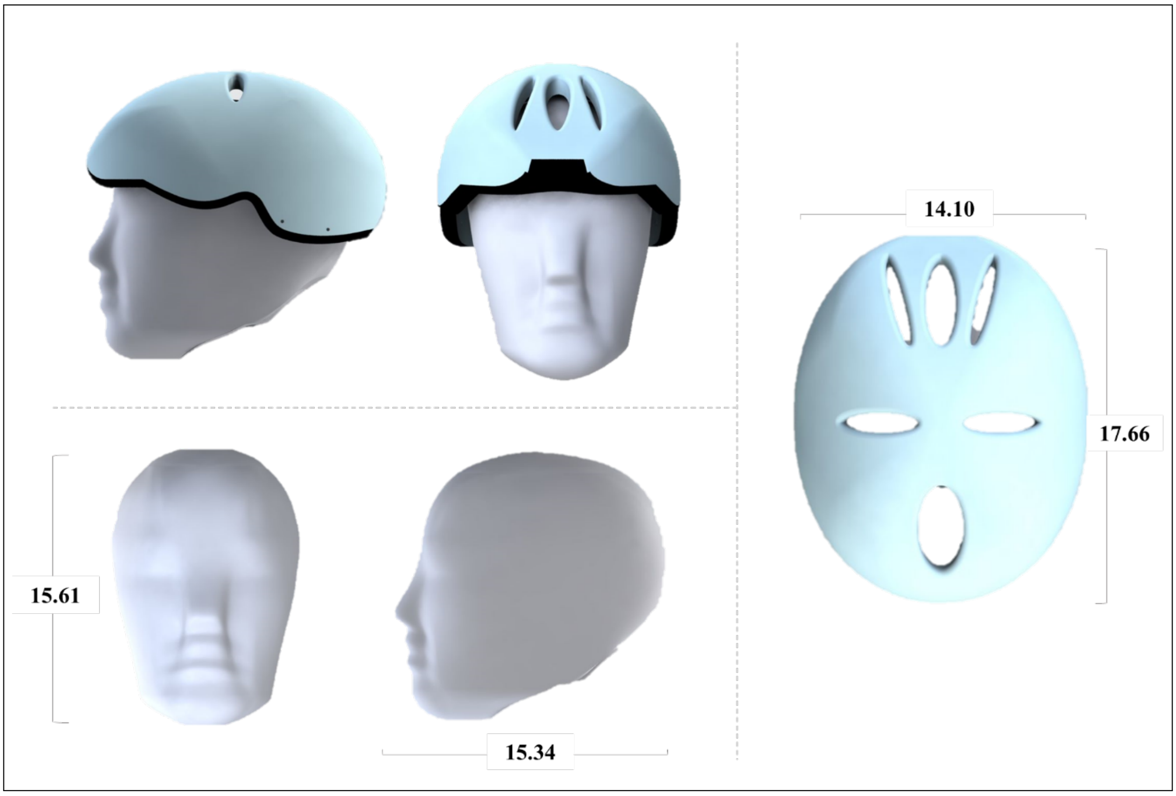

Figure 1: Helmet and Anatomic Head CAD Render Geometry [cm]

2.1 Computational Fluid Dynamics

Using ANSYS Academic 2019R2 software a pre-processed geometry was created to represent the low velocity/turbulent wind tunnel scenario. Table 1 outlines the elements used in the geometry with a visual representation shown in Figure 2. The geometry was read into ANSYS Fluent 2019R2 software to create a mesh using a watertight geometry. Local sizing values were used for each simulation and its respective geometry elements as reported in Table 1. Based on application and time feasibility, the k-ω Shear Stress Transport (SST) viscosity model was chosen in conjunction with a Low-Reynolds Model to better investigate boundary layer interactions. Due to the moderate speed and concern for efficiency, it is appropriate to resolve the flow and turbulence by an averaged model as is supported by the k-ω.Prior studies conducted by Zaid et. al. (2010) support implementing this model with bluff bodies due to its ability to resolve wall bounded flows. Each simulation had 5 sub-layers for additional accuracy. Boundary conditions were set as follows: Inlet velocity = 5 m/s, Turbulence Intensity = 0.1%, turbulence viscosity ratio = 2. All Discretization models were set to Coupled Second Order Upwind. To increase time efficiency, the ANSYS FMG algorithm was incorporated post initialization and before simulation calculation.

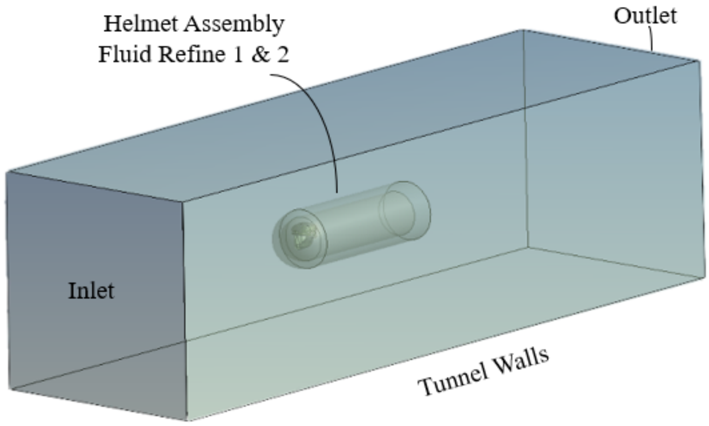

Figure 2: ANSYS Design Modeller Geometry Used to Create Volume Mesh

Table 1: ANSYS Design Modeller Geometry Element Dimensions

Element	Geometry [m]	Growth Size	Face Type	Target Mesh Size [Head | Helmet]
Tunnel	5 x 1.5 x 1.5	1.2	Face Size	5
CAD Assembly	See Figure 1	1.2	Face Size	5
Fluid Refine 1	R = 0.15; L = 2	1.2	Body of Influence	10 | 10
Fluid Refine 2	R = 0.25; L = 2	1.2	Body of Influence	30 | 50

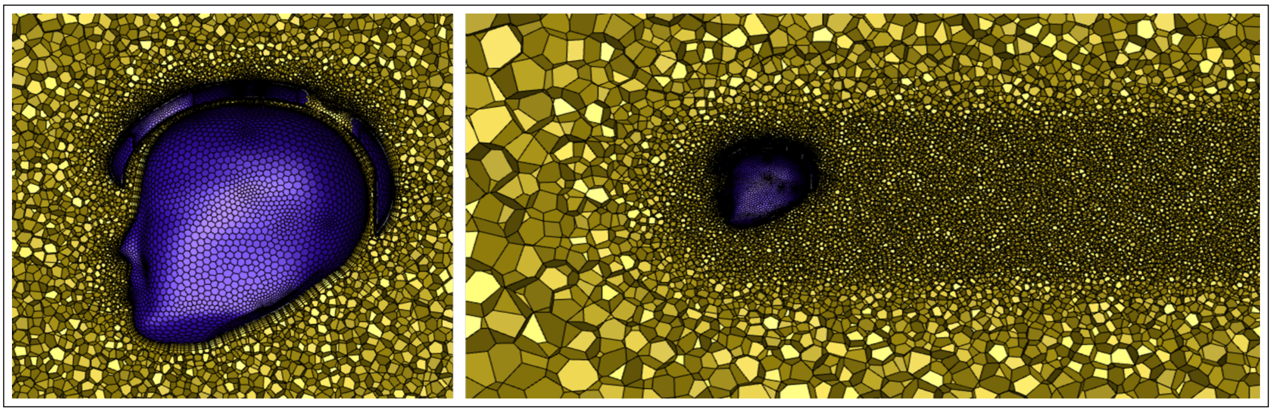

Figure 3: Volume Mesh Output | Polygon Geometry

3 Results

As previously mentioned, this study used a qualitative visual approach which numeric support via measures such as Y+ and drag coefficients to compare the two simulations. The simulations were run at 1000 iterations, and were stopped once Force monitors (Drag Force and Coefficient) were deemed to have converged. This point of convergence was further validated by monitoring the residual plots, Figure 4, in which the difference between iterations supported a solution converging. Table 2 provides an overview summary of the performance metrics of both completed simulations.

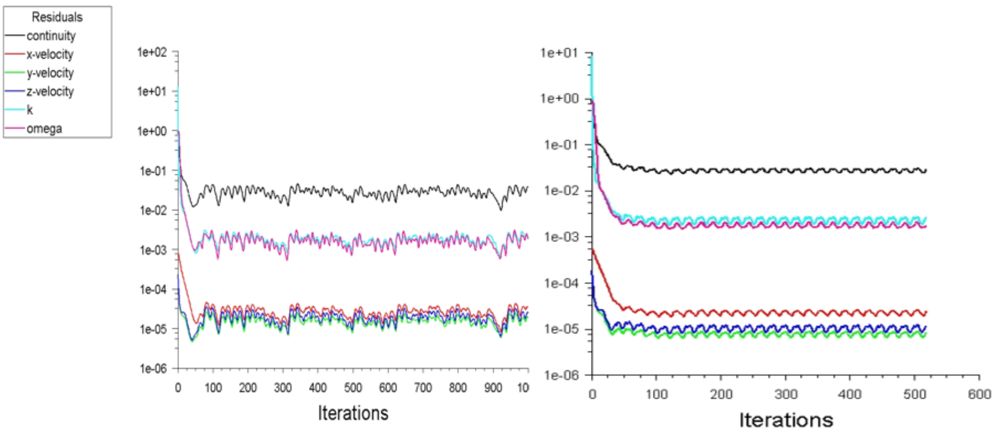

Figure 4: Output residual plot for Bare Head and Helmet Assembly Simulations

Upon simulation completion, a quantitative analysis shows that the helmet geometry creates a similar drag coefficient 0.290, to that of the bare head 0.252. The drag forces reported in Table 2 show a correlation to the findings of Sidelko (2007) who reported a drag force range of -0.288 to 0.319 N at 13 m/s and 0 yaw for a road cycling helmet. This indicates that the helmet provides limited obstructions to the rider and supports an aerodynamic experience. This conclusion is further supported by the visual evidence shown in Figure 5 and Figure 6. The skin friction coefficient plot

Table 2: Summary Results for Simulations: Bare Head Helmet Assembly

Simulation	Cell Count	Fd [N] - AVG	Cd - AVG	Y+ - MAX	Y+ - MIN	Y+ - AVG
Helmet Assembly	1,532,705	0.106	0.290	12.579	0.031	2.596
Head	169,652	0.075	0.252	5.582	0.073	2.030

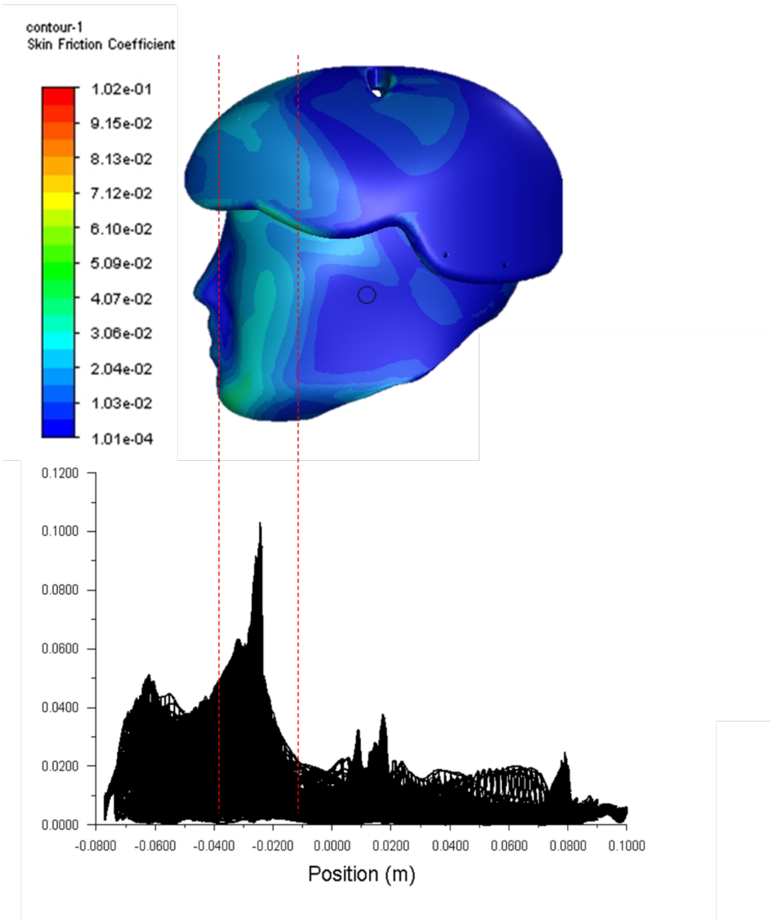

Figure 5: Visual Analysis of Skin Friction Coefficient Contour to Skin Friction Coefficient x-y plot

shown in Figure 5 indicates that there is a flow separation point towards the front of the helmet, approximately at the back of the topmost cut out. This flow separation point is also visible in Figure 6 in which the lower pressure regions (light blue) visibly indicate a change of pressure at the same locations. Figure 6 furthest most right images - describe the velocity magnitudes progression across the surface. The comparison of helmet to bare head shows a greater wake region in the posterior of the helmet compared to the bare head. There are also local acceleration regions present at the top of the helmet and head which supports the flow separation created by the top most hole.

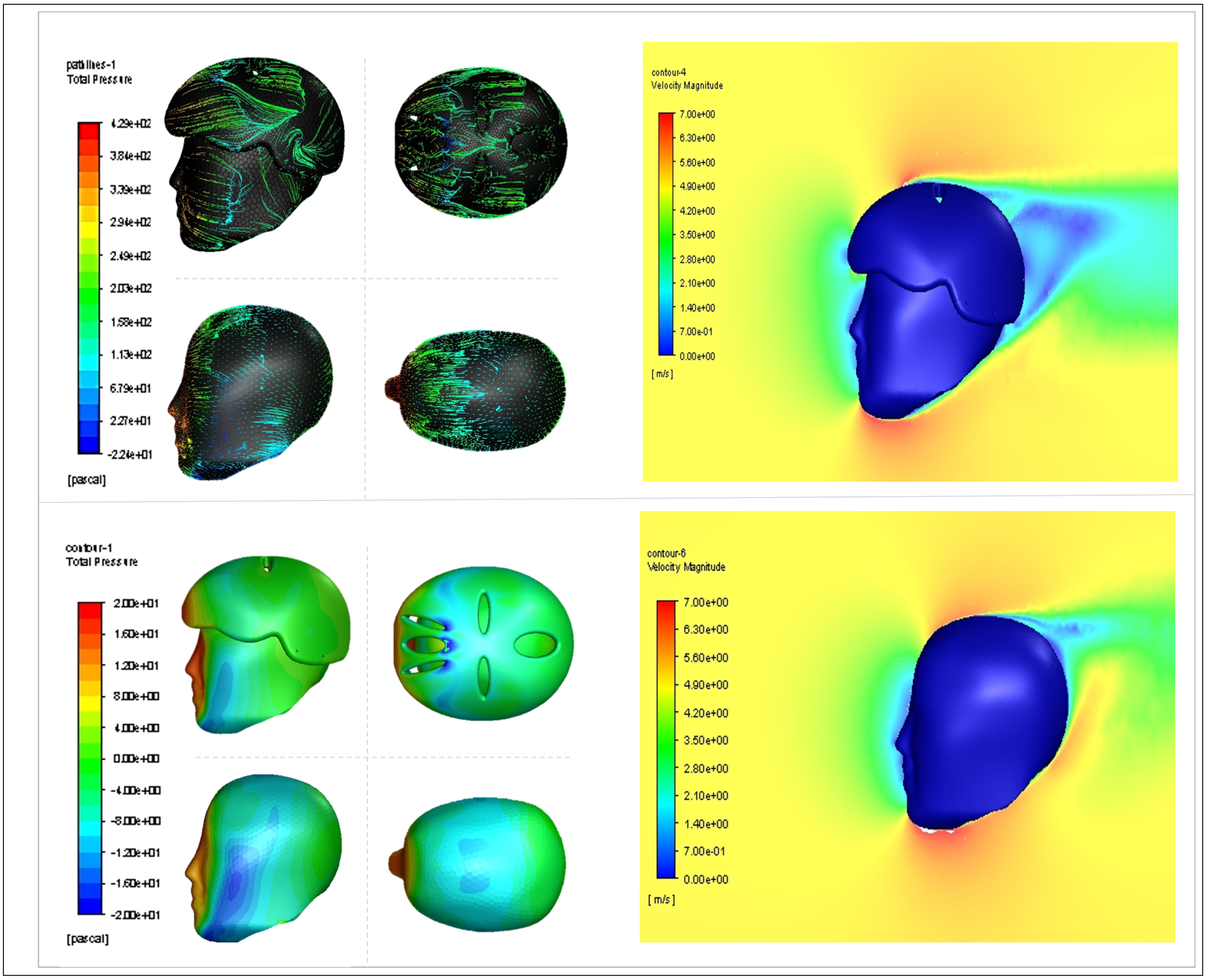

Figure 6: Simulation Results: Top left: Total Pressure Vector Lines, Bottom Left: Total Pressure Contour Gradient. Right: Velocity Magnitude Turbulence Generations Regions

4 Conclusion

Although the simulation results depict a supported narrative overviewing the progression of drag effects upon placing a helmet on a head, there are several limitations to the quantification of its impact and application. Due to the limitations of available licensing, geometry intricacy, and overall time and resource the results of the simulation must be viewed at a high-level starting point for future iterations and investigation. This process outlines a vital step in the iterative design process as it progresses from ideation, CAD modelling, to baseline simulation. The study shows promising results to conclude that the helmet does not significantly stagnate performance of a child as the reported drag coefficient does not significantly deviate from that of just the bare head. This study should be validated with experimental data as was done in Defraeye et. al. 2010. This information will be used to influence further design iterations of the helmet in conjunction with prioritized design factors.

Although a valid proof of concept for a first design iteration of a child bicycle helmet, the current study present strong limitations. In respect to thoroughness, this study recognizes that further work and a more in-depth analysis is required to support the continuation of developing the proposed helmet design.

The most prevalent limitations are provided in Table 3 below:

Table 3: Summary of Limitations and respective discussion

Limitation	Discussion	Actions for Mitigation
Mesh Refinement	Due to limited processing capabilities, the volume meshes were not intended to exceed 1 - 2 Million cells. This inherently creates a simplified interaction of fluid analysis to surface interactions and limits the accuracy of turbulence detection and computations such as drag coefficients and force. Only polygon mesh geometries were used in the volume mesh creation. Although the final output had a maximum skewness of 0.62, the cell transitions might have been improved with a hybrid of geometries	Further iterations closer to product design finalization, could use larger mesh refinement volumes via smaller face sizes and combined geometries.
Simplified Geometry and Surfaces	Important to note that the head does not fully represent what a non-helmet child would experience in terms of drag force as the smooth surface would experience greater drag with hair and roughness of skin/additional accessories	The CAD geometry may be refined using different modelling techniques to better create transitions between surfaces and fillets or holes. Surface characteristics such as roughness and additional components (visors, strap hardware) will also be added for complexity and trueness.
Economic Considerations for Time and Processing Resources	Due to limitations of using an ANSYS Academic license, large mesh sizes were not supported for simulation. Furthermore, the need for a fast turn around of analysis and informing the design process overrides the necessity for a highly refined mesh. Furthermore, the limited number of licenses available called for a conservative time required for simulation as several hours could not be given to the task.	More time may be dedicated to completing a simulation with proper licensing to handle larger mesh sizes.
Lower Priority Placed on Aerodynamic Efficiency	The target population is not interested in maximum efficiency for speed and might conversely prefer a lower performance range	-
Static Wind Tunnel Angle/Orientation	Model was analysed at a yaw of 0 and degree rotation of 0, this does not fully comply with realistic performance scenarios as children would likely be more dynamic in their movements with some degree of Yaw and rotation.	Iterative simulations at varied Yaw angles and rotation may be conducted to properly simulate the
Lack of Verification from Alternative Models	Other performance models were not investigated due to lack of verification data from experimental data to verify outputs. Therefore k-omega model was chosen due to past verification and reliability of method.	This study chose to utilize the k-w model based on prior research and supporting documentation for models of such simplicity. A comparison study that investigates other models should be completed to confirm the validity of this model in this application.
Inherent Computational Uncertainty	Despite having an appropriately scaled Y+ value, the inherent existence of uncertainty derived from iterative computational modelling presents a significant level of potential error that must be further investigated and compared to experimental values for verification.	Due to a simplification of turbulence and flow modelling there is a natural level of uncertainty that this method presents. A combination of above actions would aid in mitigation of computational errors, although it would not solve nor replace the differences to an in-situ analysis.

Word Count: 2,166

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