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Computational Fluids Dynamics as a Learning Tool in Introductory Thermofluids Education

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ABSTRACT

CONTEXT

Demand for practical skills in university graduates is increasing. This study considers the introduction of Computational Fluid Dynamics (CFD) as a learning tool in an introductory thermofluids course. The integration of CFD aims to enhance understanding and application of fluid mechanics principles in real-world scenarios through modelling and visualisation. While traditional theoretical instruction remains valuable, providing students with simulation tools to approach problem-based learning offers hands-on experience with industry-standard tools, helps to bridge the gap between theory and practice, and provides near instant feedback into how thermofluidic concepts and design are coupled. The student experience is improved by the employment of such tools as a compliment to lecture and workshop-based activities.

PURPOSE & APPROACH

The motivation behind this initiative is to equip students with practical skills essential for their future careers while fostering a deeper understanding of thermofluids concepts through real-world application. The research question driving this change in practice is whether integrating CFD modelling software into the curriculum enhances students' grasp of fluid mechanics principles and their ability to apply them to design problems effectively. Student perceptions were assessed by combining qualitative open-ended feedback and quantitative surveys to capture their experiences with the integrated CFD component.

OUTCOMES

Students appeared to demonstrate enhanced proficiency in applying fluid mechanics principles through their design projects and reporting increased confidence in using CFD software as a result of the integrated learning experience. Additionally, students expressed positive feedback regarding the relevance of CFD software in their engineering education and its value for their future careers.

CONCLUSIONS

The evidence presented supports the conclusion that integrating CFD software into thermofluids curriculum effectively enhances students' understanding and application of fluid mechanics and thermodynamics principles, while giving them experience in industry-standard tools. This conclusion aligns with the growing recognition in engineering education of the importance of practical, hands-on learning experiences. Recommendations include further refining the integration of CFD software and expanding its implementation across other relevant courses.

KEYWORDS

Thermofluids; computational fluid dynamics, problem based learning

Introduction

The ‘best’ way to prepare design and engineering graduates for their future careers is a well debated topic. Whist consensus has yet to be reached, research shows a growing trend of moving away from ‘classic’ lecture-and-exam based classrooms, and into more open-ended and problem-based challenges, wherein students learn by doing. Whilst this approach has a great deal of merit, the ability of all students to effectively synthesise complex theory and apply this into logical practice needs to be addressed. This concern is heightened in the fields of Product Design and Product Design Engineering which often recruit a student cohort with a more diverse range of backgrounds compared to typical engineering disciplines.

Computer Aided Engineering (CAE) harnesses simulation methods to improve design and engineering workflows, and hence may offer support within modern classroom spaces. This is explored in the literature; for example, numerous researchers have integrated computation fluid dynamics (CFD) into undergraduate engineering curriculums (Diehl, 2023; Pines, 2004; Stern et al., 2006; Wismer et al., 2022; Wright, 2020) to aid with Thermofluids education. In these studies, many of the authors reach overlapping conclusions, notably that undergraduates enjoy the “hands on” challenge of harnessing CAE methods to problem solve. However, the CAE tools themselves risk adding a layer of additional complexity to the challenge, and authors to date have noted that learners have wide ranging need for support. Research shows that the level of learner support required is typically a function of prior learning.

The Anonymous offers ‘technically-aligned’ design degrees, aiming to develop graduates that have a working understanding of engineering principals and the knowledge of how to practically apply these within the field of industrial product design. The cohort has a diverse range of backgrounds, many of whom have limited interest in STEM-aligned subject matter. It should also be noted that New Zealand high school students' Science and Maths achievement has recently been shown to be significantly lower than Australia, England and the United States further compounding the challenge (Mullis et al., 2020). As a result, educators have reported that cohorts can develop resistance towards engineering subject matter, a challenge with others have also encountered (Hu et al., 2008).

A popular solution to overcome motivational challenges has been to make judicious use of Problem-Based Learning (PBL) activities (Mills & Treagust, 2003). These activities typically involve longer time frame, ongoing continuous assessment styles of assessment, in design education these are often captured through the production of a portfolio of work, or poster-and-presentation style outcomes. Such assessment meshes well with the studio style education environment advocated for by many design schools, combining the creative aspects of design and the analytical aspects of engineering (Cotantino et al., 2010).

The potential of combining Problem Based Learning with Computer Aided Engineering has been gathering momentum as an effective pedagogical approach (Mora-Melia et al., 2024; Wright, 2020). In particular the observations made by Diehl (2023) in aspiring to take student work and understanding in this area from “ugh” to “wow!”. The aim of this study, therefore, was to explore the visual learning and immediate feedback offered by CAE tools within a PBL environment to instil a sense of wonder and appreciation of fundamental engineering principals as applied to design. The paper contributes to improving the quality of engineering and design education by integrating innovative pedagogical tools that enhance learning outcomes and prepare students for future challenges in the field, in direct support of Sustainable Development Goal (SDG) 4.

Technological developments in CAE software help to support the intention of the study. Through recent years, the integration of complex simulation tools for manufacture, moulding, structural, thermal and fluidic analysis into user-friendly Computer-Aided-Design (CAD) packages has grown. Most CAD packages now offer simple to use and Intuitive Graphical User Interfaces (GUI), reducing some of the previous barriers to access found in analysis software. The integration of cloud-based solvers adds to the approachability, allowing complex analyses to be ‘run’ from relatively low specification terminals. Introducing these tools to such cohorts fosters innovation by equipping students with relevant skills for sustainable industrial development and technological advancement (SDG 9).

Approach

The 'problem’ defined for the PBL challenge focussed around the redesign and optimisation of a high-performance bicycle light. Students were arranged into pairs, and each pair was tasked with addressing two intentional deficiencies with the existing design. These challenges were selected to allow students to explore key theories from the course (heat transfer and aerodynamics). For the first part, students were asked to address cooling issues with the design. The design given to students had an undersized heat sink, leading the ABS body of the light to exceed a maximum service temperature of 89 ºC. Students were asked to ‘fix’ this specific issue through redesign. For the second part, students were asked to ‘improve’ the aerodynamic performance of the light. This task was intentionally broad and open-ended, allowing some room for interpretation. Successfully completing either challenge without the use of simulation tools would be a considerable task for the student cohort, and would likely require significant simplification.

The students were required to model the thermal and aerodynamic performance of the existing design to get a baseline for comparison. The teams then had to create a design revision that ensures that the temperature of the ABS stays below the 89 ºC limit whilst all 5 LEDs are engaged, and simultaneously improves on the aerodynamic design (reducing the drag force). Students documented their outcomes through a poster presentation, in which they demonstrated the baseline performance of the original design, the redesign details, and the performance of the final redesigned bike light. The final submission only required students to present a baseline case and an improved design, but many took the opportunity to explore an iterative redesign process, documenting incremental improvements in response to design changes.

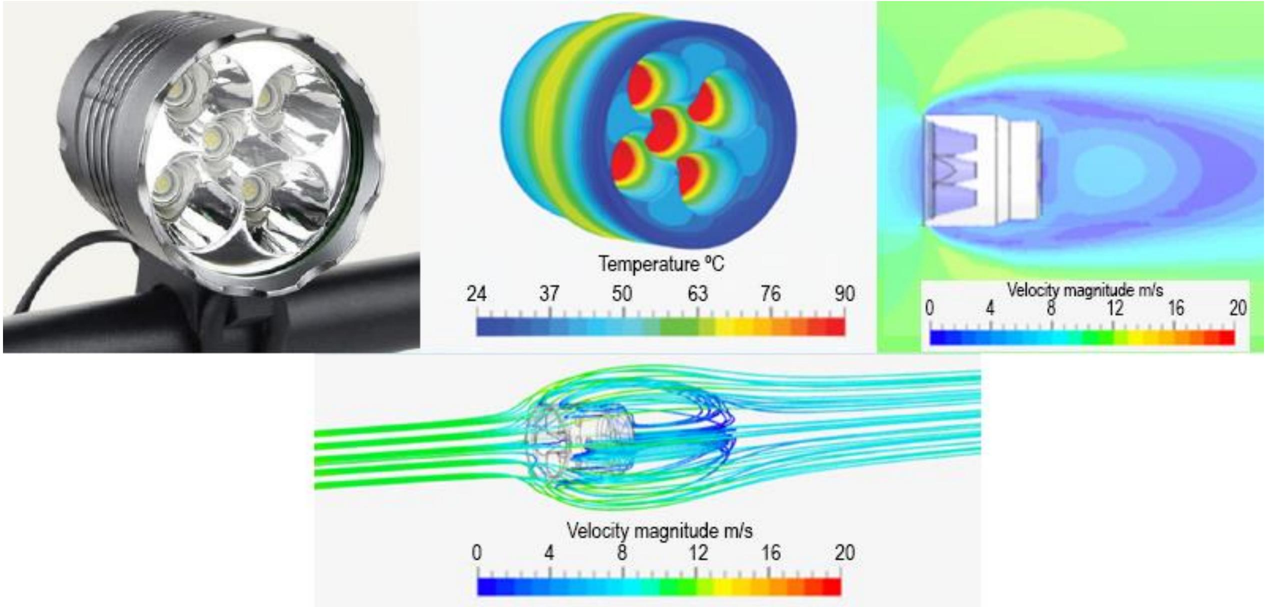

Figure 1: The original basic “canister” bike light for the redesign project assignment. Clockwise from left; render of the original bike light design, heat simulation, velocity profile simulation, particle trace simulation.

SimScale (Simscale, 2024) was chosen as the simulation platform for students. SimScale is a cloud-based engineering simulation platform that allows users to perform Computational Fluid Dynamics (CFD), and Finite Element Analysis (FEA) thermal simulations, through their web browsers. The course team selected SimScale due to its ease of licensing, simple CAD integration through .STEP file import, and cloud-based solving capabilities. The latter reduces the hardware burden for students and also offers cross-platform (both macOS and Windows) support, which is particularly important for design cohorts who often favour Apple products.

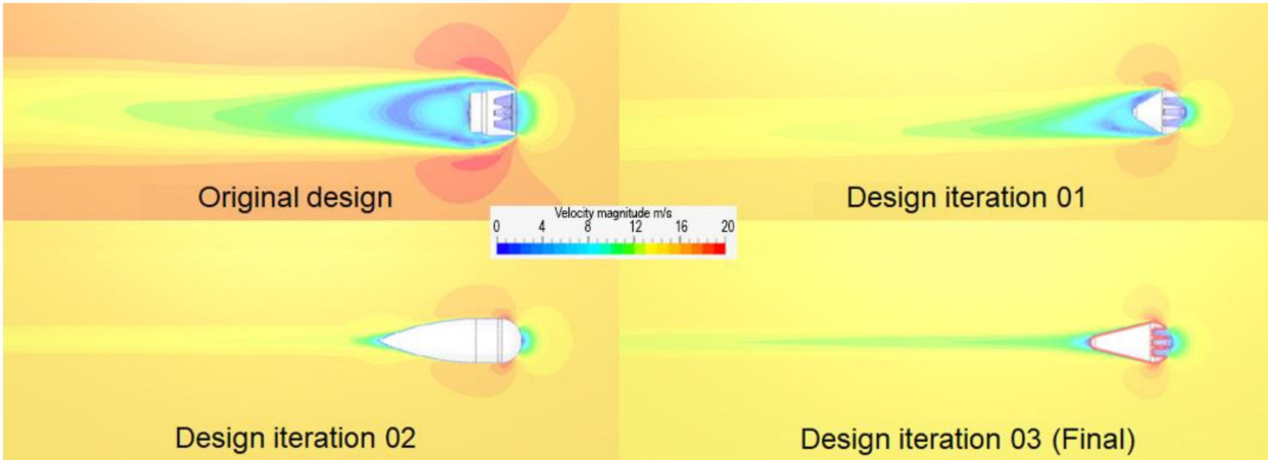

Figure 2: Excerpt from a completed assignment poster demonstrating the iterative design process adopted by one of the student groups.

The (free) education license of SimScale also permits students to access an extensive library of tutorials and examples, which serve as valuable educational resources. These materials facilitate self-guided learning and allow students to deepen their understanding of complex simulation techniques. The platform also includes collaborative design features, including processes for sharing simulations outcomes with peers and teaching staff, simplifying the process of troubleshooting and receiving feedback.

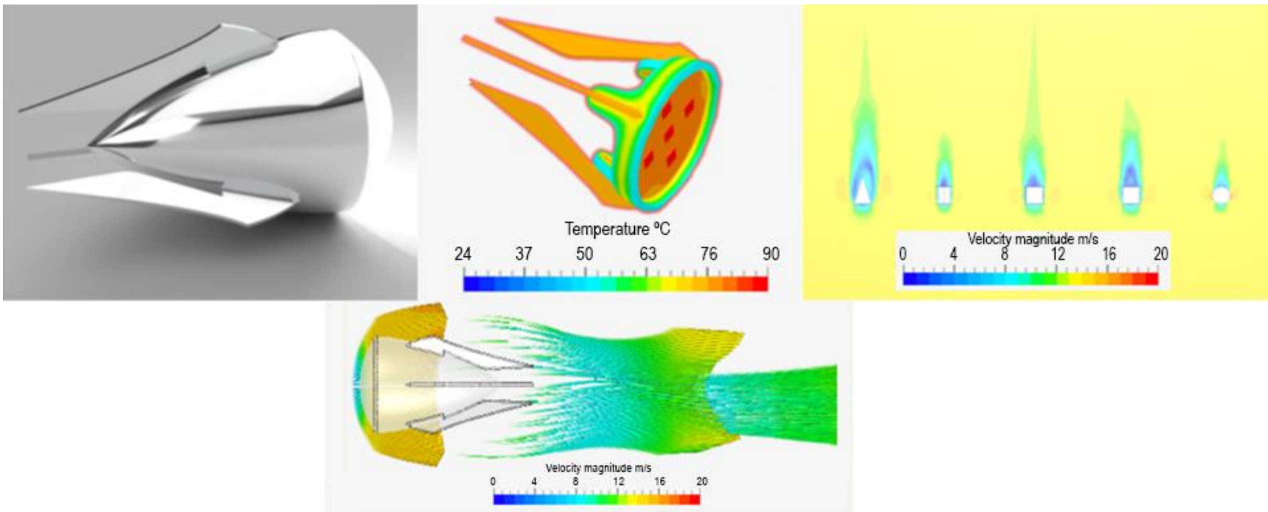

Figure 3: an example of one of the redesigned bike lights created by students. Clockwise from left; render of the redesigned bike light, heat simulation, velocity profile simulation for different geometry choices, particle trace simulation.

To facilitate the teaching of CFD, the staff began with a well-known classroom demonstration where a ping pong ball is suspended in the air by the force of a hair dryer. This demonstration is commonly used to illustrate the Bernoulli effect and the principle of conservation of momentum. By incorporating SimScale into this demonstration, it was possible to provide a visual and quantitative analysis of the flow phenomena while at the same time introducing fundamental concepts of CFD.

The core of our CFD learning outcomes focused on the basics of modelling, providing students a solid foundation in key CFD techniques and concepts. These included selecting an appropriate model type (e.g., incompressible flow), setting up an appropriate domain and boundary conditions, and checking for model convergence before post processing results. More advanced topics such as turbulence models and meshing algorithms were not covered in depth.

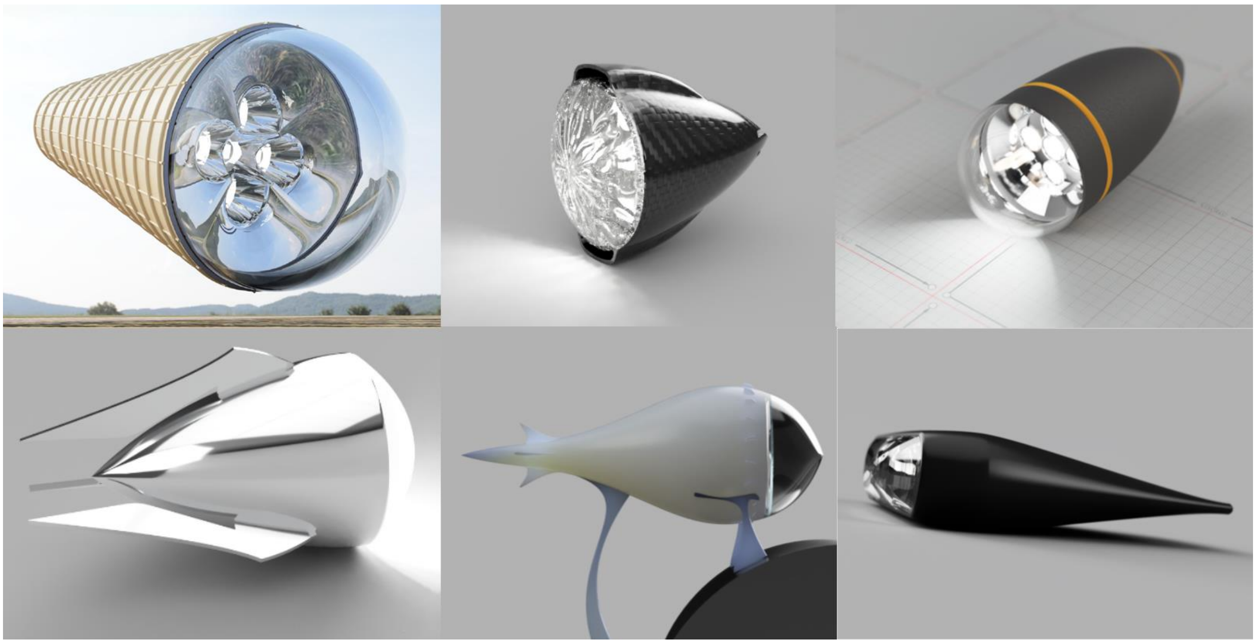

Figure 4: A selection of redesigned bike lights created by students.

In a subsequent class, the students actively engaged with SimScale by analysing the airflow over a golf driver, following along on their individual computers. This hands-on exercise not only reinforced their learning from the initial demonstration but also introduced them to practical applications of CFD in design and engineering. By examining the airflow around the golf driver, learners were able to discuss the design implications and optimization strategies. This interactive approach, combining theoretical concepts with practical simulations, underscored the utility of simulations in professional contexts, empowering students to leverage advanced simulation tools in their future endeavours.

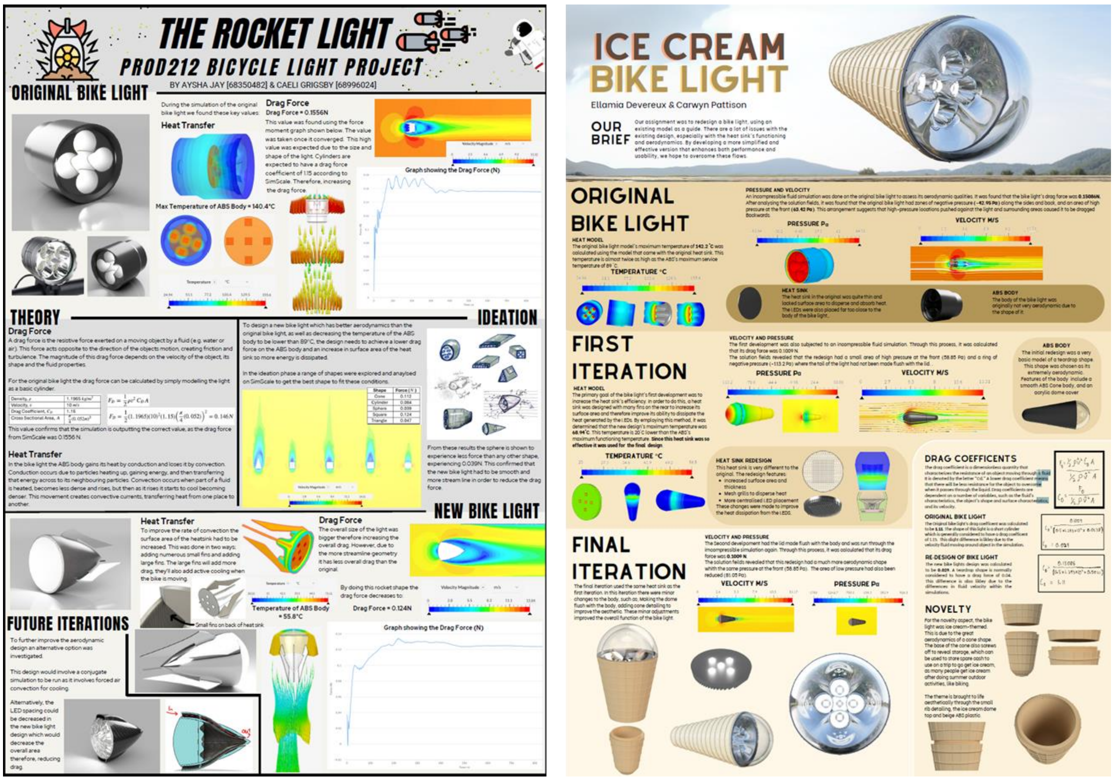

Figure 5: Examples of completed student poster submissions.

Methods

This study set out to consider design students' experience with CAE tools within a PBL environment. In particular, the aim was to determine the extent to which students felt that CAE tools helped them understand core theoretical content, and how comfortable they felt while using the tools. The students were surveyed by means of a qualitative and quantitative questionnaire. In the first part, students were asked to respond to eight simple questions by means of a 5-point Likert scale. In the second part, students were asked to elucidate on their previous responses through open ended questions.

The survey was made available to students after the completion of all assessment items of this element of the course. The survey was anonymised, and was completely optional, requiring students to 'opt-in' to complete their feedback.

The study also considers the feedback of the course delivery and support team, in particular the observations of class staff, including technical team and teaching assistant. These observations are more anecdotal but do support the responses of the survey.

Results & Discussion

The results gathered from the eight quantitative questions are presented as percentages in the form of a heat map in Figure 6. Unfortunately, the voluntary nature of the survey led to a poor overall response rate. Of a 71-learner cohort, only 11 respondents completed the full survey within the designated week-long response period. Despite the low uptake, the results on the whole are encouragingly positive, with almost all responses indicating support for the approach used. The highest instances of neutral or negative responses appear in the earliest questions on whether or not the projects had an influence on students' understanding of subject principles. However, here there is still an indication that on the whole students felt it did influence their understanding.

Question/Response	A great deal	A lot	A moderate amount	A little	Not at all
How much did the bike light project reinforce your understanding of fluid dynamics principles?	9%	36%	55%	0%	0%
How much did the bike light project reinforce your understanding of heat transfer principles?	9%	36%	55%	0%	0%
How much did you enjoy the bike light project?	18%	55%	27%	0%	0%
How much do you feel you have learned from this bike light project compared to traditional coursework?	11%	56%	33%	0%	0%
How relevant do you think the bike light project project was to real-world product design applications?	56%	33%	11%	0%	0%
How satisfied are you with the final outcome of your bike light project?	44%	56%	11%	11%	0%
How difficult did you find learning and using the modeling tools for the bike light project?	0%	33%	11%	33%	22%
How comfortable do you feel about using fluid and heat transfer modeling tools in future projects?	44%	33%	11%	11%	0%

Figure 6: Responses to quantitative questionnaire questions

The value of such problem-based learning activities tends to fosters a sense of engagement and participation in the subject matter and that discovery style challenges can be beneficial for students more prone to ongoing continuous assessment style activities. These observations would appear to ring true, evidenced by responses to the quantitative questions detailed in Figure 6 and further supported by student commentary in the open choice questions. In response to the open choice question "Summarize your overall experience with the bike light project in terms of learning and personal growth" a selection of typical answers were:

"I think it was really cool to be able to put what we learnt in the lectures to use and actually create a system that works well."; "Fun"; "Afterwards, I am now more confident in my cad skills and better understanding of making more aerodynamic designs"

Interestingly, to expand upon the point made earlier regarding the interdisciplinary nature of our degree programme students also offered unprompted commentary in the open choice questions which would also appear to support this observation:

"Linking the bike light (especially heat transfer) to previous material science courses was great as we don't often see the outcomes of our material selections as they're usually conceptual"

Indicating the employment of such simulations tools harnessed and reinforce learning from not just within the 2nd year class but also other preceding 1st year classes as well. A selection of final open choice commentaries made by students would also appear to demonstrate an enthusiasm for the subject matter which was not prevalent before undertaking the PBL simulation assignment:

“I now have an interest in designing highly aerodynamic vehicles.”; “It showed that there’s a lot more to CAD models than just the basic exterior shape and was cool to be able to think about the actual reasoning behind the design”

Such commentary would appear to suggest that the assignment has been successful in achieving the aim of employing visual learning and immediate feedback offered by CAE tools within a PBL to instil a sense of wonder and appreciation of fundamental engineering principals taking the experience from “ugh” to “wow”.

However, there were some observations made that indicate there is room for improvement in the pedagogical design of both the assignment and the class (and by association the broader curriculum). One particular piece of commentary stands out in this regard:

“Me nor my lab partner have taken a CAD course before. Was hard to learn, but a useful skill as we'll need it for next semester CAD courses”

As this is a 2nd year class, the enrolment does capture a number of students who are taking non-standard pathways through the degree programme, for instance those undertaking conjoint degrees or those who have transferred directly into the 2nd year of the programme from another programmes’ first year. Where this is the case, it can occur that such students have not had the same opportunities (for various reasons) to become competent to a baseline level that would place them on an equal footing.

Class staff, particularly teaching assistants, reported a greater incidence of students sketching out other tutorial problems set in the class compared to previous years. While this is anecdotal it is speculated that this is a result of the simulation tools providing a source of visualisation for the concepts involved in the class subject matter. Moreover, exposure to advanced modelling tools equips students with critical skills that are essential in modern engineering practice. By encountering and resolving errors, students develop a keener sense of critical thinking and problem-solving. They learn to question and verify their results, a crucial habit for identifying flawed models and avoiding incorrect conclusions. This early exposure to the complexities of modelling and simulation can help students build a robust foundation for more advanced studies and professional applications.

Conclusion

The principal advantage of incorporating advanced modelling tools like SimScale into the curriculum is that they provide students with a pathway to discovery and experiential learning. These tools enable students to visualize complex phenomena and conduct experiments that would be impractical or impossible in a traditional classroom setting. By engaging with simulations, students can observe the immediate effects of changes in variables, fostering a deeper and more intuitive understanding of fluid dynamics and heat transfer topics. This hands-on approach can make abstract concepts more tangible and accessible, enhancing overall comprehension. The additional benefit is that cohorts can make mistakes *in silico.* Through simulation, students are able to explore design iterations without the need for physical prototyping, reducing the inherent environmental impact of a classic product design process (SDG 13).

This paper represents the first iteration of CFD being integrated into this course, and the evidence gathered so far supports the proposal that this change enhances students' understanding and application of fluid mechanics and thermodynamics principles. It is noted that the statistical power of the data collected thus far could be improved. Accordingly, future iterations of the course will focus effort in both streamlining the delivery of the content, and gaining deeper and more tangible insights into the intervention from the student cohort.

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