Desktop experiments to visualise boundary layer flows in water

Abstract

The theory of boundary layers, which is well established and taught in all undergraduate fluid mechanics courses, can be challenging for first-time learners to comprehend. Three challenges are identified in this paper, namely to visualise the existence, thinness, and attachment/separation of boundary layers. We approach these challenges through the lens of threshold concepts and discovery-based learning. We present a new desktop experiment to address these challenges. Water flow is visualised in a small transparent flow loop. A 'guided discovery' approach allows students to experiment with the equipment during a three-hour session working in pairs.

Student lab books and reports show that, using the equipment, they can effectively identify the existence of boundary layers, and their relative thinness. Boundary layer separation was also observed by most students. The nuance of separation requiring strong positive gradients was ascertained by approximately half of the students.

A survey on the student experience was used over four years (717 students, 297 replies — 41%). Seven dimensions of the student experience were analysed. Overall results showed that students found the experiment very helpful in gaining a conceptual understanding of the boundary layer.

On the basis of student work and survey results, we identified limitations of the work, in particular clarity on the relationship between flow reversal and boundary layer separation. We suggest improvements to equipment, and the introduction of computational fluid dynamics (CFD). We show example CFD results for this purpose. Overall, on the three challenges we identified, the equipment and the 'guided discovery' activity were judged to be successful.

1 Introduction

Boundary layer theory has its origins in the early 20th century with Prandtl's seminal work [25]. The theory then developed to become an essential part of fluid mechanics theory across disciplines in engineering sciences [2]. The theory is described in many textbooks, for example [28, 22], and is briefly summarised in the Appendix A.

Learning about boundary layers is challenging. We decompose the problem here into three sequential challenges which provide a kind of 'problem definition', to which this paper proposes and evaluates a solution.

1.1 Three challenges in learning boundary layer theory

The first challenge stems from the fact that boundary layers cannot be seen in everyday life. Students are provided with technical information such as written and sketched explanations; lectures; videos; measurements of velocity profiles near a wall in a wind tunnel; and theoretical results. However, the existence of the layers is still often not intuitively clear.

Education challenge §1: evidence that boundary layers exist

Create a physical demonstration to be conducted by the student themselves to see first-hand the existence of boundary layers.

When the first challenge is solved, the existence of the boundary layer will be established in the mind of the learner, and it can then be analysed. Approximation of the equations of motion is required to perform the analysis. It is convention to write the equations of motion and state the order of magnitude of each term, highlighting which can be neglected. A summary of the analysis is in the Appendix B.

There are two problems with the analysis for students. Firstly, the mathematical expression, using 'order of magnitude' symbols, lacks *meaning* to the uninitiated learner. Secondly, the commonly invoked assumption that $\delta/L \ll 1$, where δ is the boundary layer thickness and L is its characteristic length, is not always true. It is not clear to the student that this assumption is based on physical observations.

Some comments from students over the years that illustrate the difficulty include:

> "I find it extremely difficult"
>
> "seem like jumps in reasoning"
>
> "Theres too much reading in between the lines to understand the theory"
>
> "order of magnitude analysis and general approximations content ... it's hard to see 'how' to do stuff, I just watch the lecturers 'do' stuff."

Clearly students are confused. We summarise the challenge as revolving around identifying the geometry of the boundary layer.

Education challenge §2: physical observations that boundary layers are thin

Students need to appreciate that boundary layers are thin relative to the length over which they develop ($\delta \ll L$) for high Reynolds numbers, and that this physical observation is the basis of the theory developed by Prandtl. Showing velocity profile data does not seem to have a strong meaning to students. Visualisation is required.

When the learner has established that the 'thinness' of boundary layers (for high Reynolds numbers) is a physical observation, they can use this observation to develop a theory. Specifically, they can approximate the equations of motion following Prandtl [25], and solve them following Blasius [5]. The result of that analysis suggests that boundary layers remain attached in negative, zero, and light positive pressure gradients; but that flow reverses in the presence of strong positive ('adverse') pressure gradients. When a boundary layer reverses, the thin shear layer 'separates' from the boundary and proceeds into the main flow. The foregoing statement is not an obvious conclusion to the student.

Education challenge §3: boundary layers attach or separate depending on pressure gradients

Students need to observe the key behaviour of boundary layers in different pressure gradients:

- Attached: in negative, zero, and light positive pressure gradients.
- Separated: in strong positive ('adverse') pressure gradients.

In summary, all three challenges relate to concepts that are not clear or obvious to students. The problem we aim to solve in this paper is to provide experimental equipment, and appropriate classroom processes, to help students discover the key physical phenomena — existence, thinness, and separation of boundary layers — for themselves.

1.2 Overview

The paper is structured as follows. In the next section we review the educational frameworks of threshold concepts and learning by discovery. We also review experiments in education from which we can draw inspiration. In Section 3 we present a new desktop experiment that allows students to visualise flow over

Characteristic	Representation in boundary layer theory
Conditional	Mastery of underlying concepts in fluid mechanics, in particular those of velocity fields, and force-momentum balances. The latter is the basis on which the relative importance of viscous effects can be discussed. The relative importance of viscous effects is a key concept to appreciate when employing boundary layer theory.
Discursive	Learners need to internalise the inter-related concepts in order to use them in their internal language of thought [23] and when expressing themselves. This includes the conditional (foundational) knowledge, and the concept of different regions of the flow; the dominant role of Reynolds number; the interaction of pressure gradients and velocity profiles.
Integrative	Only by combining the key discursive concepts can the boundary layer be appreciated.
Liminal	The inter-related nature of the relevant concepts leads to a liminal space where the learner builds blocks of partial understanding, which may lead to temporary set-backs, before emerging as full understanding.
Bounded	Boundary layer theory is bounded to thermofluid sciences. Basic boundary layer theory has further limitations such as not accounting for instabilities, transition, turbulence, three-dimensional and compressibility effects.
Transformative	A 'new way' of seeing high-Reynolds-number fluid flows, with thin but influential regions of viscous boundary layers adjoining larger, inertially dominated flows.
Irreversible	The transformed way of seeing is so simple and powerful that it becomes hard to 'unsee'.
Reconstitutive	According to Meyer and Land, learning threshold concepts can lead to a change in identity of the learner as they become members of a discipline (see [29] and legitimate peripheral participation). Evidence for this concept is beyond the scope of the present paper.

Table 1: Mapping key characteristics of Threshold concepts to the specific case of boundary layer theory.

an object, including in the boundary layer. We describe how the kit is deployed in the curriculum to facilitate discovery, and how we evaluated the process.

In Section 4 we present results after 4 years of deployment and over 700 students having used the kit. We present student outputs, and quantitative results of a survey of student experience. In Section 5 we discuss the extent to which the kit and activities presented in this paper solve the problem. We outline future work in Section 6 and conclude in Section 7.

2 Literature review

In this Section we review literature two educational frameworks that can be applied to teaching boundary layers, namely threshold concepts and discovery learning. We then review practical teaching interventions that are relevant to boundary layers.

2.1 Threshold concepts

We have established that learning and teaching the topic of boundary layers is often *troublesome*. The framework of *threshold concepts* [19, 20] can be used to analyse learning troublesome knowledge, subject to further definitions listed in Table 1. For each definitive characteristic of a threshold concept in Table 1, we use the second column to provide an informal justification for applying threshold concepts to boundary layers. The order of the rows is both logical to allow reading top-to-bottom, but also travels from the strongest to the weakest evidence that we have to justify the use of threshold concepts.

Consideration	Application in boundary layer theory
Jewels in the curriculum	Not relevant at the detailed level of focus in this paper.
Importance of engagement [16, p.57]	A key concept, highly applicable: • Develop a genuine understanding; use questions • Active engagement (not simply recall) • Ways of thinking and practicing (see Wenger (1998) [29]; ‘thinking like an [engineer]’) • Provocations: ‘something else happening — other than the return of the same’
Listen for what is known	Give time for students to express themselves and identify their (lack of) understanding
‘Supportive liminal environment’	Facilitate discomfort, give space for experimentation, making mistakes, exploring
Uncertainty	Use questions and a supportive culture; encourage uncertainty
Excursive journey	Facilitate discovery. Introduce recursiveness, e.g. multiple exposures to ideas, from different perspectives.
Pre-liminal variation	Account for the different states of knowledge with which students enter the process
Don’t simplify	Break it down, but not beyond what is functional. Avoid ‘false proxies’.
The underlying game	Beyond the scope of this paper

Table 2: Nine considerations when teaching a threshold concept, from abbreviated from [16].

While the justifications in Table 1 are not rigorous, we note that more generally the rigorous identification of threshold concepts is not well established [4, 10]. We continue on the basis that ‘threshold concepts’ is a relevant framework to help consider how to teach boundary layer theory, on the condition that it is used critically. For example, it helps narrow down which teaching techniques used by others may be relevant to the problem of learning about boundary layers; but it does not guarantee that those techniques will help.

Land et al. [16] considered the implications of threshold concepts for course design and evaluation. Their nine considerations are listed in Table 2, with the application to boundary layer theory added in the second column. The recommendations in Table 2 — for teaching a threshold concept — are applicable to teaching boundary layers because boundary layers can be considered a threshold concept.

Reflecting on the recommendations in Table 2, they point towards providing a prolonged experience where students are free to explore and discover the key properties of boundary layers. An umbrella term for this approach is ‘Discovery learning’.

2.2 Discovery learning

Armstrong, in 1898, introduced learning by discovery as ”methods of teaching which involve our placing students as far as possible in the attitude of the discoverer — methods which involve their finding out instead of being merely told about things.” [3, p.236]. Bruner further developed discovery in education, arguing for the ”powerful effects that come from permitting the student to put things together for himself, to be his own discoverer” [7, p.21].

‘Discovery’ applies beyond scientific progress for mankind as a whole, to one discovering for oneself, even if already known by others. In the context of education, Armstrong referred to ‘old results for new men’, and Bruner to ‘obtaining knowledge for oneself’ [7, p.21]. Bruner defines discovery as ’rearranging or transforming evidence in such a way ... to go beyond the evidence so reassmebled to additional new insights’. Bruner’s definition is applicable for threshold concepts, especially physical concepts where concrete evidence plays a key role.

Bruner made a further point that ”it may well be that an additional fact ... makes ... transformation ... possible. But it is often not even dependent on new information”. With this clarification the emphasis is on the *process* of discovery, not just which facts are presented. The challenges of learning about boundary layers are an example of the process of discovery being important. We stated in our introduction that when we (didactically) provide the full information to students, boundary layers are troublesome to understand. Bruner's approach encourages us to put an extra emphasis on the process of 'discovery', and not just the acquisition of sufficent facts.

Discovery based learning, which departed from behaviourist theories, inspired many educationalists and led to many educational experiments [21]. Evidence for the effectiveness of discovery based learning is plagued by confusion, however. Disagreements over definitions and appropriate experimental paradigms followed [8, 12]. For example, the difference between learning for discovery (learning how to discover — how to learn), and learning by discovery (learning specific knowledge by a different process). Also the distinction between completely free discovery; guided discovery; and didactic teaching. One comprehensive meta-review claims that free discovery has a limited benefit, while guided discovery is superior — as a means to acquire knowledge or understanding — to either free discovery or didactic teaching [1]. While a systematic review does provide strong evidence, there is still debate; for example another meta-review claims a complete ”failure of Constructivist, Discovery, Problem-Based, Experiential, and Inquiry-Based Teaching” [14].

To conclude on Discovery Learning, Bruner's emphasis on process is useful and will be applied in this paper. For specific implementations that work most effectively, the literature paints a mixed and inconclusive picture. Hard evidence for a particular teaching method is not available, which is often the case in education where context is such a dominant influence the process. The brief review we provide here suggests, however, that if didactic teaching has been troublesome, then introducing a component of discovery is worth trying and evaluating. Practically speaking, 'guided discovery' is probably a good place to start.

2.3 Practical approaches in the literature

Lock et al. [18] appear to be the only researchers to publish work specifically on teaching boundary layers. They used oil flow visualisation on wings to improve understanding of boundary layers, reporting positive results from student surveys. In a closely related study, Pour et al. [24] used visualisation of thermal boundary layers to motivate students to study heat transfer. Student surveys in [24] showed that students found the demonstrations to be helpful, interesting, well-explained and informative. A particularly relevant comment from a student was that ”it is really hard to picture the boundary layer, so seeing it was great” [24, p.523]. Thermal boundary layers are analogous to 'momentum' boundary layers that are the focus of this paper, so the visualisation is likely to help equally in both cases. The common factors in [24] and [18] were the application to boundary layers and the use of visualisation.

Brown et al. [6] studied the effect of using a desktop demonstration module for open channel flow; with controlled tests they showed a large effect size (0.98) [9]. Richards et al. [26] reviewed simple hands-on fluid mechanics experiments and presented new equipment. They created a desktop flow loop to aid learning basic concepts in fluid mechanics, with an emphasis on the Bernoulli equation and using Venturi shapes. A controlled test of students using the kits, and those with an equivalent hand-out, showed similar levels of learning — measured by pre- and post-activity test scores — in both cases. The work of [6, 9, 26] all uses fluid mechanics experiments, but with less emphasis on visualisation. The contrasting outcomes, as measured by assessment of students, shows that context, and details of implementation, are a vital factor in the success of these approaches.

Visualisation more generally has received further attention. A meta-study by Lis [17] showed that 'visualisation' can enhance engineering education, however the focus was more on the use of images in learning materials. Savander and Kolari [27] argue that visualisation helps with engineering problem solving, basing their claims on a mechanistic explanation of how visualisation helps. The literature on visualisation emphasises visualisation images with images; or visualisation as a means of developing thought or communication; there is limited research on the benefits of personally seeing a physical phenomenon as a means of learning troublesome concepts.

In their well-cited review of the role of laboratory studies in engineering education, Feisel and Rosa defined 13 objectives for using the laboratory [11]. Improving conceptual understanding was not one of those objectives. Learning troublesome concepts is not the only reason to visit the laboratory, and it is not always an important part of laboratory activities; in the case of boundary layers and the work presented here, it is the primary reason.

2.4 Summary of literature

The key points from the brief review are:

- Threshold concepts are relevant to boundary layers.
- Guidance on course design for threshold concepts (Table 2), suggests a discovery-based approach.
- Bruner's work on discovery puts an emphasis on the *process* by which we reach insight, not just the intended outcome.
- 'Guided discovery' is an intermediate point between purely didactic or discovery based learning.
- Practical efforts in the literature suggest that hands-on and visualisation are helpful approaches, although conclusions are always context-dependent
- The laboratory as a place to visualise troublesome concepts is not a common approach

The theoretical review helped focus on the type of challenges — threshold concepts — faced when teaching boundary layer theory. Further, a framework to discuss teaching approaches has been identified, namely 'discovery'. The question of course design is *where on the spectrum*, between didactic and free discovery, we should position ourselves; and *how* to do this. To address this question, we need to try a new approach with an increased element of discovery, and to critically evaluate the results.

3 Method: experimental equipment and laboratory arrangements

We have implemented new experimental equipment and an associated teaching teaching with undergraduate engineering students. In this Section we describe our implementation, begin with the educational context and prior experience that led to the present implementation. Then we describe the new apparatus that we have developed. Following that we describe the scaffolding that was provided to aid students during the activity. As methods of evaluation, we define the student outputs that were available for analysis, and a survey that was used to evaluate student experience.

3.1 Educational context

The work in this paper is from a single, dedicated mechanical engineering degree programme. Fluid Mechanics is one of the subjects that students study in their first year, learning about hydrostatics, kinematics, the Bernoulli equation, and control volume analyses. Following that, in their second year they study a more advanced module deriving and applying the differential equations of motion: Cauchy, Navier-Stokes, Euler, Isentropic flow. The second year module is the focus of this paper. Students spend approximately 125 hours on the subject over one academic year. The module comprises weekly lectures, weekly self-study exercises, bi-weekly group tutorials, and a 3-hour experimental activity. Within the module, approximately 20-25 hours of study is focused on Boundary Layer theory; the experimental activity is also dedicated to boundary layers.

Prior to implementing the work described in this paper, the laboratory session was organised as follows: Students were allocated three hours to visit a wind tunnel in groups of four or five. Students measured the velocity profile near a flat wall, and would subsequently analyse the profile, e.g. calculate momentum thickness and drag coefficients. Laboratory visits (prior to the changes implemented) were scheduled over an eight-week period after boundary theory was delivered in a lecture.

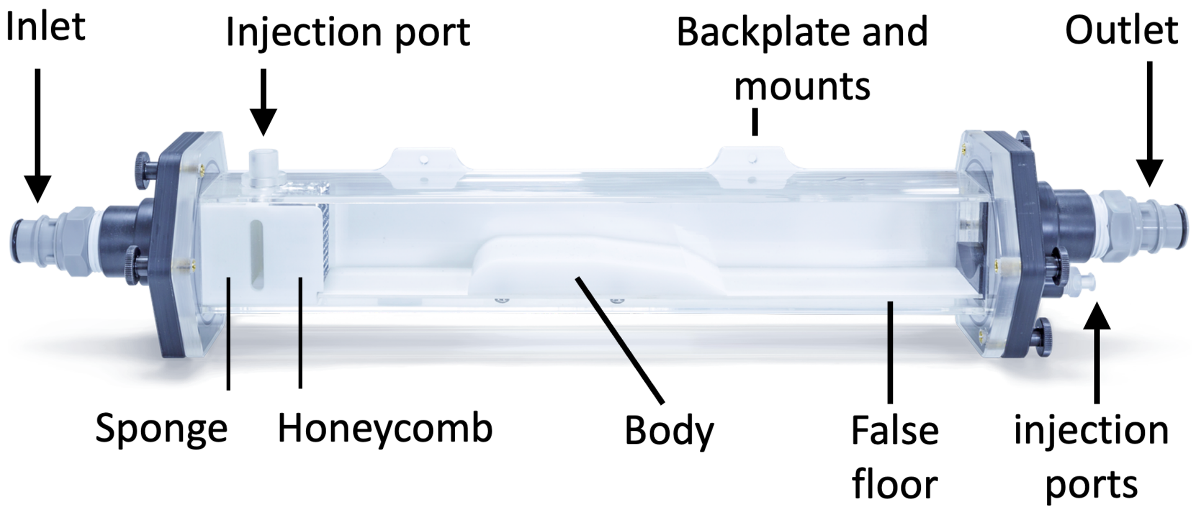


Figure 1: The desktop flow loop showing key features. Tracer fluid is introduced through injection ports: one upstream for a needle to inject into the main flow from an adjustable height; and two downstream that dock with the false floor and are routed to the body to eject from the surface.

The original activity was instructional, i.e. students were given asked to follow pre-determined instructions. The other seven activities for the same cohort also followed an instructional approach. The implementation of discovery-based learning described in this paper is therefore unique for the students who experience it.

One early attempt to introduce 'discovery' to the Fluid Mechanics activity, prior to the period described in this paper, was to reschedule the visits to be *before* the lectures. The concept was to 'observe first', providing personal experience and empirical context for the theoretical lectures. Feedback from students in focus groups suggested that they had forgotten about the visit by the time the relevant lecture came. They suggested that observing first is fine in principle, but needs to be in close temporal vicinity to the associated lessons on theory. Logistical constraints make this difficult to achieve for large cohorts.

The catalyst for wider change was that during the pandemic, in 2021, we needed students to meet the same learning outcomes while being locked down in their homes around the world — without access to the wind tunnel. To meet this need we developed a water visualisation kit that could be delivered to students and that they could use without expert assistance. The success of the kit led us to continue using it after lockdown (2022, 2023, 2024, and in future) but in a classroom environment.

3.2 Description of the apparatus

The apparatus is a transparent water flow loop, with flow visualisation features, illustrated in Figure 1. It is small enough that it can be used on a table top in a classroom, with students working in pairs or alone. The ability to schedule large numbers of students together — while still working in pairs on their own equipment — makes scheduling in-sync with whole-class lectures possible.

The working section of the flow loop is a transparent square tube with internal sides of $h = 44\,\mathrm{mm}$ and a length of at least $300\,\mathrm{mm}$ depending on the model. Water is pumped from a source by an electric submersible pump, for example an aquarium pump, and flow rates on the order of up to 300 litres per hour ($Q = 83 \times 10^{-6}\,\mathrm{m}^3/\mathrm{s}$), leading to channel Reynolds numbers up to $Re_h \equiv Q/(h\nu) \approx 1900$ where ν is the kinematic viscosity. At these flow rates the flow is laminar, but the channel boundary layers are thin.

Flow conditioning using a sponge and honeycomb was effective to achieve a uniform flow at the entrance — if bubbles are absent. Tracer fluid with neutral buoyancy can be sourced from commercial suppliers (CAS 3536-49-0) or as a reasonable alternative pen ink can be mixed with water at a ratio of approximately 1:40.

A body shape was engineered to be placed inside the working section and provide flows of interest. The body is a simplified version of the 'Ahmed body', with a circular nose, a flat top, and angled downstream

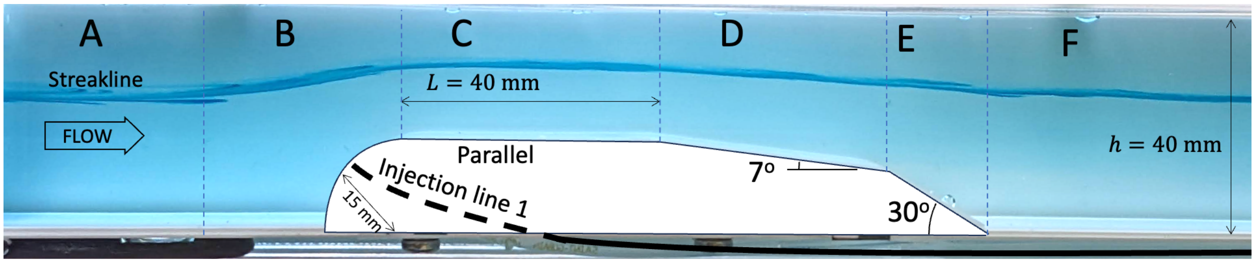


Figure 2: The working section with water flowing and a streakline from upstream. Geometry is annotated, and labelled zones (A-F) identify the different pressure gradients. The length scale L is indicated.

sides at $7°$ and $30°$ — see Figure 2.

Tracer fluid can be injected upstream from an adjustable height; and additionally from within the body. The latter is important to ensure the boundary layer can be visualised with relative ease. Flow visualisation should represent the same flow that would be present in the absence of the visualisation. Therefore it is recommended that injections are at 90 degrees to the flow at a gentle pace, or counter to the flow at a gentle pace, in both cases this is to avoid creating an artificial jet when injecting.

Measurements that are possible from the basic experiment include measuring volume flow rate, inferring Reynolds number and pressure gradients (using the Bernoulli equation). Visualisation can capture streaklines of flow over the body; the existence of uniform flow in the main flow; slower flow on the boundaries; velocity profiles at the boundaries; attachment and separation of the boundary layer; re-circulation regions; and more exotic flows when employed by a curious user, such as turbulent jets, free surface flows, and wake patterns. The working section can handle alternative bodies for example cylinders, wings, or other shapes. The primary means of capturing flow visualisations is by photos and videos, typically by students using their own smartphones.

3.3 Activity management

The kits were used annually for four years (2021–2024). In the first deployment (2021), students were at home due to lockdown and were sent their own kits and worked physically alone, with peers on a video call. In later years (2022–2024) students were accommodated on campus and worked in pairs.

Students are managed in groups of up to 50, in pairs working at their own pace. Cohorts of up to 200 were managed, requiring four separate sessions. In our context these sessions were scheduled twice per week, allowing all students to complete the exercise within 9 calendar days, and in-sync with the lecture course. Lectures were weekly, and three of the lectures were on boundary layers. Half of the students used the equipment in the same week as, but before, the first lecture on boundary layers; the other half used the equipment between the first and second lectures. The same equipment is also used during lectures for demonstration purposes.

To prepare for the activity, students were provided with six short videos, totalling 30 minutes. Videos were watched by about 55% of students (some of whom may have been in pairs or groups so total viewing may be higher), with a 90% completion rate for those who viewed them. Written slides were also available as an alternative. The briefing was to familiarise students with the equipment and how to use it; and to establish the goals of the session. The goal was to record evidence of the existence, thickness, and behaviour (attachment/separation) of boundary layers.

Guidance for students

An outline for the session provided 'guided discovery':

- Setup the equipment, and show a risk assessment before water is provided (15 mins)
- Activity 1: Measure the flow rate, calculate the channel Reynolds number, and observe streak-lines in the main flow (30 mins)
- Activity 2: Answer questions about the velocity and pressure fields (30 mins)
- Mid-session review (optional depending on tutor and class dynamic) (15 mins)
- Activity 3: Observe the boundary layer (20 mins)
- Activity 4: Custom experiment - optional (20 mins)
- Discussion, conclusions, clear up, and support (20 mins)

Activity 2 reminds students of a question that they answered for self study in the previous term, using a photo of the working section. Here they conclude, on the basis of incompressible flow, that the velocity increases in thinner cross-sections; and, from application of the Bernoulli or Euler equations, the pressure gradient in each section can be inferred (negative at B, zero at C, positive at D and E but stronger at E than D).
Activity 3 is the three Challenges in this paper, i.e. to observe the existence, thickness, and behaviour of boundary layers, where behaviour is attachment or separation related to pressure gradients.

The briefing before the lab sets expectations that students will conduct their own experiments. A key part of cementing these expectations is the first minute of the activity in the room. Tutors welcome students into the room and say "Welcome, you may start your experiments. I'm here to help so feel free to ask". This introduction makes it clear that students are the agents of the activity. The tutor checks in regularly to maintain a dialogue with the students, but without dictating their activities.

In addition to the 2.5 hours described above, students can optionally visit the Wind Tunnel in a different room for 30 minutes, and collect a velocity profile from the wall. Use of the wind tunnel is outside the scope of this paper. Students who didn't visit the wind tunnel used the extra time for the flow visualisation experiments. Tutor-student ratios were 12-to-1. Tutors were trained with video footage of the teacher working with students in previous years. Tutors then met as a group with the module leader to reflect on good practice. An abbreviated version of a written summary of the training is as follows:

Guidance for tutors

- Reflect on the purpose of the activity and how students experience it
- Students have written guidance and can complete the activity independently
- Avoid telling students things directly or giving them instructions
- Listen to students, understand their point of view first and use that as a starting point
- Be positive and encouraging, give them positive feedback
- Share your passion for the subject
- Discuss their results with them
- Challenge high performing students and encourage them to be critical in their analysis

An example of a tutor with a pair of students is illustrated in Figure 3. At the time illustrated, the students have previously suggested how they will conduct an experiment to gather evidence. The students are the

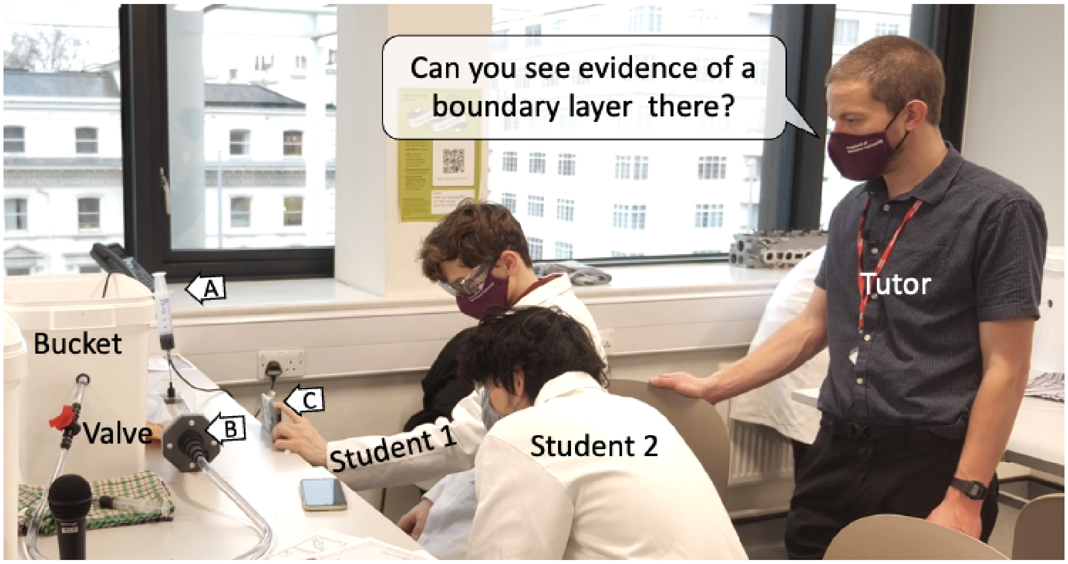


Figure 3: A tutor visits a pair of students. The students are actively using the kit to experiment, while the tutor prompts with questions. A: tracer fluid injection. B: working section. C: student smartphone to record evidence. The kit in use is a previous version to the one in Figure 1 but with the same working section. Masks were mandatory at the time the footage was taken. Permission to publish was given prior to filming.

agents of the experiment, and the tutor is positioned separately so as not to take control or dictate activities. The tutor's question is open, but focusses the students' attention on the important aspect of the experiment.

3.4 Assessment of outputs

Two aspects of summative assessment relate directly to the laboratory session: the lab book, and a report.

All students have their lab book assessed, with a relatively low stake (3.75% of 5 ECTS where one year is 60 ECTS). Students record their findings in a lab book, which is scanned and submitted at the end of the three-hour activity. The lab books provide qualitative data on student learning, and quantitative data based on the assessment. The rubric for assessment includes evidence relating to the three Challenges presented in Section 1, which means that we have statistics available on the extent to which students successfully observed the phenomena that were intended.

Students also wrote a lab report on an activity allocated at random after all activities were complete. One quarter of students wrote a lab report on the activity described in this paper (weighted at 15% of 5 ECTS). Similar to the lab books, the reports provide qualitative insight into student learning after reflection and consolidation, and more time to process and present their work. There was also a rubric that can be used to statistically analyse learning evident by students.

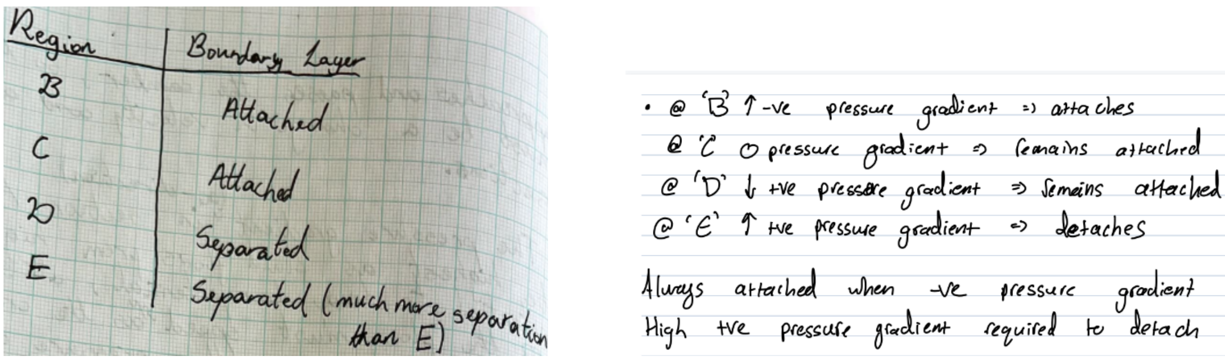
3.5 Survey of student experience

To evaluate the student experience we used a survey developed by [13]. The same survey was common across 13 different activities in the degree programme, including eight activities in the same cohort that used the experiments described in this paper. The survey comprises quantitative (Likert) questions on nine dimensions of experience across all activities; free comments are also solicited for qualitative analysis. The survey is described in more detail in [13], showing good repeatability and sensitivity. The nine dimensions are purpose, conceptual learning, positive challenge, documentation and guidance, engagement, support, collaboration, feedback, and technical communication skills. The last two dimensions are omitted in this paper because of censoring effects — only one in four students writes a report and receives feedback on the report for a particular activity, yet the survey questions apply to the whole cohort; hence the data related to report writing and feedback cannot be disentangled. This issue will be resolved in future by asking respondents which report they wrote.

In the survey results, Likert scores of 5.0 correspond to ‘strongly agree’, 4.0 ‘agree’, 3.0 ‘neutral’, 2.0 ‘disagree’, and 1.0 ‘strongly disagree’. Average scores above 4.0 are considered good and not needing improvement, although aspirational teachers aim for 4.5. Changes of approximately 0.5 are considered significant. The benefits of the survey are to provide high level feedback on the quality of a laboratory experience and to highlight areas that may need further attention. The comparative study with different activities provides a level of validation, along with the statistical stability over a number of years.

4 Results

We begin by presenting results of student outputs and assessments. Then we review the results of evaluating the student experience.



(a) Observed separation but made incorrect conclusions.

(b) Correctly distinction between positive gradients.

Figure 4: Examples of student lab books.

4.1 Student outputs

Examples of student lab books are presented in Figure 4. In Figure 4a a student correctly identified the existence and thickness of the boundary layer, and has recorded observations on separation. The observations on separation are incorrect, suggesting separation at D (incorrect), and ‘more separation’ at E[1] which is not a valid concept.

In contrast, the student in Figure 4b has correctly concluded that, specifically, a strong positive gradient is required in order to observe separation. Some students also recorded observations of flow reversal in section E, although neither of the examples in Figure 4 did.

The proportion of students who presented evidence in the lab book for each of the three challenges addressed in this paper is plotted in Figure 5. There is a trend over the four years where students became more successful at recording evidence for these key phenomena. For the last two years, results were stable and the two students in Figure 4 each represent about half of the cohort (see data in Figure 5).

Reports written after the activity enabled students to provide more detailed evidence. Figure 6 shows some highlights of how students reported their work. The series of photos in Figures 6a show that the existence of the boundary layer is evident. All students informally observed the existence of a slow layer near the body. ‘Seeing’ by eye had a low barrier to entry; however, recording convincing evidence for others was less common. The evidence in Figures 6a required a significant level of innovation in pumping tracer fluid by different amounts to visualise different layers, and in processing the results. Most students could not provide such a compelling case.

[1] Written as D in the logbook, presumably a basic error.

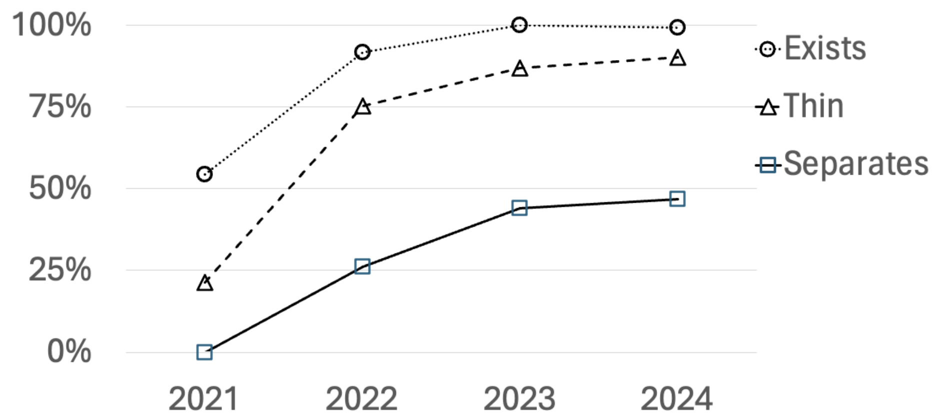


Figure 5: Proportion of the cohort who provided evidence in the lab book for the three key conclusions about boundary layers.

Figures 6a also provides evidence for a limit to the thickness of the boundary layer. The cyan circle is close to the body ($\ll L$), while moving at the speed of the main flow, providing a limit to δ and showing that $\delta \ll L$. Most students effectively provided evidence for this case.

Figure 6b shows work from a different student, effectively identifying attachment and separation explicitly. Figure 6c is from another student, who has annotated recirculating arrows to highlight the phenomenon and emphasise the role of flow reversal.

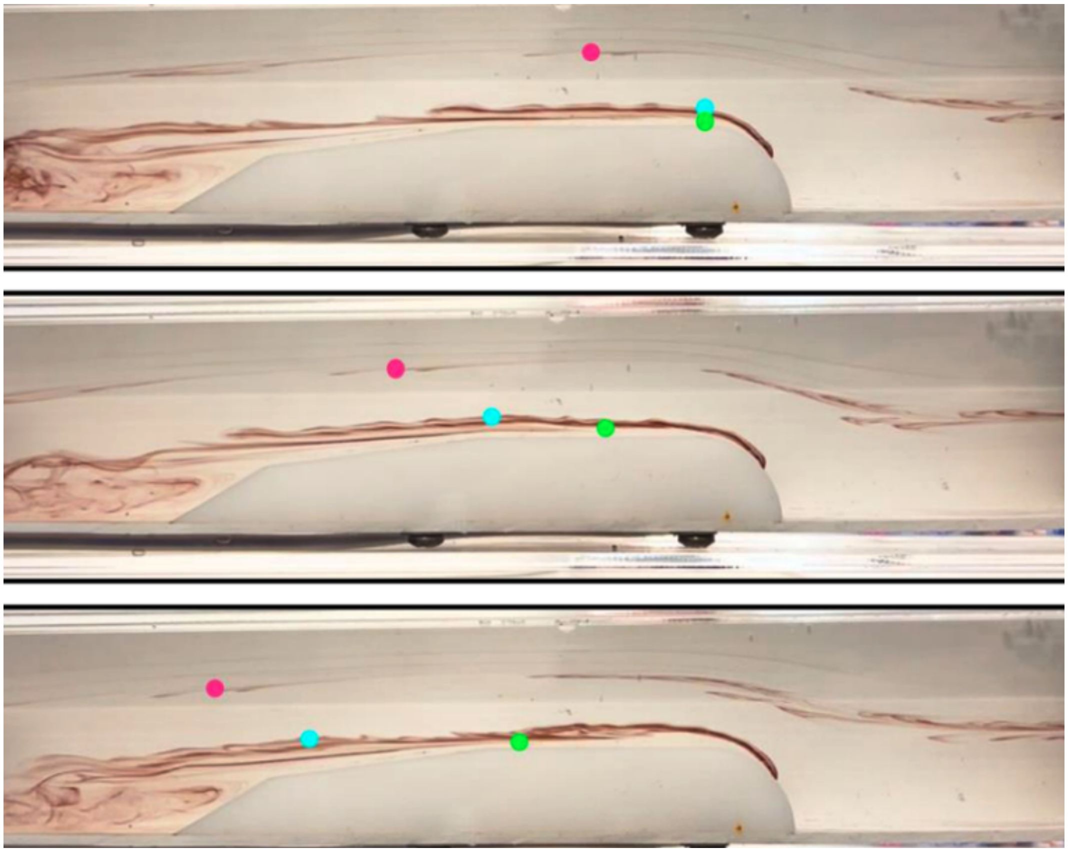
While Figure 6 shows that some students provided evidence satisfying all three Challenges provided in the introduction, not all students were so successful. Some students, as with their lab books and despite written feedback on this point, still failed to grasp that separation is a distinct event associated with flow reversal. Some reports insisted that the boundary layer separated in region D, despite this not being the case.

Assessment scores for reports were relatively consistent over four years (in contrast to the lab book marks illustrated in Figure 5). On the measure of completeness of results, the proportion receiving a grade 'A' was 54%, 48%, 67%, 63% for years 2021 to 2024 respectively. The drop in 2022 is consistent with results across the cohort in all subjects, associated with the previous (first/freshman) year of study in lockdown. The trend was similar for conclusions in the report (68%, 54%, 65%, 79%) with a possibly significant increase in 2024, which correlates with the purpose of the lab being clarified in the handout.

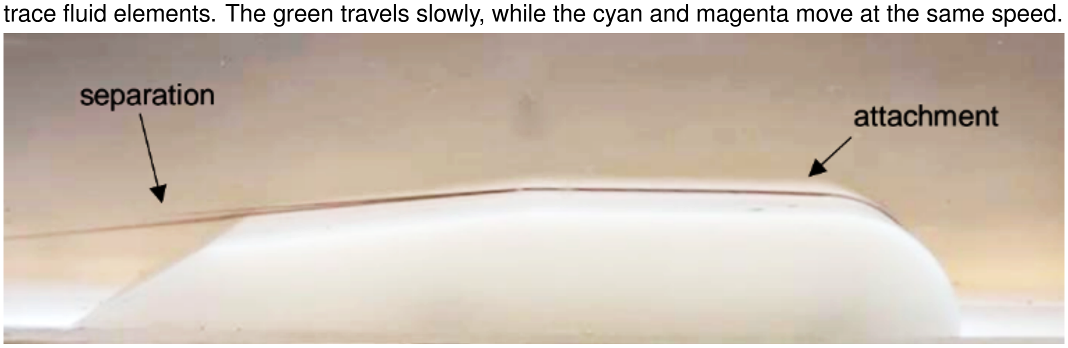
4.2 Survey results

Survey statistics are provided in Table 3 showing good response rates. Figure 7 shows average survey scores for the seven dimensions of the lab activity that were tested by Likert scales. The nine dimensions are described by the legend in Figure 7. The score for collaboration was understandably lower during lockdown (2021), and consistently higher in later years as students worked in pairs to complete the activity. The remaining six dimensions show a common pattern: they began in lockdown (2021) with very high values showing a strong success. In 2022, with activities back in-person, scores converged to averages of approximately 4.1. In 2023, scores reduced further, to below-average values, although the delivery was nominally identical. In 2024, with a renewed emphasis on gathering evidence, and improved staff training, scores all increased again to very high levels.

Qualitative ('free') comments in the survey were limited. There were 17 comments that specifically mentioned the activity discussed in this paper. While some themes such as engagement (positive; four comments), and lack of clarity of purpose or other practical confusion (negative; four comments) were informally evident, the qualitative data was not sufficient to conduct a more rigorous thematic analysis.



(a) Photos from the same student are separated by time intervals of 0.5s and show coloured circles to trace fluid elements. The green travels slowly, while the cyan and magenta move at the same speed.



(b) Attachment and separation are identified.

(c) Re-circulation is identified.

Figure 6: Results from student lab reports, taken during first-time use in a three hour session. Flow is right-to-left and annotations are original from student reports.

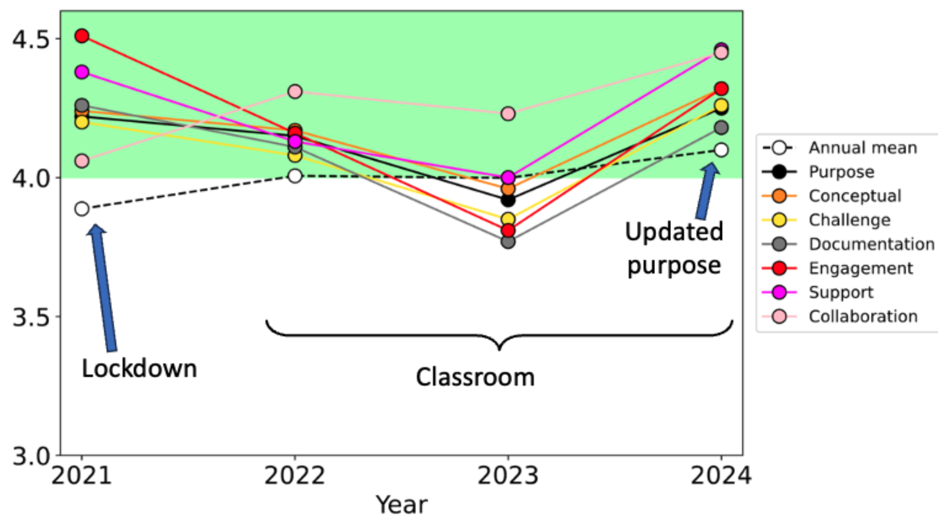


Figure 7: Average scores for seven dimensions of the lab activity over four years. Additionally, the 'annual mean' is the mean of means for all seven dimensions and all eight activities; this serves as a reference for inter-year trends.

	2021	2022	2023	2024
n	87/167 (52%)	81/172 (47%)	72/196(36%)	86/182 (47%)*
Annual mean for fluid mechanics	4.27	4.16	3.93	4.26
Annual mean for 8 activities	3.89	4.01	4.00	4.05

Table 3: Statistical information about the survey that was administered to students. The 'mean for 8 activities' is the 'Annual mean' in the plots. *For 2024 results were not complete when this paper was published.

5 Discussion

The three Challenges defined in the Introduction were for students to personally identify the existence, thickness, and separation of boundary layers through visualisation. The literature review suggested that these are threshold concepts and that an element of discovery would aid students in grasping them. We have implemented a new activity for students where they can personally experiment with flow visualisation. The questions that we discuss here are:

- Were students able to visualise boundary layers as intended?
- How did they experience the 'guided discovery'?

The first success achieved by introducing the new equipment was that it enabled all students to experiment personally, and to do so at a time that was in-sync with the theoretical instruction (lectures). The laboratory session was long enough (three hours), and free enough, that students could work at their own pace, which is a key requirement to facilitate discovery.

The results in Figure 5 from student lab books, and Figure 6 from student reports, show that at least some students could successfully reach all three desired conclusions. The vast majority of students successfully reached two out of three conclusions. Half of the students in the cohort reached the third conclusion successfully during the three hour activity. Overall this outcome is a major improvement on previous activities, which didn't visualise the boundary layer at all, and did not address flow separation at all.

Identifying a phenomenon, such as existence of a boundary layer, has a binary aspect — students either did or didn't record it — but also a qualitative aspect. The first two challenges, on the existence and thinness of the boundary layer, were successfully recorded by students in the binary sense, but the quality of reporting could still be improved. Students were not trained from prior experience to emphasise concrete, repeatable (i.e. scientific) evidence as a warrant for stating their conclusions. We note that the wider context for the students is more instruction-orientated. If a discovery approach were taken more often during their studies, then students would likely improve at this skill earlier — rather than learning it when conducting an intermediate level activity. There is an important lesson here, which is that 'discovery' approaches need to be consistent across multiple activities, both for the broader benefits of adopting a discovery mindset, but also for efficacy of the approach. Habit and routine are important parts of a successful educational approach.

Efforts to solve the third challenge have been partially successful. While some students were completely successful, approximately half struggled with the nuance that flow separation only occurs specifically in strong positive pressure gradients. Further, a significant minority of students struggled to identify separation as a distinct point, associated with stagnation and reversal; for example notes like 'more separated at E [than D]', which is a misconception.

There is a key limitation with the equipment that affects the third challenge. Visualising flow reversal requires some innovation by the student. Tracer fluid does not automatically enter the closed wake region. The user must play with the valve until tracer fluid serendipitously settles in the wake region, and then remains there for future steady experiments. Without this innovation, which many students did not discover, it is not clear to students that the flow reverses in Region E but not in Region D. Flow reversal is essential to boundary layer separation but this point was overlooked by many students.

The student experience, based on quantitative scores in the survey, had a stable mean across all eight activities, but varied for the Fluid Mechanics activity described in this paper. In 2021, with students receiving kits at home in lockdown, this was a welcome excitement at an otherwise very difficult time. The survey scores show clear appreciation for these efforts. In 2022 and 2023, in the classroom, scores reduced consistently each year until they were below average for the programme in 2023. The causes of this reduction are difficult to identify because they do not correlate with any known changes in the delivery.

The key difficulty we identified following the 2023 survey was an unclear purpose to the activity. Improvements to the messaging, with an emphasis on 'gathering evidence', rather than simply 'exploring' may have caused the positive change in the scores in 2024. However other confounding effects may be present, such as the nature of the support in the room, which increased from 4.00 to 4.43 and may have have wider impacts on student perception.

The data available for the activity in question only cover the period from the new innovation onwards, without reference data for the prior activity. Despite these limitations in the data, it is clear that students have learned more about boundary layers in the sense of the three challenges presented in this paper; the strongest evidence to warrant this statement is the lab books that students recorded. In prior years there was no evidence at all that students grasped these concepts first hand.

The depth of insight we can gain into the student learning of threshold concepts, and their experience of a discovery-based approach, is limited using the available data. Focus groups would be a way to gain further insight into the student experience.

6 Future work

6.1 Equipment improvements

The equipment can be improved to help discover flow reversal in the wake region. A third tracer injection point can be added to the downstream side of the object (in Region E). A prototype is illustrated in Figure 8. Tracer fluid injected at the centre-point of Section E travels upstream before turning to join the main flow. The flow is much slower in the wake, so the effect requires some nuance to identify, but the addition of the new port makes the situation much clearer and will be used in future.

Pressure gradients are key to the conclusions that students reach about boundary layers. With the current equipment, pressure gradients are inferred from theoretical arguments. The equipment could be improved by including pressure taps that allow direct measurement.

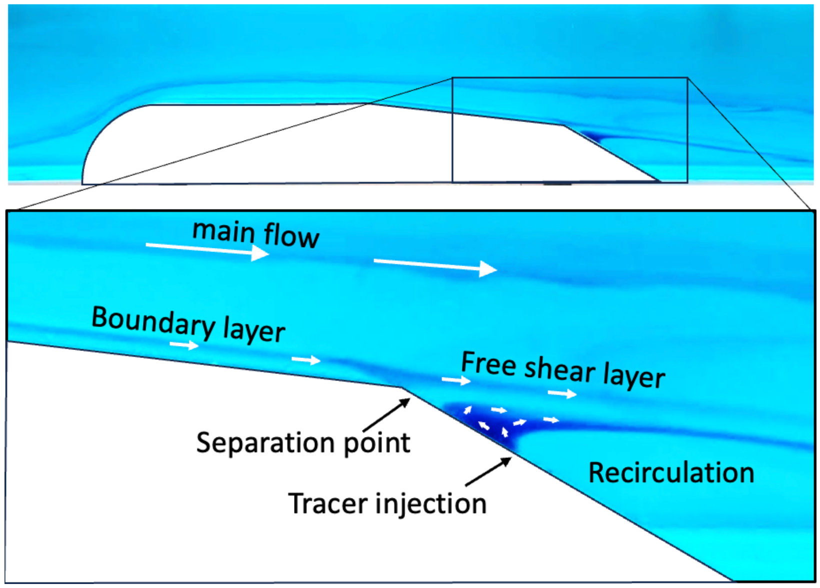


Figure 8: New experiments by the authors with an additional injection point in the recirculation zone, providing clearer evidence of flow reversal and boundary layer separation.

6.2 Computational fluid dynamics (CFD)

In addition to the suggested equipment improvements, further insight can be gained by students by using results from computational fluid dynamics (CFD). For example, simulations can be used alongside experiments [24]. Preliminary simulations of the apparatus have been carried out in OpenFoam. For these steady state laminar flows it was appropriate to use simpleFoam. Details of the simulation are given in [15].

Using CFD, velocity profiles (normal to the body surface) of the tangential velocity at different locations along the channel can provide useful insight. Example velocity profiles from CFD simulations are plotted in Figure 9. At B-C the boundary layer has developed in a negative pressure gradient, showing a characteristic bulge. At C-D the boundary layer has developed in a zero pressure gradient and exhibits a classic boundary layer velocity profile. At D, in a light positive ('adverse') pressure gradient, the profile begins to inflect with clear deceleration of the boundary layer velocity. At E the profile has reversed in the lower section, showing that the boundary layer has separated. The reverse flow is an order of magnitude slower than the main flow, but is still critical as it leads the boundary layer to separate and generate a wake.

The insight provided by velocity profiles may help clarify the relationship between flow reversal and boundary layer separation. The combination of physical experiments for primary evidence, and computational models for more detailed insight, could provide a more complete understanding for students.

In future we will carry out a more thorough comparison between the CFD and the experiments, including comparing streamlines in the bulk flow, to give confidence that the CFD is giving an accurate representation of the flow. We also need to develop practical ways to give students access to the computational results with an adequate level of scaffolding, following the same 'guided discovery' approach articulated in this paper.

6.3 Educational practice

If no improvement is achieved through equipment modifications and augmentation with CFD, then interventions can be considered. Two possible actions are suggested here.

Firstly, students can normalise to the basic 'discovery' approach, and to flow visualisation generally, at an earlier stage. A staged approach would be consistent with cognitive load theory, which suggests that some students may be overwhelmed by the range of novel aspects to the current activity. Students could participate in multiple, e.g. thirty-minute, experimental sessions in preceding weeks. Each session could have smaller goals such as measuring flow rate, visualising streamlines, and identifying pressure gradients.

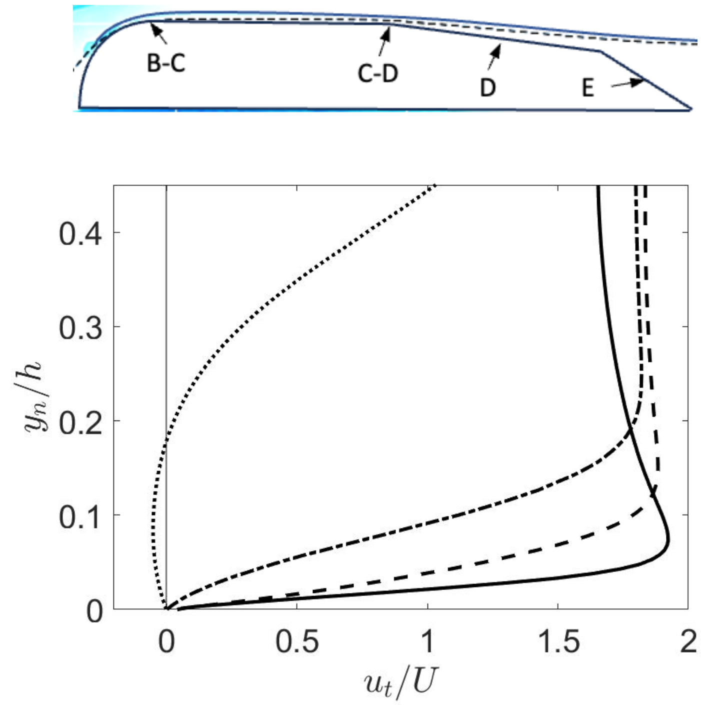


Figure 9: Combined velocity profiles from CFD, where u_t is the component of velocity tangential to the surface of the body; y_n is the distance normal to the surface of the body. Profiles are taken at locations B-C (—); the transition C-D (– –); the middle of section D (– ·); and the middle of section E (· ·) where the flow has reversed.

Secondly, students can be invited back to the lab if they do not correctly conclude. This additional attention will ensure they reach correct conclusions. For equity and inclusion, and potentially motivation for the students, this would be a positive change. However, economic viability is potential barrier to both suggested changes.

The student experience also warrants further investigation. For deeper research beyond the student outputs and the survey, focus groups would provide more insight. The question of 'how guided' discovery should be would be a valuable focal point.

7 Conclusion

This paper described a desktop experiment for students to visualise water flow, with an emphasis on learning about boundary layers. We outlined three educational challenges to be addressed around students gaining a deeper understanding and stronger intuition about boundary layers. Specifically students need to learn that boundary layers *exist*, are *thin* for high Reynolds numbers, and *attach or separate* depending on the pressure gradient.

A literature review concluded that the challenges to be addressed can be considered 'threshold concepts' and that a 'guided discovery' approach would be worthwhile implementing. We provided detail in this paper about how we implemented guided-discovery.

We presented results from student use of the desktop experiment, and survey data on their experience of the activity. The equipment meets all the technical requirements to address the three challenges identified. The experiment works well to visualise boundary layers in ways that are not otherwise possible.

The first two challenges were met in practice by most students. The third challenge was met by about half of students. The difficulties with the third challenge centered around the conceptual idea of separation and its link to flow reversal. The equipment we provided can visualise these effects, but requires some innovation on the part of the student to obtain evidence.

To address the third challenge more effectively, we proposed an equipment modification to directly introduce tracer fluid into the wake to see flow reversal directly and reliably. We also suggest using computational fluid dynamics (CFD) as an additional tool, and we showed velocity profiles from CFD that help identify flow reversal.

Based on survey data, the student experience was positive overall. Changes to clarify the purpose of 'obtaining evidence', and improved tutor training, were correlated with increases scores in the most recent year.

The 'discovery' approach discussed here was implemented as an exception to other activities in the degree programme, which are more instructional. A broader change, within the programme, toward guided discovery would likely influence the general attitude of our students to take more of a discovery mindset.

In conclusion desktop flow visualisation experiments presented here can help students discover boundary layers as a tangible, intuitive concept to complement the abstract theory. Careful delivery of the activity in practice is essential for the experiment to bear fruit.

Appendix

A: Summary of boundary layer theory

Boundary layers are a viscous phenomenon. The governing equations in the case of incompressible flow and Newtonian viscosity are the Navier–Stokes equations. The force per unit volume within the fluid due to viscous effects is represented by

$$\mu \, \overrightarrow{\mathrm{Laplacian}} \, (\vec{u}) \,, \tag{1}$$

where μ is dynamic viscosity, $\vec{u}$ is the velocity vector, and the Laplacian operator is the divergence of the gradient — sometimes written alternatively as ∇^2. The numerical value of viscosity, μ, is low for common fluids and flows which tempts analysts to consider the whole of (1) to be small enough to neglect, and to remove it from the governing equations. Prandtl's insight was that the smallness of the viscosity is not sufficient to conclude that the viscous forces (1) are small because the term (1) is the product of two terms: the viscosity *and* the Laplacian. Viscous effects are only small if the Laplacian of the velocity field, i.e. second gradients in velocity, is also small.

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For flows that are uniform or have high Reynolds numbers, the velocity gradients and second gradients may be small throughout most of the fluid, but they become very large at the boundary of an object. At the boundary the velocity rapidly decreases to zero relative to the object, known as the 'no-slip' condition. Due to the high gradients at the boundary, viscous effects not negligible in that region.

B: Analysis of boundary layers

In two-dimensional Cartesian coordinates (x, y), with x parallel to the flow, with velocity components $\vec{u} = [u \;\; v]^T$, the first component of the viscous force per unit volume (see (1) in the Appendix) can be written as:

$$\underbrace{\mu\frac{\partial^2 u}{\partial x^2}}_{\mathcal{O}(\mu U/L^2)} + \underbrace{\mu\frac{\partial^2 u}{\partial y^2}}_{\mathcal{O}(\mu U/\delta^2)} \; . \quad (2)$$

The 'order of magnitude' of the terms are obtained using U and V for the streamwise- and transverse-velocities; and L and δ for the streamise- and transverse length scales. The scale L is indicated in Figure 2 and U is the bulk velocity. V and δ are to be determined. Using the relation $U/V \sim L/\delta$ from mass conservation and grouping terms gives:

$$\frac{\mu U}{L^2}\left[\mathcal{O}\left(1\right) + \mathcal{O}\left(\frac{L}{\delta}\right)\right]. \quad (3)$$

In the case that $\delta/L \ll 1$, we can neglect the first term in (2).

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