Using On-Going Laboratory Problems as Active Learning Research Projects in Transport Phenomena

ABSTRACT

This report evaluates the use of on-going, open-ended research problems taken from the instructor's laboratory and assigned as projects in Transport Phenomena. Projects were structured following a hybrid active learning model and designed to engage student groups by providing them the opportunity to impact research in their department. The impact of these assignments on student comprehension and engagement is evaluated by comparing exam performance of student cohorts with and without projects and through student surveys.

KEYWORDS

transport phenomena, active learning, POGIL, microfluidics

INTRODUCTION

While informational lectures remain the most common method of teaching engineering at the undergraduate level, there is a large body of evidence suggesting that active and collaborative learning methods can have positive impacts on student learning outcomes.[1-7] As a result, active learning activities have become increasingly common in the engineering classroom. These activities can range from simple practices such as think-pair-share and muddiest point exercises to flipped classroom models[8] or peer-led activities. Common pedagogical models for peer-led activities are process oriented guided inquiry learning (POGIL),[9] problem-based learning (PBL),[10] peer-led team learning (PLTL),[11] and combinations of these,[12,13] among others. Common in active learning models is the opportunity for student teams to master concepts through investigation of opened-ended problems. For example, POGIL activities are designed to guide small, student-led teams (3 to 4 students) through creative exploration of a concept. These activities are commonly used in place of lectures to develop conceptual understanding while the instructor's primary role is to promote learning and creative thought.[14]

Application of peer-led classroom activities has proven to provide specific benefits to students, including improved exam performance, long-term retention of material, the ability to apply conceptual knowledge to new contexts, as well as development of process skills such as communication and critical thinking which often align with the broader mission of a university.[9,14,15] Walker et al. provided a recent analysis of 21 studies comparing student success in POGIL and traditional lecture courses and found that POGIL activities significantly increased student success, particularly by reducing the number of students who failed a course.[16] While POGIL has been traditionally developed around chemistry courses,[17-21] these activities and benefits have been expanded to other disciplines such as anatomy and physiology,[22] biosciences,[23] and engineering.[14] In chemical engineering (ChE), POGIL-based methods are not widely used, however, other active learning methods have been successfully implemented. This includes creative game-based learning to introductory students,[24] PBL activities in process design,[25] and hybrid active learning approaches in process control.[26]

Within the ChE curriculum, the subject of transport phenomena (TP) presents a unique opportunity for active learning projects. While fundamental to the discipline, TP is commonly perceived as mathematically complex, highly abstract, and often incompatible with real-world application. As a lack of understanding of how classroom concepts apply in professional or practical situations is frequently cited as a factor that de-motivates student learning,[27] providing TP students with real-world, active learning projects that have potential impact while also reinforcing TP concepts may provide an avenue for improvement.[28-30] As an example, Galán et al. presented market-oriented, chemical product design problems through TP I and TP II courses.[30] This approach provided high course satisfaction and shifted student perception of the mathematically rigorous problems typical in TP from isolated exercises to development of a skill set useful for practical application.

Driven by this potential, the goal of this study is to evaluate the impact of active learning research projects (ALRPs) in TP. Problems are based on on-going laboratory research, which often provides well-suited content for these types of activities as they are inherently open-ended and thus generate creative inquiry amongst students while impacting research activities at their university. These attributes can enhance student interest and motivation by instilling a sense of ownership around the material, a trait that promotes effective learning.[31] Further, PBL and POGIL-structured projects can be well integrated with research.[23,28,32] For example, Murray et al. designed POGIL activities in general biochemistry courses around relevant research articles and reported that these activities developed undergraduate confidence in reading, interpreting, and applying literature resources.[23] A research-oriented project also presents an opportunity for the instructor to collect a large number of diverse perspectives on an on-going laboratory problem, ideas that might be uniquely generated from group interaction and thought. Broad engagement of a larger student body in this context may also give the instructor means for effective undergraduate recruitment into their laboratory.

ALRPs were designed according to an active learning format following a hybrid POGIL-PLTL-PBL model[12] and assigned to junior-level students in TP I and II, courses that cover fundamental principles of momentum, heat, and mass transfer using *Introductory Transport Phenomena* by Bird, Stewart, Lightfoot and Klingenberg (BSL) as the primary textbook.[33] Two ALRPs were designed using on-going experiments in the instructor's laboratory that aligned with the class material at the time of the assignment. Projects centered around lab-on-a-chip devices, useful tools for student engagement due to their direct connections to momentum and mass transfer and their visual appeal.[34] To quantify the project impact on student comprehension of course material, comparisons of student exam scores on related problems are made between students from different semesters when the project was either given or omitted from the course. Surveys were also given to students after the project to gauge their perception of the impact of the project relative to their learning and engagement levels.

When designed appropriately, the inclusion of research-related problems in an active learning format has mutual benefit for students and instructors. The results show that ALRPs have a positive impact on student comprehension, particularly for lower-performing students. Student feedback was generally positive with broad enthusiasm for implementation in future coursework. Students enrolled in the course, the majority who are not directly involved in undergraduate research, were each able to get hands-on experience with academic research to decide if it was a path of interest to them. The instructor was able to provide the graduate students and other lab members with new, outside perspectives and ideas on the task at hand for an improved understanding of the research.

METHODS

Course and Project Structure

Transport Phenomena I and II are taken during the fall and spring semesters of the junior year for chemical engineering majors at Kansas State University and serve as the introductory course to momentum, heat, and mass transfer. TP I requires Differential Equations and Chemical Process Analysis (i.e. Mass and Energy Balances) as prerequisites. The author instructed all TP courses that offered an ALRP. The courses consisted of weekly homework assignments that contained problems from BSL or similar problems developed by faculty (120-150 pts total), three semester exams (100 pts each) given every 4 to 5 weeks throughout the semester, and a comprehensive final (150 pts). During the project semester, the project was worth a total of 40 pts, which was ~7% of the overall semester grade.

The project was structured according to a hybrid active learning format that incorporated aspects of POGIL, PLTL, and PBL. Following PLTL format, [11] students were introduced to the project following traditional lectures, homework, and the second semester exam (herein referred to as the mid-semester exam). Groups contained three or four students and were assigned randomly by the instructor. This was done in effort to evenly distribute student skill level across the groups and provide a real-world environment where students are unable to choose who they work with. At this point, the instructor emphasized that teams would be self-managed, following a POGIL-based format.[14] The project background and assignment details discussed in detail during class time; students then worked on these assignments outside of the classroom. Teams were provided with a two-page description of the project that detailed the background and significance, the lab problem, the technical goal of the assignment and expectations for the final submission. These teams were treated as "consultants" to the instructor and expected to describe their approach, assumptions made, and final recommendations on the research in the one-page memo. This memo incorporated consulting and written communication as process development skills. Students were given two weeks to complete the project and were expected to work independently from other groups. The project required a 1-page memo that summarized the group's analysis of the project worth 10 pts, calculation and analysis worth 20 pts, and a peer evaluation worth 10 pts. The peer evaluation followed the format described by Oakley et al.[7]

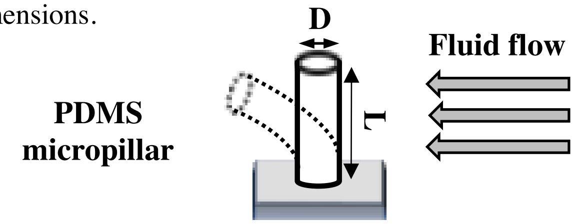
Throughout the assignment, the instructor stressed the open-ended nature of the assignment, particularly that students would not be primarily evaluated by their final numerical answer, as was typical, but more by the depth of their analysis and the clarity of their communication. It was also emphasized that more than one correct approach was likely, and that the work was interdisciplinary, requiring students to use information from outside disciplines (e.g. mechanics of materials, microbiology, etc.) to successfully assess the problem, typical of a PBL model. Finally, the instructor's role of promoting creative thought with student groups was stated.

Project Content

Active Learning Research Project #1: Fluid Forces on Three Dimensional Structures in a Microfluidic Device

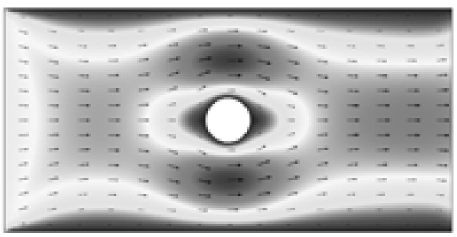
In the instructor's laboratory, microfluidic devices were used to study the effect of fluid shear on affinity-based cell capture to three-dimensional surfaces. Soft-lithography methods can be implemented to introduce three-dimensional elastomeric polydimethylsiloxane (PDMS) structures (e.g. micro-pillars) in rectangular microfluidic channels, increasing the surface area available for cell capture during sample perfusion.[35] Because pressure-driven fluid flow can deform PDMS,[36] fluid flow could possibly cause micro-pillar deformation, which would be undesirable for the application. Students were asked to provide the instructor and his lab with an understanding of the effect of channel flow rate on any micro-pillar deformation that could occur during sample perfusion (Figure 1), a full description of the project assignment is also provided (Supplementary Figure S1). To provide guidance, specific information on the current system was given (pillar and channel dimensions, PDMS base to catalyst ratio), but students were encouraged to look beyond the immediate system specifications and develop a thorough understanding of the dependencies of pillar deformation with system variables. For example, students were encouraged to explore the effect of pillar aspect ratio or pillar stiffness on critical flow rates for bending or deformation during their analysis.

Assignment: For the described micropillars, determine the fluid force required for bending. Using this calculate the volumetric flowrate for water that would result in such a fluid force for the given channel dimensions.



To solve this problem, some things to think about:

- Laminar flow conditions make flow around a cylinder something that can be modelled by the equations of motion/Navier-Stokes equation.



Fluid flow streamlines for laminar flow around a cylinder

- The material properties of PDMS cast at different base:catalyst ratios will be important in your calculations.
- This problem involves more than just transport principles (statics, strengths of materials, for example). Even if you haven't taken all the relevant courses, you will need to learn what's required to solve the problem on your own, just like you will in the real world.
- Inevitably, assumptions and approximations will have to be made. You will need to clearly communicate this.

Figure 1. *Summary of problem statement for ALRP #1 provided to students during the momentum transfer portion of the course. Along with the written statement, students were also provided with a small presentation discussing the scope and significance of the research, group assignments and expected deliverables.*

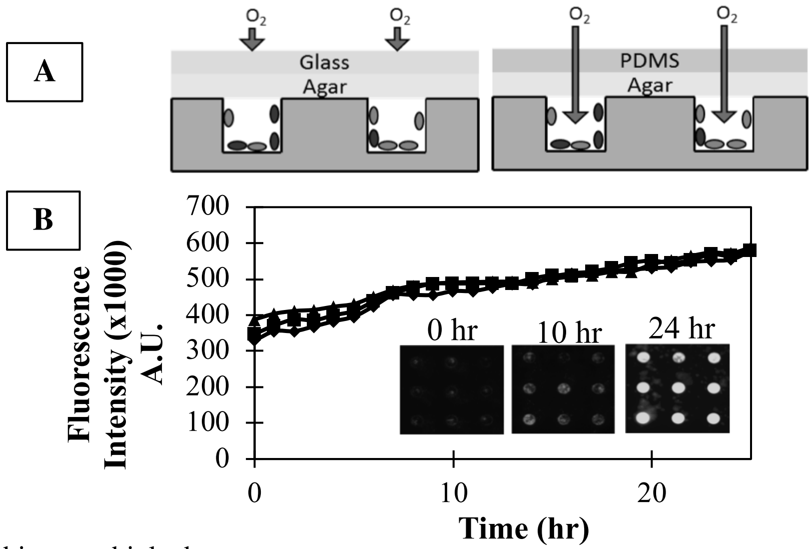
The project was assigned shortly after the equations of motion / Navier-Stokes equations were taught and tested (BSL Ch 3.1-3.7, pages 80-103).[33] The equations of motion are well-suited for modeling many aspects of this system as flow is characteristically laminar due to the small channel dimensions (500 μm width, 50 μm height). These devices were typically operated at flow rates ranging between 0.1 and 5 μL/min, corresponding to Reynolds numbers on the order of 10^0 to 10^2

($Re = \frac{4 \cdot R_h \cdot <v>}{\nu}$ where the hydraulic radius, $R_h = \frac{W \cdot H}{2W+2H}$, W and H are the channel width and height, respectively).[37] For student groups seeking additional guidance, the instructor suggested exploring the use of the Naiver-Stokes equation for describing traverse flow across a cylinder as a possible starting point. The instructor also emphasized that inclusion of principles in statics and mechanics of materials was likely necessary, areas with which many students were unfamiliar.

Active Learning Research Project #2: Design of a Membrane for Bacteria Co-Culture Studies

ALRP #2 was given during Spring 2017 and was assigned as an extra credit assignment. This project was not used in evaluation of exam performance, but is included here to provide an additional ALRP example. The project was driven by findings in the instructor's laboratory during the development of a lab-on-a-chip device designed to co-culture a bacteria test species with other microorganisms from an environmental microbiome. The device is designed to screen for interactions that promote or inhibit the growth of the GFP-labeled bacteria test species when other microbes are present in small (5 to 40 μm diameter) wells. Growth can be monitored during culture with a fluorescent microscope to identify wells where growth is inhibited or promoted. Cells can then be removed from individual wells for 16S rRNA sequencing to identify species that inhibited or supported growth of the test species. Early in platform development, it was found that motile cells must be physically confined to inhibit cellular transport out of the wells.[39,40] Cells can be trapped using a base substrate coated with a 10 μm thick agar layer loaded with culture media. It was found that aerobic organisms did not grow when the base was glass, but grew consistently when the base was PDMS, presumably due to the high diffusivity of oxygen in PDMS.

Assignment: *A. tumefaciens* cells are cultured in silicon microwell arrays for growth screening experiments. These cells are motile, and must be trapped in wells using agar-coated coverslips. The agar coating is ~10 μm thick. We have recently found that cells won't grow if the coverslip is glass, but they do grow if the coverslip is PDMS, presumably because PDMS creates aerobic conditions in the wells (Fig. A). With PDMS, we can track reproducible growth kinetics with a fluorescent microscope (Fig. B). We are interested in finding the appropriate PDMS thicknesses that are required to deliver enough oxygen for cells to grow.



Some things to think about:

- The initial number number of cells in the wells can range from 2 to 100 cells/well.
- The environment consists of air at atmospheric pressure.
- The wells range in diameter from 5 to 40 μm and are all 20μm deep.
- The rate of oxygen consumption per cell during growth will be important.

Figure 2. *Summary of problem statement for ALRP #2 provided to students during mass transfer portion of the course. The project was presented in the same manner as the previous project.*

Driven by this finding, students were asked to design a membrane for the application (Figure 2). Specifically, students were asked to suggest PDMS thicknesses that could meet the oxygen demands of growing cell populations in the wells. To set the conceptual framework, the project was preceded by a lecture on one-dimensional shell mass balances, with a particular emphasis on the diffusion of gases through solids (BSL Ch 18.2).[33] As with the previous project, the need to incorporate outside disciplines was stressed, such as calculating oxygen metabolism of the cells during different growth stages in the wells. This required students to consult outside literature in order to supplement any prior knowledge they had about bacterial growth. A full description of this project assignment is also provided (Figure S2).

Data Collection and Analysis

Student Cohort Information

The cohort from the ALPR semester (n=74 students) was taught during the Fall 2017 semester, who were given ALRP #1. This cohort was 73% male / 27% female, 65% had junior standing, 34% had senior standing, and 1% sophomore standing. The second cohort of students from the control non-ALRP semester (n=47 students) was taught two years later, during the Fall 2019 semester. This cohort was 72% male / 28% female, 53% had junior standing, 45% senior standing, and 1% had graduate student standing. It should be noted that the majority of students with senior-level standing were in their third year in the ChE curriculum but classified as seniors due to transfer credits.

Analysis of Exam Data for Active Learning Research Project #1

The objective of this analysis was to evaluate the impact of ALRP #1 by investigating student exam performance on a closely related Navier-Stokes problem describing flow around a cylinder. To do this, scores on a relevant problem from a mid-semester exam (given before project assignment) and a final exam (given after project assignment) were recorded and analyzed for both student cohorts. The timeline of events is given below (Figure 3A).

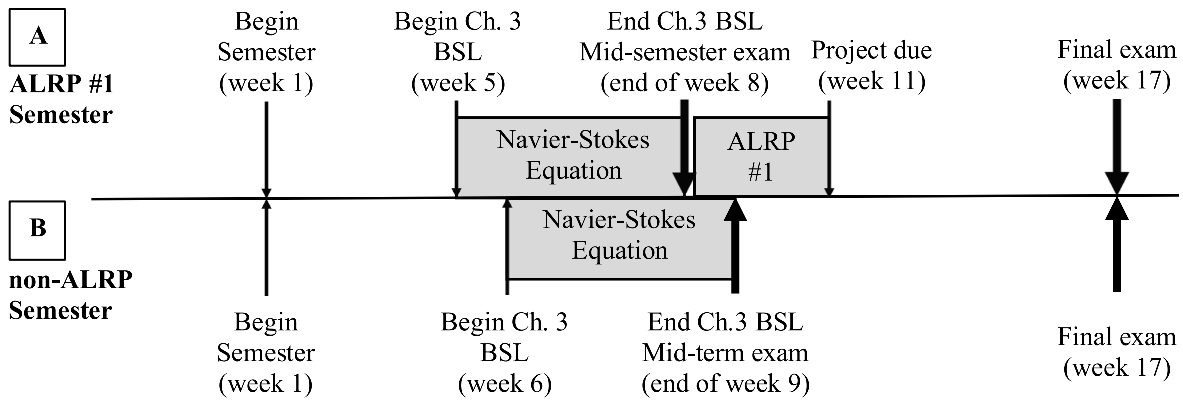


Figure 3. *Timeline of events for quantifying student comprehension during (A) the ALRP semester when ALRP #1 was used to re-enforce a transport concept and (B) a non-ALRP control semester that was structured similarly but did not include an ALRP project. Bold arrows denote events where data collection occurred.*

These students were taught from Chapter 3 of BSL[33] according to a traditional lecture format and homework assignments covering the derivation and application of the equation of continuity, the equations of motion, and the Navier-Stokes equation. This content was the sole focus of the mid-term exam. Homework was based on problems from BSL and other problems developed by faculty within the department. To assess student comprehension at that point, a problem modified from Welty, Rorrer, and Foster[38] was given in the mid-term exam (Figure 4A). It was selected because it involves laminar flow of a Newtonian fluid over a post, concepts similar to ALRP #1. Following this exam, ALRP #1 was assigned. The final exam problem (Figure 5A) was given two months after the mid-term exam and six weeks after ALRP #1 was completed. The final exam was comprehensive, covering all portions of momentum transfer, with emphasis on rheology, equations of motion, friction factors and mechanical energy balances (BSL chapters 1-3, 6, 7), as well as aspects of heat transfer that included conductive heat transfer and shell energy balances (BSL chapters 9,10). Prior to the final, students had the opportunity to review for the final through a comprehensive, end of semester review session and practice final. The final exam contained a closed book portion followed by an open book portion. The problem that tested student comprehension of the Navier-Stokes equation was similar to the mid-term problem but with different boundary conditions. The initial equation was listed in the problem statement here because this portion of the exam was closed book.

The control cohort was taught the exact same material over the semester, lectures were structured in the exact same way and taught by the same instructor following similar timelines (Figure 3B), and the homework covered the exact same concepts. The difference was that the control group had no ALRP. The control group of students was assigned the same problem on the mid-semester exam (Figure 4A) and the same problem on the closed book portion of the final exam (Figure 5A). Prior to each exam, both cohorts were given access to old exams from previous years to study off of; these old exams did not contain the exam problems. The mid-term problem was given as the second problem of the exam and the final problem was given as the fifth problem on the closed book final exam in both semesters to maintain consistency. Students in this cohort were also offered a comprehensive end of semester review and practice final to prepare for the final. It should be noted that the control cohort (Fall 2019) was not given access to the 2017 exams that contained these problems. The grade keys used to grade both the mid-term and final problem for each cohort were identical. Because of the similar course and exam structure and identical exam problem and grade key, a comparison of scores between the two cohorts of students on the mid-term problem and then on the final problem enabled an assessment of the impact of the ALRP.

Data analysis

Paired student data was generated by calculating an individual's score change (score change = exam score on final problem (%) – exam score on mid-term problem (%)). An unpaired two-sample student t-test was used to determine significance in score changes between students within the non-ALRP and ALRP cohorts. Student t-test results are reported as $t(\nu)$ = t statistic, p = p value, where ν is the degrees of freedom.

Survey Data

At the conclusion of all project-related activities, students were given an anonymous survey containing seven questions designed to gauge student perception of the project impact, its effect on their comprehension, and student interest in incorporating more ALRPs into core chemical engineering curricula. Surveys were given on paper and in class. No points were awarded or benefits given for completing the survey.

Research Compliance

All data collection and reporting methods were reviewed by an institutional review board (IRB) for human subjects research at Kansas State University. The project received an IRB exemption status (IRB exemption #9158.1).

RESULTS

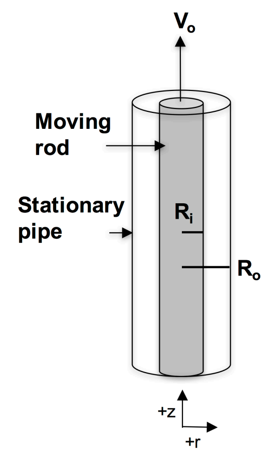
Pre and Post-Project Exam Performance

The mid-semester exam problem (Figure 4A) was worth a total of 40 points. For the cohort from the ALRP semester, the average score on this problem was 27.5 ± 8.9. Students in the non-ALRP control semester were also given this problem on their mid-semester exam; up to this point the course was structured in an identical manner as in the ALRP semester. The average score for students in the control semester on this problem was 30.4 ± 9.3. The distribution of scores on this problem (Figure 4B) shows that a higher percentage of students from the control semester had an

A-level understanding of the problem (35/40 or better), while a higher percentage of students from the ALRP semester had an unsatisfactory performance (24/40 or lower). This suggests that up to the mid-point of the semester, students from the control cohort had an equivalent, if not better, understanding of this material than students from the ALRP cohort did.

A Consider a stationary, vertical pipe with radius R_o that contains water moving under the influence of gravity. At the pipe center is a solid rod of radius R_i that is pulled in the positive z direction with a velocity of V_o. Assuming laminar flow and steady state, derive a general expression for the velocity profile between $R_i<r<R_o$ and solve for your integration constants using the relevant boundary conditions.

(Note: to save time, you do not need to plug your equations for C_1 and C_2 into your general velocity profile expression)



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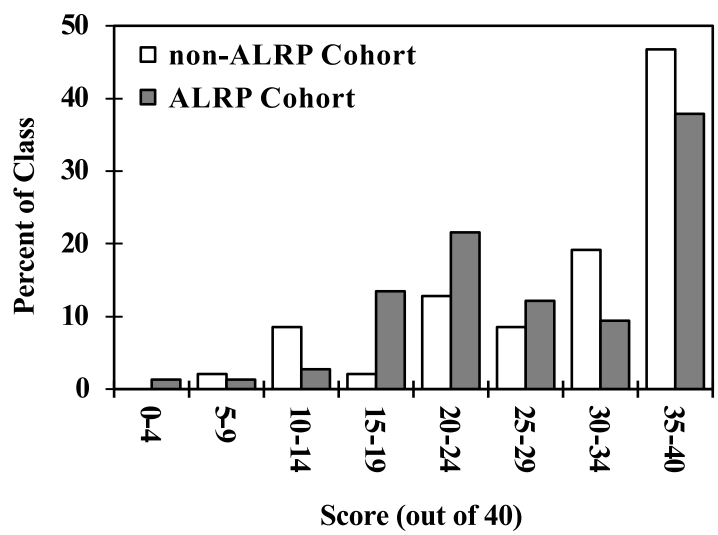
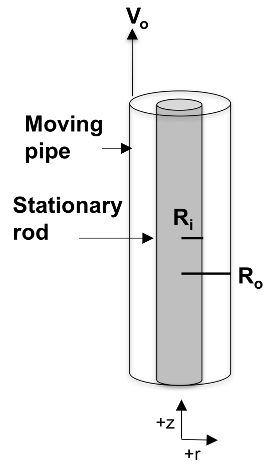


Figure 4. *A: Mid-term exam question used to evaluate student comprehension of the Navier-Stokes equation and its application prior to assignment of the ALRP. The problem was modified from Welty, Rorrer, and Foster*[38] *and was given as the second problem on an open book mid-term exam after traditional lectures. B: Histogram showing the distribution of scores*

for the cohort with the ALRP and the control cohort without the ALRP. Data is displayed as the percent of class with scores falling within the given point range. The problem was worth a total of 40 points.

The Navier-Stokes problem included on the final (Figure 5A) was worth a total of 9 points. The average score on this problem for the ALRP cohort was 7.4 ± 2.0 while the average score for the control cohort was 6.4 ± 2.6. The distribution of scores for this problem for each semester (Figure 5B) shows that only 57% of students from the control cohort had a satisfactory performance on the problem (6/9 or higher), which was lower than the 74% of students from this group that had a satisfactory performance on the mid-term exam problem. The decrease in the control cohort may be attributed to the fact that the material was not re-enforced after the mid-semester exam, that there was a two-month time period between the mid-term and final exam, and due to the fact that the final was comprehensive and given during finals time, when students had multiple exams. Students from the ALRP semester trended in the opposite direction. Here, 82% of students showed a satisfactory performance on the finals problem, an improvement from the 59% of students from this group with a satisfactory performance on the mid-semester exam problem. The improved exam performance from students in the ALRP cohort relative to the control cohort strongly suggests that the ALRP had a positive impact on student comprehension for application of the Navier-Stokes Equations.

A Consider the system shown to the right, a vertical pipe with radius R_o that contains water flowing under the influence of gravity. The pipe is being pulled in the positive z direction at a velocity V_o. At the pipe center is a stationary solid rod of radius R_i. Assuming laminar flow and steady state, derive a general expression for the velocity profile between $R_i<r<R_o$ and identify the relevant boundary conditions. You do not need to solve for C_1 and C_2.



Relevant Navier-Stokes Equation:

$$\rho\left(\frac{\partial v_z}{\partial t}+v_r\frac{\partial v_z}{\partial r}+\frac{v_\theta}{r}\frac{\partial v_z}{\partial \theta}+v_z\frac{\partial v_z}{\partial z}\right) = -\frac{\partial P}{\partial z}+\mu\left[\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial v_z}{\partial r}\right)+\frac{1}{r^2}\frac{\partial^2 v_z}{\partial \theta^2}+\frac{\partial^2 v_z}{\partial z^2}\right]+\rho g_z$$

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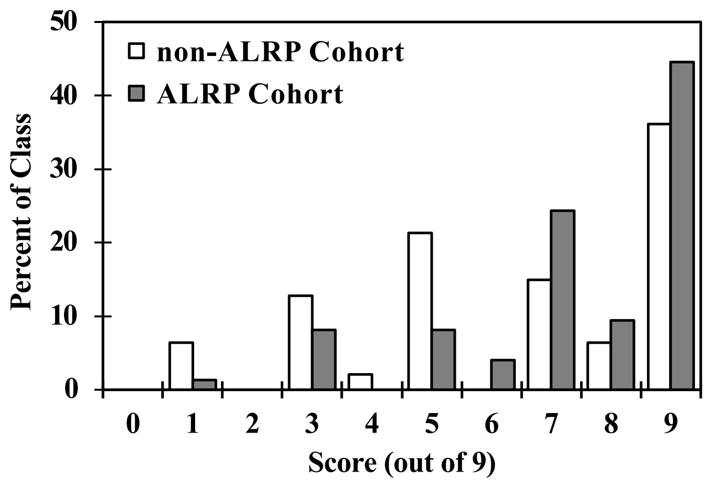

Figure 5. *A: Final exam question used to evaluate student comprehension of the Navier-Stokes equation and its application following assignment of the ALRP. The problem was modified from Welty, Rorrer, and Foster*[38] *and was given as the fifth problem on the closed book portion of the final exam. B: Histogram showing the distribution of scores for the cohort with the ALRP and the control cohort without the ALRP. Data is displayed as the percent of class with scores falling within the given point range. The problem was worth a total of 9 points.*

Project Evaluation Using Paired Student Data

Further insight on project impact can be gained by comparing changes in individual student performance on the mid-semester and final problem from each cohort. Students from each cohort were first binned into one of three groups according to their initial, mid-term exam performance. This included high-performing students with an A-level score (35/40 pts or higher) on the mid-semester exam, intermediate performing students with a B or C-level score (34-25/40 pts), and low performing students with an unsatisfactory, D or F-level score (24/40 pts or lower). Individual student scores from the mid-term were then paired with their finals score and the change was computed for each group. Due to testing constraints, the mid-term and final were worth a different amount of points, comparisons were therefore made on a percentage basis.

A comparison of score changes between the ALRP and non-ALRP control cohorts show that for each group, the ALRP cohort showed higher levels of improvement compared to the non-ALRP cohort (Figure 6). Students who were low-performers on the mid-term showed the most significant levels of improvement ($t(40) = -2.65$, $p = 0.0116$), suggesting that the ALRP had highest impact on the students who struggled to understand the Navier-Stokes Equation based on traditional lecture and homework alone. In fact, from the non-ALRP cohort, only 25% of the low-performing students were able to score a passing grade on the final problem (6/9 or higher). This percent was much higher in the ALRP cohort, here 70% of students with an unsatisfactory score on the mid-term exam were able to improve their performance to a passing score on the final problem. Intermediate and high performers from the ALRP cohort also appeared to receive benefits from the project as they showed higher performance on the final than the control cohort, albeit with lower levels of confidence (intermediate performers: $t(27) = -2.01$, $p = 0.0367$; high performers: $t(48) = -1.96$, $p = 0.0401$).

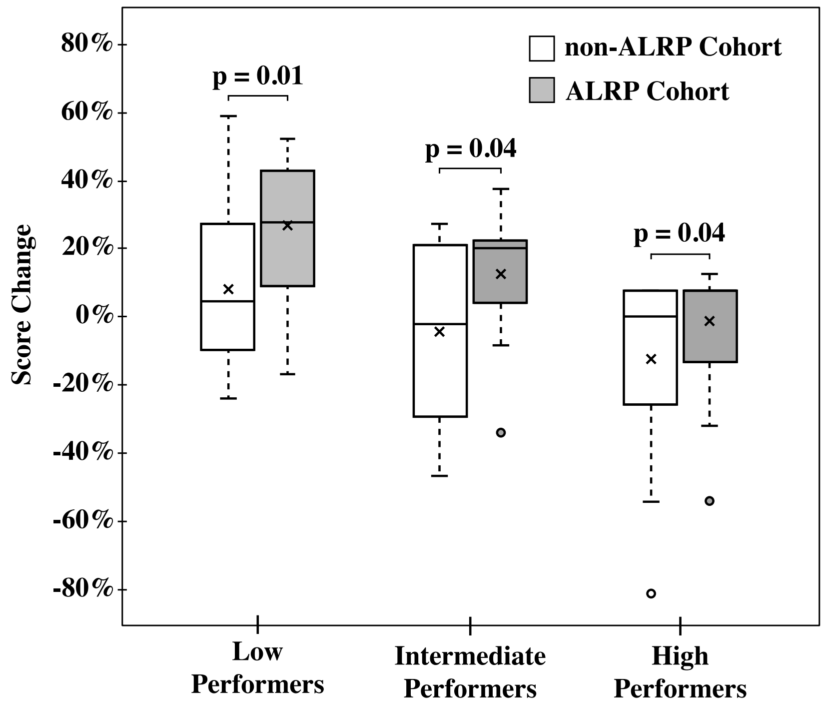

Figure 6. *Box-plots showing the differences in scores between the final exam problem and the mid-term exam for low performers, intermediate performers, and high performers in the ALRP and non-ALRP control cohorts. Values were calculated according to each individual student's score change (score change = exam score on final problem (%) – exam score on mid-term problem (%)). P-values were determined using an unpaired two sample student t-test.*

Student Surveys and Feedback

Students were given post-assignment surveys to gauge their interest in the project and its perceived impact on their comprehension. Two separate sets of students were surveyed, students who either had ALRP #1 (Fall 2017) or students who had ALRP #2 (Spring 2017), this was done to maximize the number of student responses (n=98 students total). Survey questions were given Likert-type scale responses and are displayed in Figure 7. As an initial indicator, students were asked to benchmark the ALRP assignment against conventional textbook problems, and asked if the assignment enabled them to gain a deeper understanding of fundamental transport principles. The majority of students (75%) responded saying they either slightly or strongly agreed that the ALRP assignment made a positive contribution to their understanding, while a small portion (7%) disagreed. As another indicator of project interest, students were asked if they would be supportive of similar research projects being assigned in future semesters. This response had direct implications, as many of them were enrolled in TP II the following semester. The majority of students (61%) responded saying they would either be slightly or highly supportive. Students were also asked what they thought the most beneficial part of the assignment was; the majority (54%) of students identified that the chance to gain experience working on a real problem was most beneficial. This was consistent with feedback the instructor received from individual interactions with students.

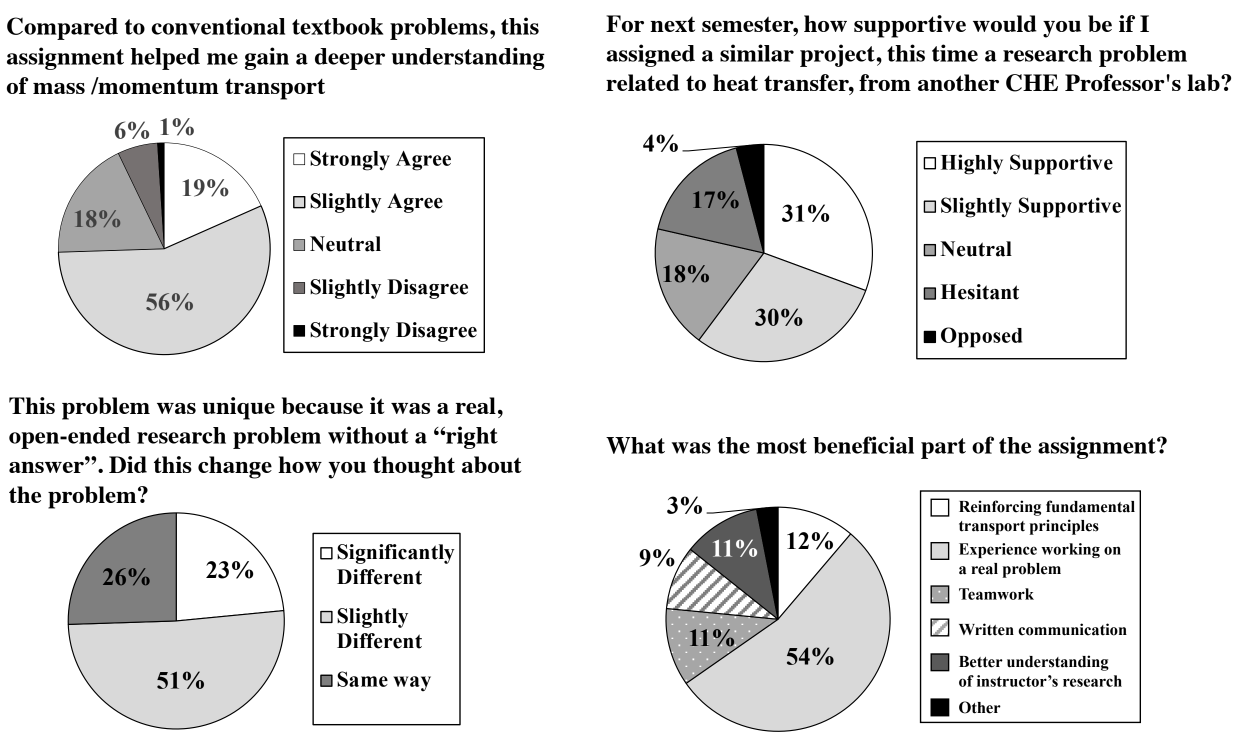

Figure 7. *Combined survey data from TP students after completing Projects #1 or #2. n = 98 students.*

While the overall student response to the project was positive, there was a minority of students who expressed significant hesitations about the project and a few that opposed its use. In the survey, students were asked if they saw any potential drawbacks of moving towards more open-ended, research-oriented problems with less emphasis on traditional textbook problems. The most common response from the students was that the ALRP should not serve as a replacement for traditional problems; multiple students stressed that without establishing a foundational framework for complex concepts and without giving students an opportunity to reinforce or apply those concepts using classic textbook problems, these projects would likely lead to misconceptions and frustration. This is particularly true with complex topics (such as the Navier-Stokes equation) that are often intimidating to students the first time they see them. While traditional POGIL and other active learning models rely more on student exploration to establish conceptual understanding, a balance between standard lecture format and student-led exploration was required for TP.

CONCLUSIONS

In summary, integration of active research projects into core chemical engineering undergraduate courses can serve as an attractive addition to a course as it provides unique benefits to both the student and the faculty member. Exam data and student surveys demonstrated that ALRPs bolstered student understanding and interest in TP concepts after a foundational framework was established. Statistically significant differences were found when comparing individual changes in student exam performance between ALRP and non-ALRP student cohorts, which supports a large body of literature demonstrating that student-led active learning approaches improve comprehension and course performance relative to traditional, lecture-based courses.[9,14,15,41] In particular, improvements were most pronounced amongst lower performing students who struggled to understand the material when taught in a traditional lecture format, a trend consistent with numerous findings that active learning projects significantly decrease the number of students that fail a course.[16,17,22] These projects also provide a memorable and tangible learning experience that improves long-term retention,[41] noted here as students who participated in ALRPs had improved performed on the final exam problem despite a six-week time period between the project due date and the final.

ALRPs were well-received, as undergraduates showed general enthusiasm for the work and a willingness to participate in future ALRP activities. In particular, student enthusiasm stemmed from the opportunity to apply TP principles to real problems that had potential to impact work at their university. This finding is consistent with student survey results from other active learning efforts in TP that seek to connect TP principles with practical and applicable market-driven problems.[30] Indeed, connecting TP concepts to applications that have perceived value as opposed to classic textbook problems can overcome many of the hurdles that are traditionally associated with the abstract and complex topics prevalent in TP.

In consideration of other ChE faculty interested in future implementation of ALRPs, we recommend they carefully weigh out the potential benefits of such projects with the challenges of its implementation. Developing a project around an on-going research problem in the instructor's lab has potential to benefit the faculty member by providing his or her research lab with new insights into their research. It may not only be the number of students at work on a problem, but also the combinations of students that could lead to the generation of a creative approach or solution to a research problem that would otherwise not be realized. Engagement in research with the undergraduate student body may also provide a unique and effective avenue for recruitment of top undergraduate and future graduate students into the lab. However, with these potential benefits also come barriers to implementation, the most significant being identification of an on-going and suitable research problem that aligns well with the course material at the time of project assignment. As faculty are commonly assigned courses that directly tie to their research fields, overlap does become likely at some point. However, the research problem must also be addressable with an undergraduate-level skill set in TP. For more effective implementation, a mechanism could be established to incorporate other faculty within the department, college or university who may have a wider variety of appropriate research projects on hand that fit the subject material to expand the variety of problems available. In selection of an appropriate ALRP problem, it was also important to identify other accessible problems that could serve as a useful reference to students in case they struggled to start the problem. In the case of ALRP #1, problem 3B.9 in BSL (Ch 3, pages116-117) [33] which describes transverse flow of an incompressible Newtonian fluid around a cylinder under creeping flow, proved to be a useful reference.

Others have noted that active learning projects should not replace traditional assessment mechanisms in TP.[30] We also emphasize that the ALRPs described here are most useful for re-enforcing TP concepts after they were are first taught in a traditional format. However, they should not be used as a replacement for the classic TP problems that are proven to establish an initial foundation in the subject. A benefit of this structure is that it allows faculty to add in an ALRP without significantly restructuring of the course, keeping the faculty workload within a reasonable limit. Finally, with the recent rapid shift to remote learning, further research is needed to understand the best practices for implementing ALRPs in an online mode. As others have begun successful adaptation of POGIL and other active learning models virtual-remote-online formats,[42-44] we expect that ALRPs will continue to be effective in a remote environment.

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