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Project based design in microfluidic modeling– learning the basics of momentum and mass transport

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Background

Undergraduate learners in heat, mass, and momentum transfer courses frequently report difficulty visualizing transport processes and mapping continuum-scale phenomena onto mathematical models. This difficulty in visualization and conceptualization not only undermines problem solving but hinders the fundamental understanding of the subject matter [1-2]. Courses such as transport phenomena often foreground derivations and complex differential formulations that many students find mathematically burdensome, leading instructors to adopt computational strategies (i.e. simulations or numerical methods) to help students focus more on physical intuition and conceptual reasoning.[3] Empirical investigations within the lab also show these common cognitive obstacles: students can struggle with nonintuitive microscale behaviors and interactions between multiple physical processes, retain persistent misconceptions and learn better when hands on activities require them to design apparatus or connect measurements to theory [4-7].

Collectively, the literature indicates that recurrent learning barriers occur in transport phenomena curricula due to the heavy algebraic manipulation, high level of abstraction and limited opportunities for explicit visualization inherent in the material of these courses. These educational challenges provide ample motivation for the creation of pedagogies that make complex processes more concrete and accessible to students [1,2].

Conceptual gaps in engineering courses disproportionately affect students from underrepresented and under-resourced backgrounds, creating systemic barriers that perpetuate inequities in retention and academic performance. Quantitative analyses reveal that students of color and working-class students experience significantly lower graduation rates, have a longer time to degree, and showed reductions in GPA as compared to their peers. These statistics are amplified when race and socioeconomic status overlap [8]. Critically, active learning and project based pedagogical interventions show promise in narrowing these equity gaps [9-11].

Design-based learning and project-based learning represent innovative pedagogical approaches that engage students in authentic, real-world design challenges to deepen conceptual understanding. Using these techniques instructors can connect abstract theoretical principles to concrete applications. Previous approaches in transport phenomena classes have included hands-on learning modules, computational tools and open-ended design projects [1,12-13]. Evidence demonstrates that these approaches produce measurable learning gains, address diverse learning needs and support students who benefit from applied, active learning models [14-17].

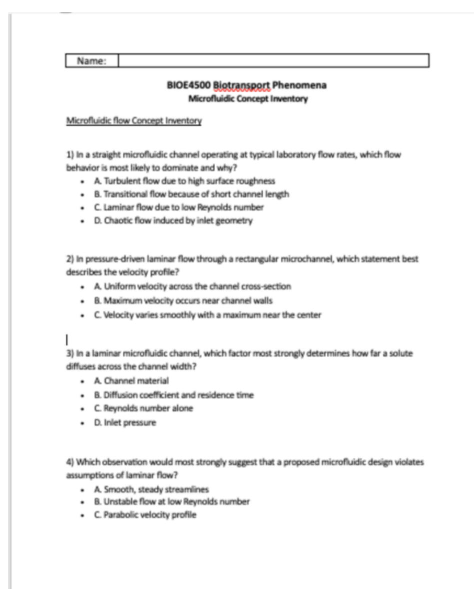
This paper describes a project based, student led design challenge based on the creation of a microfluidics reactor module within an upper-level undergraduate transport phenomena class with a particular focus on conceptual understanding and broadening participation on these topics.

Classroom setting

The student design challenge was performed at Wentworth Institute of Technology Wentworth Institute of Technology, founded in 1904, is a renowned STEM university in Boston, Massachusetts. The School of Engineering is the largest school at Wentworth, with about 1500 undergraduate engineering students and 50 graduate students. Wentworth encourages hands - on, inclusive learning environments and curricula at the institute is focused on real-world engineering and technology challenges. The classroom setting for the design challenge was a senior level undergraduate transport course in the biological engineering program of the engineering department (BIOE 4500 Biotransport Phenomena). Typical class sizes in the biological engineering department currently range from 7-15 students. BIOE 4500 is a senior level course that focuses on the exploration of transport phenomena, including momentum transport, heat transport and mass transport with a particular focus on biological systems. Prerequisites for BIOE 4500 include sophomore and junior courses in fluid mechanics, thermodynamics, calculus and programing. Students are expected to have basic proficiency with Matlab and knowledge of basic transport concepts such as viscosity, average velocity, and Reynold's number from prerequisite courses (although review of these concepts does occur within the class). Biotransport Phenomena (BIOE 4500) is designed using Wentworth's unique emphasis on hands-on active learning, with laboratories and simulation integrated directly within the lecture environment. The design challenge spans the semester integrated into both the laboratory and lecture portions of the course.

Student-led design challenge

The design challenge was implemented as a student-led activity within a senior transport phenomena classroom setting. This activity complemented existing computational and experimental investigations in the areas of diffusion, momentum transport and mass transport that are performed within this class. Briefly, this activity began with an introduction to basic flow elements of microfluidic reactors which included information about the specific flow regime and mixing characteristics of each element. Initial concept inventories give to students can be seen in Figure 1. These concept inventories assessed basic student knowledge of diffusion, momentum and mass transport.



Name:

BIOE4500 Biotransport Phenomena
Microfluidic Concept Inventory

Microfluidic flow Concept Inventory

1) In a straight microfluidic channel operating at typical laboratory flow rates, which flow behavior is most likely to dominate and why?
- A. Turbulent flow due to high surface roughness
- B. Transitional flow because of short channel length
- C. Laminar flow due to low Reynolds number
- D. Chaotic flow induced by inlet geometry

2) In pressure-driven laminar flow through a rectangular microchannel, which statement best describes the velocity profile?
- A. Uniform velocity across the channel cross-section
- B. Maximum velocity occurs near channel walls
- C. Velocity varies smoothly with a maximum near the center

3) In a laminar microfluidic channel, which factor most strongly determines how far a solute diffuses across the channel width?
- A. Channel material
- B. Diffusion coefficient and residence time
- C. Reynolds number alone
- D. Inlet pressure

4) Which observation would most strongly suggest that a proposed microfluidic design violates assumptions of laminar flow?
- A. Smooth, steady streamlines
- B. Unstable flow at low Reynolds number
- C. Parabolic velocity profile

Figure 1 Concept inventory microfluidic design

During the design challenge activities, students were tasked with designing a microfluidic mixer capable of combining two streams of food dye within water. Basic parameters for the fluid density and viscosity of food dye and water were provided to students along with simple assumptions (food dye is miscible, no reaction occurs etc.). Each team was responsible for creating its own design objectives and defining the metrics for both success and failure of the model. Constraints of the design were designed to be minimal and included minimum size of channels (~40 µm, necessary for consistent results in 3D printing) and the minimum number of inlets and outlets allowed per design (2 and 1 respectively). During design setup, a brief instructor-facilitated discussion aided the development of individual team design objectives where relevant physical concepts were analyzed such as advection and diffusion. Students discussed the analytical evaluations they generated within their groups such as mixing efficiency, resistance time of the material within the reactor and flow regime, creating a shared set of class evaluation criteria for the mixer. During the discussion students were able to connect the physical processes occurring in the device, such as laminar flow, bulk transport and cross-stream transport with potential methods of evaluation both qualitative and quantitative. At the end of this process, the class synthesized these insights into a collective understanding of the constituents of a successful microfluidic reactor design. This exercise encouraged students to engage with real-world processes typical in industrial settings such as rapid prototyping and engineering design.

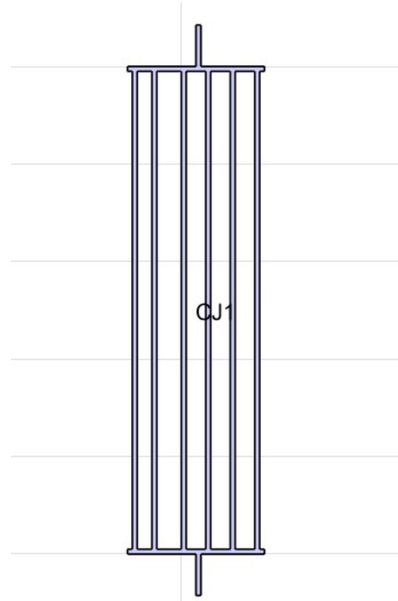


Figure 2 Preliminary Geometric Design of Microfluidic

Following the establishment of performance metrics, teams first developed and analyzed a 2D planar representation of their microfluidic reactor using computational fluid dynamics (CFD) modeling software, with FEATool Multiphysics provided and widely adopted due to its accessibility and multiphysics capabilities. This initial stage allowed students to rapidly explore transport behavior, evaluate design concepts, and refine geometries under simplified assumptions prior to increasing model complexity

Building on insights from the 2D analysis, teams then constructed a corresponding 3D model of their reactor geometry, at this stage teams could choose to incorporate additional physical realism such as channel depth effects (although models that required 3D depth effects for efficient mixing (such as herringbone mixers) were not included in this exercise to make this activity accessible for all skill levels). Once the 3D geometric designs were completed each team again analyzed reactor performance using CFD simulation. At a minimum teams evaluated flow fields and pressure drop across the device. Some teams extended their analysis to include further Multiphysics modeling such as concentration gradients within the device.

Simulation results from the 2D (and if included the 3D models) formed the basis for a formal design pitch in front of the class. Briefly during the design pitch, students presented a 1-slide PowerPoint presentation highlighting the key metrics of their system. This was expected to include the following: A schematic design with dimensions of all channels labeled (or the equivalent), a depiction of average velocity across the 2D channel, pressures at each inlet and outlet of the channel, the calculated pressure drop, the mixing index at the chosen outlet). Students could also make their case using other measures including but not limited to (the residence time, flow regime, mixing length, or outlet uniformity).

Students then selected the top two reactor designs through a ballot-based process that selected designs using three factors, innovation of design, feasibility of fabrication and strength of each team's justification (i.e. strength of ability to mix dye samples). One to two models were selected based upon class size and selected designs were subsequently fabricated using 3D printing services. Flow through the devices was experimentally assessed in a later laboratory session. Briefly, a dilute solution of dye in water was added to each device using a syringe pump system found within the labs. Pictures were taken at short intervals (< 1 min) and analyzed by image J for changes in greyscale values.
Overall, this activity promoted student ownership, collaborative learning, and the integration of modeling, design, and communication skills within a realistic microfluidic engineering context.

<u>Assessment tools</u>

Assessment tools within this module consisted of concept inventories and design reports. Concept inventories were used to assess students foundational knowledge of core concepts of flow based transport before and after the activity. This helped students to evaluate their learning and identify any misconceptions in core concepts that they encountered. Design reports were used to assess progress during the creation of the microfluidic model. This tool helped to capture conceptual understanding of higher order design and analysis and complemented concept inventory assessment.

<u>Results</u>

Student performance on concept inventories and related exam questions increased following implementation of the instructional activity. On a representative set of exam items about momentum transfer concepts, average scores increased by approximately 30% between the cohorts occurring prior to implementation and the cohort in which the activity was incorporated. Figure 3 illustrates differences in student responses to a representative momentum transfer question administered before and after implementation of the activity, demonstrating an increase in correct responses at the class level.

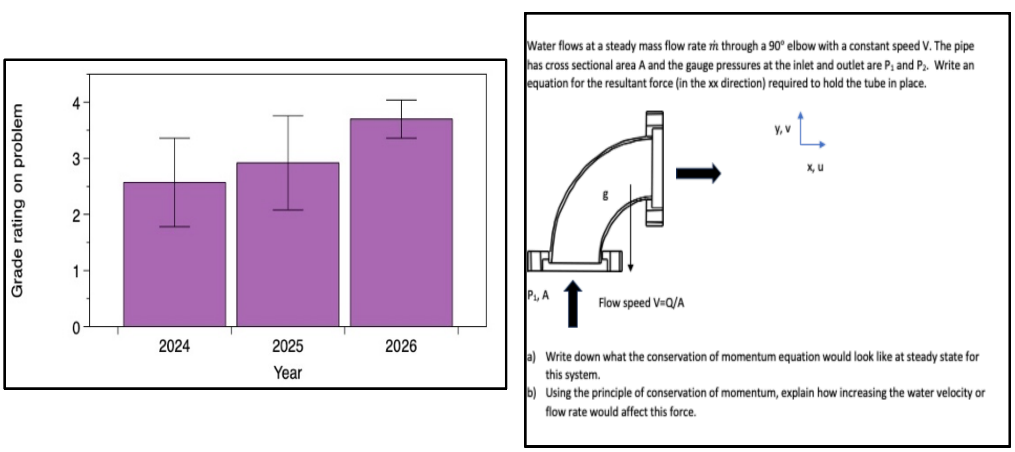


Figure 3 Comparison of student responses at the class level to a representative momentum transfer question administered before and after implementation of the instructional activity.

Much conceptual difficulty in momentum transfer analysis stems from difficulty in understanding velocity field direction. Similar results were seen on related conceptual analysis in heat transfer and mass transfer in later sections of the course.

Student teams were able to create clear design objectives and performance metrics, and the majority connected simulation outputs to physical interpretations of flow behavior, mixing, and residence time under laminar conditions within design reports. Student assessment of the activity was overwhelming positive, with the majority of students noting the activity as "Interesting", "Fun to do". Students also liked the ties to industry-based design standards such as rapid prototyping and computational fluid dynamics. Importantly the activity showed promise in lessening the barrier created by the high level of abstraction found within these courses. Students surveyed reported that they finally "understood" what the variables from the Navier-Stokes equations meant and that they felt they "finally got it."

For the future the instructor of this course would like to replicate these results over several more years.

Conclusions

This study shows that integration of a project based design experience with a hands on laboratory provides beneficial improvements in understanding of the often esoteric concepts of transport phenomena. Using assessment tools such as concept inventories and design reports students in this activity saw measurable gains in core microfluidics concepts and were able to translate theory into functional design decisions. Student perception of these topics also improved. These results suggest that similar project-based investigations may be useful in reducing barriers to understanding in engineering topics and should be studied in greater depth.

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