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Board 28: Work in Progress: Glucose Analyzer Learning Module for Chemical Engineering Education Theory

Riley Jackson Fosbre, Washington State University
Prof. Bernard J. Van Wie, Washington State University

Prof. Bernard J. Van Wie received his B.S., M.S. and Ph.D., and did his postdoctoral work at the University of Oklahoma where he also taught as a visiting lecturer. He has been on the Washington State University (WSU) faculty for 41 years and for the past 27 years has focused much of his effort on developing, implementing, assessing and propagating use of hands-on modules and interactive exercises that can be used in standard lecture classrooms so students do not need to wait till their senior year to see examples of process equipment. He also leads a strong program in bioreactor design for biomanufacturing of cartilage tissue and cells for immunotherapy.

Dr. Prashanta Dutta, Washington State University

Prof. Prashanta Dutta has received his PhD degree in Mechanical Engineering from the Texas A&M University in 2001. Since then he has been working as an Assistant Professor at the School of Mechanical and Materials Engineering at Washington State Universit

David B. Thiessen, Washington State University

David B.Thiessen received his Ph.D. in Chemical Engineering from the University of Colorado in 1992 and has been at Washington State University since 1994. His research interests include fluid physics, acoustics, and engineering education.

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Work in Progress: Glucose Analyzer Learning Module for the Classroom

Fosbre, RJ, Dutta, P, Thiessen, DB, Van Wie, BJ

Washington State University

Violand School of Chemical Engineering and Bioengineering

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The goal of the greater project is to provide students with hands-on learning experiences while removing cost as a barrier to participation. Our Low-Cost Desktop Learning Modules (or LCDLMs) help students visualize and experience engineering concepts where books prove less than adequate and provide class members with the opportunity to learn as a group and collaborate with one another. LCDLMs have been found to improve motivation and attention while providing direct and vicarious learning opportunities, encouraging information retention in a learning environment. The goal of this paper is to introduce the latest LCDLM in development, for glucose analysis, which will mark the first LCDLM to feature a chemical reaction. In this paper we will also go over future work to be done to make the glucose analyzer viable for classroom use.

The new module will feature a glucose solution meant for analysis, a set of reagents to convert the solution from transparent to a red-violet color of intensity correlated to the glucose concentration, and a simple apparatus students can use to read the concentration of the sample. The apparatus is meant to be used to teach students multiple engineering concepts through visual demonstration. In this LCDLM concept, chemicals from a set of reservoirs flow through a transparent microfluidics mixing chamber, which leads to a colorimetric reaction based on the amount of glucose present, teaching students about kinetics and, to a lesser extent, microfluidics. Dissolved oxygen is a limiting reagent, which will demonstrate to students the relevance of stoichiometry and mass transfer in a closed system. The mixture then collects in a chamber with two transparent sides. Green light passes through the red solution and into the lens of a smartphone camera to measure the intensity of the light. This is meant to demonstrate Beer's law and complimentary colors. The more light that can pass through, the lower the glucose concentration. Students will need to measure a series of solutions with varied but known concentrations, construct a calibration curve, and then find an unknown solution concentration based on where an absorbance reading falls on the curve, modeling a routine wet lab test but without the need for expensive instrumentation.

Prototyping is needed before a definitive version can be implemented in the classroom. The final design for the analyzer, how it will be assembled, parts to be used, etc., is being determined, and up-to-date results will be presented. The geometry of the mixing chamber with attached reservoirs for adding reagents must be optimized for small samples. The plan is to design a 3D model in SolidWorks and then cut out a prototype from an acrylic sheet with a laser cutter. The prototype will then be tested for leaks. The module itself will consist of the channel sheet glued between two other sheets, making assembly straightforward.

Introduction:

Over the course of the past five years, our project group has developed several Low-Cost Desktop Learning Modules, or LCDLMs, for the purposes of miniaturizing and subsequently visualizing real applications of complex engineering topics.[1,2] The original four modules include a hydraulic loss kit, meant to illustrate conservation of mass and the mechanical energy balance equation, a venturi meter, which shows students the conversion of flow work to kinetic energy when an incompressible fluid enters a narrowing pipe, and two heat exchanger modules, which demonstrate how temperature gradients and flow configurations affect heat transfer efficiency.

The four modules and their corresponding topics were chosen because undergraduate students often have misconceptions related to them, allowing them to repair these misunderstandings prior to encountering related processes in the real world. The purpose of using physical models to complement traditional classroom lectures is twofold: 1) they provide a way for students to visualize the phenomena about which they are learning, lowering the cognitive load of the lesson; and 2) they also provide professors with an opportunity to have students work in groups. The first point is mostly intuitive. If students must visualize in their own minds the phenomena taking place, they must exert extra effort they could be spending on solving problems or exploring the topics in more detail. This also leads to misconceptions, as students likely will not have a complete model of the phenomena with their current knowledge and will need a form of reference material to avoid making mistakes. This is often why, in a traditional engineering class, students are encouraged to draw out the situation when problem solving rather than hold all the details mentally or in writing. Additionally, having applied the knowledge students learned during lectures and independent study, their observed self-efficacy will be set appropriately. This refers to an individual’s belief in their ability to learn or perform a specific task and is an important indicator of motivation. Students with higher self-efficacy are more willing to engage in learning actively, and thus have a higher chance of success.

As for the latter point, according to Bandura’s social cognitive theory, learning happens best as a social activity where information is more readily retained with other individuals present.[3,4] The reason for this is that individuals acquire knowledge both actively, or by doing, and vicariously, via observation. Both approaches are provided by the learning module but also applicable to peers during a group activity, as students work with and observe group mates to accomplish a collective task. Bandura’s theory also assumes learning is an active process where an individual will adjust their behavior and performance based on their environment, such as the group they are a part of, and personal factors, like their observed self-efficacy. According to Bandura, group activities allow students with the same level of knowledge to share and listen to differing ideas and thus observe, imitate, and challenge the approach of their peers, providing the optimum environment for learning. Models formulated by students which do not hold up to their peer's scrutiny are discarded in favor of stronger ones, while observations made by students with differing perspectives can be shared to repair an incomplete approach. This is further reinforced by the instructor, who will correct any conclusions not in line with the model and provide missing pieces of information students may lack.

The current set of LCDLMs focused on fluid mechanics and heat transfer is relevant to both mechanical engineers and chemical engineers. Aside from non-toxic fluid dye used to enhance visibility, these DLMs did not involve any chemicals. Our team is interested in developing chemical engineering-specific DLMs that involve chemical reactions, such as the microfluidic glucose analyzer described in this paper.

The goal of this project is to create a cost-effective and easy-to-use learning module intended for the classroom, like the previous LCDLMs mentioned above, but with the added challenge of including a common chemical reaction used in biomedical contexts, glucose oxidase. To mitigate potential exposure to large quantities of hazardous chemicals and lower costs, the glucose samples and reagent included in the kits need to be only milliliters in volume, necessitating a specialized design incorporating microfluid flow behavior into the mixing process. We intend for this paper to describe work-in-progress on the design of the glucose analyzer LCDLM and future developments that need to be made prior to implementation in a classroom.

Lab Module Description:

Reservoirs and pumps

Milliliter amounts of sample and reagent will be stored in two separate reservoirs built into the DLM. The liquid in the two reservoirs will be released simultaneously to flow through a mixing channel and into a holding chamber where the reaction will proceed. Vent holes will provide an escape for displaced air and for ease of cleaning between uses.

Mixing Channel

As shown in Figure 1 a mixing channel is provided as a Y-shaped conduit with two inlets and one outlet at the bottom. Most of the length is in the “stem,” where the two fluids will flow through baffles in a serpentine pattern to create mixing even when Reynolds numbers are in the laminar regime. Dimensions are preliminary and shown to provide mixing through COMSOL modeling. The exact dimensions will likely be adjusted and numbers from a prototype will be available by the time of the conference.

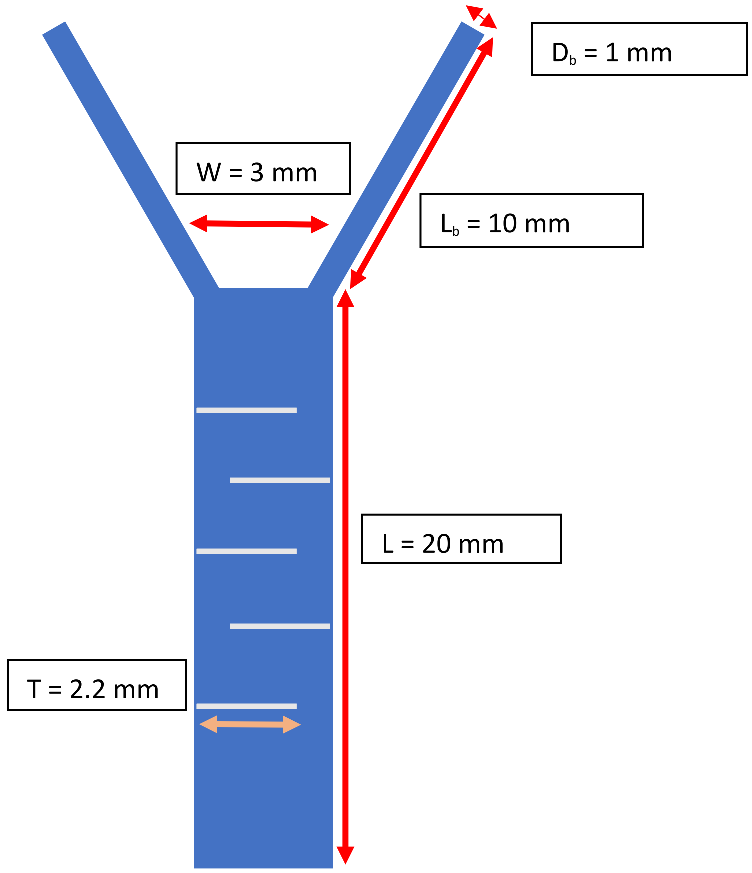

Fig 1. Rough outline of the module's dimensions, top portion. Subject to change based on material limitations.

To aid in mixing, the added baffles lead to secondary flows and increased surface area between streams.[5,6] The rectangular cross-section mixing channel, and by extension the baffles, are small with a width of only approximately 3 mm across and the baffles extending from alternating sides by 1.8 – 2.0 mm. The depth of the mixing channel needed for complete mixing is estimated to be around 5 mm based on our model. The intention is to optimize the channel design via a COMSOL model to ensure that complete mixing can occur with a single pass. Other designs that would take advantage of chaotic advection are also possible.[7,8]

Reservoir Monochromator System

After the fluid is mixed in the mixing channel, it will enter a reservoir as shown in Figure 2 with transparent sides, allowing students to see the color change from a reaction occurring between the reagent and solute in the sample. White light from a flashlight will be directed through a green filter and then the sample chamber. The transmitted light intensity may need to be reduced to avoid saturating the sensor. This could be done with a variable-intensity light source or a neutral-density optical filter.

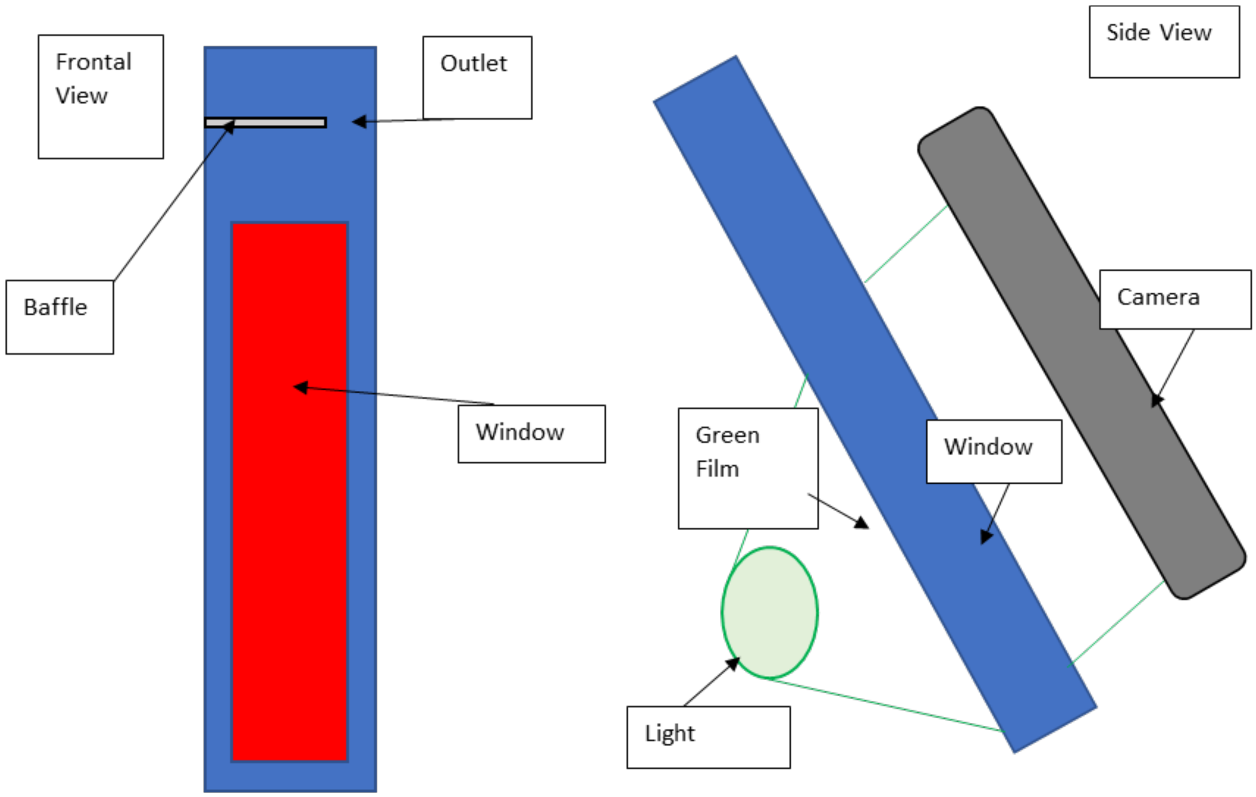

Fig. 2 Depiction of the bottom portion of the module (see Figure 1), showing the reservoir for the mixed sample and pathway for the green light used for measuring the glucose concentration.

Cell Phone Camera for Analysis

The module described above will have a frame, both to support any tubing attached while keeping it upright and to allow affixing of a cellphone and accompanying camera on top of a glass cover. Light will enter the reservoir from a film filter that only allows green light to enter, and the cellphone will be used to get a saturation reading for green light. The frame will be constructed to compensate for as many different models of cellphones as feasible. Students must download an accompanying absorbance software app before the activity. Smartphone light sensors have been previously demonstrated to work for simple spectrophotometric measurements.[9] Free options for measuring color saturation already exist for Apple and Android cellphone models.

Learning Objectives:

Chemical Reaction Kinetics

The first step of the reaction involves glucose oxidase enzyme catalyzing the reaction of glucose with oxygen to form gluconate and hydrogen peroxide. In the second step, the hydrogen peroxide oxidizes a reduced dye, catalyzed by the peroxidase enzyme, leading to a red color, which absorbs green light in proportion to the glucose concentration. The peroxidase mediated reaction is much faster than the first glucose oxidase reaction and therefore serves as a probe for the rate of change caused by the first reaction. We note oxygen, involved in the first reaction, may be a limiting factor depending on the concentration of glucose. In cases where the glucose exceeds a certain concentration, the oxygen in water at room temperature will be consumed before an accurate measurement can be made.[10] In this case, two options exist, beyond simply diluting the sample solution further:

- Measure how quickly the concentration of red dye changes over time, which is dependent on kinetics.
- Wait for enough oxygen to diffuse into the liquid mixture to achieve a complete reaction, allowing for an "endpoint measurement."

To do this, students need to understand reaction rates and orders, to determine how the amount of glucose in a sample will affect the rate it is converted to red dye.

Light Spectroscopy and Beer's Law

The method used to measure glucose concentration is absorption spectroscopy, wherein the intensity of colored light that passes through a sample is measured. By comparing that to the intensity of a blank containing only the solvent, we can use Beer's law to find sample concentration.

Absorbance is a function of the ratio of the intensity of light passing through the sample, , to that passing through the blank, , as follows.

Since absorbance depends on the ratio of the intensities, units are effectively removed, meaning that, even if students are using different software or phones to measure intensity, as long as the calibration curves are made consistently, results will not be affected.

Sample absorbance is directly proportional to three terms: the length of sample through which the light passes, , the concentration of the sample, , and the molecular absorptivity, , a constant for the chemical of interest.

Constructing a curve of measured absorbance for several known solute concentrations will provide a linear relationship between concentration and absorbance, allowing students to find the concentration of an unknown solution based on the fractional amount of green light passing through the liquid relative to that of the blank.

Microfluidics

Normally, increasing the flow velocity will allow for turbulence, which would improve mixing, but on the micro scale this is not possible due to fluid interactions with the walls of the chamber leading to a laminar flow profile. Instead, the primary source of mixing in our context is folding of reagent and sample layers back and forth until adequate mixing is accomplished.

Future Work:

While the module is meant to be microscale to mitigate student exposure to potentially hazardous chemicals, the exact dimensions of the apparatus are left variable for optimization. The primary source of uncertainty is the optimal size and placement of the baffles in the mixing chamber for both performance and assembly constraints. Before moving to the assembly of the prototype, a rough estimate of the chamber layout needs to be appropriately determined via computer modeling.

After an appropriate design is determined, a working prototype will be built to begin planning for classroom implementation. The finished design needs to be water-tight and cheap to build for mass production since the intention is to ship the systems to multiple universities for beta testing. We achieved this with earlier LCDLMs through a manufacturing process, wherein the channels for the module are 3D printed to produce a mold from which the modules were made through vacuum forming.[11] Given the relative size of the channel in this case, however, it will be more efficient to machine the channel from a plastic sheet of acrylic or PETG and then seal the channel between two sheets with an adhesive. Assuming a minimum cost of $15 per kit for the laser cutting service and $8.16 for the materials (PETG, 12”x12”, .177” thickness), the module itself would cost around ~$30 to produce.[12] Compared to the more complex shell and tube heat exchanger LCDLM used currently, with an estimated price of $115 per kit,[8] the cost of this prototype proves promising, however this does not account for the chemical components, which will affect the initial and maintenance costs associated with each module, since each kit needs to be properly stocked for each experiment.

From here, once the prototype is verified to work and a finalized version constructed, the implementation process can begin. Like the other LCDLMs currently in use, classroom implementation will involve a series of assessments and guided activities to ensure students are aware of the learning objectives and are able to operate the module correctly. This includes a pre-test to record their prior knowledge, an in-class worksheet and after-class homework section for students to collect data using the module and interpret their results, and finally, a posttest to determine what students have learned from using the DLMs and, thus, the efficacy of this approach.

Ultimately this is a tool students can use to collect data. The inclusion of the cellphone mechanism removes the need for a built-in camera, but it also adds an extra but simple commitment for the students to complete the activity. The tests and worksheets will be used to ask students about concepts like microfluidics and reaction kinetics to address their understanding of these subjects. In addition, students will create a calibration curve using spectrometry, something they may need to do in the future should they choose a career that involves chemical analyses.

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