A gas absorber design experiment for the chemical engineering laboratory

James M. Munro, Bhavani Puli, David J. Dixon and Jan A. Puszynski
Department of Chemistry and Chemical Engineering
South Dakota School of Mines and Technology

Summary

An open-ended, gas-absorber design experiment has been developed for the undergraduate chemical engineering laboratory. The experiment utilizes the Design-Build-Test (DBT) approach. Student teams are asked to design a column to perform a specific task, partially build or configure the physical equipment for their design and operate the gas absorber to test their design. Each laboratory team conducting the experiment is assigned a unique objective involving the absorption of carbon dioxide, ammonia or ethanol from an air stream flowing at a specified rate. The experiment provides several choices of column diameter and packing types and size from which students can choose to complete their design.

Introduction

While the traditional chemical engineering laboratory experiments provide valuable exposure to process equipment and unit operations, they often do not provide students with open-ended design experiences that include real choices of equipment selection and economic factors. Design experiences are, however, required of accredited engineering programs; the Accreditation Board for Engineering and Technology (ABET) accreditation criteria require that graduates of engineering programs possess "an ability to design a system, component or process to meet desired needs."1

The faculty of the chemical engineering program at South Dakota School of Mines and Technology (SDSM&T) has begun developing open-ended laboratory DBT experiments for the chemical engineering laboratory. The first such experiment created was a DBT experiment in pump selection and piping system design,2 which has been integrated into the junior-level fluid mechanics laboratory course. The faculty has established a goal of having at least one undergraduate DBT experiment in each of the three major areas (fluid mechanics, heat transfer, mass transfer) of transport phenomena. The present paper reports the details of our DBT experiment involving design of a packed column for gas absorption. The project was undertaken by the faculty of the chemical engineering program at South Dakota School of Mines and Technology (SDSM&T) and was funded by the National Science Foundation and the Dow Corning Foundation.

The goal of the present experiment is for students to design, build and test a gas
absorption process. As with other DBT experiments, students must make choices between competing alternatives and are expected to make their decisions based on valid engineering design modeling and sound economic reasoning.

Students are divided in teams and are expected to utilize Aspen-Plus® process simulation software in completing their design. The team’s design is approved and recorded by the laboratory instructor; the team builds the process by physically filling the selected column with the required amount of their choice of packing and by connecting process streams and instrumentation to the selected column. The experiment utilizes a Camile (Argonaut®) control system to provide safety interlocks and feedback control of process variables.

**Background**

The baccalaureate program in chemical engineering at SDSM&T has as part of its mission to prepare students "to become practicing chemical engineers, ready to enter the workforce and make immediate contributions."

Until recently, baccalaureate programs in engineering have traditionally used laboratory experiences to reinforce engineering science theory presented in lecture classes. Design concepts were presented in a senior capstone design course but were not incorporated into laboratory experiments. In the last fifteen years there has been a move toward integrating design experiences throughout the curriculum in response to ABET accreditation requirements for engineering programs. A number of engineering programs have developed courses or methods to introduce design at early stages of the engineering curriculum, or even at the secondary or elementary school level. In their text Teaching Engineering, Wankat and Oreovicz note that "hardware projects, which mix design and laboratory skills, can be extremely motivating because students can see what they have designed." The freshman level projects often involve inexpensive materials or kits from which students construct some article (for example: bridges, egg carriers, rubber-band powered vehicles) to meet a performance standard.

Design concepts are being integrated into sophomore and upper level engineering laboratories, albeit at an apparently slower pace than at the freshman level. Marchese et al. have described a sophomore-level course of open-ended laboratory projects that incorporate a multidisciplinary approach to solving design problems. Al-Dahhan has described a series of lectures and a manual on selection of process components as a way of introducing design into the chemical engineering unit operations laboratory.

Recently, a Design-Build-Test (DBT) approach has been used in undergraduate engineering laboratories. In most DBT projects, students are required to design an article, typically small and inexpensive, using design guidelines that include mathematical calculations. Allen et al., developed a curriculum in electronic materials that "abandon the cookbook" approach in favor of a multi-course sequence of open-ended laboratory
experiences.\textsuperscript{10} Sherwin and Mavromihales have described a senior year DBT project in which students design, fabricate and test a cross flow multi-tube heat exchanger.\textsuperscript{11}

**Features of the experiment**

The Gas Absorption Design Experiment at SDSM&T was created to provide the following features.

1. **Flexibility:** The experiment was designed to be flexible enough so that no two laboratory teams ever have the same assigned objectives, or the same final design. In the gas absorption design experiment, the instructor imposes this variability by adjusting the pH, temperature, composition, or viscosity of the available absorbing liquid. Other variables that can be assigned by the laboratory instructor are the gas flow rate, the choice of solute gas (CO\textsubscript{2}, NH\textsubscript{3}, or ethanol), the concentration of the solute, and eventually the temperature of the entering gas. Student teams have the flexibility of choosing from three different column diameters and several available column-packing materials, as well as the flow rate of the absorbing liquid.

2. **Design:** Student teams are required to produce a design of their system, including the selection of specific items of equipment. We require that their design include their simulation results from ASPEN-PLUS\textsuperscript{®} process simulation software with the RATE-FRAC model for non-equilibrium separation processes. From the process simulation, students determine the height of packing and other factors required for the separation assigned to their group. Students are provided with performance and cost data on process components so that they can take those factors into account in their design. Students were required to include safety considerations in their designs.

3. **Build:** Once the laboratory instructor approves a design, each team assembles part of the experiment and configures the process equipment for their design. For the gas absorption experiment, this step includes the placement of the selected packing material into the selected column to the design depth, and making appropriate piping, sensor, and control signal connections. Students are expected to follow proper safety practices in the construction phase of their project.

4. **Test:** Once built, the team tests their design by operating the process and measuring output variables to determine the validity of their design. Students must demonstrate safe operating practices during the testing phase of their project. If their process is either over-designed or under-designed, they may be given the opportunity to refit the column by changing either the packing type or packing depth, to achieve their design goals. Students also compute the cost of the process they have designed, including both capital and operating costs. The operating costs can be inferred from the pressure drop, liquid flow rate, and gas flow rate through the column.
Equipment and Instruments

Columns of 6-, 8-, and 12-inch diameter PVC pipes are mounted vertically on a fabricated steel structure for students to use as absorber columns. The schematic of the apparatus is shown in Figure 1 and a list of the major pieces of instrumentation and equipment is shown in Table 1. Figure 1 illustrates the setup in which ethanol is the solute and the figure shows only one of the three absorber columns. A continuous gas analyzer is utilized to measure both inlet and outlet solute concentrations. The apparatus was constructed to allow for the vaporization and injection of a low-flow alcohol stream into the air. Care has been taken to ensure that the lower explosive limit of the selected alcohol cannot be reached during operation by a combination of equipment sizing, use of a nitrogen carrier gas, and process control interlocks programmed into the Camile® process control system.

![Diagram of Equipment and Instruments](image)

Figure 1: Process Schematic (showing 1 of 3 columns)

The equipment has been designed to allow easy removal of the top column heads for placement and removal of the column packing materials. We found that the plastic packing materials are easily removed from the columns with a portable wet-vacuum. The control functions are accomplished with the use of CamileTG version 4.1 software via an Ethernet link to Camile Connection® Control Hardware with Powerpak process control computer, which has been purchased as part of the project. The computer is placed in a
centralized process control room within the chemical engineering laboratory. A second monitoring computer is integrated into the control panel (See Figure 2), which is located adjacent to the process equipment. Both computers receive and transmit signals to the process through an Ethernet cable. The Camile Connection® “brain” module on the process is simply connected to the campus computer network, much as any computer is connected. The control computer communicates directly with the Camile Connection® module, which has its own unique IP address.

**Implementation**

The gas absorption design experiment was constructed in the summer of 2002. In the fall of 2002, student teams in our senior chemical engineering laboratory course were assigned projects on the experiment. The system that was brought up in this first semester of operation was the absorption of ethanol from a stream of air containing between 0.5 and 1.0 percent ethanol by volume. These concentrations are well below the lower flammability limit of approximately 3 percent. Each student group was given a handout that described the nature of the experiment, the safety considerations, and their unique design objectives.

In each case, students were asked to perform the design calculations first, to visit with the laboratory instructor about their design prior to beginning any actual assembly of components, and finally to demonstrate to the instructor or laboratory assistant that their constructed design met the objectives and the safety requirements.

In one typical assignment students created an air stream with 1.03 mole percent ethanol flowing at 69 cubic feet per minute at a temperature of 28 C. The students configured the 8-inch column packed with 1-inch plastic FlexiRing® random packing to a packed height of 6.0 ft. Water at a temperature of 14 C and a flow rate of 1.0 gal/min. was used as the absorbing solvent. The Aspen-Plus® simulation of the process predicted an exit concentration of 0.28 mole percent, while the experimental measurement of the exit concentration was 0.21 mole percent.
Table 1. Instrumentation and Equipment List

<table>
<thead>
<tr>
<th>Components</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Columns</td>
<td>6- and 8- inch diameter transparent columns and a 12-inch diameter opaque column, 6 ft. high packable sections, with removable top and bottom heads, and appropriate column internals.</td>
</tr>
<tr>
<td>Blower, pumps, tanks, piping and valves</td>
<td></td>
</tr>
<tr>
<td>Rel-Tek® continuous hydrocarbon (ethanol) analyzer</td>
<td></td>
</tr>
<tr>
<td>Rosemount Analytical Model 880A continuous Non-dispersive Infra-Red CO₂ analyzer</td>
<td></td>
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<tr>
<td>Dräger NH₃ detector tubes and Dräger Accuro bellows Pump.</td>
<td></td>
</tr>
<tr>
<td>Indicators for local and remote measurements of flows, temperature and pressures. Air and electrically actuated control valves.</td>
<td></td>
</tr>
<tr>
<td>Camile Connection® Process Control System</td>
<td></td>
</tr>
<tr>
<td>Ethanol Vaporizer: electrical pipe clamp heaters, with N₂ sweep gas.</td>
<td></td>
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<tr>
<td>Air sampling system with electrically heat-traced sample line.</td>
<td></td>
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<tr>
<td>Structure for mounting of, and access to, the equipment</td>
<td></td>
</tr>
</tbody>
</table>

Project Evaluation

A survey was prepared to assess the effectiveness of the new experiment. The survey posed six questions to students and provided space for written comments. Table 2 summarizes the results of the responses.

Table 2: Student Survey Results

<table>
<thead>
<tr>
<th>Numbers represent the percentage of students responding in each category*</th>
<th>SA</th>
<th>A</th>
<th>D</th>
<th>SD</th>
<th>NA</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. The experiment was effective as a learning tool.</td>
<td>46</td>
<td>54</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2. The experiment was just another cookbook lab.</td>
<td>8</td>
<td>61</td>
<td>31</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3. The handouts were effective in conducting the laboratory exp.</td>
<td>16</td>
<td>38</td>
<td>15</td>
<td>31</td>
<td></td>
</tr>
<tr>
<td>4. The gas absorber experiment helped reinforce the principles learned in lecture class (ChE 318.)</td>
<td>23</td>
<td>77</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5. Working on the gas absorber experiment increased my understanding of the principles of gas absorber design.</td>
<td>38</td>
<td>46</td>
<td>15</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6. Working on the gas absorber experiment increased my competency to operate and troubleshoot gas absorber systems.</td>
<td>31</td>
<td>38</td>
<td>31</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* SA = Strongly Agree; A = Agree; D = Disagree; SD = Strongly Disagree; NA = Not Applicable
The response to question no.’s 1, 4, 5, and 6 reflect a high degree of agreement that the experiment was a positive learning experience for the students and the negative response to question 2 indicates clearly that the experiment was not perceived as a “cookbook” experience.

When asked to provide comments on the design experiment, students responded with comments such as:

- “I think that being able to see the workings of the columns makes it easier to understand what is really happening in a packed column.”
- “Forced us to revisit principles learned in ChE 318 [the theory course].”
- “The students can see all aspects of an absorption column and vary any of several parameters to affect the performance of the column.”
- “The control system will greatly increase the experience of this lab.”
- “Good experiment.”
- “This lab was the best one in the whole class.”

**What we've learned**

We are generally pleased with how the experiment has been received by students and by the results we have observed in students completing their design, building and finally testing the system. Most of the students felt that the experiment was effective as a learning tool. The students were able to design a gas absorber for a unique gas absorption process using RATE-FRAC simulation on the Aspen-Plus® software, and then observed the experimental performance of the process that compared well with the simulation result. The students demonstrated an understanding of the design process by reporting their design and the results of their experiments. Once the automatic control system is completed, students will also have the experience of operating the process through a combination of manual operations and automatic controls.

The problem that troubled most of the students was with the performance of the continuous hydrocarbon gas analyzer, which had to be calibrated every time they started the experiment. The calibration procedure involved preparing standards made by injecting a known quantity of alcohol into a Kevlar® gas sampling bag and filling it to capacity with air. Once the alcohol was completely evaporated, the sample of air could be used as a calibration gas. In addition, some parts of the process control system were not in place during this first semester of using this experiment; thus, students controlled the liquid level in the column bottoms by manually adjusting the liquid outlet valve and controlled the airflow rate with a manual valve. In the future, these process variables will be automatically controlled by the Camile® system.

**Conclusions**
An open-ended design experiment for the mass transfer laboratory was developed. It was first implemented in an undergraduate laboratory course in fall of 2002 in the Chemical Engineering program at South Dakota School of Mines and Technology. Students were able to accomplish the objectives of the experiment within a three week laboratory period by designing, building and testing a gas absorption system to meet a unique objective. The initial assessment of the experiment indicated that it met the objectives of providing a unique design-build-test experience for senior-level chemical engineering students.

Acknowledgements

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Dr. James M. Munro is a Professor of Chemical Engineering at South Dakota School of Mines and Technology (SDSM&T). He is a registered professional engineer in South Dakota. He holds a BS in Chemistry and an MS in Chemical Engineering from South Dakota School of Mines and Technology and a Ph.D. in chemical engineering from the University of Utah. He worked for the Dow Corning Corporation for three years and for Hoechst Celanese for 1 year. He teaches fluid mechanics and transport phenomena courses at the undergraduate and graduate levels, an undergraduate process control course, and is engaged in creating meaningful laboratory experiences for undergraduate students in engineering.

Bhavani Puli is a graduate student in the Chemical Engineering program at SDSMT. She did her Bachelors program in Chemical engineering from Amravati University, India. She is working as a Research Assistant under Dr. Munro. Her research project involves the design and control of a laboratory gas absorption column.

Dr. David Dixon is an Associate Professor of Chemical Engineering as SDSM&T. He earned a BS and MS in Chemical Engineering from SDSM&T and a Ph.D. in Chemical Engineering from the University of Texas at Austin. Prior to teaching at SDSM&T he worked for the Dow Corning Corporation. He teaches freshman engineering, programming, separations, reactor design, process dynamics, graduate thermodynamics, and is involved in undergraduate and graduate research. He also continues to be involved in improving undergraduate curriculum and laboratory experiences.

Dr. Jan Puszynski is a Professor of Chemical Engineering and Dean of the College of Materials Science and Engineering at SDSM&T. At SDSM&T, Dr. Puszynski is responsible for teaching capstone design courses. His sponsored research is focused on combustion synthesis of ceramics and intermetallics, gas phase formation of nanopowders, and reactivity of nanoenergetic materials. For more information http://nanotech.sdsmt.edu/

References

1. ABET Engineering Accreditation Criteria, Criterion 3: Program Outcomes and Assessment.


