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Tennessee Technological University

Author Guidelines for the LABORATORY Feature

The laboratory experience in chemical engineering education has long been an integral part of our curricula. CEE encourages the submission of manuscripts describing innovations in the laboratory ranging from large-scale unit operations experiments to demonstrations appropriate for the classroom. The following guidelines are offered to assist authors in the preparation of manuscripts that are informative to our readership. These are only suggestions, based on the comments of previous reviewers; authors should use their own judgment in presenting their experiences. A set of general guidelines and advice to the author can be found at our Web site: <<http://che.ufl.edu/~cee/>>.

- c Manuscripts should describe the results of original and laboratory-tested ideas. The ideas should be broadly applicable and described in sufficient detail to allow and motivate others to adapt the ideas to their own curricula. It is noted that the readership of CEE is largely faculty and instructors. Manuscripts must contain an abstract and often include an Introduction, Laboratory Description, Data Analysis, Summary of Experiences, Conclusions, and References.
 - An Introduction should establish the context of the laboratory experience (e.g., relation to curriculum, review of literature), state the learning objectives, and describe the rationale and approach.
 - The Laboratory Description section should describe the experiment in sufficient detail to allow the reader to judge the scope of effort required to implement a similar experiment on his or her campus. Schematic diagrams or photos, cost information, and references to previous publications and Web sites, etc., are usually of benefit. Issues related to safety should be addressed as well as any special operating procedures.
 - If appropriate, a Data Analysis section should be included that concisely describes the method of data analysis. Recognizing that the audience is primarily faculty, the description of the underlying theory should be referenced or brief. The purpose of this section is to communicate to the reader specific student-learning opportunities (e.g., treatment of reaction-rate data in a temperature range that includes two mechanisms).
 - The purpose of the Summary of Experiences section is to convey the results of laboratory or classroom testing. The section can enumerate, for example, best practices, pitfalls, student survey results, or anecdotal material.
 - A concise statement of the Conclusions (as opposed to a summary) of your experiences should be the last section of the paper prior to listing References.

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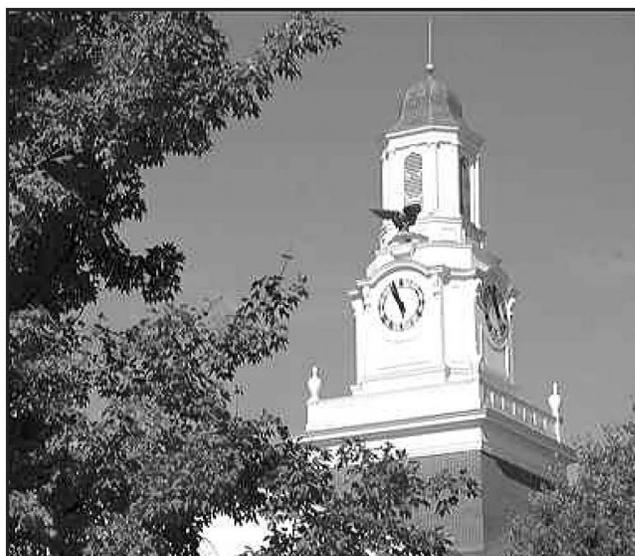
ChE at Tennessee Technological University

JOSEPH J. BIERNACKI,
WITH FACULTY AND STAFF

Tennessee Technological University (Tennessee Tech) began its life as Dixie College in 1909, with a few small but elegant Georgian buildings on 7th Street and Dixie Avenue in Cookeville, Tennessee. The tiny, then-private college* evolved into Tennessee's only technological university with a strong engineering, science, business, and education emphasis. By the end of the 1940s the seed for what would eventually become chemical engineering was planted within the Department of Chemistry, but the sapling soon withered and became dormant for another two and a half decades. In 1966, a young man named **John C. McGee**, a Ph.D. from North Carolina State University, was hired. Kindled by the presence of a growing chemical industry in Tennessee, McGee and a colleague from the already established Mechanical Engineering Department officially became the Chemical Engineering Department and McGee served as its first departmental chairperson. Not long after, **W.D. (Denny) Holland** (Ph.D., Georgia Tech) was hired, followed by **David W. Yarbrough** (Ph.D., Georgia Tech) and **Clayton P. Kerr** (Ph.D., Louisiana State University). These four men, young and energetic, would build the department from grass fields and empty rooms, lay the foundation for a strong unit-operations tradition, construct a lasting laboratory infrastructure, cultivate the master's program, embrace the college-level Ph.D. when introduced in 1971, pioneer computational techniques that were budding ideas at the time—and become respected and dedicated educators, researchers, and friends for the next three-plus decades, thus sowing the seeds that would grow into the present-day Department of Chemical Engineering.

While Professors McGee, Holland, Yarbrough, and Kerr would, from time to time, be joined by other faculty, they alone would remain for a life's career at Tennessee Tech.

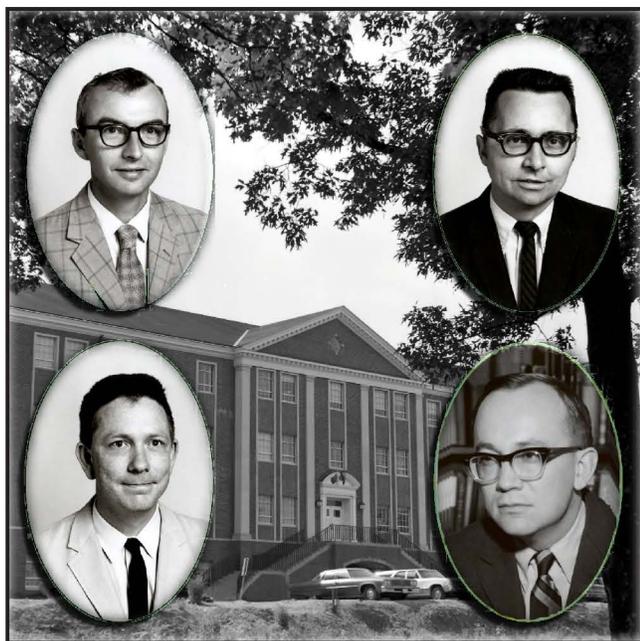
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The clock tower at Derryberry Hall.

These historical notes are brief yet important. The present faculty acknowledges and owes much of the department's ongoing success to the foundation that Professors Emeriti McGee, Holland, Yarbrough, and Kerr established. In 1999, both McGee and Holland retired, followed by Yarbrough and Kerr in 2001 and 2002, respectively. Since then, the department's faculty has been re-created, ushering in a new wave of excitement and productivity. Much as the department's founders laid the cornerstones and built a tradition and legacy, the present faculty has initiated a renaissance: introducing new research thrusts, modernizing both the undergraduate and graduate curricula in content and pedagogy, and stepping forward in service to regional outreach and their respective professional communities. The remainder of this article deals with the present, and to some extent, a vision for the future.

* Dixie College, formally Dixie University, was founded by the Church of Christ in 1909.



Yearbook photos (ca. 1976) of (clockwise from upper left) early faculty W. Denny Holland, John C. McGee, Clayton P. Kerr, and David W. Yarbrough, superimposed on a picture of Prescott Hall, home of the Department of Chemical Engineering since 1971.

PLAYING LIKE A TEAM—INSIGHTS FROM OUR VISITING SPEAKERS

Each academic term the department hosts what has become a model research seminar series within the university, bringing in eight to 10 regional and national speakers. If you have been one of our speakers, you know that this will not be a day of rest for you. A full day of interaction with the students and faculty will be carefully planned and integrated with your seminar and, in the end, you will likely know who we are and we will know something about you. Consistently and almost universally, at the end of the day our guests tell us that the single most striking characteristic of our department is how the faculty clearly demonstrates collegiality, teamwork, and a sense of scholarly community.

This is a posture that we cultivate and strive to perfect. **Pedro Arce**, the department's chairperson, is a well-known educator, having developed several strategies for teaching and learning including "The Coach Model."^[1, 2] It is no coincidence that we view the department as a team. Arce mentors the junior faculty, gives them opportunity to grow as team members, listens to his players, is sensitive to the environment of the game and, in the end, lets his team play. Formally, one might call our management structure distributed and unoriginal.[†] Faculty empowerment is the factor that changes the equation.

Our faculty members represent the department and carry their own authority as well as the confidence of the chairper-

son and each other. Each faculty member is empowered to "play his/her position" and to "pass or shoot" when he or she sees the opportunity.

A team has many elements; not all are on the field. Our team has two additional individuals without whom the game could not be played: **Rebecca (Becky) Asher**, our departmental office coordinator, and **Perry Melton**, our laboratory and machine shop technician. While Asher is holding the department together by responding to the many requests of the faculty and day-to-day student needs, Melton is keeping the unit operations running and working with students to build equipment that they design, as well as helping the faculty and graduate students with research labs.

EDUCATIONAL OBJECTIVES—INSIGHTS FROM OUR CONSTITUENTS

As part of our recent Southern Association of Colleges and Schools (SACS) accreditation, Tennessee Tech has a newly established Quality Enhancement Program (QEP) and, accordingly, a QEP Committee.[‡] This committee surveyed the constituency of the university—our students, alumni, employers of our students, and the faculty—and found that unilaterally, "what really counts" are critical thinking skills and the ability to solve "real-world problems."^[3] When it came time to review our departmental Program Educational Objectives (PEOs) it was simple: We would integrate critical thinking and real-world problem solving in some way, and we would write PEOs that were timeless.

The result is our present statement of PEOs that are our driving force and motivation:

Within roughly five to seven years our graduate population will collectively exhibit the following traits:

- be critical thinkers
- be real-world problem solvers
- have continued their formal education
- be working at the frontiers in chemical engineering

In addition to real-world problem solving and critical thinking, we have chosen to explicitly call for the continuation of formal education and working at the frontiers in chemical engineering. These two objectives complete the characteristics of our program: an environment that empowers students to take responsibility for their own learning (lifelong learning) wherein research (the frontier) is highly integrated with, and pushes the boundaries of, undergraduate education—making it compatible and forming a continuum with graduate studies.

[†] Technically, the department uses a transformational-based managerial structure with a strong team-based component.

[‡] Several ChE faculty members have received seed grants from the University-wide effort to integrate critical thinking and real-world problem solving activities across campus.

THE FACULTY—INSIGHTS FROM OUR AMBIDEXTROUS SCHOLARS

If you ask any one of us what characterizes the departmental faculty best, we will tell you it is balance. We strive to create an effective balance between research and education so that students are exposed to an environment that maximizes their learning, and we do it across the department as a pervasive way of being. Such balance between excellence in teaching and research is taken seriously, and our faculty members demonstrate this characteristic by being active and visible in both arenas—endeavoring to integrate research and education in unique ways and to create new paradigms for student achievement. Professor **Donald Visco**, for example, has received both a Presidential Early Career Award for Scientists and Engineers (PECASE) for his research on solving inverse design problems, and the American Society for Engineering Education ChE Division's Ray W. Fahien Award for his vision and contribution to chemical engineering education.

So, what are the characteristics that lead to a balanced faculty member? The answer, apparently, is that many boundary conditions can lead to similar outcomes.

Chairperson and Professor Pedro Arce was born in Argentina and received his undergraduate education in his homeland's practice-oriented engineering system at the Universidad Nacional del Litoral (Santa Fe). He started his transformation as a member of the prestigious National Council of Research (CONICET) at one of the leading research and development institutes (INTEC) of Argentina before coming to the United States in 1983. Arce's transformation was completed by the great research and education scholars at Purdue University, fusing—as his mentors have—the desire to achieve the perfect balance between the two ideologies.

Professor Biernacki is the undergraduate product of

Case Western Reserve University's research-driven program of the late '70s and the more applied Doctor of Engineering (DRE) program at Cleveland State University. He has 15 years of industrial experience, yet retains a fundamental approach to his research and says that "Teaching is a performance, and I simply love the audience, the stage, and the script."

Assistant Professor **Ileana Carpen**, who is finishing up her third year at Tennessee Tech, represents a great milestone for the department. With a B.S. from Stanford, a Ph.D. from Caltech, and a post-doctoral appointment at the University of Twente, this faculty member demonstrates that it is possible to recruit the finest academically trained individuals into our program because it places an equal emphasis on both education and scholarly research.

Assistant Professor **Holly Stretz** is the rarest of all—a high school teacher turned Ph.D. chemical engineer. Stretz has a

TABLE 1
Various Awards and Honors of the Faculty

| Educational Scholarship and Related Service | |
|---|--|
| 2008 | Outstanding Teaching Award, ASEE Southeastern Section |
| 2008, 2007 | Outstanding Faculty Award for Teaching, Tennessee Tech |
| 2008, 2007, 2006 | Tennessee Tech College of Engineering Brown-Henderson Award, for outstanding Engineering faculty |
| 2008, ^[1] 2006 ^[12] | ASEE, Southeast Section, Thomas C. Evans Award, for best paper |
| 2007 | Outstanding Campus Representative, Zone 2, ASEE |
| 2007 | Outstanding Campus Representative ASEE Southeastern Section |
| 2006 ^[12] | ASEE Corcoran Award, for best paper |
| 2006 | Quality Enhancement Program Award for Innovative Instruction, Tennessee Tech |
| 2006 ^[13] | Annals of Research in Engineering Education, invited feature article |
| 2006 | Ray E. Fahien Award, ASEE |
| 2004 | Outstanding Campus Representative, 2nd Place, ASEE Southeastern Section |
| 2001 | ASEE Membership Award, ASEE Southeastern Section |
| Research Scholarship and Related Service | |
| 2007 | Distinguished Faculty Fellow, Tennessee Tech |
| 2007 | American Concrete Institute (ACI), Fellow |
| 2007 | ACerS (American Ceramic Society) Profiles in Excellence |
| 2007 | Oronzio De Nora Postdoctoral Fellowship, The Electrochemical Society |
| 2006 | Invited Visiting Professor, University of Wollongong, Australia |
| 2006 | Oronzio De Nora Young Author Award, International Society of Electrochemistry |
| 2006, 2005, 2002 | Leighton E. Sissom Innovation and Creativity Award, Tennessee Tech |
| 2006, 2005 | College of Engineering Dean's Advisory Board Award for Excellence |
| 2005 | New Faculty Research Award (1st Place), ASEE Southeastern Section |
| 2004 | Presidential Early Career Award for Scientists and Engineers, DOE |
| 2004 | NNSA DOE-DP Early Career Scientist and Engineer Award, DOE |
| 2003 | New Faculty Research Award (2nd Place), ASEE Southeastern Section |
| 2003 | Outstanding Faculty Award for Professional Service, Tennessee Tech |
| 2002 ^[14] | Sigma Xi Research Award, Tennessee Tech |
| 2002, ^[15] 2000 ^[16] | Kinslow Engineering Research Award, for best paper, Tennessee Tech |



The faculty and staff of the Department of Chemical Engineering, from left to right, front row: Ileana Carpen, Rebecca Asher, and Holly Stretz; back row: Don Visco, Vijay Boovaragavan, Perry Melton, Venkat Subramanian, Pedro Arce, Joe Biernacki, and Mario Oyanader.

B.S. degree in chemistry from Texas A&M, worked in the polymers and semiconductor industries for five years, taught high school in the public school system, and studied in the world-renowned research laboratories of Don Paul^[4] at the University of Texas, Austin.

Associate Professor **Venkat Subramanian** came to the United States with an undergraduate degree from India's distinguished Central Electrochemical Research Institute, to join Ralph White's group at the University of South Carolina. Subramanian merges his passion for applied mathematics with electrochemistry and likely has one of the most productive research groups on campus. He is presently digesting his work into a text for undergraduate and graduate students.

Professor Visco, mentioned previously, studied at the University at Buffalo, State University of New York. He tutored as an undergraduate student, an experience that he reports would ultimately shape his career. Visco had an extended industrial internship, served in the U.S. Navy, and is now recognized as one of the nation's finest young researchers in the field of inverse design, yet found time to be the department's undergraduate program coordinator for the past four years—weaving the fabric of our curriculum and creating new and exciting opportunities in undergraduate chemical and biomolecular engineering.

The department is also home to two other faculty members. Adjunct Assistant Professor **Mario Oyanader** (originally from Chile) is both an outstanding researcher and rising young educator. Trained in Arce's own group at Florida State University (where Arce taught prior to becoming our chair), Oyanader has the characteristics of both a scholar and an educator who is "all about critical thinking." He is leading the renaissance effort in process design and helping to re-cast the Unit Operations Laboratory role within the new integrated curriculum. Research Assistant Professor **Vijayasekaran (Vijay) Boovaragavan** joined Subramanian's group as a

post-doctoral researcher and was recently hired to his current position. He received two international competitive distinctions for his research while at Tennessee Tech and presently co-teaches our Operations course.

The ChE Department at Tennessee Tech offers another answer to the old question, "Research or education?" Scholarship in both is achievable, although a balance must be accepted. Collectively, the Tennessee Tech chemical engineering faculty have earned 35 awards and distinctions since 2000 (see Table 1). Many of these are top Tennessee Tech honors, others are national recognitions, and yet others are international distinctions—the sum of which paint a picture of balance, combining elements of research scholarship and excellence in education. This does not happen by chance; emphasis must be placed on maintaining a rational balance. Furthermore, our experience is that an undergraduate program's excellence is enhanced by strengthening the graduate program. The adage "one cannot have a strong graduate program if too much attention is paid to undergraduate education" is simply contrary to the Tennessee Tech experience.

STUDENT-CENTERED LEARNING—INSIGHTS FROM HOW OUR STUDENTS LEARN

It is well accepted that students learn best by doing,^[5] and while there are a range of learning styles, most education researchers would agree that active participation is key to retention and ultimate internalization of learned information.^[6] Furthermore, most would also agree that educators must relinquish their tradition of teacher-centered control and place control in the hands of the students who must be empowered to learn,^[7] *i.e.*, we must provide student-centered learning environments.^[8] These pedagogical principles guide the many changes that we are presently implementing across the curriculum.

Active learning is one of several guiding principles being

The 2005 National Champion AIChE Chem-E-Car Team from Tennessee Tech, from left to right: Jonathan Phillips, Braxton Sluder, Jason Miller, Regan Chandler, Robert Phillips, Jennifer Pascal, and Haley Hunter.

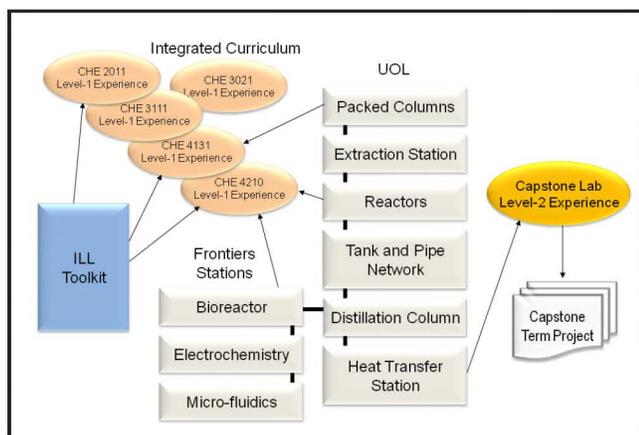


Figure 1. The integrated lab-lecture (ILL) concept.

advocated at Tennessee Tech on a universitywide basis. The Department of Chemical Engineering, however, has adopted active and collaborative (team-based) learning at large, and all of us are using some form of these approaches in our classes. The most ambitious of these efforts is growing out of our laboratory-and-lecture integration initiative. Our departmental founders established and passed on what we refer to as a “laboratory-oriented tradition.” Four laboratory courses, totaling five credit hours, were required up until 2006 when the one-hour sophomore lab, the two-hour junior lab, and the one-hour first-semester senior lab were integrated with lecture courses across the curriculum. The remaining one-hour, second-semester senior lab was preserved for what is now called Capstone Lab. This bold move was met with some skepticism when first introduced; however, the extraordinary effort of the faculty to embrace this initiative has shaped and defined this concept in unexpected ways.

Motivated by the observation that students are unable to independently synthesize theory, computation practices, and the “real world,” Biernacki proposed to adopt the lab-integration concept across the entire ChE curriculum in 2005.[§]

Having pioneered small-scale labs and demonstrations as a regular part of some of their courses already (*e.g.*, courses on momentum and heat transfer, reaction engineering, thermodynamics, and process controls), the faculty team agreed that it could be done on a larger, curriculumwide scale. Thanks to the energetic leadership of Undergraduate Program Coordinator (2003–2008) Visco, official integrated labs are now part of six courses: Introduction to Mass Balances, all three transfer science courses, Chemical Kinetics, and Solution Thermodynamics/Separations. Newly named Curriculum Coordinator Stretz is working diligently with Oyanader and other faculty to re-create the role of the unit operations laboratory (UOL) within the new curriculum. Figure 1 illustrates the concept. Here, Level 1 experiences are related to our integrated labs. These integrated activities draw from a variety of physical resources including a growing lab tool-kit, the existing UOL, and New Frontiers chemical engineering stations. By the time students reach the Capstone experience (Level 2), they have numerous examples of how theory, computation, and observation (experimentation) work together, thus they are prepared to transition to a more independent, open-ended capstone experience.

One final note is that the integrated lab and lecture is not intended to be a course with a lab section (*i.e.*, a lecture with a lab). The single most important outcome of the lab-lecture integration is to break down the barriers between theory, computational practices, and the real-world. In Arce’s view,^[7] “Traditional lectures give way to integrated environments with a seamless transition from class to lab where the student is in the learning driver’s seat.” The approach effectively uses these three key elements of engineering education (classroom, simulation, and lab activities) to create a continuum that is seamlessly woven together, each providing input for validation of the other, and all working together. Certainly, some individuals are gifted experimentalists and others, theoreticians, yet the broader general education of the undergradu-

ate must include a continuum that explores the relationship between concepts (theory), calculations (the computer), and the behavior of real things (the real world).

THE STUDENT CONTINUUM, RESEARCH AND EDUCATION—INSIGHTS FROM LESSONS IN SCALING

Arce was recently a recipient of the 2008 ASEE-SE Section's Thomas C. Evans Award for best paper published in engineering education during 2007. Arce is the only three-time winner of this prestigious award, this time sharing the honor with two co-authors, departmental adjunct faculty member Mario Oyanader, and Steven Whitaker of University of California at Davis, for their paper entitled, "The Catalytic Pellet: A Rich Prototype for Up-Scaling."⁹ In this paper, Arce, Oyanader, and Whitaker explain that the traditional chemical engineering curriculum and, for that matter, the traditional engineering curriculum, attempts to teach design—a study in scaling, if you will—in the final year of the program, thus creating a sort of "step function" in design content of the traditional curriculum. This approach effectively expects that students will synthesize everything they have learned in the past three years during two semesters, thereby transforming them into "engineers." This approach, the paper argues, has a long history but is fundamentally flawed. Many have advocated "design across the curriculum," and similar programs, with some success. The paper's concept is to *exploit* distributed laboratory courses and use real-world activities (e.g., the experimental prototype^{7, 10}), thereby introducing concepts of scale and effectively "scaling up" the knowledge of students as they move through the curriculum—instead of trying to accomplish the same all in one year. The approach introduces a progressive type of curriculum that will require new didactic materials (e.g., textbooks, simulations) and a new vertical integration of the curriculum that, for Transport Phenomena, is already in place at Tennessee Tech.

We take the concept even further in the department and, in fact, view the student body, both graduate students and undergraduates, as a continuum in the lifelong-learning process. Barriers among student groups—juniors, seniors, master's degree-seeking graduate students, Ph.D.-seeking students, etc.—are considered obstacles to learning, growth, and scholarly productivity. While there are a number of effective tools that can be used to unify the student body, we feel that research is by far the most productive and learning-rich vehicle. Research not only promotes critical thinking and facilitates learning development, it also promotes the idea of a community of learners among undergraduates, graduates, postdoctoral students, and faculty. Although not every undergraduate will engage (formally) in research, we feel that research activities should be a ubiquitous "fluid" that permeates every classroom/lab and catalyzes as many elements of the curriculum as possible, facilitating student learning and

critical thinking. To this end we have initiated a number of integrating elements to our curriculum, and we advocate that students engage in them along with university-led research activities.

While there are numerous aspects of the program that emphasize integration, several merit special mention in addition to the lab-lecture integration:

- 1) *the Distinction in the Major (DITM) option, a formalized and intensive undergraduate research track that leads to a written and oral thesis defense;*
- 2) *the Research Seminar Series,¹¹ briefly mentioned above;*
- 3) *the Chemical Engineering Graduate Research Association (CEGRA), a student-governed organization that serves the needs of the graduate student body.*

We feel these aspects are critical to the departmental success. In combination with pedagogy that empowers students to take charge of their own learning, we hope these aspects will create a culture of scholarship emphasizing critical thinking, problem solving, lifelong learning, and extending the frontiers of knowledge. Our faculty, although relatively small compared to others in the Southeast, is able to offer Tennessee Tech's students a cross-section of frontier areas in which to work. Arce and Oyanader are interested in electric field-based processing, e.g., electrokinetic hydrodynamics, corona discharge processing. Biernacki's main research focus is experimental reaction kinetics, most recently emphasizing portland cement-based materials. Carpen's interests focus on complex fluids (the rheology of colloidal suspensions and polymer composites) and on biomedical systems (tumor growth and tissue engineering). Stretz's efforts focus on the experimental characterization of nano-particle polymer composite behavior, and nano-particle ordering and high temperature behavior of similar materials. Subramanian's computational research brings together electrochemistry, complex transport modeling, applied mathematics, and computer programming for the development of ultra-efficient algorithms for real-time batteries and fuel cell performance prediction, system optimization, and control. Subramanian is joined by Boovaragavan, who is presently funded by a prestigious international grant award from the The Electrochemical Society. Finally, Visco's work involves a spectrum of computational thermochemistry and molecular design initiatives as well as laboratory research on phase equilibrium. Collectively the faculty are or have been funded by numerous government and private-sector organizations working closely with Tennessee Tech's three state-funded research centers, and have many ongoing or prior research collaborations. Such collaborations enhance opportunities for our students and faculty to work with leading scholars amid some of the finest research

§ *The concept parallels the "High Performance Learning Environment (HiPeLE)" developed by Arce and collaborators, 2004, CEE.*

infrastructure in the world.

The outcomes are remarkable. In the last five years our undergraduates have amassed top honors in numerous competitions:

- *Our Chem-E-Car team has consistently been in the top tier and has pioneered first-of-a-kind competition vehicles, having established the current national record and first place at the national competition in 2005 and second at the AIChE Southeast Regional Meeting this year (2008) with one of the first Bio-Cars to be entered in the competition.*
- *Collectively, our students have received top paper and poster awards at regional and national competitions.*
- *In 2006, Jennifer Pascal (one of our first DITM graduates and a current Ph.D. student) received the AIChE Othmer Award, and Hope Sedrick was selected as one of 10 students to receive a NIST SURF internship.*

Recent graduate students have performed similarly well.

- *Ph.D. student Vinten Diwakar received The Electrochemical Society's Industrial Electrolysis and Electrochemical Engineering Division Student Achievement award in 2006 for his research on battery and fuel cell modeling, (Subramanian, his Ph.D. advisor, was also a recipient of this prestigious award as a student).*
- *Ph.D. student Pravin Kanan was selected for the BASF International Summer Course in Bohn, Germany, in recognition of his research on polystyrene foam thermal decomposition.*
- *Master's student John M. Richardson received an NSF Graduate Research Fellowship in 2002 for his research on nano-pore structure of hydrated portland cement, a first for Tennessee Tech.*
- *In addition, our B.S. and M.S. graduates are being hired by leading companies. Recent Ph.D. graduate Dr. Baburao was highly sought by design companies and Dr. Swaminathan is currently a post-doctoral research associate at the Technical University of Denmark.*

The list of similar awards and achievements is long, but these illustrate the excitement and success among our students and, we believe, the result that is achievable with a program that focuses on scholarship in both education and research through integration rather than separation.

ABOUT TOMORROW—INSIGHTS FROM OUR VISION OF THE FUTURE

It seems appropriate to dream and to speculate just a bit at this point in the department's story. We recently revised our vision statement as well as our PEOs, and after considerable debate over two words—"will be"—we were convinced by our Board of Advisors to phrase our vision statement in the present tense and to use the word "is." Thus, our official Vision now reads as follows:

The Department of Chemical Engineering is a recognized leader in chemical engineering education through excellence in teaching, research, and service.

This statement "is" a vision of the future for us—simple, yet a bold supposition that we believe "will be." The path from here to there for us is clear: (1) continue to respect and build upon the foundations of our legacy; (2) develop and grow a faculty that "plays like a team;" (3) have clearly stated educational objectives that are simple and timeless; (4) maintain a balance between research scholarship and education, and strive to excel in both; (5) fervently maintain a student-centered learning environment; and (6) integrate the student body, integrate research with education, and do not let "size effects" influence the *scale* of our productivity.

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“FINGER KITS:”

An Interactive Demonstration of Biomaterials and Engineering for Elementary School Students

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From personal computers to cell phones, there is no dispute that technology developed by scientists and engineers greatly influences the lives of U.S. residents. Despite the increasingly important influence that science and engineering have on our lives, however, the numbers of undergraduate and graduate degrees awarded in these areas to U.S. students have decreased steadily for the past several decades.^[1] In addition, the numbers of women and minorities in this field remain low compared to our nation's demographics (e.g., New Mexico is now a minority-majority state).^[2] For these reasons, many efforts have emerged with the goal of attracting students into engineering and science disciplines, including outreach efforts such as those sponsored by the National Science Foundation.

The authors of the present work include researchers from both the University of New Mexico (UNM) and the University of Washington (UW). The technical expertise of the authors is in the field of biomaterials, or the interaction of man-made materials with biological systems. The term “biomaterials,” therefore, encompasses a number of research interests including microbially induced corrosion of ship hulls, the development of DNA microarrays, and the optimization of materials used for biological implants. While it is unlikely students in the fifth grade (the target audience of the following demonstration) are familiar with DNA microarrays,

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many have already been exposed to implanted materials, as they or members of their families may have contact lenses, use a glucose monitor for their diabetes, or have hip or other implants. Therefore, giving students a project that emphasizes biomaterials taps into something with which they already may be familiar and that is becoming increasingly important in the lives of millions of people around the world. As noted by Tobias,^[3] tying science to societal issues via cooperative and interactive learning styles may increase participation by women and other under-represented minorities in science and engineering. Furthermore, as more people are going to be affected by biomaterials, there will be more opportunities for exciting, rewarding jobs in the field of biomaterials. It has been estimated that by the end of this decade, there will have been more than a 30% increase in bioengineering-related employment positions.^[4]

To capture part of this excitement, we present a real-world problem to the student: Someone has an injured finger joint, and the students in the class need to design an implant to replace it. After presenting the problem, we discuss how the students could go about making a replacement finger joint. In order to do this, the students need to understand what comprises a finger. Next, the students have to consider what materials are available that match the properties of the components in a finger. As this is an engineering project, we ask students to develop design goals for the finger (*e.g.*, that it is flexible, bends only in one direction, is able to pick up an object).

At UNM, we made a number of adaptations to the original design. For instance, to better communicate with the bilingual and monolingual (Spanish-only speaking) students within the Albuquerque Public School (APS) district, we translated the text used in our brief presentation into Spanish and recruited Spanish-speaking volunteers. Furthermore, our participating volunteers are typically a combination of undergraduates, graduate students, postdocs and faculty to show representatives of women and minorities that have gone on to successful engineering careers. This hands-on activity engages the students' creativity while also teaching them a basic understanding about what biomaterials are and how one would go about designing and building them.

BEFORE THE VISIT

Prior to any outreach events, the following should be addressed: 1) provisions of key ideas and vocabulary necessary to understand the les-

son, 2) assembly of kits, and 3) training of volunteers.

Vocabulary

To achieve the first task, our outreach coordinator (co-author Stanton), when scheduling outreach visits, provides teachers and principals with vocabulary words and concepts necessary to understand the lesson. Table 1 presents the key vocabulary that the outreach director (co-author Canavan) and elementary school teacher (co-author López) discussed prior to the first UNM visit to López's classroom. These vocabulary words are also defined early in the interactive talk portion of the visit to reinforce these concepts before more difficult matter is discussed. In addition, each of the visits is scheduled such that it follows instruction on the human body. Table 2 identifies the parts of the body especially important when considering restoring the function of the finger joint. While this is not a comprehensive list (*e.g.*, fingernail is not listed), these are the body parts that make primary contributions to the function of the joint, which is the focus of the lesson. For example, it is the contraction and expansion of the muscles that lead to joint movement, and bone which provides structural support.

Assembly of Kits—Materials

Table 3 lists the contents to be included in each kit. No additional supplies are required to perform this activity. For each of the suggested materials (*e.g.*, chalk), a potential use in the finger kit design is listed (*e.g.*, bone). Therefore, each of the materials listed in Table 3 should approximate those of the human body listed in Table 2. It is important to note that we provide this list to aid volunteers using this demonstration, but we do not provide it to the students themselves. Also, we often see students find creative uses for the materials provided that we had not initially envisioned (*e.g.*, the use

| Vocabulary word | Definition |
|-----------------|---|
| Biology | The study of living organisms. |
| Engineer (noun) | A person who designs, builds, or maintains engines or machines. |
| Implant | A tissue or an artificial object in a person's body introduced by surgery. |
| Material | The substance of which a thing is made, such as wood, glass, or metal. |
| Prosthetic | An artificial body part, such as a leg or a heart. May be internal or external. |

| Part of the Finger | Function |
|--------------------|--|
| Arteries and veins | Blood flow |
| Bone | Structural support, mechanical strength |
| Muscles | Contract and extend to move joints |
| Nerves | Sensation of heat/cold, movement of body via attachment to muscles |
| Skin | External surface of body |
| Tendons | Attach muscles to bone |

of a paperclip as a fingernail to make the finger aesthetically more pleasing, instead of as a structural element to hold the design together). Although most of the parts can be re-used (e.g., pipe cleaners, straw, etc.) and the kits recycled through many events, at UNM each kit is used only once, and the students retain possession of their designs. Therefore, to maximize the number of students we can interact with over a year, the materials used in the finger kits are low-cost items that can be purchased in bulk (e.g., Popsicle sticks vs. tongue depressors). We estimated that, when the contents of the kits are purchased in bulk (e.g., to make 400 kits), the cost of the

kits fall to ~\$1/student.

Training of volunteers

It is advisable to train all volunteers prior to the outreach “season” so they understand what to expect from the events. In particular, the volunteers should understand how the materials in the kit can be used in designs. Such an event will also yield a number of diverse designs (as illustrated in Figure 1), demonstrating to the volunteers that they may see many different ways the materials will be used by the elementary school students. Also, the volunteers should be briefed about what to expect from a visit to an elementary school, including any necessary information about the school’s dress code. If possible, the teachers participating in outreach visits should be invited to speak with the volunteers about the general level of knowledge and understanding, as well as modes of learning, that young students demonstrate.

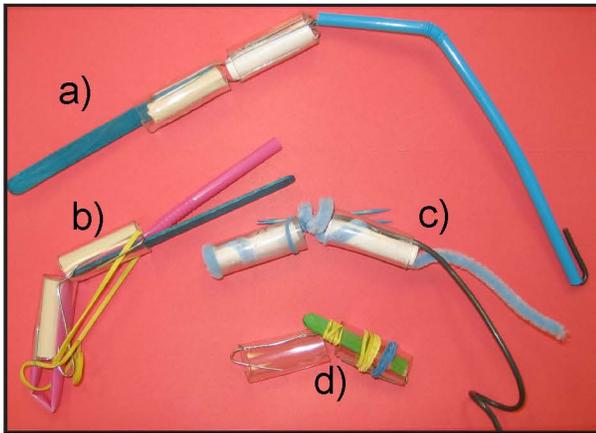


Figure 1. Examples of finished finger designs. Note that the resulting design will reflect the design considerations agreed to by the students at the beginning of class, as well as their own individual preferences. For example, design a) uses a Popsicle stick as a fingernail, while design d) uses it as a brace to prevent backward movement.

DURING THE VISIT

The outreach visit contains several elements: 1) a brief presentation outlining the topic and project (~15-20 minutes); 2) discussion and formulation of the design and test parameters (~2-5 minutes); 3) fabrication of the designs by the students (~30 minutes); and 4) evaluation of the design according to the parameters previously outlined (~10 minutes). In addition, a fifth step (evaluation of the efficacy of the visits) may be conducted after the visits to allow for any modifications or improvements to be made as needed.

Introductory Talk

At the beginning of the visit, the lead volunteer will give a brief talk^[5] to introduce the range of topics in bioengineer-

TABLE 3

Contents of the Finger Kit. Note that all materials are meant to be commonly commercially available and of low cost. Substitutions, deletions, and additions to the kit may be made to accommodate the preferences of the demonstrators, as well as the availability of material.

| Qty | Item | Potential Use in Finger Design |
|-----|---|---|
| 1 | Zip-close sandwich bag | None (used to contain other parts listed below) |
| 3 | Pieces of clear, flexible tubing: pieces ~1.5” long and wide enough for dowel pieces/chalk to slip into | “Skin” that holds all parts together |
| 1 | Tongue depressor/Popsicle stick | “Brace” to prevent fingers from bending backwards |
| 4 | Toothpicks | “Brace” to prevent fingers from bending backwards/sideways |
| 1 | Pipe cleaner | Actuator (muscle/tendon) or body part (blood vessel/nerve) |
| 1 | Piece of copper wire 10” long (~24 gauge) | Actuator (muscle/tendon) or body part (blood vessel/nerve) (muscle/tendon) or body part (blood vessel/nerve) |
| 1 | Flexible straw | Actuator (muscle/tendon) or body part (blood vessel/nerve) |
| 4 | Rubber bands | Actuator (muscle/tendon), body part (blood vessel/nerve), or to hold design together (tendons) |
| 3 | Wooden dowels, ~1.5” long x 0.25” diameter | Bones |
| 3 | Half-pieces of chalk | Bones |
| 2 | Small paper clips | To hold design together (tendons) or body part (fingernail) |
| 2 | Large paper clips | To hold design together (tendons) or body part (fingernail) |

ing, including examples of biochemical engineering (e.g., pharmaceuticals and dialysis), biomechanics (e.g., grafting procedures, prosthetics, and implants), and biomaterials (e.g., contact lenses). These subjects, which were first introduced to the students using the vocabulary list (see Table 1), are used to lay the groundwork for the design students will be performing. Therefore, it is imperative they understand what the terms mean. It is important to remember that most fifth-grade students are (at best) unfamiliar with even the most basic language traditionally used in bioengineering, and often hold erroneous beliefs (such that the term “engineer” solely applies to people who repair car engines).

We have found that the best way to engage the students’ attention and get these concepts across is to make the talk highly interactive, with the lead volunteer asking the students questions and listening to their responses. For instance, the students become quite animated when asked: “Do you know anyone who has contact lenses or hearing aids?” Such questions solidify ideas in the students’ minds, as they are able to make connections between the new material and something they are already familiar with. In fact, according to elementary school teacher and co-author López, the most important factor for a successful demonstration is to pay attention to cues from the students to determine if they are understanding the material, and therefore connecting bioengineering to their lives.

Later in the talk, the materials used in biomaterials are discussed. In particular, there is significant emphasis placed on how the properties of a material are used to match a specific function. For instance, metal implants are often used in bone replacements (due to their mechanical strength), whereas flexible rubber would not be a suitable replacement. Also, the idea that a design may be perfected over time (such as the early use of ear trumpets prior to the invention of a hearing aid) can show students that rarely is a design “perfect” from its first prototype.

Finally, we use the talk as a chance to educate the students about the career path that bioengineers take, from their current position to college and graduate school. Many of our participating volunteers are from the local community (20% of UNM volunteers attended APS as students, and 78% of APS participants attended APS as students). As importantly, many volunteers are members of groups traditionally underrepresented in science and engineering (45% are women, and 50% identify themselves as Latino, Hispanic, or Chicano) and are Spanish speakers (35%).

Formulate Design and Test Parameters

At the conclusion of the talk, the students are told they will not have to wait until college or graduate school to start their research career, and that they will be “bioengineers for a day.” The students are told they will design a replacement finger and will test their designs according to parameters they agree upon. This leads to a discussion to elicit design goals from

the students themselves. For instance, the volunteers may ask, “What do fingers do?” [They bend.] “Could you play the piano/push a doorbell if your fingers ‘bent’ in all directions?” [No, your finger would just bend backwards if you pressed on the keys/buzzer.] “Can you be more specific about how they should bend?” [In one direction only.] “What could you do to allow them to bend, but in just one direction?” [This is where students tend to start equating the materials to what actually makes up their fingers.] We have found that asking the students to come up with their own rubric for a good design is far more engaging than providing these parameters directly. In addition, this method requires higher-order thinking skills and often causes a great deal of excitement among the students. Figure 2 shows a page from a student’s notebook that lists the design considerations students agreed a finger should have, as well as the parts of the body that should be included (mitriols [*sic*]).

Fabrication of the Designs

Once the design parameters have been agreed upon, the volunteers distribute the kits to the students, and fabrication of the designs begins. During this portion of the visit, the volunteers and teacher should circulate among the students. While we discourage the volunteers from telling the students how to make the design, they can provide guidance, reminding students about the parameters (e.g., if the finger bends, but does so in many directions, it hasn’t been optimized). If students are stumped, the volunteers can help provide prompts to get the students working on their designs. For instance,

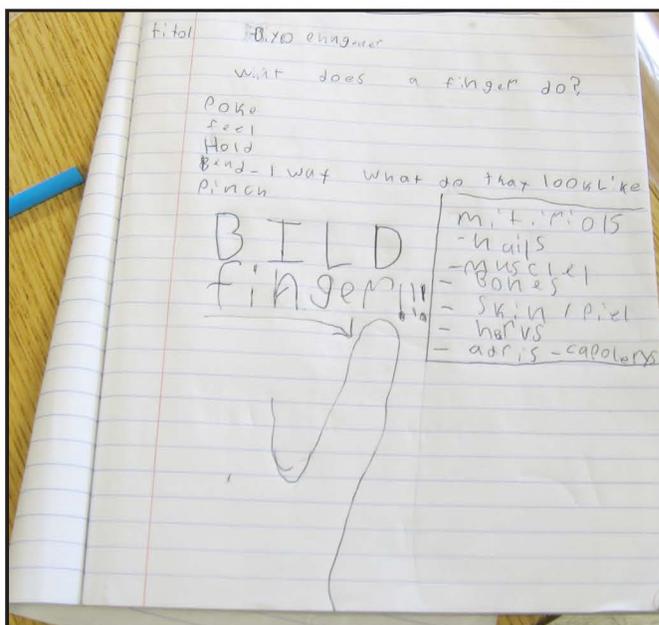


Figure 2. Page from a student’s notebook at Longfellow Elementary. The student has listed the design considerations the students agreed a finger should do, as well as the parts of the body that should be included (materials). She has also illustrated her own finger for the design.

the volunteers can ask: “What body parts are in a finger? [Bone.] Is there anything in this kit that reminds you of that part? [Chalk or wooden dowel.] This also gives the students a chance to interact with their potential role models and ask them questions about themselves while they work on the designs. Furthermore, this gives the volunteers a chance to stress the creative aspects of science and engineering. In addition, the students often begin to observe the designs used by others to overcome a particular challenge (e.g., the use of toothpicks

as “braces” to prevent their design from bending backward) and incorporate it into their own. Such peer mentoring is a natural occurrence in this environment. Figure 3 illustrates each of these modes of learning during a visit from the UNM Biomaterials Engineering Outreach Program to Longfellow Elementary School.

Evaluation of the Design

At the end of the visit (or in a post-visit session with their teacher), students evaluate their designs according to the parameters to which they previously agreed. Table 4 is an example of a rubric designed by the students in co-author López’s fifth-grade class, including the design parameters (or criterion) considered important by the students, as well as their standards for the design. For example, the students considered the ability to hold something up as an important criterion, and a design that is capable of holding up a pencil in the middle section of the finger may be considered an advanced design. Often, the students come up with new designs or improvements not initially listed as criteria in the rubric. For instance, some students will attempt to improve the aesthetics of the design by including a paperclip as a fingernail. The volunteers and teacher may then remind students that many designs are improved over time for aesthetic reasons (e.g., less noticeable dental fillings and hearing aids).



Figure 3. Examples of the different modes of learning during a visit to fifth-grade students at Longfellow Elementary School (Albuquerque, NM). UNM volunteers circulate throughout the classroom giving guidance and providing translation into Spanish, where necessary (a); students often teach each other lessons learned from their designs, a classic example of peer learning (b); a student consults the hand of a skeleton to determine the parts of the finger (c); the students’ teacher reminds the fifth-grade bioengineers that one criterion of their design is that it must bend (d).

AFTER THE VISIT

The design evaluation is considered the final stage of the formal visit, and the students are allowed to keep their designs. As well, some teachers may want to display the top designs or keep them for follow-up. In most cases, students from the classrooms we visited sent “thank you” letters to the demonstrators, relating what they learned, how much they enjoyed

| Criterion | Emergent (1) | Nearing proficient (2) | Proficient (3) | Advanced (4) |
|------------------------------------|--|---|---|---|
| Moves like a finger. | Doesn’t move. | Moves somewhat, but in too many directions that are not appropriate. | Moves forward. | Moves forward, not backwards. Does not move to side; only the whole finger can move side to side. Has two places where it can bend. |
| Has components of a finger. | Has components that don’t function like a finger. Components are not in the right place. | Has only two components: possibly bone and muscle or skin and bone. Components may not be in the right place. | Has bone, skin, muscles, and fingernail. Components are generally in the correct place. | Has bone, skin, muscle, fingernail, capillaries, nerves and other sensors. Components are in the correct place. |
| Holds something up (e.g., pencil). | Doesn’t hold it up at all. | Barely holds it up—falls quickly. | Holds up pencil. | Holds up pencil in the middle section of finger. |

...the hands-on “finger kit” demonstration addresses a number of benchmarks from the State of New Mexico^[6] as well as the Project 2061 Benchmarks for Science Literacy (from the American Association for the Advancement of Science, AAAS), after which many states have modeled their standards.^[7]

the visit, and their interest in science. The letters are always appreciated by the volunteers, and help reinforce the value of outreach activities to them. In addition, it is also a chance for the outreach organizers to get valuable feedback. For instance, due to the large number of students who mentioned in their letters how much they wanted to keep their designs (to show their parents or siblings, or to improve on the design), we at UNM now make kits for each student, rather than attempting to recycle them (as had been done previously).

EXPECTED IMPACT

As previously stated, one of the primary complaints that elementary school teachers have about outreach projects is that they are often considered stand-alone demonstrations with little thought to how they will be integrated into the regular curriculum. As it is described above, the hands-on “finger kit” demonstration addresses a number of benchmarks from the State of New Mexico^[6] as well as the Project 2061 Benchmarks for Science Literacy (from the American Association for the Advancement of Science, AAAS), after which many states have modeled their standards.^[7] The individual benchmarks pertaining to the fifth grade are outlined below.

NM Benchmarks Addressed

Strand I/Standard I/Benchmarks I & II (Scientific Thinking and Practice): By observing and experimenting on their model, and analyzing their product (using the rubric), the students learn to understand the scientific method. In addition, the students learn to communicate their findings during the class discussion at the end of the event, and learn that their conclusions are subject to peer review.

Strand II/Standard I/Benchmarks II & III (Physical Science): By addressing how the muscles of the finger work and discussing the energy source that makes fingers move, this project addresses the state benchmark pertaining to forces and motions. While studying the action of muscles and tendons on the finger joint, the students learn that when a force acts upon an object, it will move in a different direction.

Strand II/Standard II/Benchmark III (Life Science): By addressing the purposes of the finger joint (in relation to replacing that function using a prosthetic), the students learn the properties, structures, and processes of living things, and how cells and tissues are related to the behavior of an entire organism.

Strand III/Standard I/Benchmark I (Science and Society): With its emphasis on how machines have been engineered

to aid in human health (*e.g.*, glucose monitors, hearing aids, etc.), the introductory talk demonstrates to students how technology has affected the lives of individuals. Emphasizing how rudimentary prosthetics have evolved allows students to understand how scientific discoveries, inventions, practices, and knowledge are influenced by individuals and societies. Furthermore, in an integrated elementary curriculum, the progress of bioengineers could be connected to the effect on social issues.

AAAS Benchmarks Addressed

Benchmark 1B (The Nature of Science/Scientific Inquiry): Developing the rubric to evaluate their designs allows students to learn that scientific investigations may take many different forms, including observing what things are like or what is happening somewhere, collecting specimens for analysis, and doing experiments.

Benchmark 1C (The Nature of Science/The Scientific Enterprise): Discussing their results reinforces to students that clearly communicating their results is an essential part of doing science. Because the volunteers participating in this event are both men and women of many different ages and backgrounds, it is reinforced that people who perform scientific work come from all populations.

Benchmark 3A (The Nature of Technology/Technology and Science): As they learn to design replacement finger joints, students learn that technology extends the ability of people to change the world, often in response to the need to meet basic survival needs.

Benchmark 3B and C (The Nature of Technology/Design Constraints and Systems and Issues in Technology): While building their designs, the students rapidly grasp the need to match properties of materials and engineering principles while designing solutions to problems. Simultaneously, the students learn about design tradeoffs. For instance, the finger design with the best side-to-side stability may aesthetically be the least pleasing.

Benchmark 6C (The Human Organism/Basic Functions): As they learn how nerves stimulate the muscles in a joint to contract, the students learn how the human body functions as a system—with the brain giving signals to the body to stimulate movement.

Benchmark 8F (The Designed World/Health Technology): By learning about prosthetics and designing a replacement body part, students learn that technology has made it possible

to repair and sometimes replace some body parts.

Benchmark 11A (Common Themes/Systems): By learning about how the materials in their kits (and the parts of the body) work together as a system, students learn that the parts of a system influence each other and may not work well if they are broken, worn out, or misconnected. This is applicable to both their own creation as well as the body part it is meant to replace.

Benchmark 12C (Habits of Mind/Manipulation and Observation): By asking the students to relate the material properties of the objects in their kits (*e.g.*, chalk) to those in the human finger (*e.g.*, bone), the students learn to choose appropriate common materials for making simple mechanical constructions and repairing things.

CONCLUSIONS

This work describes one hands-on activity and demonstration developed at UW and further refined at UNM. The goal of the project is to provide a hands-on experience with an engineering project. While the project itself is goal-oriented, it is also creative and open-ended, with many possible solutions to the problem presented. In this way, the creativity involved in the project is emphasized, rather than only relying on science and math ability. In our experience, the demonstration works best when it is tailored to suit the needs of the community, and we recommend that anyone adopting this outreach demonstration take the time to do so with their own community. It is for these reasons that we at UNM chose to focus our activities on one grade level (5th grade) in one school system (APS). Furthermore, the specific needs of the community (*e.g.*, bilingual students in NM) should be addressed (*e.g.*, translation of the slides into Spanish). Finally, we chose simple, low-cost materials to maximize

the number of students that can be reached with the activity. Ultimately, we strove to develop a fun experience that will get students excited about career opportunities in science and engineering. After all, although not all students will ultimately pursue science and engineering-related careers, we feel that a general population more educated in the area of science and engineering is also a valuable pursuit.

ACKNOWLEDGMENTS

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The object of this column is to enhance our readers' collections of interesting and novel problems in chemical engineering. Problems of the type that can be used to motivate the student by presenting a particular principle in class, or in a new light, or that can be assigned as a novel home problem, are requested, as well as those that are more traditional in nature and that elucidate difficult concepts. Manuscripts should not exceed 14 double-spaced pages and should be accompanied by the originals of any figures or photographs. Please submit them to Professor James O. Wilkes (e-mail: wilkes@umich.edu), Chemical Engineering Department, University of Michigan, Ann Arbor, MI 48109-2136.

GEOHERMAL COGENERATION: ICELAND'S NESJAVELLIR POWER PLANT

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Energy use in Iceland (population 283,000) is higher per capita than in any other country in the world.^[1] Some 53.2% of the energy is geothermal, which supplies electricity as well as heated water to swimming pools, fish farms, snow melting, greenhouses, and space heating.

The Nesjavellir Power Plant is a major geothermal facility, supplying both electricity and heated water to Reykjavik. The purpose of this paper is to interest students in geothermal energy, describe a simulation of this plant, and determine the plant's suitability for classroom study.

PLANT DESCRIPTION

The plant (commissioned in 1998^[2]) is located near one of the largest high-temperature fields in Iceland.^[3]

Iceland's high-temperature fields are so rich in gas and minerals that the waters cannot be used directly in the distribution system.^[4] Its high pressure and thermal energy, however, makes it suitable for heating fresh water and generating electricity.

Ballzus, et. al.,^[2] provide a plant flow diagram (Figure 1) on which stream flows and temperatures are indicated. Where data is specified, the diagram is modified to include stream

names (e.g. {S1}, {S2}). In addition, the heat exchangers are labeled ({HX1}, {HX2}, {HX3}).

Steam mixed with water {S1} is conveyed from boreholes through collection pipes to the separation station, where the water is separated from the steam. Excess steam and unused water go into a steam exhaust outside the separation station. From the separation station, steam and water proceed by separate pipes to the power plant at a pressure of about 12 bara and a temperature of 190 °C. The steam (after passing through a mist eliminator) is conveyed to steam turbines, where electricity is generated. Each turbine (two of them) produce 30 MW of electricity (MWe).



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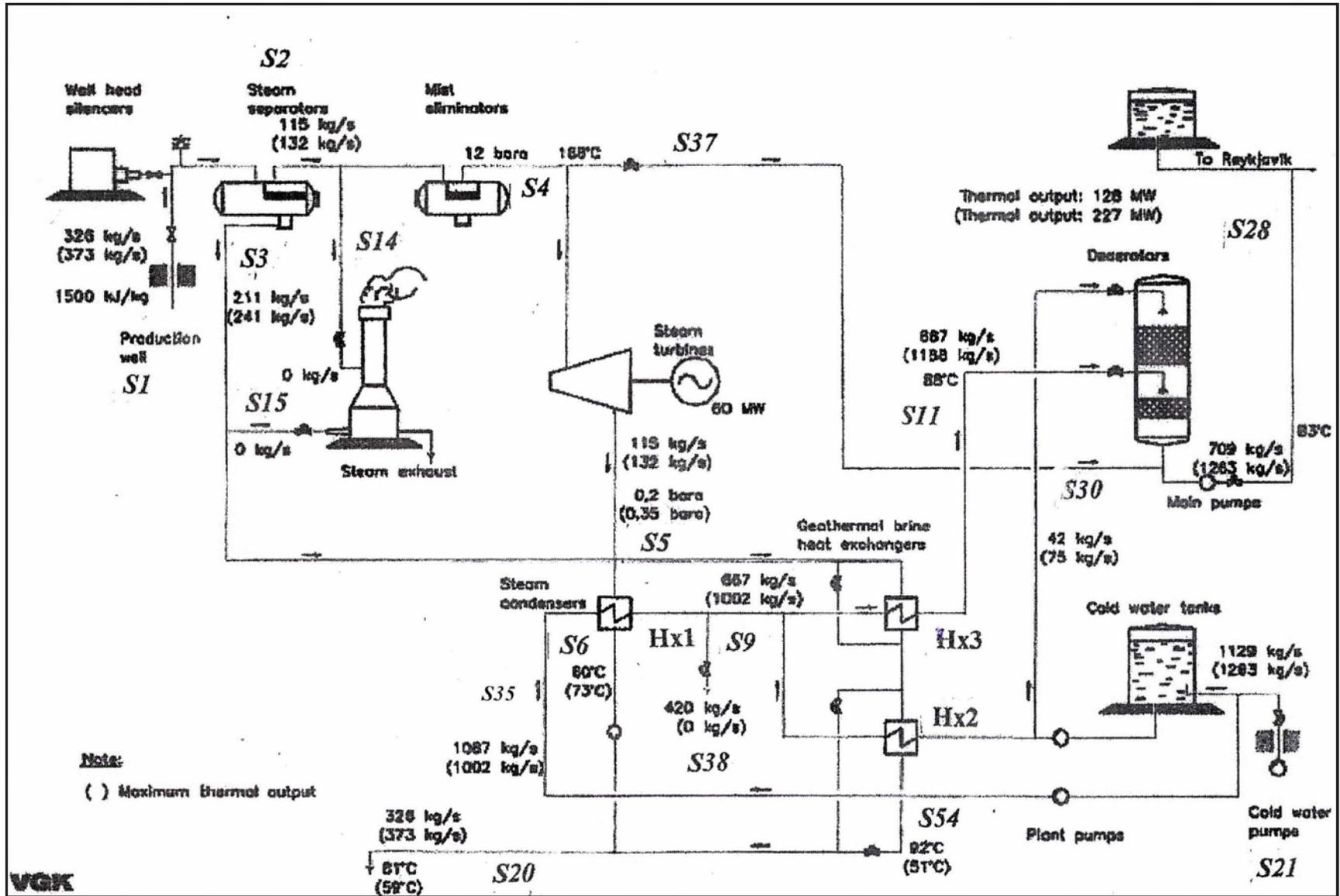


Figure 1. The Nesjavellir Geothermal Plant Process Flow Diagram (Adapted from Ballzus^[2]), placed vertically to preserve clarity.

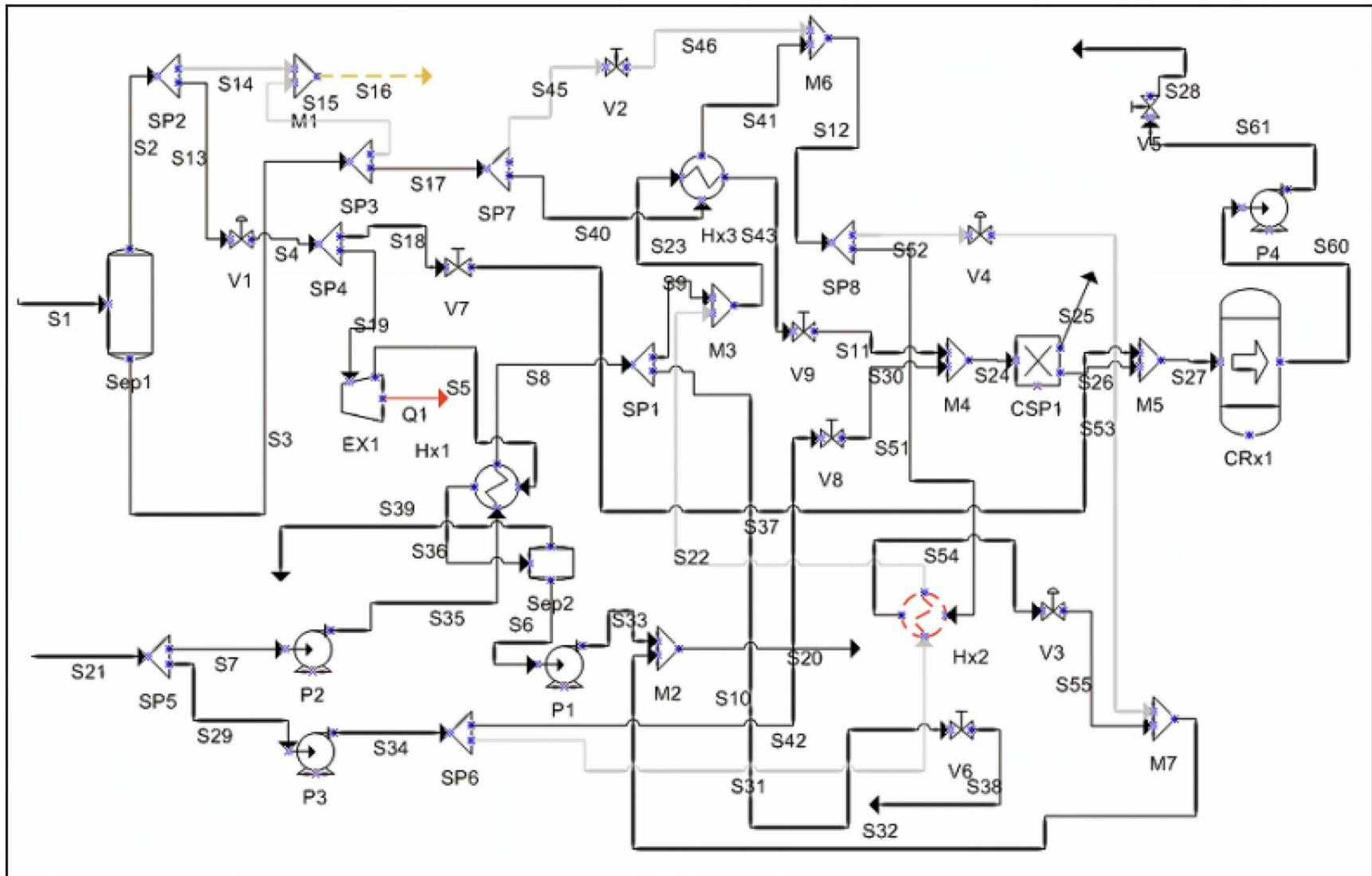


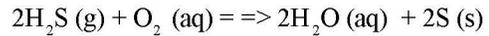
Figure 2. VMGSim Flowchart of Iceland's Nesjavellir Power Plant (placed vertically to preserve clarity).

In the condenser {HX1} the steam exhaust from the turbines is utilized to preheat cold water {S35}. This cold water is then further heated in the heat exchanger {HX3} by the separated geothermal fluid {S3}. (A second heat exchanger {HX2} can be utilized to preheat a portion of the cold water with the separated geothermal fluid from {HX3}. In this simulation, however, {HX2} is not utilized). Since the mineral-rich geothermal fluid causes scaling that coats the heat exchanger pipes, steel particles are allowed to circulate in the stream, impacting against the pipes to remove any scaling as it occurs.^[5]

The cold water {S21} is saturated with dissolved oxygen that corrodes steel after being heated. To rid of the oxygen, the water is sent to a vacuum deaerator.^[6] The main flow {S11} enters the central part of the deaerator. The water boils vigorously (due to a vacuum) and sprays over filling material. Steam and gas rise to the top. The steam is condensed through the injection of cold water {S30} before the gas is ejected.

Finally, a very small quantity of steam containing acid gases {S37} is mixed with the water to eliminate the last traces of dissolved oxygen and lower the pH of the water in order to

prevent precipitation in the distribution system. The following reaction takes place.^[7]



Small quantities of H₂S ensure the dissolved oxygen that could get into the storage tanks is eliminated. The H₂S also gives the water the “good smell” for which the water from the water supply system in Reykjavik is known today.

THE VMGSIM SYSTEM^[8]

The VMGSim system is a modern interactive process simulation system. One of the partners of VMG (Virtual Materials Group) founded Hyprotech and another created and wrote most of HYSIM. As a general policy, VMGSim is provided to universities free of charge when used for academic purposes.

The system uses Microsoft Visio for the graphical input engine. A menu is provided that allows the user to drag streams and unit operations onto a graphical screen to build a complex system. The system uses the interactive calculation principles of nonsequential unit operation calculations with partial data flow. It is considered to be the fastest approach developed for creating and evaluating process models. Equilibrium stream calculations are carried out as pressure-enthalpy flashes.

The physical property system has been carefully crafted and evaluated to allow the user to have confidence in it. A simple click of the mouse will allow the user to evaluate different physical properties for his/her simulation. Similarly, different units (SI, Field, etc) can be implemented with a simple click of the mouse. Custom models can be created using Excel (VBA).

| | |
|-------------------------|--------|
| Vapor Fraction | 0.3527 |
| Temperature (Deg C) | 189.2 |
| Pressure (kPa) | 1235 |
| Flow (kg/s) | 326 |
| Enthalpy (kJ/kg) | 1500 |
| Water (kg/s) | 325.56 |
| Hydrogen Sulfide (kg/s) | 0.1495 |
| Carbon Dioxide (kg/s) | 0.2875 |
| Oxygen (kg/s) | 0 |
| Sulfur (kg/s) | 0 |

| | |
|-------------------------|-----------------------|
| Vapor Fraction | 0 |
| Temperature (Deg C) | 5 |
| Pressure (kPa) | 101.33 |
| Flow (kg/s) | 1129 |
| Enthalpy (kJ/kg) | 21.1 |
| Water (kg/s) | 1128.985 |
| Hydrogen Sulfide (kg/s) | 0 |
| Carbon Dioxide (kg/s) | 9.889 ^{E-04} |
| Oxygen (kg/s) | 0.0144416 |
| Sulfur (kg/s) | 0 |

| Pump Pressure | | |
|------------------------|-----------------------------------|----------------------------------|
| | Specified Rise (Δ P - kPa) | Specified Efficiency % |
| P1 | 82.33 | 85 |
| P2 | 150 | 80 |
| P3 | 150 | 75 |
| P4 | 75 | 75 |
| Heat Exchangers | | |
| | Specified Drop Tube (ΔP - kPa) | Specified Drop Shell (ΔP-kPa) |
| HX1 | 30 | 1 |
| HX2 | 30 | 20 |
| HX3 | 30 | 20 |
| Valves | | |
| | Specified Drop (Δ P - kPa) | |
| V1 (Mist Eliminator) | 35 | |
| V2 to V9 | 68.94 | |

| TABLE 4 Expander {Ex1}, Condenser {Hx1} and {Hx3} | |
|---|-------|
| Expander | |
| ΔP drop kPa (specified) | 1180 |
| Energy MWe (specified) | 60 |
| Adiabatic Efficiency % (calculated) | 82.45 |
| Condenser (Hx1) | |
| Tube side Temperature Rise (specified) ^[14] | 50 |
| Heat Exchanger (Hx3) | |
| Shell Side Temperature Rise (specified) ^[14] | 96.9 |

| POLYMATH Report Nonlinear Equations | | | | |
|--|----------|-----------|-----------|---------------|
| Calculated values of NLE variables | | | | |
| | Variable | Value | f(x) | Initial Guess |
| 1 | x1 | 2159.089 | 0 | 4338.9 |
| 2 | x2 | 32.52249 | 0 | 32.52 |
| 3 | x3 | 0.0052474 | 0 | 0.009 |
| 4 | x4 | 2.552E+06 | 0 | 2.552E+06 |
| 5 | x5 | 2.5524 | 2.193E-15 | 4.53 |
| 6 | x6 | 5.431066 | 0 | 9.31 |
| 7 | x7 | 2.55E+06 | 0 | 2.548E+06 |
| 8 | x8 | 0.1275113 | 8.882E-16 | 0.13 |

| Nonlinear equations | |
|---------------------|--|
| 1 | $f(x1) = x4 + x5 + x6 - \text{TotS28} = 0$ |
| 2 | $f(x3) = x5 / (x4 + x5 + x6) - \text{H2SinS28} = 0$ |
| 3 | $f(x2) = x8 / (x7 + x8) - \text{O2inS26} = 0$ |
| 4 | $f(x8) = \text{CO2inS4} * x3 - x6 = 0$ |
| 5 | $f(x7) = \text{WatinS4} * x3 / 18.016 + x7 / 18.016 + x8 / 16 - x4 / 18.016 = 0$ |
| 6 | $f(x6) = \text{H2SinS4} * x3 / 34.06 - x8 / 16 - x5 / 34.06 = 0$ |
| 7 | $f(x5) = \text{O2inS24} - x2 - x8 = 0$ |
| 8 | $f(x4) = \text{WatinS24} - x1 - x7 = 0$ |

| Explicit equations | |
|--------------------|---------------------------------|
| 1 | $\text{WatinS24} = 2552384.23$ |
| 2 | $\text{H2SinS28} = 1\text{E-}6$ |
| 3 | $\text{TotS28} = 2552400.$ |
| 4 | $\text{O2inS26} = 50\text{E-}9$ |
| 5 | $\text{H2SinS4} = 538.14$ |
| 6 | $\text{O2inS24} = 32.65$ |
| 7 | $\text{WatinS4} = 412914.84$ |
| 8 | $\text{CO2inS4} = 1035$ |

| |
|----------------------------------|
| # x1 = Mass Water in S25 |
| # x2 = Mass Oxygen in S25 |
| # x3 = Fraction of S4 to reactor |
| # x4 = Mass Water in S28 |
| # x5 = Mass H2S in S28 |
| # x6 = Mass CO2 in S28 |
| # x7 = Mass Water in S26 |
| # x8 = Mass O2 in S26 |

Figure 3. Equations to determine deaerator performance.

Overall the system is very flexible and easy to learn and use. It allows very rapid evaluation and optimization of different cases.

PLANT SIMULATION

VMGSim is used to simulate the plant and match the data given in Figure 1. Steam Table is selected as the physical property system. The components in the simulation are:

1. Water
2. Hydrogen Sulfide
3. Carbon Dioxide
4. Oxygen
5. Sulfur

Figure 2 (p. 134) is the VMGSim flow sheet depiction of the process

There are two feed streams to the plant. In the first, geothermal fluid {S1} contains water, H₂S, and CO₂. Table 1 (p. 135) gives the stream composition based on the values of H₂S and CO₂ (CO₂ 2500 ppm, H₂S 1300 ppm) in the high-pressure steam {S2}.^[9] The VMGSim system is used to determine (by iteration) the values of the temperature and pressure of {S1} from the composition of the high pressure steam, the enthalpy and vapor fraction (=115/326) of {S1} specified in Figure 1.

The cold water (Table 2, p. 135) at 1 atm and 5 °C is assumed saturated with oxygen and carbon dioxide. Values of Henry's Law constants (H) are taken from Perry:^[10]

$H(\text{O}_2) = 29100 \text{ atm/mole fraction (air 20.94\% oxygen)}$

$H(\text{CO}_2) = 878 \text{ atm/mole fraction (air 0.0314\% carbon dioxide)}$

where partial pressure(atm) = H x (mole fraction)

The pressure drops throughout the system are generally not specified in Figure 1 (an exception is the pressure drop across the turbine: 12 bara – 0.2 bara). As a result, literature suggestions^[11, 12] for pressure drops in the valves and heat exchangers and pressure rises in the pumps (arbitrary) are used as shown in Table 3 (p. 135). Exit streams are assumed to be at about atmospheric pressure. The mist eliminator is simulated as a valve {V1}.

The steam turbine {Ex1} is simulated by an expander, and the electrical energy (MWe) is specified as 60 MW. The condenser is simulated

as a heat exchanger ({Hx1}) and a separator that purges the noncondensable gases (Table 4) .

VMGSim does not have a model of a vacuum deaerator.^[6] It is simulated, however, with a mixer {M4} and a Component Splitter {CSP1} . A determination is made^[13] to find the amount of water and O₂ that the deaerator is required to purge in order to meet specifications on the exit water content of O₂

{S26} and the H₂S content of the water delivered to Reykjavik {S28}. (All CO₂ is assumed to go overhead)

Figure 3 is a set of eight equations (in eight unknowns), but with just three manipulated variables to achieve three specifications.

Values To Be Determined:

1. Fraction of high pressure steam that goes to the reac-

| TABLE 5 | | | | | | | | | | |
|--|---------------------|-----------|---------|------------|---------|----------------|---------|--------------|---------|--------|
| Calculated Streams Compared to Reference Number 2 | | | | | | | | | | |
| Iceland's Nesjavellir Co-Generation Power Plant | | | | | | | | | | |
| Stream | Description | Flow kg/s | | Temp Deg C | | Enthalpy kJ/kg | | Pressure kPa | | Frac |
| | | | Ref [2] | | Ref [2] | | Ref [2] | | Ref [2] | Vapor |
| S1 | Geothermal Fluid | 326 | 326 | 189.2 | | 1500 | 1500 | 1235 | | 0.3527 |
| S2 | High Pressure Steam | 115.13 | 115 | 189.2 | | 2775.36 | | 1235 | | 1 |
| S3 | Geothermal Fluid | 210.86 | 211 | 189.2 | | 803.57 | | 1235 | | 0 |
| S4 | High Pressure Steam | 115.13 | | 188.2 | 188 | 2775.96 | | 1200 | 1200 | 1 |
| S5 | Low Pressure Steam | 114.53 | 115 | 60 | | 2251.9 | | 20 | 20 | 0.8519 |
| S6 | Condensate | 112.62 | | 56.3 | 60 | 235.74 | | 19 | | 0 |
| S9 | Warm Water | 667 | 667 | 55 | | 230.39 | | 221.33 | 0 | |
| S11 | Warm Water | 667 | 667 | 86.4 | 88 | 361.96 | | 122.89 | | 0 |
| S14 | High Pressure Steam | 0 | 0 | | | | | | | |
| S15 | Geothermal Fluid | 0 | 0 | | | | | | | |
| S20 | Geothermal Fluid | 323.48 | 326 | 79.9 | 81 | 334.65 | | 101.33 | | 0 |
| S21 | Cold Water | 1129 | 1129 | 5 | | 21.1 | | 101.33 | | 0 |
| S28 | Warm Water | 709 | 709 | 81.7 | 83 | 342.19 | | 118.45 | | 0 |
| S30 | Cold Water | 42 | 42 | 5 | | 21.3 | | 182.39 | | 0 |
| S35 | Cold Water | 1087 | 1087 | 5 | | 21.29 | | 251.33 | | 0 |
| S38 | Warm Water | 420 | 420 | 55 | | 230.39 | | 152.39 | | 0 |
| S54 | Geothermal Fluid | 219.86 | | 92.3 | 92 | 387.41 | | 1146.06 | | 0 |

Turbine Output: Ref [2]= 60 MWe, Simulation = 60 MWe ; Thermal MWt: Ref [2] = 127 MWt, Simulation = 123.88 MWt

*Note: Numbers in bold are those specified in Figure 1

| TABLE 6 | | | | | | | | |
|---|---------------|---------------|-----------------|----------------|----------------|----------------|--------------|--------------|
| Distribution of Noncondensable Gases | | | | | | | | |
| H ₂ S | | | CO ₂ | | | O ₂ | | |
| | In | Out | | In | Out | | In | Out |
| Stream | kg/h | kg/h | Stream | kg/h | kg/h | Stream | kg/h | kg/h |
| S1 | 543.67 | | | | | S1 | 51.99 | |
| S20 | | 12.34 | S1 | 1035.09 | | S25 | | 32.52 |
| S28 | | 2.55 | S21 | 3.56 | | S32 | | 19.34 |
| S39 | | 528.51 | S20 | | 2.75 | Reaction | | 0.13 |
| Reaction | | 0.27 | S25 | | 2.24 | | | |
| | | | S28 | | 5.43 | | | |
| | | | S38 | | 1.32 | | | |
| | | | S39 | | 1026.91 | | | |
| Sum | 543.67 | 543.67 | Sum | 1038.65 | 1038.65 | Sum | 51.99 | 51.99 |

tor in separator {SP4}

2. The amount of water purged in the deaerator {S25}
3. The amount O₂ purged in the deaerator {S25}.

It is assumed all the CO₂ will be purged.

Specifications

1. The ppb of O₂ in the liquid leaving the deaerator {S26} – 50 ppb^[5]
2. The ppm of H₂S in the exit water {S28} - 1 ppm^[5]
3. The total flow of the exit water {S28} - 709 kg/s

The results of the computation are used to enter the fractions overhead into the Component Splitter Block in the VMGSim simulation. The exit temperature of the deaerator (81.2 °C) is determined by an enthalpy balance around the deaerator.

Thermal power (MWt) is calculated based on the flow of heated water {S28} and its temperature above 40 °C:

$$\begin{aligned} \text{MWt} &= \text{mass flow of heated water} \times \text{heat capacity} \times (\text{Output Temperature} - 40) \\ &= 123.88 \end{aligned}$$

Table 5 (p. 137) gives the results of the simulation. Numbers in bold are those taken from Figure 1. Other values are results of the simulation.

DISCUSSION OF THE SIMULATION

As shown in Table 5 the VMGSim simulation matches the indicated conditions^[2] reasonably well. Two important factors, however, impact the comparison of the simulation and the data of Figure 1.

1. *The plant data of Figure 1 does not indicate any venting from the condenser {Sep2} or specify the amount of high pressure steam in stream {S37}. The simulation calculates both {S37} and {S39}.*
2. *The plant data of Figure 1 does not indicate any venting from the deaerator. The deaerator vents both water and noncondensable gases.*

Small changes in the flow to the expander cause considerable changes in downstream streams {S5}, {S6}, and {S20}. Similarly, small changes in the concentration of H₂S in the heated water {S28} greatly affect the amount of water purged in the deaerator.

The deaerator design is based on data suggested by an author^[5] other than Ballzus.^[2]

The distribution of the noncondensable gases was not addressed in Figure 1 but is discussed by Gislason.^[14] Table 6 (p. 137) lists the distribution in this simulation. A comparison with Gislason is difficult as he lumps the flows of H₂S and CO₂ together and indicates different amounts of the noncondensable gases in the entering streams ({S1} and {S21}) than used in this study. Also, Gislason does not account for O₂.

CONCLUSIONS

Study of Iceland's Nesjavellir Power Plant appears to be well suited for classroom instruction and inclusion in undergraduate energy courses.^[15] Such a study illustrates both the advantages of geothermal energy as well as indicating some of its limitations in terms of the suitability and source of geothermal fluids.

Carrying out a simulation draws attention to a variety of energy tradeoff issues, material balance questions, physical property estimates, equipment design selection, water chemistry, and environmental control. Interest in geothermal energy generated by this study can be pursued by searching (e.g., on the Internet) for other ways of using this source of energy.^[16]

ACKNOWLEDGMENT

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Random Thoughts . . .

HOW TO WRITE ANYTHING

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“I write when I’m inspired, and I see to it that I’m inspired at nine o’clock every morning.”

(Peter De Vries)

Here’s the situation. You’re working on a big writing project—a proposal, paper, book, dissertation, whatever—and in the last five weeks all you’ve managed to get done is one measly paragraph. You’re long past the date when the project was supposed to be finished, and you just looked at your to-do list and reminded yourself that this is only one of several writing projects on your plate and you haven’t even started most of the others.

If you’re frequently in that situation (and we’ve never met a faculty member who isn’t) we’ve got a remedy for you. First, though, let’s do some truth in advertising. Lots of books and articles have been written about how to write clear and persuasive papers, proposals, dissertations, lab reports, technical memos, love letters, and practically everything else you might ever need to write. We’re not going to talk about that stuff: you’re on your own when it comes to anything having to do with writing quality. All we’re going to try to do here is help you get a complete draft in a reasonable period of time, because that usually turns out to be the make-or-break step in big writing projects. Unless you’re a pathological perfectionist (which can be a crippling obstacle to ever finishing anything), once you’ve got a draft, there’s an excellent chance that a finished document suitable for public consumption won’t be far behind.

We have two suggestions for getting a major document written in this lifetime: (1) commit to working on it regularly, and (2) keep the creating and editing functions separate.*

- **Dedicate short and frequent periods of time to your major writing projects**

* We didn’t invent either technique—you can find variations of both in many references on writing. A particularly good one is Robert Boice, Professors as Writers, Stillwater, OK: New Forums Press, 1990.

See if this little monologue sounds familiar. *“I don’t have time to work on the proposal now—I’ve got to get Wednesday’s lecture ready and there’s a ton of e-mail to answer and I’ve got to pick the kids up after school tomorrow . . . BUT, as soon as fall break (or Christmas, or summer, or my sabbatical) comes, I’ll get to it.”*

It’s natural to give top priority to the tasks that can be done quickly or are due soon, whether they’re important (preparing Wednesday’s lecture) or not (answering most e-mails), and so the longer-range projects keep getting put off as the weeks and months and years go by. If a major project has a firm due date, you panic when it approaches and quickly knock some-

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thing out well below the best you can do. If it's a proposal or paper, subsequent rejection should not come as a surprise. If there is no firm due date, the project simply never gets done: the book you've been working on for the last 10 years never gets into print, or your graduate students leave school with their research completed but without their Ph.D.s because they never finished their dissertations.

The strategy of waiting for large blocks of time to work on major writing projects has two significant flaws. When you finally get to a block, it's been so long since the last one that it can take hours or days to build momentum again and you're likely to run out of time before much gets written. Also, as soon as the block arrives other things rush in to fill it, such as your family, whom you've been neglecting for months and who now legitimately think it's their turn.

A much more effective strategy is to *make a commitment to regularly devote short periods of time to major writing projects*. Thirty minutes a day is plenty, or maybe an hour three times a week. One approach is to designate a fixed time period on specified days, preferably at a time of day when you're at your peak, during which you close your door, ignore your phone, and do nothing but work on the project. Alternatively, you might take a few 10–15 minute breaks during the day—times when you would ordinarily check your e-mail or surf the Web or play Sudoku—and use them to work on the project instead. Either way, when you start to write you'll quickly remember where you left off last time and jump in with little wasted motion. When you've put in your budgeted time for the day, you can (and generally should) stop and go back to the rest of your life.

These short writing interludes won't make much difference in how many fires you put out each day, but you'll be astounded when you look back after a week or two and see how much you've gotten done on the project—and when a larger block of time opens up, you'll be able to use it effectively with very little warm-up. You can then be confident of finishing the project in a reasonable time . . . provided that you also take our next suggestion.

- **Do your creating and editing sequentially, not simultaneously**

Here's another common scenario that might ring a bell. *You sit down to write something and come up with the first sentence. You look at it, change some words, add a phrase, rewrite it three or four times, put in a comma here, take one out there . . . and beat on the sentence for five minutes and finally get it where you want it. Then you draft the second sentence, and the first one is instantly obsolete and you have to rewrite it again . . . and you work on those two sentences*

until you're satisfied with them and go on to Sentence 3 and repeat the process . . . and an hour or two later you may have a paragraph to show for your efforts.

If that sounds like your process, it's little wonder that you can't seem to get those large writing projects finished. When you spend hours on every paragraph, the 25-page proposal or 350-page dissertation can take forever, and you're likely to become frustrated and quit before you're even close to a first draft.

At this point you're ready for our second tip, which is to *keep the creating and editing processes separate*. The routine we just described does the opposite: Even before you complete a sentence you start criticizing and trying to fix it. Instead of doing that, write whatever comes into your head, without looking back. If you have trouble getting a session started, write *anything*—random words, if necessary—and after a minute or two things will start flowing. If you like working from outlines, start with an outline; if the project is not huge like a book or dissertation and you don't like outlines, just plunge in. If you're not sure how to begin a project, start with a middle section you can write easily and go back and fill in the introduction later.

Throughout this process you will, of course, hear the usual voice in your head telling you that what you're writing is pure garbage—sloppy, confusing, trivial, etc. Ignore it! Write the first paragraph, then the next, and keep going until you get as much written as your budgeted time allows. Then, when you come back to the project the next day (remember, you committed to it), you can either continue writing or go back and edit what you've already got—and then (and *only* then) is the time to worry about grammar and syntax and style and all that.

Here's what will almost certainly happen if you follow that procedure. The first few sentences you write in a session may indeed be garbage, but the rest will invariably be much better than you thought while you were writing it. You'll crank out a lot of material in a short time, and you'll find that it's much easier and faster to edit it all at once rather than in tiny increments. The bottom line is that you'll find yourself with a completed manuscript in a small fraction of the time it would take with one-sentence-at-a-time editing.

We're not suggesting that working a little on big projects every day is easy. It isn't for most people, and days will inevitably come when the pressure to work only on urgent tasks is overwhelming. When it happens, just do what you have to do without beating yourself up about it and resume your commitment the next day. It may be tough but it's doable, and it works. □

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INCORPORATING RISK ASSESSMENT AND INHERENTLY SAFER DESIGN PRACTICES *into Chemical Engineering Education*

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Process safety is a fundamental component of sound process design. Although the chemical industry has demonstrated an excellent safety record over the years,^[1] the quantities and hazardous nature of many of the substances typically handled by chemical manufacturers make the potential for large-scale disasters a constant concern. Because safety is so critical in industry, it is vital to introduce the concept of safe process design practices during undergraduate chemical engineering education. From famous historic disasters such as Flixborough and Bhopal to recent events such as the Texas City BP Refinery explosion in 2005, the importance of process safety in chemical process design is abundantly clear. An appreciation of this gained during a chemical engineer's education can only enhance chemical manufacturing safety in the future.

In industry, the concept of process safety is firmly rooted in the concept of risk. From government regulatory requirements, such as those outlined by OSHA and the EPA,^[2-4] to industry initiatives such as Responsible Care, the requirement of quantifying and managing risk is paramount. In addition to working within economic and environmental constraints, the process design engineer is also tasked with reducing the risk of operating a chemical manufacturing process to an acceptable level for employees, regulatory authorities, insurance underwriters, and the community at large. Therefore, a

holistic approach to process safety as an integral component of sound process design is critical.

In addition to the study of toxicological impacts and quantifying release scenarios, an understanding of how risk is quantified in the chemical process industries will allow future process design engineers to mitigate those risks at the earliest



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stage of conceptual process development—the stage where an engineer has the greatest influence on the final process design. This paper will present, by case-study example, how the fundamental concepts of inherently safer process design can be integrated into chemical engineering education.

RISK ASSESSMENT METHODOLOGY

Quantifying Risk

In order to begin understanding the benefits of inherently safer process design, the chemical engineering student must first understand risk. The concept of risk is often misunderstood by both the general public and students of chemical engineering. It is important to separate the concept of risk from the concept of hazard. While the concept of hazard relates to the potential for adverse consequences, risk is rather a combination of both the severity of the consequences of an upset scenario and the likelihood of that scenario's initiating

cause. This is an important distinction. The potential hazard associated with a substance or process is an inherent property that cannot be changed. The risk associated with handling a substance or operating a process can be high or low, depending upon the safeguards included in the design. Thus, for chemical engineers, the most important distinction between hazard and risk is that risk can be reduced through process design.

In order to begin to discuss risk, the process design engineer must first consider potential upset scenarios. In other words, answer the question, "What is the worst thing that can happen?" Answers to this question typically involve loss of containment of a process chemical with causes ranging from failure of control loops and operator errors to external events such as fire, among many others. It is critical to note that the answers to the aforementioned question must be considered independently of the likelihood of the worst-case scenario occurring. Again, it is the combination of both the severity and

the likelihood that determines the risk. In order to ensure a complete and consistent assessment of potential upset scenarios, a structured approach must be applied. The need for such an approach is the basis for a Process Hazard Analysis.

Process Hazard Analysis

A Process Hazard Analysis (PHA) is a methodology for reviewing and assessing the potential hazards of a chemical process by using a structured, facilitated, team brainstorming approach. A PHA is typically facilitated by a trained team leader and attended by a wide variety of plant personnel, including engineers, managers, operators, maintenance technicians and safety, health, and environmental (SHE) personnel. Although several techniques are available for performing PHAs,^[3] the goal of the PHA is always the same

| What If... ? | Initiating Cause | Consequence | Safeguards |
|--|--|--|--|
| 1. There is High Pressure in the Cyclohexane Storage Tank? | 1.1 Failure of the pressure regulator on nitrogen supply line to Cyclohexane Storage Tank. | 1.1 Potential for pressure in tank to rise due to influx of nitrogen pad gas through failed regulator. Potential to exceed design pressure of storage tank. Potential tank leak or rupture leading to spill of a flammable liquid. Potential fire should an ignition source be present. Potential personnel injury should exposure occur. 2.1 Potential environmental release requiring reporting and remediation. | 1. Conservation vent sized to relieve overpressure due to this scenario. 2. Pressure transmitter with high alarm set to indicate high pressure in Cyclohexane Storage Tank. |

| Hazard Scenario | Process Operation | Potential Upset Case | Inherently Safer Design |
|-----------------|---|---|--|
| Overpressure | Filling a process vessel with a pump. | Overpressure by pump deadhead due to overfill. | 1. Vessel design pressure greater than pump deadhead pressure 2. Static head due to vessel elevation plus vessel design pressure greater than pump deadhead pressure. |
| Overpressure | Operating a vessel under inert gas pressure. | Failure of inlet gas regulator leading to overpressure. | 1. Vessel design pressure greater than inert gas supply pressure. |
| Underpressure | Emptying a process vessel with a pump. | Blocked vent leading to vessel collapse due to vacuum pulled during pump out. | 1. Vessel designed for full vacuum |
| Underpressure | Draining an elevated process vessel by gravity. | Blocked vent leading to vessel collapse due to vacuum pulled during draining. | 1. Vessel designed for full vacuum. 2. Liquid drain lined sized to be self-venting. |

—to identify the potential hazards of a process and determine whether sufficient safeguards are in place to mitigate those hazards.

CLASSROOM EXAMPLE OF APPLYING PHA METHODOLOGY

The following is a simple example that can be used to illustrate the basic concepts of a PHA in the chemical engineering classroom. Consider a low design pressure API storage tank filled with cyclohexane. API type storage tanks are typically designed for no more than 2.5 pounds of pressure and only a few inches of water of vacuum. Therefore, careful control of pressure is critical. Furthermore, assume that the storage tank is equipped with a “pad/de-pad” vent system to control pressure, and is located in a diked tank farm. Table 1 illustrates a typical scenario that might be developed during a PHA using the “What If...?” methodology.

In Table 1, the listed safeguards would be effective means of mitigating the personnel exposure and environmental impact consequences identified for this scenario. In addition to the cause illustrated, other causes of high pressure that might be considered by a PHA Team include the following:

- *External fire in the area, leading to increased vapor pressure in the storage tank.*
- *Overfill via the supply pump, leading to overpressure by deadhead pump pressure.*

If the safeguards identified by the PHA team are not deemed adequate, recommendations are made for the implementation of additional safeguards. This technique, called Layer of Protection Analysis (LOPA), is often employed by PHA teams to quantitatively assess the risk associated with an upset scenario so that appropriate layers of protection can be applied to adequately mitigate the risk.^[5]

Hazard assessment and layer of protection analysis are complex subjects. As such, a formal hazard analysis is typically not performed during the conceptual phase of process design. In most cases, the PHA is performed during

the engineering phases of a project. A basic understanding of the fundamentals of risk assessment, however, is extremely beneficial to the development of inherently safer designs during the conceptual phase of process design. To make inherently safer design choices during conceptual development of a process, the design engineering student must be aware of the types of hazard scenarios that may be identified for each piece of equipment or system.

Inherently Safer Process Design

Inherently safe process design practices can generally be grouped into five categories:^[6, 7]

- *Intensification*
- *Substitution*
- *Attenuation*
- *Limitation of effects*
- *Simplification*

Some examples of inherently safer design choices for typical process applications are included in Table 2.

Typically, however, these types of design choices are made in later stages of engineering development. Although these are important design considerations, it is very beneficial to begin evaluating inherently safer design strategies at the earliest stages of process development, when the process design engineer has the greatest opportunity to affect the safety

| Process Design Choice | Inherently Safe Design Category | Potential Process Safety Impact |
|-------------------------------|---------------------------------|---|
| Reactor type | Intensification | Continuous reactors are typically smaller than batch reactors for a given production volume. |
| Feed stocks | Substitution | Less hazardous raw materials may be available to make the same products. |
| Process solvents | Substitution | Less hazardous and/or less volatile solvents may be available. |
| Reaction mechanism | Attenuation | Endothermic reactions present less potential for runaway. |
| Operating conditions | Attenuation | Temperatures and pressure close to ambient are typically less hazardous. |
| Process utilities | Attenuation | Low pressure utilities such as hot oil may be a safer choice than high pressure steam. |
| Alternative technology | Attenuation | Use of alternative technology, for example pervaporation instead of azeotropic distillation using a solvent entrainer. |
| Production rate | Limitation of effects | A continuous process making just what is required can be safer than a batch process with a large hold-up volume. |
| Storage volume | Limitation of effects | Minimization of volume limits the potential effects of a release. |
| Equipment layout | Simplification | Utilizing gravity flow minimizes the need for rotating equipment. |
| Cooling by natural convection | Simplification | Utilizing natural convection simplifies the process and eliminates the potential for process upsets due to loss of utilities. |

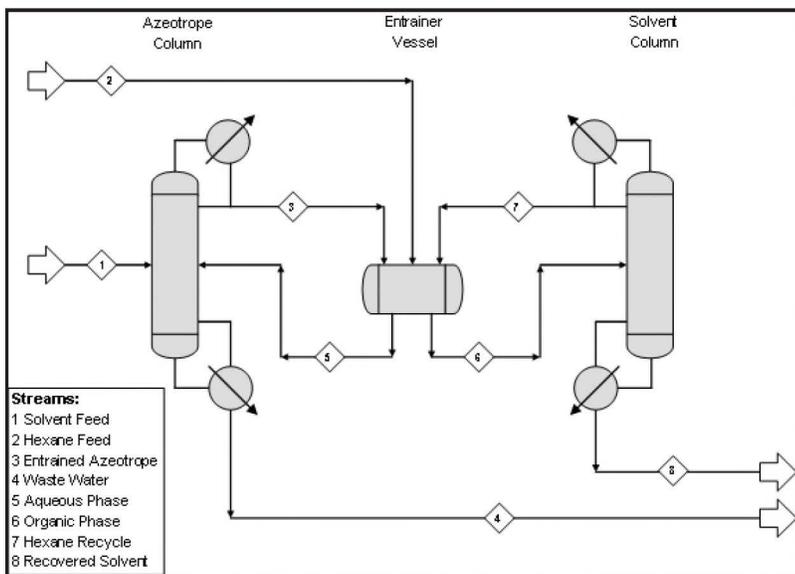


Figure 1. Flow diagram of traditional solvent recovery process.

aspects of the process. Some examples of design choices that are typically made at the onset of conceptual engineering are illustrated in Table 3 (previous page).

Initially, inherently safer designs may seem to be more expensive than applying traditional safeguards to processes. When the total cost of the process is considered, however, the inherently safer design is often more cost effective. Installing and maintaining multiple independent layers of protection can be quite expensive, but these costs are often ignored during initial cost estimates. Conceptual phase cost estimates are usually based on stand-alone major equipment costs that are simply multiplied by factors to obtain the total installed cost. These factors are intended to account for instrumentation and controls, among other items needed for the complete process installation. To apply the same factors to traditional and inherently safer processes, however, can lead to an erroneous comparison and conclusion. Inherently safer processes will typically require fewer safety controls, which leads to lower installation and operating costs. These factors should be considered when evaluating processes during a hierarchical approach to process design. Additional cost savings for inherently safer processes that are often overlooked include insurance costs and costs associated with regulatory compliance.

Case Study—Solvent Recovery

The following case study is presented as a classroom engineering design problem to illustrate the techniques of applying inherently safer design choices.

Consider a chemical process using 1-propanol as a solvent. Currently, the waste solvent ends up as a waste-water stream for disposal. The task

for the process design engineer is to develop a process to recover the 1-propanol from the waste-water stream. This separation is complicated by the fact that water and 1-propanol form a minimum-boiling azeotrope. Therefore, separation by ordinary distillation is not possible.

Traditional Process

The traditional method employed for breaking this azeotrope uses a third solvent, or entrainer. For the water/1-propanol system, cyclohexane works well for the separation. A sample flow diagram of the azeotropic distillation process is given in Figure 1.

In this process, the minimum-boiling azeotrope is separated from the water in the Azeotrope Column and is collected as an overhead product. The azeotrope is then mixed with the cyclohexane in the Entrainer Vessel. The 1-propanol is soluble in cyclohexane, while the water is not. The water phase, with a small amount of 1-propanol, is then recycled back to the Azeotrope Column, while the cyclohexane/1-propanol mixture is fed to the Solvent Column, where 1-propanol is recovered as a bottoms product and the cyclohexane—with a small amount of 1-propanol—is recycled to the Entrainer Vessel. This simple system is easily modeled using any process simulation software package.

Potential Upset Scenarios

From a process design perspective, this process is certainly acceptable. From the perspective of safety, however, some significant concerns arise. In order to break the azeotrope, a highly volatile solvent, cyclohexane, is introduced to the process. A sample of some of the potential hazard scenarios that might be generated during a PHA is illustrated in Table 4.

Some potential safeguards that might be used to mitigate these hazards include safety relief valves, redundant in-

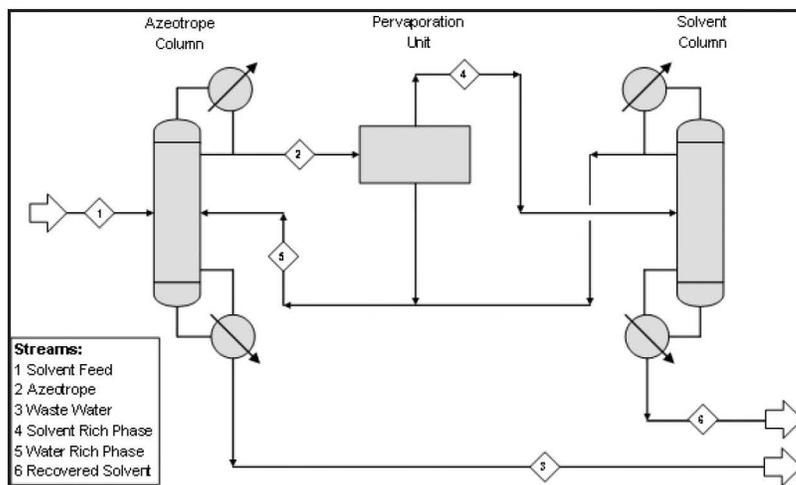


Figure 2. Flow diagram of inherently safer solvent recovery process.

strumentation, and hardwired interlocks independent from the primary basic process control system (BPCS). All of these safeguards would be applied to the process during later stages of process design, as considering inherently safer design choices could make such safeguards unnecessary.

An Inherently Safer Process

An inherently safer approach to this design problem will include technology to break the azeotrope without introducing additional, flammable solvents to the process. One possible solution is the use of a pervaporation membrane. A pervaporation membrane separates two liquids by partial vaporization through a nonporous membrane, such as ceramic. The pervaporation membrane is able to break azeotropes due to its ability to separate components based on polarity differences between the molecules, rather than relying on differences in vapor pressure, like distillation does.

Although the pervaporation technology could be used to completely separate 1-propanol from the water in one step, such a sharp split would most likely prove to be prohibitively expensive. An optimum design using a combination of distillation and pervaporation can be achieved, as illustrated in Figure 2.

In this design, the azeotrope is again separated from the water as an overhead product in the Azeotrope Column, but in this process, instead of using an entrainer, the Pervaporation Unit is used to separate the liquids. Because this technology is used in conjunction with distillation, a sharp split is not needed. The water-rich phase leaving the Pervaporation Unit is returned to the Azeotrope Column, and the 1-propanol is recovered as a bottoms product from the Solvent Column, with the azeotrope being collected overhead and returned to

| What If... ? | Initiating Cause | Consequence |
|--|--|--|
| 1. There is higher pressure in the Entrainment Vessel? | 1.1 External fire in the process area. | 1.1 Potential increased temperature and pressure leading to possible vessel leak or rupture. Potential release of flammable material to the atmosphere. Potential personnel injury due to exposure. |
| | 1.2 Pressure regulator for inert gas pad fails open. | 1.2 Potential for vessel pressure to increase up to the inert gas supply pressure. Potential vessel leak or rupture leading to release of flammable material to the atmosphere. Potential personnel injury due to exposure. |
| 2. There is higher level in the Entrainer Vessel? | 2.1 Vessel level transmitter fails and indicates lower than actual volume. | 2.1 Potential to overflow vessel with cyclohexane. Potential to flood vent line with liquid leading to flammable liquid reaching the vent gas incinerator. Potential to overwhelm incinerator leading to possible explosion. Potential personnel injury due to exposure. |

the Azeotrope column. This design is advantageous because it can be optimized to minimize the impact of the cost of the Pervaporation Unit.

Process Safety Improvements

The inherently safer design has the obvious advantage of having eliminated the flammable solvent, cyclohexane, from the process. Taking a wider view, not only is the cyclohexane eliminated from the process itself, but also from storage areas, unloading areas, and waste treatment. In addition to the benefit of eliminating a flammable solvent from the process, the Pervaporation Unit minimizes the circulating flow of material through the system. Therefore, the column and associated heat exchangers are smaller than with the traditional process design. Based on the hazard scenarios identified for the traditional process, illustrated in Table 4, the benefits of the inherently safer process are illustrated in Table 5.

From this assessment, the benefits of the inherently safer process are clear. The pervaporation process addresses three of the five categories of inherently safer design choices: Attenuation, Simplification, and Limitation of Effects. Attenuation is due to the use of alternative technology, Simplification is due to the elimination of the entrainment solvent from the

process, and Limitation of Effects is due to the smaller equipment and chemical inventories. Of course, 1-propanol is a flammable liquid, so all of the upset scenarios listed in Table 4 would still need to be considered, but by eliminating the cyclohexane from the process, the overall severity of the consequences would be reduced. Since, as discussed previously, risk is a combination of both severity and likelihood, the overall risk of the inher-

| Upset Scenario | Traditional Process | Inherently Safer Process |
|----------------|---|---|
| External Fire | Large volume of flammable liquid circulating in process. | Flammable volume limited to recovered solvent only. |
| Overflow | Cyclohexane entrainer more volatile than 1-propanol. | Minimal liquid hold up in Pervaporation Unit. |
| Overpressure | Larger liquid hold-up leads to higher severity in the event of a release. | Volume limited to solvent distillation hold-up. |

ently safer design would be reduced. Although a more in-depth study would be required before making the choice of which solvent recovery process is preferred, it should be clear that these decisions must be made in the early stages of conceptual process development in order to benefit the process.

CONCLUSIONS

One of the responsibilities of every chemical engineer is to ensure that the excellent safety record enjoyed by the chemical process industry is maintained. Therefore it is important to begin introducing the fundamentals of process safety during undergraduate chemical engineering education. The purpose of this work has been to underscore, by case-study example, the natural relationship between inherently safe process design and conceptual process development, and describe how it can be integrated into undergraduate process design education. As has been illustrated by this case study, taking a holistic approach to process safety education can serve to reinforce the benefits of beginning to consider the safety implications of the decisions made during conceptual process development. By reinforcing the benefits of making inherently safe design choices during conceptual process development, students

of process engineering will be better prepared for the challenges of meeting the high standards of safety set by today's chemical industry.

ACKNOWLEDGMENTS

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A LAB EXPERIMENT TO INTRODUCE GAS/LIQUID SOLUBILITY

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The concept of the solubility of a gas in a liquid is familiar in many everyday ways. When we drink a bottle of carbonated beverage, we understand it contains dissolved carbon dioxide, and we know animals can live in oceans and rivers because oxygen dissolves in water and animal life depends on the dissolution of oxygen in blood. For chemical engineers, this everyday phenomenon is important from both practical and theoretical points of view.^[1, 2] From a practical point of view, this concept is used in the design of absorption columns where a gaseous mixture is separated by contact with suitable solvents that dissolve its components differently. Further, knowledge of gas solubility in water is important in the processes that control environmental distribution of contaminants, such as halogenated hydrocarbons. From the theoretical point of view, the solubility of gases in liquids is an excellent tool to investigate solute-solvent intermolecular forces in the liquid state, since solute-solute interactions are almost negligible.

In this paper we present a simplified version recently developed by Fonseca, et al,^[3] for experimental determination of the solubility of a gas in a liquid. This experiment is implemented in the chemical engineering department of Coimbra, and is a part of one of the third-year laboratory courses in phase equilibria domain. The experiments are carried out by groups of a maximum of three students during approximately four hours. The full report of the experiment is completed by the group at home and must be presented to the teacher



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the following week and discussed one week later. The report consists of the following sections: introduction, experiment objectives, background of the experiment, description of the apparatus, experimental procedure, and a discussion/results section. The analysis of uncertainties must also be done using the propagation law of errors, and the relative contribution of each measured variable uncertain in the final result—*i.e.*, the solubility—evaluated. The students must also include in the report a section of conclusions, where they can also present comments and recommendations for improvements.

THEORY

When a gas is in contact with a liquid it tends to dissolve in the liquid and the liquid evaporates until equilibrium is reached. Consider a binary mixture of components 1 and 2 at temperature T and pressure P , represented schematically in Figure 1. The component 2 is near or above its critical temperature, which means this component is a gas at temperature T . (A pure fluid above its critical temperature is called a gas, and a vapor below T_c). When the liquid-phase mole fraction, x_2 , is small and the equilibrium vapor-phase mole fraction, y_2 , is large (near unity), it is conventional to call species 2 a “dissolved gas,” and to label the physical situation one of “gas solubility.”^[4] Gas/liquid solubility is a particular case of vapor/liquid equilibrium; therefore, the classical treatment of this subject is similar in some important aspects.

Let's consider species 1 the major component of the liquid phase (the solvent) and species 2 the dissolved gas (the solute). The liquid phase mole fraction, x_2 , represents the solubility of gaseous solute 2 in liquid solvent 1. For component 2, the thermodynamic condition of phase equilibrium states:^[5]

$$f_2^G = f_2^L, \quad (1)$$

where f_2^G and f_2^L are the fugacities of component 2 in the vapor and liquid phases, respectively. f_2^G is given by the expression:

$$f_2^G = \varphi_2 y_2 P, \quad (2)$$

where φ_2 represents the fugacity coefficient of component 2 in the vapor phase and P is the total pressure. f_2^L is represented by:

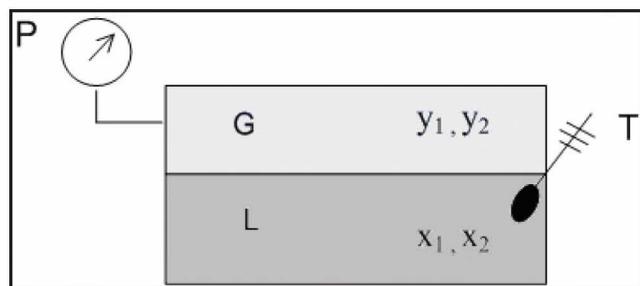


Figure 1. Schematic representation of gas/liquid solubility.

$$f_2^L = \gamma_2 x_2 f_2^0, \quad (3)$$

where γ_2 is the activity coefficient of component 2 in the liquid and f_2^0 the standard-state fugacity of the same component, which is usually assumed to be the fugacity of the pure liquid at the temperature and pressure of equilibrium ($f_2^0 = f_2^{*,L}$). The substitution of Eqs. (2) and (3) in Eq. (1) gives:

$$y_2 \varphi_2 P = \gamma_2 x_2 f_2^{*,L}. \quad (4)$$

The above equation can be simplified if we consider the following assumptions:^[5]

- (i) $\gamma_2 = 1$ ($\gamma_1 = 1$), *i.e.*, the liquid phase is an ideal solution;
- (ii) $\varphi_2 = 1$ ($\varphi_1 = 1$), *i.e.*, the vapor phase is an ideal mixture;
- (iii) $f_2^{*,L} = P_2^*$ (P_2^* is the pure vapor pressure of component 2 at temperature T) *i.e.*, the effect of pressure on the fugacity of the pure liquid phase is negligible (Poynting correction = 1) at moderate pressures; and $\varphi_2^* = 1$, (φ_2^* is the fugacity coefficient of pure component 2) which is valid if P_2^* is low at temperature T .

Therefore Eq. (4) reduces to Raoult's law:

$$P_2 = y_2 P = x_2 P_2^*, \quad (5)$$

where P_2 represents the partial pressure of component 2.

The solubility x_2 , as given by Eq. (5), is called the “ideal” solubility of the gas. This expression states that the solubility is independent of the solvent and for a given gas, at a constant partial pressure, the solubility always decreases with rising temperature, which is not always true. Because of these disadvantages, the ideal solubility expression usually gives no more than a rough estimate of gas solubility.

The solubility of gas in a liquid is often proportional to its fugacity in the vapor phase. This situation is described by a more realistic expression, Henry's law:

$$f_2^L = H_{2,1} x_2, \quad (6)$$

where $H_{2,1}$ is a constant that for a given solute and solvent depends only on temperature.

Again the assumptions leading to Eq. (6) can be readily recognized by comparing it with Eq. (4). The more important thing is to consider the constancy of the activity coefficients (independent of the composition), which means that Henry's law is only valid at infinite dilution. This can be stressed writing Eq. (6) in more convenient form:

$$H_{2,1} = \lim_{x_2 \rightarrow 0} \frac{f_2^L}{x_2}, \quad (7)$$

which is equivalent to

$$H_{2,1} = \lim_{x_2 \rightarrow 0} \frac{\varphi_2 y_2 P}{x_2}, \quad (8)$$

taking into account Eqs. (1) and (2).

EXPERIMENTAL SECTION APPARATUS

The determination of the solubility of gas in a liquid is made using a volumetric method.^[6] The principle of this procedure is to bring a measured volume of liquid into contact with a known volume of gas at a given temperature and pressure. After equilibrium has been attained, the change in the gas volume yields the amount of gas dissolved in the liquid and hence the solubility. The solubility apparatus is shown schematically in Figure 2. The apparatus is housed in a water thermostat where the temperature is maintained constant using a temperature controller, TC. The temperature is measured with a precision thermometer graduated in 0.01 °C. The level of the thermostat bath can be adjusted using an elevator, E, in order to immerse the whole vacuum line.

The main features of the apparatus are: EQ, equilibrium vessel, (~50 cm³) where the dissolution of the gas takes place; GB, gas burette, which consists in a piston-cylinder arrangement; PT, pressure transducer, for total pressure readings; LA, linear actuator, which moves the piston in the gas burette; and PC, pressure controller.

PROCEDURE

The experimental procedure begins with the evacuation of the whole apparatus. After this two fundamental steps in any gas solubility measurement need to be performed:

- (i) degassing of the solvent
- (ii) dissolution of the gas

To accomplish step (i), the equilibrium vessel is removed from the line, lowering the level of the thermostat bath, and filled with a known amount (~6 g) of solvent. After this, it is again connected to the line and the position of the thermostat bath re-established. The stopcocks V2 and V4 are opened to degas the solvent in EQ during about 10 min. The magnetic stirrer must be on. This degassing procedure should be repeated two or three times until the measured pressure equals the solvent vapor pressure at the equilibrium temperature. Then EQ must be removed from the line in order to be weighed. After this procedure, EQ is connected again to the vacuum line.

Step (ii) begins with slowly opening stopcock V1, with V2 opened (V3 and V4 must be closed) to admit the gas to the equilibrium vessel. The total pressure is adjusted to ca 1 atm and, after this, stopcock V1 is closed and V3 is opened. This pressure acts as a reference value for the pressure controller, which commands the linear actuator, LA. As the gas dissolves the pressure decreases and this is detected by PT. The linear actuator, LA, drives the piston down the cylinder to maintain the pressure constant at the reference value. The number of encoder pulses is counted and displayed, and a conversion is made to determine the volume of gas displaced from the precision-bore tube that

comprises that cylinder of the burette. This volume represents the volume of the gas dissolved. The detailed experimental procedure is described in Appendix A.

ADDITIONAL INFORMATION FOR INSTRUCTORS

In this experiment it is important to use gases, such as CO₂, N₂O or CH₃F, that are highly soluble in water. Methyl fluoride has the disadvantage of being very expensive. Less soluble gases (O₂, N₂, etc.) should not be used in this experiment since the time of dissolution increases substantially. For these kinds of gases an equilibrium vessel with a greater volume should be used.^[3] Other solvents such as primary alcohols (*e.g.*, methanol, ethanol, propan-1-ol, butan-1-ol) can also be used. They must have purities greater than 99.8 percent.

The accuracy of the method can be improved using lecture bottles of gases, which have higher purity (>99.5%) than other commercial gases. A pressure reducer should be used connected to the lecture bottle. The lecture bottles are quite appropriate to classroom experiments and must be used in these experiments. An adequate pressure reducer must be coupled to the lecture bottle. In the present experiments we have used a pressure reducer HSB – 280 – 5 (from PRAXAIR), but other reducers can be adapted depending on the mark of the lecture bottle. This allows a safe use of the lecture bottles. The linear actuator, LA, consists of a permanent magnetic DC motor, which drives a worm screw coupled to an optical encoder. The worm screw moves the piston inside the cylinder of the gas burette and the displacement is proportional to the number of encoder pulses (n_p). The proportionality constant

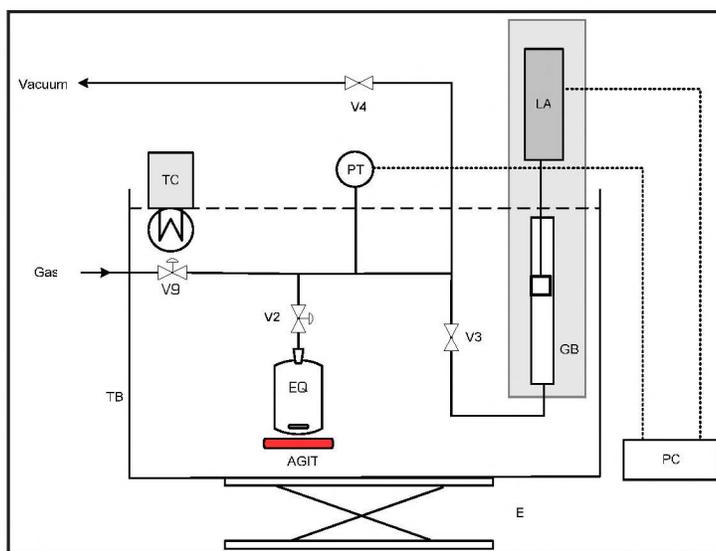


Figure 2. Solubility apparatus: TB, thermostated bath; TC, temperature controller; PT, pressure transducer; LA, linear actuator; PC, pressure controller; EQ, equilibrium vessel with connector; GB, gas burette; V1,... V4, high vacuum Teflon stopcocks; AGIT, magnetic stirrer; E, elevator.

The students must also include in the report a section of conclusions, where they can also present comments and recommendations for improvements.

indicated in the manual of the linear actuator should be given to the students. In the present apparatus, the displacement is obtained from: $\Delta h / (\text{mm}) = 2.20189 \times 10^{-4} n_p$. In this experiment we have used a pressure transducer from Honeywell, model PPT0015AWN2VA-A.

The thermostat bath can be built using Perspex or glass (71 × 26 × 38 cm) where a thermostatic control unit is immersed. The whole setup costs about 1,800 euros.

CALCULATIONS

Solubility Calculation

To simplify the treatment of the raw data we consider some assumptions: neglect the volume change of the liquid sample during saturation and ideal solution behavior.

The raw data obtained from experiment are: n_p , the number of encoder pulses from the linear actuator, the equilibrium temperature, T , the reference pressure, P , and m_1 , the mass of solvent. The number of encoder pulses is converted in Δh , the displacement of the piston, using a conversion factor indicated in the user manual of the pressure controller. The change of the volume of gas in the gas burette due to gas dissolution is obtained from:

$$\Delta V = \pi r^2 \Delta h, \quad (9)$$

where r represents the internal radius of the gas burette. The quantity of the gas absorbed in the liquid, n_2 (in moles), can be obtained from ΔV using the equation,

$$PV_{\text{mix}}^G / (RT) = 1 + B_{\text{mix}} RT / P, \quad (10)$$

where V_{mix}^G represents the molar volume in the vapor phase and B_{mix} the second virial coefficient of the binary mixture, given by the expression,

$$B_{\text{mix}} = y_1^2 B_{11} + y_2^2 B_{22} + 2y_1 y_2 B_{12}, \quad (11)$$

where B_{11} , B_{22} , and B_{12} are the second virial coefficients of pure components 1 and 2, and the second cross coefficient, respectively.

Substituting, in Eq. (10), $V_{\text{mix}}^G = \Delta V / n^G$, where n^G represents the total number of moles contained in the V volume, one obtains,

$$\Delta V / n^G = (RT / P) + B_{\text{mix}}, \quad (12)$$

which multiplied by $(1/y_2)$ gives,

$$n_2 = y_2 P \Delta V / (RT + B_{\text{mix}} P). \quad (13)$$

The value of the solubility, x_2 , is then obtained from:

$$x_2 = n_2 / (n_1 + n_2), \quad (14)$$

where n_1 and n_2 represent the amount of solvent and solute in moles in the liquid phase, respectively. The n_1 is obtained directly from $n_1 = m_1 / M_1$. Since we need to know y_2 to obtain n_2 from Eq. (13), this calculation requires an iterative procedure. The calculations begin with estimates of the vapour and liquid phases obtained from Raoult and Dalton laws. In the following iterations, these compositions are improved using Eqs. (13) and (14) and the following expression:

$$y_2 = 1 - (1 - x_2) \frac{P_1^* \varphi_1^*}{P \varphi_1}, \quad (15)$$

which results from the thermodynamic condition of phase equilibrium written for the solvent.

The φ_1 is the fugacity coefficient of solvent in the vapor phase, which is given by,

$$\varphi_1 = \exp \left\{ (P / RT) [B_{11} + y_2^2 (2B_{12} - B_{22} - B_{11})] \right\}, \quad (16)$$

and φ_1^* represents the fugacity coefficient of pure solvent in saturation conditions obtained from,

$$\varphi_1^* = \exp \left[(B_{11} P_1^* / (RT)) \right], \quad (17)$$

where P_1^* is the vapor pressure of pure component 1 at the equilibrium temperature, which can be obtained using a vapor pressure equation.

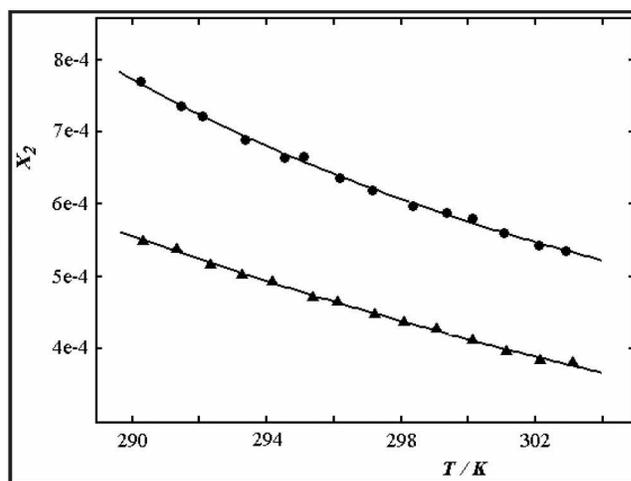


Figure 3. Solubility of carbon dioxide (•) and nitrous oxide (▲) in water. The curves were obtained from Eq.(18).

The calculation ends when convergence is obtained between two consecutive x_2 values. The determination of Henry's constant, $H_{2,1}$, is then straightforward from Eq. (8). All the solubilities found in this work were corrected to 1 atm partial pressure using Henry's law, since the literature values are referred to this pressure.

ERROR ANALYSIS

The analysis of uncertainties or "errors" is a vital part of any scientific experiment. The instructor should stress that all measurements, however careful and scientific, are subject to some uncertainties. In this experiment the determination of the uncertainty of the final result, the mole fraction solubility, provides use of the propagation law of errors.^[7] This law gives the relative magnitude of the uncertainties of the measured variables, *i.e.*, the student will be able to tell which of the experimental errors affect the solubility value more.

Appendix B presents an entrance form distributed to each group of students in order to guide them in treating the raw data and analyzing the uncertainties of the results. The data was obtained by one of these groups to determine the solubility of CO₂ in water, at the temperature 298.39 K.

RESULTS AND DISCUSSION

The experimental solubility data and the values reported in the literature for the systems CO₂/H₂O and N₂O/H₂O are shown in Table 1. The accuracy of the experimental method is found to be about 1 percent.

We have also determined the ideal solubilities of both gases at $P_2 = 101325$ Pa using Eq. (5). The vapor pressures of the pure components were obtained from the Wagner equation.^[9] The value determined for CO₂ is $x_2 = 1.57 \times 10^{-2}$ ($T = 298.39$ K) and for N₂O is $x_2 = 1.91 \times 10^{-2}$ ($T = 298.13$ K). These values are quite different from the experimental ones, since Raoult's law gives only a rough estimate of the solubility of a gas independent of the solvent.

The second virial coefficients were obtained from polynomial functions fitted to the experimental second virial coefficients taken from the Dymond and Smith compilation.^[10]

The dependence of the solubility on temperature has been represented by:

$$R \ln x_2 = A + B/T + C \ln T, \quad (18)$$

with the parameters fitted to the data by a least-squares method. The optimized parameters of Eq. (18) and the average absolute

| Solute | T/K | $x_2/10^{-4}$ | $x_{2lit}/10^{-4}$ | σ (%) ^(a) | $H_{2,1}$ / (MPa) |
|------------------|--------|---------------|--------------------|-----------------------------|-------------------|
| CO ₂ | 290.27 | 7.70 | 7.61 | 1.1 | 131.7 |
| | 291.49 | 7.36 | 7.34 | 0.3 | 137.7 |
| | 292.11 | 7.22 | 7.21 | 0.2 | 140.4 |
| | 293.39 | 6.90 | 6.94 | 0.6 | 146.8 |
| | 294.58 | 6.65 | 6.71 | 0.9 | 152.3 |
| | 295.15 | 6.66 | 6.60 | 0.9 | 152.1 |
| | 296.19 | 6.36 | 6.42 | 0.8 | 159.2 |
| | 297.19 | 6.19 | 6.24 | 0.9 | 163.8 |
| | 298.39 | 5.98 | 6.04 | 1.0 | 169.4 |
| | 299.37 | 5.89 | 5.89 | 0.0 | 172.0 |
| | 300.15 | 5.80 | 5.77 | 0.5 | 174.8 |
| | 301.10 | 5.61 | 5.63 | 0.3 | 180.5 |
| | 302.13 | 5.43 | 5.48 | 1.1 | 186.7 |
| | 302.93 | 5.35 | 5.38 | 0.5 | 189.5 |
| N ₂ O | 290.36 | 5.49 | 5.53 | 0.6 | 184.4 |
| | 291.36 | 5.38 | 5.36 | 0.4 | 188.4 |
| | 292.36 | 5.17 | 5.19 | 0.4 | 196.1 |
| | 293.30 | 5.03 | 5.04 | 0.2 | 201.5 |
| | 294.20 | 4.93 | 4.90 | 0.5 | 205.5 |
| | 295.40 | 4.71 | 4.73 | 0.3 | 214.9 |
| | 296.15 | 4.66 | 4.63 | 0.8 | 217.2 |
| | 297.25 | 4.49 | 4.48 | 0.3 | 225.6 |
| | 298.13 | 4.38 | 4.37 | 0.2 | 231.5 |
| | 299.07 | 4.28 | 4.25 | 0.7 | 236.6 |
| | 300.16 | 4.13 | 4.12 | 0.2 | 245.2 |
| | 301.15 | 3.97 | 4.01 | 1.0 | 255.0 |
| | 302.15 | 3.84 | 3.90 | 1.7 | 263.9 |
| | 303.13 | 3.81 | 3.80 | 0.0 | 266.3 |

$$^{(a)} \sigma(\%) = \left| \frac{x_2 - x_{2lit}}{x_{2lit}} \right| \times 100, \text{ where } x_2 \text{ represents the solubility value found in this work and } x_{2lit} \text{ is obtained from Reference 8.}$$

| Solute | A/(J K ⁻¹ mol ⁻¹) | B/(J mol ⁻¹) | C/(J K ⁻¹ mol ⁻¹) | AAD(%) |
|------------------|--|--------------------------|--|--------|
| CO ₂ | -2785.2 | 138287.6 | 396.617 | 0.5 |
| N ₂ O | 890.1 | -23763.0 | -153.526 | 0.5 |

deviation of x_2 , defined as,

$$\text{AAD} = (1/M) \sum \left[\left| x_2(\text{exp}) - x_2(\text{calc}) \right| / x_2(\text{exp}) \right] \times 100 \quad (19)$$

where M is the number of experimental points, are listed in Table 2 (previous page).

In Figure 3 (p. 150) we have plotted the experimental solubility data and the fitted Eq. (18) for each system. The agreement is good.

CONCLUSIONS

The apparatus used here to measure the solubility of gas in a liquid is simple and clearly illustrates this concept. It combines easy handling with automated data retrieval, leading to experimental results with reasonable accuracy for a pedagogical experiment.

The treatment of the raw data to obtain the solubilities is a good application and demonstration of some gas laws (Dalton's law of partial pressures, Raoult's and Henry's laws). This experiment also gives the opportunity to demonstrate real behavior of a gas (through the fugacity concept) to the students. The analysis of errors will allow evaluation of the relative magnitudes of the uncertainties within the measured variables and how they propagate to the final result, the solubility.

ACKNOWLEDGMENT

This work was carried out under Research Project POCTI/EQU 44056/2002 financed by FCT—Fundação para a Ciência e Tecnologia (Portugal) and FEDER. We thank Professor Margarida F. Costa Gomes from the Laboratoire de Thermodynamique des Solutions et des Polymères, Université Blaise Pascal, Clermont-Ferrand, for her advice related to the assembly of the solubility apparatus.

NOMENCLATURE

| | |
|-------------|--|
| A, B, and C | parameters of Eq. (18) |
| f_2^L | fugacity of component 2 in the liquid phase [Pa] |
| $f_2^{*,L}$ | fugacity of pure liquid 2 [Pa] |
| f_2^G | fugacity of component 2 in the vapor phase [Pa] |
| f_2^0 | standard-state fugacity of component 2 [Pa] |
| $H_{2,1}$ | Henry constant of component 2 in solvent 1 [MPa] |
| n_1 | amount of solvent [mol] |
| n_2 | amount of solute [mol] |
| n_p | number of encoder pulses |
| P | equilibrium pressure [Pa] |
| P_2 | partial pressure of component 2 [Pa] |
| P_2^* | vapor pressure of pure component 2 [Pa] |
| P_1^* | vapor pressure of pure component 1 [Pa] |
| R | ideal gas constant [$\text{J mol}^{-1} \text{K}^{-1}$] |
| T | equilibrium temperature [K] |
| ΔV | volume of dissolved gas [m^3] |
| x_2 | mole fraction of component 2 in the liquid phase |
| y_2 | mole fraction of component 2 in the vapor phase |

Greek symbols

| | |
|-------------|--|
| Δh | displacement of the piston [m] |
| φ_2 | fugacity coefficient of component 2 in the vapor phase |

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APPENDIX A

The experimental procedure to determine the solubility of a gas in a liquid using the apparatus shown in Figure 2 is as follows:

- 1) Connect the lecture bottle to the solubility apparatus by means of a pressure reducer.
- 2) With the valve of the lecture bottle closed, open the valve of the pressure reducer.
- 3) Switch on the vacuum pump and open stopcocks V1, V3, and V4 with V2 closed. Evacuate the whole apparatus during 1 h.
- 4) Close the stopcocks. Remove the equilibrium vessel from the line, lowering the level of the thermostat bath in order for the connector of the equilibrium vessel to be out of the water.
- 5) Introduce $\sim 6 \text{ cm}^3$ of water in the equilibrium vessel.
- 6) Connect EQ again to the vacuum line and re-establish the initial position of the thermostat bath.
- 7) In order to degas the water, open V2 and V4. Switch on the stirrer. This procedure lasts about 30 min until the measured pressure equals the solvent vapor pressure at the equilibrium temperature.
- 8) Close stopcocks V2 and V4 and remove the equilibrium vessel again from the line.
- 9) Weigh the equilibrium vessel and then connect it to the vacuum line, re-establishing the level of water bath using the elevator.
- 10) Open stopcock V2, (with V3 and V4 closed). Then slowly open stopcock V1 to admit the gas to the equilibrium vessel.

- 11) Slightly open the valve of the pressure reducer and then the valve of the lecture bottle in order to adjust the total pressure to ~ 1 atm (reference pressure).
- 12) Close stopcock V1 and open V3.
- 13) Switch on the magnetic stirrer to promote contact between the liquid and vapor phases.
- 14) The dissolution process lasts about 2 h. As the gas dissolves the pressure decreases, which is detected by PT. The piston comes slowly down to re-establish the reference pressure.
- 15) Record the last constant value displayed by PC, which is the number of pulses (n_p) of the linear actuator.
- 16) To convert n_p in displacement of the piston use the conversion factor indicated in the user manual of the linear actuator. The value obtained must be multiplied by the internal crosssection area of the cylindrical gas burette to obtain the volume of the dissolved gas (ΔV).

placement of the piston, using the conversion factor indicated in the user manual of PC. Using Eq. (9) calculate ΔV , the volume of gas dissolved in the liquid.

- Write a simple computer program to calculate the solubility of the gas and the Henry coefficient, at a partial pressure of 101325 Pa.

Results: x'_2 represents the mole fraction solubility calculated with Eqs. (9-17); φ_1 the fugacity of the solvent in the vapor phase obtained from Eq. (16); φ_1^* the fugacity coefficient of pure solvent in saturation conditions, from Eq. (17); x_2 is the corrected solubility at partial pressure $P_2 = 101325$

| T / K | $x'_2/10^4$ | φ_1 | φ^* | $x_2/10^4$ | $H_{2,1}/(\text{MPa})$ |
|--------|-------------|-------------|-------------|------------|------------------------|
| 298.39 | 5.88 | 0.9880 | 0.9985 | 5.98 | 169.4 |

Pa; $H_{2,1}$ is the Henry coefficient.

Error analysis

- What are the uncertainties of the measured variables?
- Using these uncertainties and the propagation law of errors, determine the uncertainty in the final result, the mole fraction solubility.
- Which uncertainty most affects the solubility value?
- Using your own results of solubility data and some of the results of other groups (at least 6 pairs of experimental data), make a fitting by a least squares method of the equation:

$$R \ln x_2 = A + B/T + C \ln T$$

to represent the temperature dependence of the solubility.

- Calculate the average absolute deviation of the fitting.
- Compare your solubility data with those of the literature. □

APPENDIX B

(The data presented in the following tables was obtained by a group of students.)

Entrance form for G/L solubility data

Gas: CO_2

Solvent: water

Raw data: n_p is the number of encoder pulses; T is the equilibrium temperature; P is the reference pressure; m_1 is the mass of the solvent.

| T / K | n_p | P / Pa | m_1 / kg |
|--------|-------|--------|------------|
| 298.39 | 82346 | 100070 | 0.007737 |

Treatment of the experimental data

- The value of n_p must be converted in Δh , the dis-

MIXING HOT AND COLD WATER STREAMS AT A T-JUNCTION

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Chemical Engineering students at the University of Alberta are taught how to write technical reports in the first term of their third year. At this point they have a very limited background, having only taken introductory thermodynamics and a mass and energy balance course. The objectives of this course are to provide a bridge between theoretical study and practical applications, and to apply these principles to critical analysis of real experimental data in a professional, clearly written, and concise format. Furthermore, the experiment described in this paper exposes many students to their first look at real equipment and measuring devices.

To teach entry-level chemical engineering students with limited theoretical and statistical analysis background to write technical reports and apply material and energy balance principles to a critical analysis of real data, it is necessary to use a simple experiment. Most previous studies involving the mixing of heated water require dynamic analysis of stirred-tank heaters;^[1, 2] however, students with a limited background would have trouble with the theory of such systems. A simpler experiment is the mixing of hot and cold water at a T-junction. This experiment can be used to demonstrate how to use steady-state material and energy balances as a troubleshooting tool to predict flow rates and temperatures of the mixed water stream. Also, this experiment emphasizes the importance of properly placing process measurement devices, *i.e.*, the thermocouples in the current experiment. Furthermore, material and energy balances can also be used to check flow rate calibration equations of the orifice meters for each of the experimental streams. It is important for students to learn the importance of proper calibration in process measuring devices since calibration equations can change over time due to corrosion, erosion, or scale buildup during its use.

THEORY

For any given continuous, nonreactive process at steady-state, the general material and energy balances can be written as (Felder and Rousseau^[3]):

$$\sum m_{\text{out}} - \sum m_{\text{in}} = 0 \quad (1)$$

$$\dot{Q} - \dot{W} = \sum m_{\text{out}} \left(h_{\text{out}} + \frac{U_{\text{out}}^2}{2} + gz_{\text{out}} \right) - \sum m_{\text{in}} \left(h_{\text{in}} + \frac{U_{\text{in}}^2}{2} + gz_{\text{in}} \right) \quad (2)$$

David Sharp is a faculty service officer at the University of Alberta. He received his BS.c. and MS.c. in chemical engineering from the University of Alberta. He has been teaching entry- and senior-level undergraduate laboratory courses. His research interests are in the area of surface phenomena, computational fluid dynamics, and separation processes.

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In the present study, hot- and cold-water streams are mixed at a T-junction to produce one mixed stream. Assuming the hot- and cold-water streams are completely mixed at the T-junction, the system is adiabatic, work is neither done by or to the system, there are no frictional losses, and that kinetic and potential energy changes are negligible, Eq. (1) and Eq. (2) can be reduced to

$$m_{\text{mix,pred}} = m_{\text{cold}} + m_{\text{hot}} \quad (3)$$

$$m_{\text{mix,meas}} h_{\text{mix}} = m_{\text{cold}} h_{\text{cold}} + m_{\text{hot}} h_{\text{hot}} \quad (4)$$

where h is the enthalpy of each stream and can be defined as (Cengel and Boles^[4]):

$$h = C_p (T - T_0) \quad (5)$$

By setting the reference temperature to 0°C and assuming the heat capacity, C_p , is constant for water in the temperature range investigated in the experiment (15 to 50°C), the temperature of the mixed stream could be predicted by combining Eq. (4) and Eq. (5) to give

$$T_{\text{pred}} = \frac{m_{\text{cold}} T_{\text{cold}} + m_{\text{hot}} T_{\text{hot}}}{m_{\text{mix,meas}}} \quad (6)$$

The predicted temperature of the mixed stream using Eq. (6) is dependent upon measured information of the streams before and after the T-junction. In order to determine which (if any) mass flow rate is wrong, Eq. (3) and Eq. (6) can be solved simultaneously to predict the mixed stream temperature. For example, if the mass flow rate of the cold stream is assumed to be wrong, the temperature of the mixed stream can be predicted by replacing the cold stream flow rate using Eq. (3) to give the predicted temperature as

$$T_{\text{pred,no } m_{\text{cold}}} = \frac{(m_{\text{mix,meas}} - m_{\text{hot}}) T_{\text{cold}} + m_{\text{hot}} T_{\text{hot}}}{m_{\text{mix,meas}}} \quad (7)$$

Similarly, if the mass flow rate of the hot or mixed stream is assumed to be wrong, the predicted mixed stream temperature can be calculated by

$$T_{\text{pred, no } m_{\text{hot}}} = \frac{m_{\text{cold}} T_{\text{cold}} + (m_{\text{mix,meas}} - m_{\text{cold}}) T_{\text{hot}}}{m_{\text{mix,meas}}} \quad (8)$$

$$T_{\text{pred, no } m_{\text{mix}}} = \frac{m_{\text{cold}} T_{\text{cold}} + m_{\text{hot}} T_{\text{hot}}}{(m_{\text{cold}} + m_{\text{hot}})} \quad (9)$$

If all three measured mass-flow rates are correct, then Eq. (7), Eq. (8), and Eq. (9) will all give the same value for $T_{\text{pred,mix}}$. If one calibration equation is incorrect, however, then only one of those three equations will accurately predict the mixed stream temperature, which will agree with the measured temperatures after the T-junction and therefore indicate that the mass flow rate of the missing stream in the equation is incorrect.

EXPERIMENTAL SETUP AND PROCEDURE

The experimental setup is shown in Figure 1. The entire setup is constructed using half-inch nominal copper pipe, fittings, and brass valves. The feed lines are connected to the domestic hot and cold water supply lines. The hot and cold water streams are mixed at a T-junction before exiting into the drain. As can be seen from this figure the experiment can be done with the hot and cold water streams flowing through either of the inlet lines by setting the appropriate valve combination at the inlet manifold. The flow rate of the water is controlled using globe valves and can be roughly set using

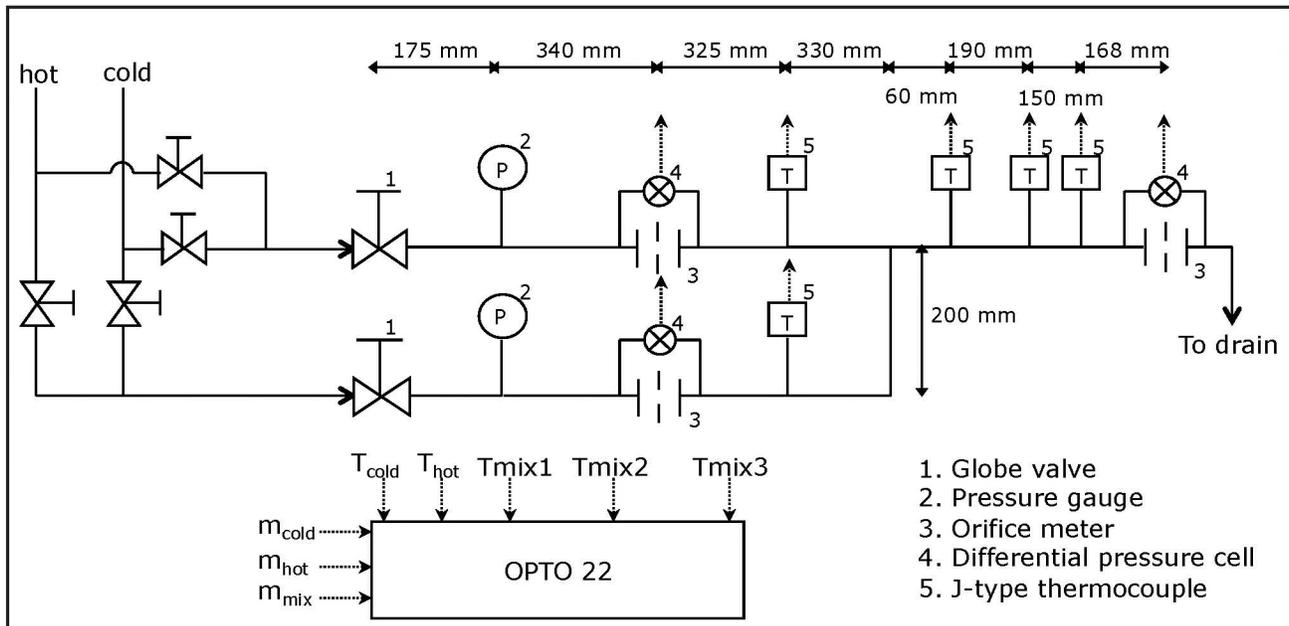


Figure 1. Schematic Diagram.

the pressure gauges (Wika). The flow rates of the hot, cold, and mixed streams are measured using a combination of an orifice meter and differential pressure cell (Validyne). The fluid temperatures are measured using J-type thermocouples. The temperature of the mixed stream is measured at 60 mm (T_{mix1}), 250 mm (T_{mix2}), and 400 mm (T_{mix3}) after the T-junction. This is done to determine the proper location for the thermocouple in order to measure the correct temperature of the mixed stream. The detailed locations of other thermocouples, orifice meters, pressure gauges, and globe valves are also shown in Figure 1. Analog signals from the differential pressure cells and thermocouples are converted to digital signals using an OPTO 22 system. These signals are sent to the personal computer, where they are stored and displayed using LabView (version 7.1) software. In this experiment, the mass flow rates of the hot, cold, and mixed streams are recorded in terms of volts and temperatures are recorded in terms of degrees Celsius. The following orifice calibration equations are needed to convert volt readings to mass flow rates.

$$m_{\text{cold}} = 0.0265\sqrt{V_{\text{cold}}} \quad (10)$$

$$m_{\text{hot}} = 0.0251\sqrt{V_{\text{hot}}} \quad (11)$$

$$m_{\text{mix, meas}} = 0.0473\sqrt{V_{\text{mix}}} \quad (12)$$

All three calibration equations have a systematic error (accuracy) of $\pm 5\%$. To run the experiment, the flow rates of the hot and cold water must be set using the globe valves in conjunction with the pressure gauges. The data acquisition system must be initiated to record the five temperature and three flow rate readings at a set time interval (usually set at either 2 or 5 seconds). When the flow rate and temperature profiles shown by the software remain constant, steady-state can be assumed for that run. At least 100 seconds worth of data for each run should be recorded to ensure the system is at steady-state and to get sufficient sample points for a reasonable analysis. The same experimental procedure is then repeated at different flow rate settings as many times as possible (this depends on class size and laboratory availability), and if reproducibility is to be examined then at least one flow rate setting must be repeated multiple times. The entire experiment can be completed in 10 to 30 minutes, depending on the number of runs students conduct. The short time span of the experiment and large number of flow rate combinations enables even large classes to do individual experiments in a rather short time period. The data is recorded in a Microsoft Excel file that contains the hot, cold, and mixed stream voltage readings from the DP/cell's and the temperatures in $^{\circ}\text{C}$ from the thermocouples.

RESULTS AND DISCUSSION

For this example, five separate runs at various hot- and cold-water flow rates were conducted to illustrate the principles of material and energy balances. Additionally, four more runs were conducted to show the reproducibility of the data. When

comparing experimental and predicted results it is necessary to do an error analysis on the variables being compared. The total error for an experimental value can be determined from the sum of the systematic (accuracy) and random (precision) errors of the data. The accuracy error comes from the maximum absolute error in calibration of the measuring device. For this study, the maximum absolute errors in the calibration equations for the measured mass flow rates and temperatures are $\pm 5\%$ and $\pm 0.3^{\circ}\text{C}$, respectively. The precision error can be obtained directly from the standard deviation, σ , of the measured values. To determine the precision error, Coleman and Steele^[5] state that when the number of data points for one time series is equal to or greater than 10, two times the standard deviation gives a good approximation for the 95% confidence interval. Therefore, the total error in the measured mass flow rates and temperatures is calculated by

$$\omega_m = \pm [0.05m + 2\sigma] \quad (13)$$

$$\omega_T = \pm [0.3 + 2\sigma] \quad (14)$$

In order to illustrate how material and energy balances can be used to determine an incorrect calibration and to predict exit stream temperature, orifice calibration Eq. (10) for the cold stream was changed to (without the students knowledge)

$$m_{\text{cold}} = 0.0168\sqrt{V_{\text{cold}}} \quad (15)$$

The students are then expected to find the incorrect calibration equation and to develop a new orifice calibration equation to fit the data they have.

Figures 2 and 3 show the measured mass flow rates and temperatures as well as the predicted values for all five runs as a function of time, respectively. The measured cold, hot and mixed stream flow rates were calculated using the calibration Eq. (15), Eq. (11), and Eq. (12), respectively. The predicted mass flow rate for the mixed stream was calculated using Eq. (3). For these calculations the average hot- and cold-water flow rates over each steady-state period were used. The predicted temperature of the mixed stream was calculated using Eq. (6) and time-averaged mass flow rates and temperatures for the hot, cold, and mixed stream water streams. The uncertainty for the predicted mass flow rate and temperature of the mixed stream were calculated using the method described by Coleman and Steele^[5] and Holman.^[6] The uncertainty in the predicted mass flow rate is based on experimental errors in the measured hot- and cold-water stream flow rates and can be calculated by

$$\omega_{m_{\text{mix, pred}}} = \pm \left[\left(\frac{\partial m_{\text{mix, pred}}}{\partial m_{\text{cold}}} \omega_{m_{\text{cold}}} \right)^2 + \left(\frac{\partial m_{\text{mix, pred}}}{\partial m_{\text{hot}}} \omega_{m_{\text{hot}}} \right)^2 \right]^{1/2} \quad (16)$$

Similarly, the uncertainty in the predicted temperatures obtained from Eq. (6) to Eq. (9) can be determined from the errors in the measured hot, cold, and mixed stream flow rates

as well as the measured hot and cold stream temperatures. The uncertainty in the predicted temperature is given by

$$\omega_{T_{pred}} = \pm \left[\left(\frac{\partial T_{pred}}{\partial m_{hot}} \omega_{m_{hot}} \right)^2 + \left(\frac{\partial T_{pred}}{\partial m_{cold}} \omega_{m_{cold}} \right)^2 + \left(\frac{\partial T_{pred}}{\partial m_{mix,meas}} \omega_{m_{mix,meas}} \right)^2 + \left(\frac{\partial T_{pred}}{\partial m_{hot}} \omega_{T_{hot}} \right)^2 + \left(\frac{\partial T_{pred}}{\partial m_{cold}} \omega_{T_{cold}} \right)^2 \right]^{1/2} \quad (17)$$

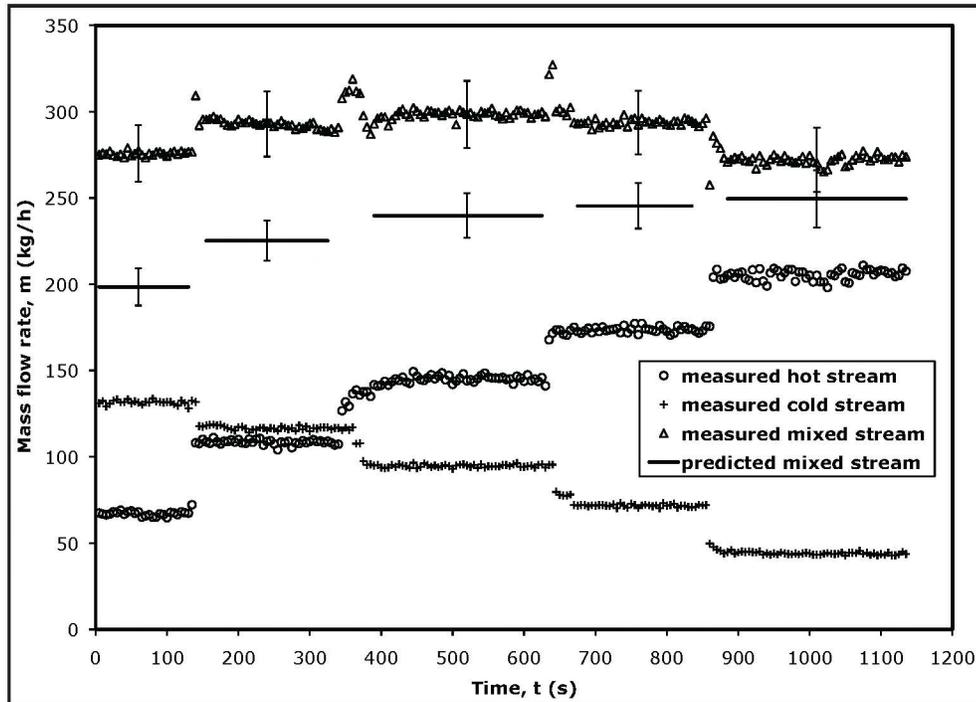
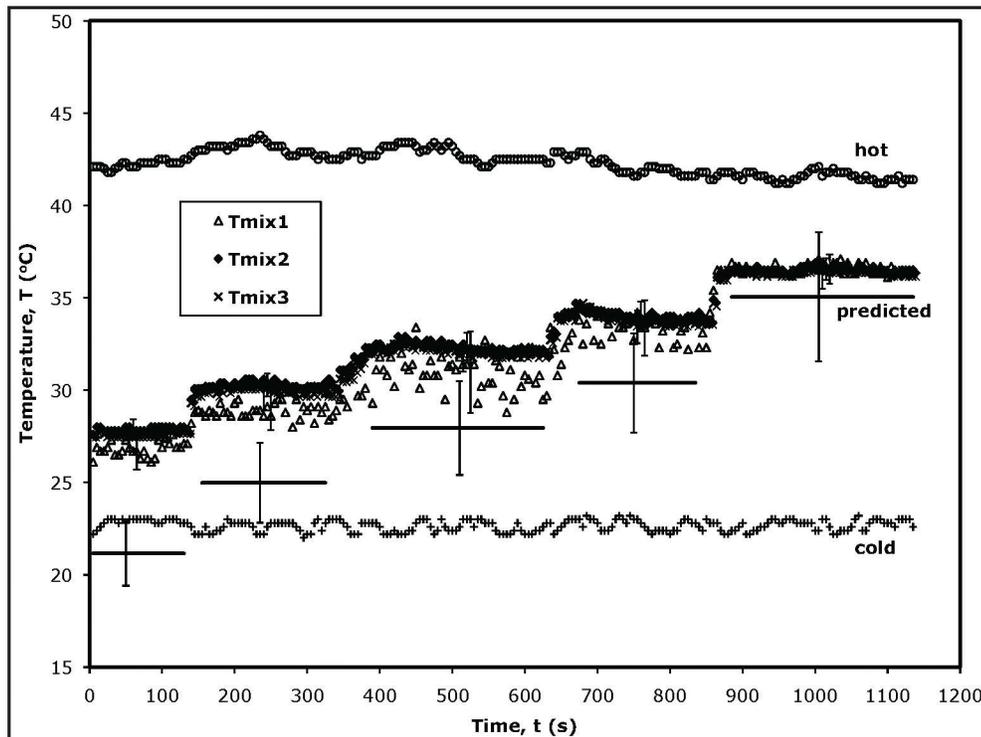


Figure 2. Mass flow rates of hot, cold, and measured and predicted mixed streams for five steady-state runs.



From these figures it is evident that there were five distinct steady-state periods having time ranges of 0 to 130 s, 155 to 325 s, 390 to 625 s, 675 to 835 s, and 885 to 1135 s. The constant flow rate profiles of the measured values in Figure 2 indicate that the system was indeed behaving at steady-state for each of the five runs. This is also evident in Figure 3 where the measured temperatures before and after the T-junction remain constant for each stream and steady-state period. Since the system is non-reactive and is at steady-state, the material balance equation, shown in Eq. (3) should be valid. Figure 2, however, clearly shows that the predicted flow rate of the mixed stream does not agree, within error, with the measured mixed stream flow rate for the first four runs—leading to the conclusion that one, or more, of the orifice calibration equations must be incorrect.

The mixed stream temperature when measured only 60 mm (Tmix1) downstream of the T-junction has larger error bars and is always approximately 1°C lower compared to the temperatures measured at 270 mm (Tmix2) and 400 mm (Tmix3) downstream of the T-junction, as shown in Figure 3. The error bars were calculated by assuming each thermocouple has the same systematic

Figure 3. Temperatures of hot, cold, measured mixed and predicted mixed water streams for five steady-state runs.

(accuracy) error of ± 0.3 °C. Therefore, the larger total error determined at the Tmix1 location must be only due to higher standard deviations. This, combined with the fact that the measured average temperature reading at the Tmix1 location is lower than the temperatures measured at the Tmix2 and Tmix3 locations, indicates that at the thermocouple closest to the T-junction the two streams have not completely mixed. Furthermore, the measured temperatures at the Tmix2 and Tmix3 locations are not only very similar, but also have very similar size error bars, which indicates that a thermocouple needs to be placed a minimum of 270 mm downstream of the T-junction to ensure complete mixing. Figure 3 also shows that the predicted temperature does not agree within error with the measured values at Tmix2 or Tmix3 for the first four runs, again indicating that there is likely an incorrect calibration equation. For each run, the difference between the measured and predicted temperatures is decreasing until the fifth run, where the measured and predicted values agree within experimental error. This agreement is likely due to the decreasing cold stream flow rate, which has less of an effect on the predicted temperature of the mixed stream.

To determine which calibration equation was incorrect, material and energy balances were solved simultaneously to predict the mixed stream temperature, which can be compared with the measured values. Table 1 shows the average temperature measured at 270 mm downstream of the T-junction (Tmix2) as well as three predicted mixed stream temperatures calculated by eliminating one of the mass flow rate terms in the energy balance equation. The mixed stream temperature was calculated using Eq. (7), Eq. (8), or Eq. (9) by eliminating the use of the flow rate readings of the cold, hot, or mixed streams, respectively. From this table, it is evident that the only predicted temperature that agrees within error of the measured temperature for all five runs is the one in which the flow rate of the cold stream, m_{cold} , is eliminated from the calculation. This finding indicates that the cold stream flow rate calibration equation was incorrect. Using linear regression analysis between the corrected flow rates of the cold stream

| Run | Tmix2 (°C) | T _{pred,nom_{cold}} (°C) | T _{pred,nom_{hot}} (°C) | T _{pred,nom_{mix}} (°C) |
|-----|------------|---|--|--|
| 1 | 27.9 ± 0.5 | 27.6 ± 0.7 | 33.5 ± 1.0 | 29.4 ± 0.7 |
| 2 | 30.3 ± 0.6 | 30.2 ± 1.0 | 34.9 ± 1.0 | 32.5 ± 0.8 |
| 3 | 32.4 ± 0.8 | 32.4 ± 1.2 | 36.4 ± 1.0 | 34.8 ± 0.9 |
| 4 | 34.1 ± 0.7 | 34.1 ± 1.3 | 37.3 ± 1.0 | 36.4 ± 0.9 |
| 5 | 36.5 ± 0.6 | 36.9 ± 1.6 | 38.5 ± 0.7 | 38.2 ± 0.7 |

| Run | m _{hot} (kg/h) | m _{cold} (kg/h) | m _{mix} (kg/h) |
|--------------------|-------------------------|--------------------------|-------------------------|
| 1 | 67.0 ± 5.7 | 131.5 ± 9.1 | 275.7 ± 16.4 |
| Standard deviation | 1.2 | 1.3 | 1.3 |
| 2 | 108.6 ± 8.2 | 116.7 ± 8.1 | 292.9 ± 18.9 |
| Standard deviation | 1.4 | 1.2 | 2.1 |
| 3 | 145.0 ± 11.2 | 94.7 ± 6.4 | 298.4 ± 19.5 |
| Standard deviation | 2.0 | 0.8 | 2.3 |
| 4 | 173.7 ± 12.1 | 71.7 ± 5.1 | 293.7 ± 18.4 |
| Standard deviation | 1.7 | 0.8 | 1.9 |
| 5 | 205.5 ± 16.2 | 44.0 ± 3.6 | 272.1 ± 18.6 |
| Standard deviation | 3.0 | 0.7 | 2.5 |

| Run | m _{hot} (kg/h) | m _{cold} (kg/h) | T _{hot} (°C) | T _{cold} (°C) |
|-----|-------------------------|--------------------------|-----------------------|------------------------|
| 3 | 145.0 ± 11.2 | 94.7 ± 6.4 | 42.8 ± 1.1 | 22.5 ± 0.9 |
| 6 | 145.6 ± 11.6 | 99.1 ± 8.6 | 41.7 ± 0.6 | 22.8 ± 0.9 |
| 7 | 144.1 ± 9.0 | 97.3 ± 7.2 | 41.9 ± 0.8 | 22.8 ± 0.8 |
| 8 | 144.4 ± 13.2 | 97.4 ± 6.9 | 42.1 ± 0.5 | 23.1 ± 0.6 |
| 9 | 148.0 ± 10.1 | 96.5 ± 7.6 | 42.7 ± 0.8 | 22.7 ± 0.9 |

obtained from Eq. (3) and the corresponding average voltage readings of the cold stream for the five runs, the correct calibration equation was determined to be

$$m_{\text{cold}} = 0.0268\sqrt{V_{\text{cold}}} \quad (18)$$

This equation is valid for voltage readings between 0.5 and 4.7 Volts, corresponding to flow rates of 66 to 210 kg/h. The R² value is 0.996, so the calibration equation should be quite accurate.

Students can also use error analysis to explain or discuss trends observed in the experimental data. Table 2 shows the measured average mass flow rate of the hot, cold, and mixed streams with total errors and the corresponding standard deviations for each steady-state run. From this table, it can be seen that the total error in the measured hot and cold streams increase as the flow rates of both streams increases. Since the total error for the experimental values was determined from both the accuracy and precision of the data, the total error

increase in the measured values is due to the increase in both the flow rates and the standard deviations in both streams as shown in Table 2. Similar observations and discussions can be made for the mixed stream.

The reproducibility of the study was also examined by repeating one of the runs four times. The time average values of the hot and cold stream flow rates and temperatures are shown for the five runs in Table 3. The flow rate of each stream was readjusted between runs and reset to the same value. Even though the way in which the flow rate is set by the student is very crude (a globe valve and a pressure gauge) and both streams were connected to the domestic cold and hot water supply lines, it can be seen that flow rates for the cold stream and for the hot stream are all within experimental error of each other—verifying the reproducibility of the flow rate settings. Table 3 also shows that the hot and cold temperatures agree within experimental error and the supply temperatures remained relatively constant for all repeat runs.

It should be noted that the experiment outlined in this report is only one of many possible ways in which the students can be asked to analyze this system. A few other examples include: 1) the thermocouples could be setup so that one or more was malfunctioning, with students asked to determine which one(s) are malfunctioning and why; 2) only one or two calibration equations could be given to the students and they then asked to determine the unknown ones; 3) all given information could be correct allowing the students to test material and energy balance principles used to predict a mixed stream flow rate and temperature. Depending on the setup and number of runs conducted, more or less emphasis could be placed on reproducibility of data and/or error analysis. To this end the experiment described here is fairly flexible and allows the instructor(s) to vary the experiment from year to year, while retaining the fundamentals.

CONCLUSIONS

A simple mixing of a hot- and cold-water stream at a T-junction was investigated. The main objective was to use mass and energy balance equations to predict mass flow rates and the temperature of the mixed stream after the T-junction, and then compare these with the measured values. Furthermore, the thermocouple location after the T-junction and the reproducibility of the data were also investigated.

It was found that the predicted mixed stream flow rate calculated using mass balance equations did not agree with the measured mixed stream flow rate for all five runs. It was concluded that one or more given orifice calibration equation must be wrong. In order to determine which orifice calibration equation was wrong, mass and energy balance equations were solved simultaneously to predict mixed stream temperature. It was found that when only the cold stream flow rate was eliminated from the energy balance, the predicted mixed stream temperature was found to agree with all three measured

mixed stream temperatures within experimental error for all five runs. This indicated that the given cold stream orifice calibration was wrong.

The mixed stream temperature measured at 60 mm (T_{mix1}) had a higher standard deviation error than the temperatures measured at 230 mm (T_{mix2}) and 400 mm (T_{mix3}) downstream of the T-junction for all five runs. It was also found that the temperatures measured at T_{mix2} and T_{mix3} locations had similar absolute and standard deviations and error values. Both observations indicated incomplete mixing at the T_{mix1} location. Therefore, to ensure complete mixing and minimize heat losses, the thermocouple should be placed at least 230 mm downstream of the T-junction.

The reproducibility of the experimental data was also studied by repeating one of the runs four times. It was found that the flow rates for hot and cold streams were all within error of each other, verifying the reproducibility of the hot and cold stream flow rate settings.

SUMMARY

In this paper, we proposed a simple experiment of mixing a hot- and cold-water stream at a T-junction to demonstrate how to use steady-state material and energy balance principles in troubleshooting of an existing process and determining the integrity and/or location of the measuring devices, such as thermocouples and orifice meters. This experiment is relatively inexpensive, requires little time to complete and is conceptually simple to understand, making it ideal for the undergraduate students who have a very limited chemical engineering background.

NOMENCLATURE

| | |
|-----------|--|
| C_p | Constant pressure specific heat, J/(kg °C) |
| g | Gravitational acceleration, m/s ² |
| m | Mass flow rate, kg/s |
| h | Enthalpy, J/kg |
| \dot{Q} | Heat transfer rate, W |
| T | Temperature, °C |
| T_0 | Reference Temperature, °C |
| U | Velocity, m/s |
| V | Pressure drop across orifice, Volts |
| \dot{W} | Work input to the system, W |
| z | Elevation, m |
| σ | Standard deviation of random variable |
| ω | Error or uncertainty in a parameter |

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To teach entry-level chemical engineering students with limited theoretical and statistical analysis background to write technical reports and apply material and energy balance principles to a critical analysis of real data, it is necessary to use a simple experiment.

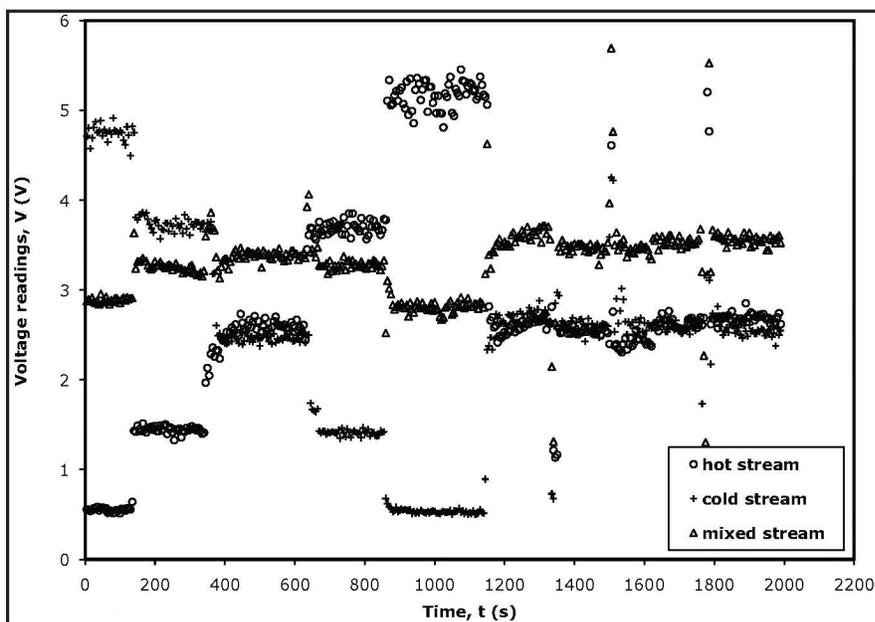


Figure A1. Voltage outputs from the DP/cells for the hot, cold, and measured mixed streams for all nine steady-state runs.

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APPENDIX A: SAMPLE DATA, CALCULATIONS AND ERROR ANALYSIS

Sample Data:

The raw data in terms of voltage vs. time and temperature vs. time are shown in Figures A1 and A2.

Sample calculations:

Using the calibration equations to get mass flow rates from known voltages (Figure A1):

Sample calculations based on the readings recorded at a time of 10 s.

$$\text{Hot stream voltage} = 0.547 \text{ V}$$

$$\text{Cold stream voltage} = 4.80 \text{ V}$$

$$\text{Mixed stream voltage} = 2.90 \text{ V}$$

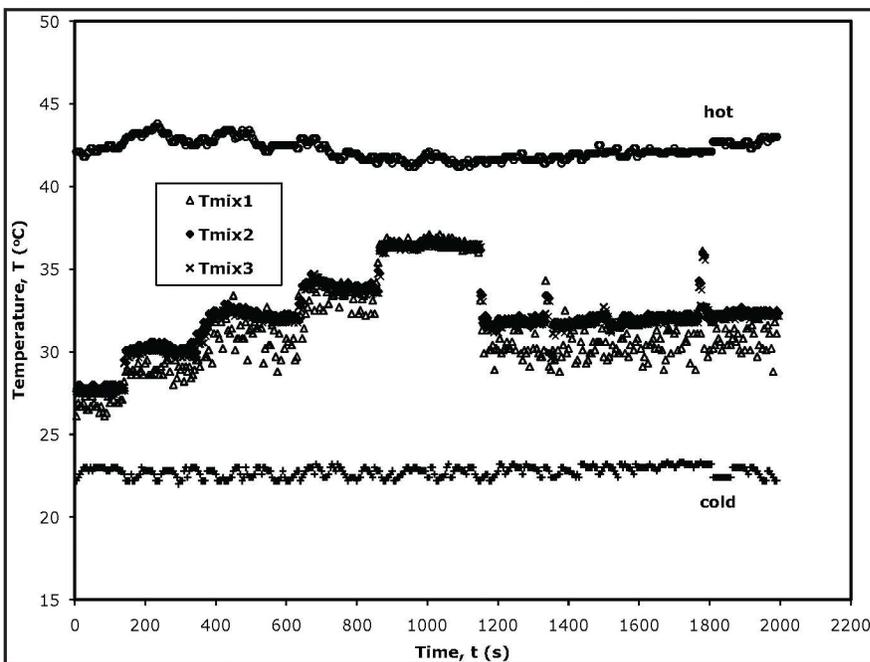


Figure A2. Temperatures of hot, cold, and measured mixed water streams for all nine steady-state runs.

To get the mass flow rates we use Eqs. (15), (11), and (12)

$$m_{\text{cold}} = 0.0168\sqrt{V_{\text{cold}}} = 0.0168\sqrt{4.80} = 0.0368 \text{ kg/s}$$

$$m_{\text{hot}} = 0.0251\sqrt{V_{\text{hot}}} = 0.0251\sqrt{0.547} = 0.0186 \text{ kg/s}$$

$$m_{\text{mix,meas}} = 0.0473\sqrt{V_{\text{mix}}} = 0.0473\sqrt{2.9} = 0.0805 \text{ kg/s}$$

The predicted mixed stream flow rate was calculated using the steady-state material balance (Eq. (3)) and average values for flow rates. The average cold stream flow rate for the first run was 0.0365 kg/s, for the hot stream it was 0.0186 kg/s, and for the measured mixed stream it was 0.0766 kg/s. Therefore, for the first run, the predicted mass flow rate of the mixed stream is

$$m_{\text{mix,pred}} = m_{\text{cold}} + m_{\text{hot}} = 0.0365 \text{ kg/s} + 0.0186 \text{ kg/s} = 0.0551 \text{ kg/s}$$

The predicted temperature of the mixed stream was calculated from Eq. (6) using average values for run 1.

$$T_{\text{pred}} = \frac{m_{\text{cold}} T_{\text{cold}} + m_{\text{hot}} T_{\text{hot}}}{m_{\text{mix,meas}}} = \left[\frac{0.0365 \cdot 22.9 + 0.0186 \cdot 42.2}{0.0766} \right] = 21.2$$

Assuming that the cold stream calibration equation is wrong, Eq. (7) can be used to predict the temperature from the average values for the first run.

$$T_{\text{pred,no m}_{\text{cold}}} = \frac{(m_{\text{mix,meas}} - m_{\text{hot}}) T_{\text{cold}} + m_{\text{hot}} T_{\text{hot}}}{m_{\text{mix,meas}}} = \frac{(0.0766 - 0.0186) 22.9 + 0.0186 \cdot 42.2}{0.0766} = 27.6^{\circ}\text{C}$$

Assuming that the hot stream calibration equation is wrong, Eq. (8) can be used to predict the temperature from the average values for the first run.

$$T_{\text{pred,no m}_{\text{hot}}} = \frac{m_{\text{cold}} T_{\text{cold}} + (m_{\text{mix,meas}} - m_{\text{cold}}) T_{\text{hot}}}{m_{\text{mix,meas}}} = \frac{0.0365 \cdot 22.9 + (0.0766 - 0.0356) 42.2}{0.0766} = 33.5^{\circ}\text{C}$$

Assuming that the mixed stream calibration equation is wrong, Eq. (9) can be used to predict the temperature from the average values for the first run

$$T_{\text{pred,no m}_{\text{mix}}} = \frac{m_{\text{cold}} T_{\text{cold}} + m_{\text{hot}} T_{\text{hot}}}{(m_{\text{cold}} + m_{\text{hot}})} = \frac{0.0365 \cdot 22.9 + 0.0186 \cdot 42.2}{0.0365 + 0.0186} = 29.4^{\circ}\text{C}$$

Error analysis:

The error in the measured flow rates is given as the maximum absolute error in the calibration equation plus two standard deviations. For the mass flow rates the systematic error (accuracy) was $\pm 5\%$ for the full scale. For the first run it was determined that the standard deviations were 0.000355 kg/s, 0.000325 kg/s, and 0.000367 kg/s for the cold, hot, and mixed streams, respectively. For the first run these standard deviations were based on 26 data points. Therefore, the total experimental error for the mass flow rates is:

$$\text{Cold Stream : } \omega_{m_{\text{cold}}} = \pm [0.05 m_{\text{cold}} + 2\sigma_{m_{\text{cold}}}] = \pm [0.05 \cdot 0.0365 + 2 \cdot 0.000355] = \pm 0.00254 \text{ kg/s}$$

$$\text{Hot Stream : } \omega_{m_{\text{hot}}} = \pm [0.05 m_{\text{hot}} + 2\sigma_{m_{\text{hot}}}] = \pm [0.05 \cdot 0.0186 + 2 \cdot 0.000325] = \pm 0.00158 \text{ kg/s}$$

$$\text{Mixed Stream : } \omega_{m_{\text{mix,meas}}} = \pm [0.05 m_{\text{mix,meas}} + 2\sigma_{m_{\text{mix,meas}}}] = \pm [0.05 \cdot 0.0766 + 2 \cdot 0.000367] = \pm 0.00456 \text{ kg/s}$$

For the temperatures the systematic error (accuracy) was $\pm 0.3^{\circ}\text{C}$ for the full scale. For the first run it was determined that the standard deviations were 0.20°C , 0.19°C , 0.40°C , 0.12°C , and 0.09°C for the cold, hot, mix1, mix2, and mix3 thermocouples, respectively. For the first run these standard deviations were based on 26 data points. Therefore, the total experimental error for the mass flow rates is:

$$\text{Cold thermocouple : } \omega_{T_{\text{cold}}} = \pm [0.3 + 2\sigma_{T_{\text{cold}}}] = \pm [0.3 + 2 \cdot 0.20] = \pm 0.70^{\circ}\text{C}$$

$$\text{Hot thermocouple : } \omega_{T_{\text{hot}}} = \pm [0.3 + 2\sigma_{T_{\text{hot}}}] = \pm [0.3 + 2 \cdot 0.19] = \pm 0.68^{\circ}\text{C}$$

$$\text{Mix1 thermocouple : } \omega_{T_{\text{mix1}}} = \pm [0.3 + 2\sigma_{T_{\text{mix1}}}] = \pm [0.3 + 2 \cdot 0.40] = \pm 1.10^{\circ}\text{C}$$

$$\text{Mix2 thermocouple : } \omega_{T_{\text{mix2}}} = \pm [0.3 + 2\sigma_{T_{\text{mix2}}}] = \pm [0.3 + 2 \cdot 0.12] = \pm 0.54^{\circ}\text{C}$$

$$\text{Mix3 thermocouple : } \omega_{T_{\text{mix3}}} = \pm [0.3 + 2\sigma_{T_{\text{mix3}}}] = \pm [0.3 + 2 \cdot 0.09] = \pm 0.48^{\circ}\text{C}$$

Uncertainty in the predicted mixed stream mass flow rates is given by

$$\omega_{m_{\text{mix,pred}}} = \pm \left[\left(\frac{\partial m_{\text{mix,pred}}}{\partial m_{\text{cold}}} \omega_{m_{\text{cold}}} \right)^2 + \left(\frac{\partial m_{\text{mix,pred}}}{\partial m_{\text{hot}}} \omega_{m_{\text{hot}}} \right)^2 \right]^{1/2}$$

in this case both partial derivatives are equal to 1 so the uncertainty in the predicted mixed stream mass flow rate becomes

$$\omega_{m_{\text{mix,pred}}} = \pm \left[(\omega_{m_{\text{cold}}})^2 + (\omega_{m_{\text{hot}}})^2 \right]^{1/2} = \pm \left[(0.00254)^2 + (0.00158)^2 \right]^{1/2} = \pm 0.0030 \text{ kg/s}$$

The uncertainty in the predicted temperatures from Eqs. (6) to (9) is given by

$$\omega_{T_{\text{pred}}} = \pm \left[\left(\frac{\partial T_{\text{pred}}}{\partial m_{\text{hot}}} \omega_{m_{\text{hot}}} \right)^2 + \left(\frac{\partial T_{\text{pred}}}{\partial m_{\text{cold}}} \omega_{m_{\text{cold}}} \right)^2 + \left(\frac{\partial T_{\text{pred}}}{\partial m_{\text{mix,meas}}} \omega_{m_{\text{mix,meas}}} \right)^2 + \left(\frac{\partial T_{\text{pred}}}{\partial T_{\text{hot}}} \omega_{T_{\text{hot}}} \right)^2 + \left(\frac{\partial T_{\text{pred}}}{\partial T_{\text{cold}}} \omega_{T_{\text{cold}}} \right)^2 \right]^{1/2}$$

For the uncertainty in Eq. (6) the partial derivatives are

$$\begin{aligned} \frac{\partial T_{\text{pred}}}{\partial m_{\text{hot}}} &= \frac{T_{\text{hot}}}{m_{\text{mix,meas}}} = \frac{42.2}{0.0766} = 550.9 \frac{^\circ\text{C}}{\text{kg/s}} \\ \frac{\partial T_{\text{pred}}}{\partial m_{\text{cold}}} &= \frac{T_{\text{cold}}}{m_{\text{mix,meas}}} = \frac{22.9}{0.0766} = 299.0 \frac{^\circ\text{C}}{\text{kg/s}} \\ \frac{\partial T_{\text{pred}}}{\partial m_{\text{mix,meas}}} &= -\frac{(m_{\text{hot}} T_{\text{hot}} + m_{\text{cold}} T_{\text{cold}})}{(M_{\text{mix,meas}})^2} = -\frac{(0.0186 \bullet 42.2 + 0.0365 \bullet 22.9)}{(0.0766)^2} = -276.2 \frac{^\circ\text{C}}{\text{kg/s}} \\ \frac{\partial T_{\text{pred}}}{\partial T_{\text{hot}}} &= \frac{m_{\text{hot}}}{m_{\text{mix,meas}}} = \frac{0.0186}{0.0766} = 0.2428 \\ \frac{\partial T_{\text{pred}}}{\partial T_{\text{cold}}} &= \frac{m_{\text{cold}}}{m_{\text{mix,meas}}} = \frac{0.0365}{0.0766} = 0.4765 \end{aligned}$$

Then, the uncertainty in T_{pred} is

$$\omega_{T_{\text{pred}}} = \pm \left[(550.9 \bullet 0.00158)^2 + (299.0 \bullet 0.00254)^2 + (-276.2 \bullet 0.00456)^2 + (0.2428 \bullet 0.68)^2 + (0.4765 \bullet 0.70)^2 \right]^{1/2} = 1.7^\circ\text{C}$$

For the uncertainty in Eq. (7) the partial derivatives are

$$\begin{aligned} \frac{\partial T_{\text{pred,no m}_{\text{cold}}}}{\partial m_{\text{hot}}} &= \frac{T_{\text{hot}} - T_{\text{cold}}}{m_{\text{mix,meas}}} = \frac{42.2 - 22.9}{0.0766} = 252.0 \frac{^\circ\text{C}}{\text{kg/s}} \\ \frac{\partial T_{\text{pred,no m}_{\text{cold}}}}{\partial m_{\text{cold}}} &= 0 \\ \frac{\partial T_{\text{pred,no m}_{\text{cold}}}}{\partial m_{\text{mix,meas}}} &= \frac{m_{\text{hot}} (T_{\text{cold}} - T_{\text{hot}})}{(m_{\text{mix,meas}})^2} = \frac{0.0186 (22.9 - 42.2)}{(0.0766)^2} = -61.2 \frac{^\circ\text{C}}{\text{kg/s}} \\ \frac{\partial T_{\text{pred,no m}_{\text{cold}}}}{\partial T_{\text{hot}}} &= \frac{m_{\text{hot}}}{m_{\text{mix,meas}}} = \frac{0.0186}{0.0766} = 0.2428 \\ \frac{\partial T_{\text{pred,no m}_{\text{hot}}}}{\partial T_{\text{cold}}} &= \frac{m_{\text{mix,meas}} - m_{\text{hot}}}{m_{\text{mix,meas}}} = \frac{0.0766 - 0.0186}{0.0766} = 0.7572 \end{aligned}$$

Then, the uncertainty in T_{pred} is

$$\omega_{T_{\text{pred,no m}_{\text{cold}}}} = \pm \left[(0 \bullet 0.00158)^2 + (-252.0 \bullet 0.00254)^2 + (120.1 \bullet 0.00456)^2 + (0.5234 \bullet 0.68)^2 + (0.4765 \bullet 0.70)^2 \right]^{1/2} = 1.0^\circ\text{C}$$

This experiment is relatively inexpensive, requires little time to complete, and is conceptually simple to understand, making it ideal for the undergraduate students who have a very limited chemical engineering background.

For the uncertainty in Eq. (8) the partial derivatives are

$$\begin{aligned}\frac{\partial T_{\text{pred, no } m_{\text{hot}}}}{\partial m_{\text{hot}}} &= 0 \\ \frac{\partial T_{\text{pred, no } m_{\text{hot}}}}{\partial m_{\text{cold}}} &= \frac{T_{\text{cold}} - T_{\text{hot}}}{m_{\text{mix, meas}}} = \frac{22.9 - 42.2}{0.0766} = -252 \frac{^{\circ}\text{C}}{\text{kg/s}} \\ \frac{\partial T_{\text{pred, no } m_{\text{hot}}}}{\partial m_{\text{mix, meas}}} &= \frac{m_{\text{cold}}(T_{\text{hot}} - T_{\text{cold}})}{(m_{\text{mix, meas}})^2} = \frac{0.0365(42.2 - 22.9)}{(0.0766)^2} = 120.1 \frac{^{\circ}\text{C}}{\text{kg/s}} \\ \frac{\partial T_{\text{pred, no } m_{\text{hot}}}}{\partial T_{\text{hot}}} &= \frac{m_{\text{mix, meas}} - m_{\text{cold}}}{m_{\text{mix, meas}}} = \frac{0.0766 - 0.0365}{0.0766} = 0.5234 \\ \frac{\partial T_{\text{pred, no } m_{\text{cold}}}}{\partial T_{\text{cold}}} &= \frac{m_{\text{cold}}}{m_{\text{mix, meas}}} = \frac{0.0365}{0.0766} = 0.4765\end{aligned}$$

Then, the uncertainty in T_{pred} is

$$\omega_{T_{\text{pred, no } m_{\text{hot}}}} = \pm \left[(0 \cdot 0.00158)^2 + (-252.0 \cdot 0.00254)^2 + (120.1 \cdot 0.00456)^2 + (0.5234 \cdot 0.68)^2 + (0.4765 \cdot 0.70)^2 \right]^{1/2} = 1.0^{\circ}\text{C}$$

For the uncertainty in Eq. (9) the partial derivatives are

$$\begin{aligned}\frac{\partial T_{\text{pred, no } m_{\text{mix}}}}{\partial m_{\text{hot}}} &= \frac{(m_{\text{cold}} + m_{\text{hot}})T_{\text{hot}} - (m_{\text{hot}}T_{\text{hot}} + m_{\text{cold}}T_{\text{cold}})}{(m_{\text{cold}} + m_{\text{hot}})^2} \\ &= \frac{(0.0368 + 0.0186)42.2 - (0.0186 \cdot 42.2 + 0.0368 \cdot 22.9)}{(0.0368 + 0.0186)^2} = 231.41 \frac{^{\circ}\text{C}}{\text{kg/s}} \\ \frac{\partial T_{\text{pred, no } m_{\text{mix}}}}{\partial m_{\text{cold}}} &= \frac{(m_{\text{hot}} + m_{\text{cold}})T_{\text{cold}} - (m_{\text{hot}}T_{\text{hot}} + m_{\text{cold}}T_{\text{cold}})}{(m_{\text{cold}} + m_{\text{hot}})^2} \\ &= \frac{(0.0186 + 0.0368)22.9 - (0.0186 \cdot 42.2 + 0.0368 \cdot 22.9)}{(0.0368 + 0.0186)^2} = -117.0 \frac{^{\circ}\text{C}}{\text{kg/s}} \\ \frac{\partial T_{\text{pred, no } m_{\text{mix}}}}{\partial m_{\text{mix, meas}}} &= 0 \\ \frac{\partial T_{\text{pred, no } m_{\text{mix}}}}{\partial T_{\text{hot}}} &= \frac{m_{\text{hot}}}{m_{\text{cold}} + m_{\text{hot}}} = \frac{0.0186}{0.0368 + 0.0186} = 0.3357 \\ \frac{\partial T_{\text{pred, no } m_{\text{mix}}}}{\partial T_{\text{cold}}} &= \frac{m_{\text{cold}}}{m_{\text{cold}} + m_{\text{hot}}} = \frac{0.0368}{0.0368 + 0.0186} = 0.6643\end{aligned}$$

Then, the uncertainty in T_{pred} is

$$\omega_{T_{\text{pred, no } m_{\text{hot}}}} = \pm \left[(231.41 \cdot 0.00158)^2 + (-117.0 \cdot 0.00254)^2 + (0 \cdot 0.00456)^2 + (0.3357 \cdot 0.69)^2 + (0.6643 \cdot 0.71)^2 \right] = 0.7^{\circ}\text{C}$$

| TABLE A1 | | |
|--|---|--|
| Corrected Mass Flow Rates and Corresponding Voltage Readings for the Cold Stream. | | |
| run | Corrected cold stream mass flow rate, $m_{\text{cold, corrected}}$ (kg/s) | Average cold stream voltage, V_{cold} |
| 1 0. | 058 | 4.7 |
| 2 0. | 051 | 3.7 |
| 3 0. | 043 | 2.5 |
| 4 0. | 033 | 1.4 |
| 5 0. | 019 | 0.5 |

Since the calibration equation for the cold stream mass flow rate is incorrect, it was necessary to find a new, corrected calibration equation. This was done using the material balance and solving for the cold stream mass flow rate. For the first run

$$m_{\text{cold, corrected}} = m_{\text{mix, measured}} - m_{\text{hot}} = 0.0766 - 0.0186 = 0.058 \text{ kg/s}$$

The average voltage reading for the corresponding run was 4.7 V for the cold stream. Table A1 shows the data for all five runs with different flow settings.

Regression analysis was done between the corrected mass flow rate and the square root of the voltage reading. The new calibration equation is

$$m_{\text{cold}} = 0.0268 \sqrt{V_{\text{cold}}}$$

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