ON IMPROVING "THOUGHT WITH HANDS"

G.K. SURESHKUMAR, K.C. KHILAR
Indian Institute of Technology, Bombay • India 400 076

Laboratory exercises are essential[1,2] toward the development of a good chemical engineering graduate with desirable skills such as independent learning, interdependent learning, problem solving, critical thinking, creative thinking, interpersonal skills, teamwork, leadership, integration, communication, and change management.[3] The standard laboratory exercise in chemical engineering, however, revolves around an apparatus that remains unchanged for several years and can lead to unethical practices among students[1,4] such as submission of data/reports from previous years. Moreover, the application of thought, which is crucial for laboratory work and developing the skills mentioned above, is almost nonexistent in the standard laboratory exercise. From an instructional-objectives viewpoint,[5] most laboratory exercises are designed to be at Bloom level 2 (comprehension) out of the possible six levels. This leads to severe resentment toward laboratory work among students and professors alike. Students consider lab courses as a formality to be completed, while faculty treat them as poor cousins of theory courses, relegating the entire responsibility for lab courses to lab supervisors or teaching assistants.

We believe that if students are challenged to think critically on laboratory exercises and encouraged to be creative, their interest in and respect for laboratory work would improve, and in turn, the faculty would be further motivated to offer better laboratory courses/projects. With this belief, a laboratory course consisting of both dual-step laboratory exercises and a recommendation/innovation exercise was conceived and assigned to third-year (junior) undergraduate students taking the fluid mechanics laboratory at the Indian Institute of Technology, Bombay.

Our laboratory guidelines state that the overall aim of this laboratory course is to inspire students to appreciate the underlying themes of the experimental aspects/approaches to engineering/science with fluid-flow aspects as a model subject. The goal is to develop students' abilities to "think with their hands." Another purpose of this course is to improve understanding of fluid-flow principles, to develop a physical feel for some fluid-flow situations, to develop a familiarity with some commonly used fluid-flow equipment, to inculcate a concern for safety, to improve communication of experimental results, to improve the quality of analysis and inquiry, and to kindle the spirit of discovery in students. Further, we expect the exercise to develop some of the above-mentioned skills in a chemical engineering graduate.

THE LABORATORY EXERCISES

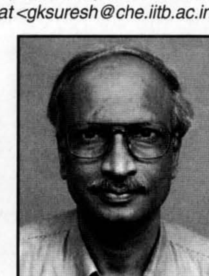
The activities for the laboratory consisted of dual-step laboratory experiments (performed by student groups) and a recommendations report (an individual activity).

The Dual-Step Laboratory Exercise

Each laboratory experiment was conducted over two lab sessions. During the first session, student groups were expected to follow the procedures given in the manual to carry out the experiment. Students were expected to become comfortable with the equipment and the experiment, and the first-session experiments were designed accordingly.

After the first session, students were required (as homework) to analyze the data taken during the lab session based on the theoretical principles in the lab manual/fluid mechanics textbook/notes and examine whether the results obtained were as

G.K. Sureshkumar (G.K.) *is currently Associate Professor in the Chemical Engineering Department at Indian Institute of Technology, Bombay. He received his BTech. in Chemical Engineering from Indian Institute of Technology, Madras, and his PhD from Drexel University. His research interest is free radical-based improvements in the productivity of bioreactors. He can be reached at <gksuresh@che.iitb.ac.in>*



Kartic C. Khilar *is currently Professor in the Chemical Engineering Department at Indian Institute of Technology, Bombay. He earned his BTech degree in Chemical Engineering from Indian Institute of Technology, Kharagpur, and his PhD from University of Michigan. He and his students work in nanoparticle production and colloid-associated contaminants transport in porous media.*

expected. The following ensued:

a) If the experimental results matched the expected results, students were expected to think of additional experiments, preferably new ones, that could be done with the same (or slightly modified) setup. But the additional experiments need to be done within the time frame of the second lab session. We believe that working with these practical constraints would help students acquire "street smarts," which are useful in handling real-world problems.

b) If the experimental results did not match the expected results, students were required to form hypotheses based on the results and design ways to experimentally (with certain calculations) prove or disprove their various hypotheses in the second lab session. The emphasis was on the technical/scientific rigor in proofs. The students were also warned that their theories could be proved false by their experiments and that it was acceptable to admit they did not understand the reasons for disagreement within the time available to them and therefore, additional study would be required.

After the second lab session, each student group was expected to submit a single report in the regular format, *i.e.,* (a) Aim and Objectives, (b) Methodology, (c) Results and Discussion (which was required to be significant), (d) Conclusions, and (e) the original data sheets. The reports were graded on the following bases:

If the actual results matched the expected results:

• Ability to follow procedures	10%
• Data analysis (1st session)	15%
• Discussion (1st session)	15%
• Creativity/originality aspects (2nd session)	20%
• Data analysis (2nd session)	15%
• Discussion (2nd session)	15%
• Presentation (mainly communication)	10%

Reports that addressed novel aspects to study in their second session were rewarded handsomely in grading the creativity/originality criterion (see the student examples presented later).

If the actual results did not match the expected results:

• Ability to follow procedures	10%
• Data analysis (1st session)	15%
• Discussion	15%
• Clarity in thought and situation/problem analysis (2nd session)	20%
• Rigor (2nd session)	15%
• Discussion (2nd session)	15%
• Presentation (mainly communication)	10%

Reports that were well developed on both the possible reasons for the disagreement between actual and expected data and the experiments to prove or disprove them were given high marks for the clarity-in-thought criterion. The difficulty level in problem analysis was also recognized in that criterion—reports that fully analyzed a difficult situation received higher marks than those that, as a matter of chance, analyzed a simple, easy-to-identify situation. Also, reports that unequivocally proved or disproved their points received high marks for the rigor criterion. Other criteria, such as data analysis, discussion, and presentation, carry their usual weight.

The Recommendations Report

Over the duration of the course, each student was expected to think about an experiment or a set of experiments that could be done in the fluid mechanics lab. Students were encouraged to be as creative as possible. Near the end of the course (a week before the last day of classes), each student was expected to submit a detailed report on this experiment (or set of experiments) and the equipment and instruments needed. *The reports were evaluated on the following bases:*

• Creativity/originality aspects	30%
• Clarity in thought	20%
• Detail	30%
• Doability	10%
• Presentation (mainly communication)	10%

The dual-step exercises evaluated through the reports carried a 70% weight, and the recommendation report carried a 30% weight toward the final grade.

IMPLEMENTATION OF DETAILS /RATIONALE

In the beginning of the semester before the experiments began, the instructor met the class and discussed the exercises and recommended strategies. In addition to experimental details for the first session, the laboratory manual carried information on safety procedures for the lab, error analysis, technical writing, and the unacceptability of academic dishonesty, all of which were seriously discussed in the initial meeting. The instructor also emphasized the need for safety procedures whenever he observed lapses during the lab sessions. Student groups were asked to select their own leaders who would assign duties for the group members and be generally responsible for the group's activities. This ensured that an avenue for the development of teamwork and leadership skills existed. Also, on many occasions, the instructor communicated to the groups through their leaders.

Before the start of the first session, the groups were advised to familiarize themselves with the details for each experiment using the lab manual and the textbook. The first-session experiments were designed as shorter versions of the experiments given in the usual lab course, and students were encouraged to spend the additional time becoming comfortable with the setup and the various equipment used. For example, the instructor encouraged the students to raise questions regarding the equipment or the reasoning behind the various experimental steps, which the students normally took for granted. The students took the first session seriously because they knew they had to consider the setup, the experimental methods, and the underlying theory in order to have an interesting second session. During the experiment (both sessions), groups were advised to record the data in duplicate using a carbon sheet, and the members were asked to sign each data sheet. The duplicate copy was submitted to the instructor at the end of each session, and nonsubmission would result in a grade of zero for that session. The instructor has never had to give a zero over the past two years for this reason.

After the data analysis for the first session, the groups were required to meet the instructor to discuss their plans for the second session. This meeting was not to guide the students on what they could do in the second session, but for the instructor to listen and comment on the possibility of doing the experiments. This meeting was normally scheduled a few days before the second session, primarily to address any special requirements for the experiment that needed to be communicated to the lab superintendent. Also, this meeting helped the instructor ensure that the second-session experiments were of proper scope (neither too large nor too small) and reasonably well thought out, especially if the actual data matched the expected data in the first session. In addition, it was communicated to the students at the beginning of the semester that no complete dismantling of the set-ups would be allowed, except in rare cases. This encouraged the students to think of "non-invasive" means for testing their theories. Also, this precaution was necessary because some piping networks in our lab had packings to prevent leaks that would be difficult for an inexperienced person to reassemble.

> ***. . . the overall aim is . . . to improve the quality of analysis and inquiry, and to kindle the spirit of discovery in students.***

The lab reports for the dual-step exercises were due before the start of the next experiment; the instructor graded them and offered constructive criticism and feedback within a week of submission. Students appreciated the timely feedback.

The grading of the recommendations report was time consuming (three to four consecutive, full days). As long as grades are important, some students may cheat to get the best grade;[6,7] therefore, a significant amount of time was spent establishing the originality of submitted reports. This was achieved through one-on-one interviews with students who had submitted "doubtful" reports. During an interview, it was easy to ascertain whether cheating had taken place by asking relevant questions, most of which were on the experiment submitted.

All experiments were run on existing equipment; therefore, this dual-step exercise does not require additional funds for equipment. It can be run anywhere, even in the face of fund crunches. It also provides a greater probability for disagreement between actual and expected data, and thus helps students develop lateral-thinking abilities while forming hypotheses for the disagreement. Therefore, the dual-step laboratory exercise provides a way to turn a seeming disadvantage in running an existing laboratory course into an advantage of improving thought in students.

SAMPLES FROM STUDENT EXERCISES

Samples from the Dual-Step Laboratory Exercises

Agreement Between Actual and Expected Data • An experiment for the lab involved studying the relationship between Power number and Reynolds number in an agitated system. One of the groups found good agreement between actual and expected data and therefore had to think of additional experiments to do on the same setup. They decided to compare the relationship between Power and Reynolds numbers for an aqueous system with and without a surfactant. They found that the Power number for the corresponding Reynolds number was lower for the system with surfactant than for plain water. Therefore, they concluded that the power requirements for an aqueous system with surfactant are lower than that for plain water. They also provided qualitative explanations for the observed results from a molecular viewpoint.

Another experiment involved studying two-phase flow characteristics in a vertical transparent tube such as the relationships between slug length and slug velocity and between pressure drop and void fraction, etc. The group that obtained results as expected decided to study the relationship between the radius of curvature of the slug's leading edge and its length. They developed a theory based on geometrical considerations for the variation of the leading-edge curvature with slug length; they also showed correspondence between the theoretically expected results and measured data.

Disagreement Between Actual and Expected Data • Another experiment involved a piping network with various types of pipes, fittings, and valves. The objectives for the first session included determination of the frictional losses across the pipe fittings and valves. The experiment required recording readings from manometers attached to the pressure taps across relevant fittings or valves and determining the water flow rate using the pressure difference measured across the orifice meter.

The first group that worked on the experiment found that the friction loss constants obtained for the various fittings on the network were higher by almost an order of magnitude than literature values. Therefore, the group first postulated that scale formation led to higher loss constants. To test the postulate, they arranged for the network to be cleaned thoroughly and repeated the experiment in the second session. This did not yield significantly different loss constants, thereby partly disproving the postulate that the scale formation alone resulted in the discrepancy. Students in one of the other groups that worked on the experiment postulated that the water-flow rate measurements using the calibration curve for the orifice meter may not have been correct; they noticed a discrepancy between flow rates measured using a measuring jar/stop watch arrangement and the orifice meter readings. So, the students prepared a fresh calibration graph for the orifice meter and found it to be different from the existing, erroneous calibration chart. They also proved that the friction loss constants obtained using the new calibration graph were comparable to the values found in the literature.

Samples from the Recommendations Report

A student named Nikhil Agarwal suggested an inexpensive, simple method for determining the viscosity of a solution by allowing it to flow over a smooth, inclined flat plate from a reservoir and taking measurements. Using suitable balances, Nikhil expressed the viscosity as a function of measurable parameters (with origins from the thickness of the liquid layer[8]) as:

$$\mu = \frac{\rho g \delta^3 \cos\beta}{3Q}$$

where ρ is the fluid density, g is the acceleration due to gravity, δ is the film thickness, β is the angle between the plate and the vertical, and Q is the flow rate. He carefully considered the details and limitations of the experimental procedure and suggested a method to study the variation of viscosity with temperature using the same setup.

Another student, Sikander Siraj, using input from a friend in electrical engineering, suggested a photoelectric diode-based (PED) device for the measurement of slug lengths in the two-phase flow experiment. The idea had its origins in the burglar alarm principle. For the measurement, he used the deviation caused by the refraction of the infrared beam when it passes through media of different refractive indices.

STUDENT AND STAFF FEEDBACK

The students were asked to send their comments through e-mail to their class representative, who removed details pertaining to the authors of the comments, compiled without editing, and forwarded the comments as a single file to the instructor. For the improved version of the lab, comments from 82 out of 83 students were received, and all except nine explicitly stated that the lab was useful to them. They said that their learning included fluid-mechanics principles, application of thought to a lab, leadership qualities, thinking creatively, and working in a group. Some positive comments over the past two years include, "Due to this lab alone, I can say that I know some 'chemical engineering,'" and "This is the first time I feel what a lab course is all about." Also, many students suggested minor changes in equipment, etc., to improve the lab. Of the nine students who did not state their liking for the lab, seven were neutral, and the other two said that the lab was not useful to them.

The staff associated with the lab were enthusiastic about fulfilling the requirements of the lab. They also said that they enjoyed setting up the various experiments although it involved additional time.

INITIAL CHALLENGES

The first time it was offered, almost all students expressed that the lab demanded a lot of their time. We believe this was because students compared it with previous editions of the same course. In addition, the same experiments that were given in previous editions were packaged into a two-session (dual-step) format, significantly increasing the work. Therefore, in the next edition of the course, the experiments were consolidated into half the original number, with all other details unchanged. Afterwards, there were very few comments (3 out of 83) that there was too much work.

The first time the course was offered, the groups were assigned according to student roll numbers, which the students hated. The next time, the students were asked to form their own groups with the average cumulative performance index (CPI) of the group members being close to the class average CPI; this incorporates cooperative learning elements. Complaints about unsuitable groups were almost eliminated.

The remaining challenge is group size. Six students in a group is nonideal and should be reduced. We intend to reduce the number by running the experiments more frequently in the future. The logistics constraint needs to be addressed first, however.

In short, a focus on developing the critical thought process in students made the laboratory course interesting to both students and instructors and also developed students' respect for experimental work.

ACKNOWLEDGMENTS

We would like to thank the students of CL333 for their enthusiastic participation in the exercise as well as O.S. Sawarkar, V.B.V. Nair, V. Ramachandran, and A.D. Kadam for their contributions.

REFERENCES

1. Middleberg, A.P.J., "Laboratory Projects: Should Students Do Them or Design Them?" *Chem. Eng. Ed.*, **29**(1), p. 34, (1995)
2. Jones, W.E., "Basic Chemical Engineering Experiments," *Chem. Eng. Ed.*, **27**(1), p. 188, (1993)
3. Rugarcia, A., R.M. Felder, D.R. Woods, and J.E. Stice, "The Future of Engineering Education. I. A Vision for a New Century," *Chem. Eng. Ed.*, **34**(1), p. 16, (2000)
4. Macias-Machin, A., G. Zhang, and O. Levenspiel, "The Unstructured Student-Designed Research Type of Laboratory Experiment," *Chem. Eng. Ed.*, **24**(2), p. 78, (1990)
5. Felder, R.M., D.R. Woods, J.E. Stice, and A. Rugarcia, "The Future of Engineering Education. II. Teaching Methods that Work," *Chem. Eng. Ed.*, **34**(1), p. 26, (2000)
6. Felder, R.M., "Cheating: An Ounce of Prevention...Or the Tragic Tale of the Dying Grandmother," *Chem. Eng. Ed.*, **19**(1), p. 12 (2000)
7. Sureshkumar, G.K., "A Choose-Focus-Analyze Exercise in ChE Undergraduate Courses," *Chem. Eng. Ed.*, **35**(1), p. 80, (2001)
8. McCabe, W.L., J.C. Smith, and P. Harriott, *Unit Operations of Chemical Engineering*, McGraw-Hill, Singapore, 6th ed., (2000) ❒