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On Improving 'Thought with Hands'

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Abstract

To improve the application of thought in laboratory exercises and to develop many useful skills in undergraduate Chemical Engineering students, a laboratory course consisting of dual-step laboratory exercises and a report of recommendations/innovation from the student, was introduced for the Fluid Mechanics laboratory. The first step of the dual-step exercise consisted of a standard exercise (concise version) followed by rigorous analysis of the data; the second step consisted of either designing and carrying out a new experiment/addressing a different question with the same/slightly modified experimental set-up, or, formulating and testing hypotheses for unexpected trends in the data. Students worked in groups under the direction of an elected group leader. The need, details, outcomes and experiences of the dual-step laboratory exercise/recommendations report are discussed and samples of some student exercises are presented. The student and laboratory staff responses are also presented.

Introduction

Laboratory exercises are essential [1, 2] toward the development of a good Chemical Engineering graduate with desirable skills such as independent-learning, interdependent-learning,

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problem solving, critical-thinking, creative-thinking, interpersonal, teamwork, leadership, integrative, communication and change management [3]. However, the standard laboratory exercise in Chemical Engineering revolves around an apparatus which remains unchanged for several years and thus, even leads to unethical practices among students [1, 4] such as submission of data/reports from the previous years. More importantly, the application of thought, which is crucial for a good appreciation of laboratory work and the development of the skills mentioned above, is almost non-existent 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 6 levels. This leads to severe resentment toward laboratory work among students and professors alike. The students consider lab courses as a formality to be completed and the faculty treat them as poor cousins of theory courses, befitting the relegation of the entire responsibility for lab courses to lab supervisors or teaching assistants.

We believe that if the students are challenged to think critically on laboratory exercises, as well as encouraged to be creative to the extent possible, their interest in and respect for laboratory work would improve, and in turn, the faculty would be further motivated toward offering good laboratory courses/projects. With this belief, a laboratory course consisting of (1) dual-step laboratory exercises and (2) a recommendation/innovation exercise, was conceived and assigned to third (junior) year undergraduate students taking the Fluid Mechanics laboratory at the Indian Institute of Technology, Bombay.

To quote from our laboratory guidance manual, 'the overall aim of this laboratory course is to help and inspire students to appreciate the underlying themes of the experimental aspects/approach to engineering/science, with the fluid flow aspects as a model subject. The main goal is to develop, in students, the ability *to think with their hands*. In addition, this laboratory course aims to better the 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 equipments, to inculcate a concern for safety, to improve the skill in communication of experimental results, to improve the quality of analysis and inquiry and to kindle the spirit of discovery, in students'. Further, we expected the exercise to develop some of the above mentioned desirable skills in a Chemical Engineering graduate.

The Laboratory Exercises

The activities for the laboratory consisted of

1. dual-step laboratory experiments, which were to be performed by student groups, and
2. a recommendations report, which was an individual activity.

The Dual-step Laboratory Exercise

Each laboratory experiment was conducted over two lab classes (sessions). During the first session, the student groups were expected to follow the procedures given in brief, in the manual, to carry out the experiment. More importantly, the students were expected to become comfortable with the equipments and the experiment, and the I session experiments were designed accordingly.

After the I session, the students were required to analyze the data taken during the lab session (as homework) based on the theoretical principles in the lab manual/Fluid mechanics textbook/notes and examine whether the results obtained were as expected by the principles. The following ensued: (a) If the experimental results matched the expected results, the students were expected to think of additional experiments, preferably new ones, that could be done with the same (or slightly modified) set-up. However, the additional experiments needed to be do-able within the time frame of a single lab (II) session. It is believed that working with these practical constraints would help students acquire some 'street-smartness' which is useful in handling the real world problems.

(b) If the experimental results did not match the expected results, the students were required to form hypotheses based on their reasons for the same and design ways to experimentally (probably along with certain calculations) prove/disprove their various hypotheses in the II lab session. The emphasis was to be on the technical/scientific rigor in proofs. The students were also warned that sometimes, all their theories may be proved false by their experiments. In such a case, it was completely acceptable to admit their inability to understand the reasons for the disagreement between the expected and the actual results, in the time frame available to them, and therefore, needing additional studies.

After the II 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 strictly on the following bases:

If the actual results matched the expected results:

Ability to follow procedures	10%
Data analysis (I session)	15%
Discussion (I session)	15%
Creativity/originality aspects (II session)	20%
Data analysis (II session)	15%
Discussion (II session)	15%
Presentation	10%

Reports which addressed novel aspects to study in their II session were graded handsomely in the 'Creativity/originality' criterion (also see the student examples presented later).

If the actual results did not match the expected results:

Ability to follow procedures	10%
Data analysis (I session)	15%
Discussion (I session)	15%
Clarity in thought and situation/problem analysis (II session)	20%
Rigor (II session)	15%
Discussion (II session)	15%
Presentation (mainly communication)	10%

Reports which developed the thought process well on the possible reasons for the disagreements between actual and expected data, and the experiments to prove/disprove them were given high marks for the 'clarity in thought' criterion. In addition, the difficulty level in problem analysis was also recognized in that criterion – reports which analyzed a difficult situation well, received higher marks under that criterion than which, as a matter of chance, analyzed a simple, easy-to-identify situation, well. Also, reports which unequivocally proved/disproved their points received high marks for the 'rigor' criterion. The other criteria such as data analysis, discussion and presentation carry their usual meanings.

The Recommendations Report

Over the entire course duration, each student was expected to think about an experiment or a set of experiments that can be done in the Fluid Mechanics lab. The student was encouraged to be as creative as possible for this exercise. Near the end of the lab course (a week before the last day of classes) each student was expected to submit a report on the experiment(s) that had been thought about, in detail, and the equipment, instruments needed for the same. The reports were evaluated on the basis of:

Creativity/Originality aspects	30%
Clarity in thought	20%
Detail	30%
Do-ability	10%
Presentation	10%

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

Implementation Details and Rationale

In the beginning of the semester, before the actual experiments began, the instructor met the class and discussed the exercises and recommended strategies, at length. In addition to the experimental details for the first session, the laboratory guidance manual carried information on safety procedures to be strictly followed in the lab, error analysis, technical writing, and the unacceptability of academic dishonesty, all of which were discussed with seriousness, in the same first meeting with the students. Also, the instructor emphasized the need for safety procedures whenever lapses were observed on his rounds during the lab sessions. Further, the student groups were asked to select their own leaders who would be expected to assign duties for the group members and in general, be responsible for the group's activities. This ensured that an avenue for the development of team-work and leadership skills existed. Also, on many occasions, the instructor communicated to the groups through their leaders.

The groups were advised to familiarize themselves with the experimental details before the start of the I session for each experiment using the lab guidance manual and textbook. The I session experiments were designed to be shorter versions of the experiments given in the usual lab course, and the students were encouraged to spend the additional time in becoming comfortable with the setup and the various equipments used. For example, the instructor went around during the I session and encouraged the students to raise questions regarding the working of the equipment or the reasoning behind the various steps in the experiment, which the students normally took for granted. Importantly, the students took the I session seriously because they knew that they have to think on the set-up, experimental methods and the underlying theory for an interesting II session. During the experiment (both sessions), the groups were advised to record data in duplicate using a carbon sheet and the group members were asked to sign on each data sheet. The duplicate copy was submitted to the instructor at the end of each session and non-submission of the data sheet would attract a zero for that session. However, the instructor never had to give a zero during the past two years, for the above reason.

After the data analysis for the I session, the groups were required to meet the instructor to discuss their plans for the II session. It should be mentioned that this meeting was not to guide the students on what they could do in the II session, but, only for the instructor to listen and comment on the possibility of doing the experiments. This meeting was normally scheduled a few days before the II session primarily to address any special requirements for the envisaged experiment which needed to be communicated to the lab superintendent. Also, this meeting helped the instructor to ensure that the II session experiments were of proper scope, neither too large nor too small and reasonably well thought, especially if the actual data matched the expected data in the I session. In addition, it was clearly communicated to the students in the beginning of the semester that no complete dismantling of the setups would be allowed, except in rare, well deserved cases. This was to encourage the students to think of 'non-invasive' means for testing their theories, as far as possible. Also, this precaution was necessary because some piping networks in our lab had packings to prevent leaks, which would be difficult to re-assemble by an inexperienced person.

The lab reports for the dual-step exercises were due before the start of the I session for the next experiment; the instructor graded the lab reports and offered his/her constructive criticisms and feedback within a week of submission. Students appreciated the timely feed-back and this helped the students improve their future approach to experiments and lab reports.

However, the grading of the recommendations report was time consuming (3 to 4 consecutive, full days). It is well known that as long as grades are important, students may have a weakness to cheat to get the best grade [6, 7] and therefore, a significant amount of time was spent in ensuring the originality of the submitted report. This was achieved through one-on-one interviews with students who had submitted 'doubtful' [7] reports. During the interview, it was easy to ascertain whether cheating had taken place by asking relevant questions, most of which were on the experiment submitted. The acutely grade conscious undergraduates have not complained that somebody who submitted a plagiarized report was not penalized; this shows that it is possible to effectively weed out the cheaters.

Also, all experiments were run on existing equipment and therefore, this dual-step exercise does not require additional funds for equipment. Thus, it can be run anywhere including places experiencing fund crunches. In addition, it provided a greater probability for disagreements between actual and expected data, and thus helped students to develop lateral thinking abilities while formulating hypotheses for the disagreements. Therefore, the dual-step laboratory exercise, provides a possibility to turn a seeming disadvantage in running an exciting 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 a good agreement between actual and expected data and therefore, they had to think of additional experiments to do on the same set-up. They decided to compare the relationships 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 that 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 from a molecular viewpoint for the observed results.

Another experiment involved studying two-phase flow characteristics in a vertical transparent tube such as the relationships between slug length and slug velocity, between pressure drop and void fraction, etc.,. A group which obtained results as expected, decided to study the relationship between the radius of curvature of the slug 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 a good 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 on it. The objectives for the I 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 the 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 they repeated the experiment in the II session. However, this did not yield significantly different loss constants, thereby, partly disproving the postulate that the scale formation alone, resulted in the discrepancy. One of the other groups which worked on the experiment postulated that the water flow rate measurements using the calibration curve for the orifice meter may not have been proper because, they noticed a discrepancy between flow rates measured using a measuring jar/stop-watch arrangement and the orifice meter readings. Therefore, the group prepared a fresh calibration graph for the orifice meter and indeed, 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, Nikhil Agarwal, had suggested an inexpensive and simple method for determining the viscosity of a solution by allowing it to flow over a smooth, inclined flat plate from a reservoir and making suitable 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. Also, Nikhil had thought well about the details of the experimental procedure and the limitations. In addition, he had also suggested a method to study the variation of viscosity with temperature using the same setup.

Another student, Sikander Siraj, with inputs from his friend in Electrical Engineering, suggested a photo-electric diode (PED) based device for the measurement of slug lengths in the two-phase flow experiment. The idea had its origins in the burglar alarm principle. He had utilized the deviation caused by the refraction of the infra-red beam when it passes through media of different refractive indices, for the measurement.

Student and Staff Feedback

The students were asked to send their comments through email to their class representative, who was then asked to remove the details pertaining to the authors of the comments, merely compile without editing, and forward the comments as a single file to the instructor. For the improved version of the lab, comments from 82 students out of 83 were received and all except 9 explicitly said that the lab was useful to them because they learned something. They said that the learning included fluid mechanics principles, application of thought to a lab, leadership qualities, thinking creatively and working in a group. Some very positive comments over the past two years include, ‘due to this lab alone, I can say that I know some Chemical Engineering’; ‘this approach gave a real meaning to the lab course’; ‘this is the first time I feel what a lab course is all about’. Also, many students had suggested minor changes in equipment, etc., to improve the lab.

Among the nine students who did not explicitly state their liking for the lab, seven were neutral and other two said that the lab was not useful to them.

The staff associated with the lab were visibly enthusiastic about fulfilling the requirements of the lab. They also said that they enjoyed setting up the various experimental set-ups, although it involved additional time.

Initial challenges

The first time it was offered, almost all students expressed that the lab demanded a lot of time. We believe this happened because the students compared the lab course with previous editions of the same lab course. In addition, the same experiments that were given in previous editions of this lab were packaged into a two session (dual-step) format, which increased the work significantly. Therefore, in the next offering of the course, the experiments were consolidated into half the original number with all other details remaining the same. Then, there were very few comments (3 out of 83) on the amount of work being enormous.

The first time the course was offered, the groups were made according to student Roll number, which the students hated. The next time the lab was offered, the students were asked to form their own groups which however, met the criterion that the average cumulative performance index (CPI) of the group members is close to the class average CPI, to incorporate co-operative learning elements. This almost eliminated the complaint about unsuitable groups.

The challenge that still remains is the group size. Six students in a group is non-ideal and needs to be reduced. We intend reducing the number by running the experiments more frequently than now. However, the logistics constraint needs to be addressed first.

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

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