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An active laboratory learning experience for chemical engineering students facilitated by hypothesis testing

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ABSTRACT

CONTEXT

The ability to think critically and to be self-directed learners are recognised as pivotal to university graduates in the evolving context of the engineering profession. Lab practices are important learning experiences in undergraduate engineering programs and are generally viewed as main occasions to develop such skills. The use of enquiry-based learning approaches in lab practices supports the development of the graduate attributes of critical thinking and independent learning.

PURPOSE

A traditional approach in engineering educational laboratories is expecting students to achieve pre-determined results by following instructions given, for example, in a laboratory manual. It is recognised that such approach is ineffective in engaging learners in critical thinking or in making design decisions, for example when dealing with multiple objectives and constraints. Holistic approaches emphasizing the use of hypothesis forming and evaluation and design of experiment (DOE) in laboratory practicals are perceived to be conducive to improved learning outcomes. An "open-ended" learning activity has been designed and implemented to foster student's engagement and deep learning. The activity includes an assessment scheme that allows an evaluation of the transformative effect on student learning approach, specifically engagement in critical thinking, and an observation of the metacognitive awareness in the learning process. The laboratory practice covers separation unit operations that are ubiquitous in several industries, nominally continuous distillation.

APPROACH

The approach adopted is rooted in inquiry-based pedagogy. Students are given the task of optimising the operation of a distillation column. Responding to the proposed problem, requires students to model the distillation system, determine optimal operating conditions by simulation, identify the most influential process variables, and design an experimental plan to validate modelling and simulation work. The use of a critical approach is encouraged by the assessment design associated to the laboratory project: students individually submit their hypothesis about the expected outcomes of the experimental practice and a reflection on it considering the results subsequently obtained. Overall, the learning activity proposed is structured to encourage learners to engage critically and, to a certain extent, independently. The use of hypothesis testing, reflections, conceptual questions in assessment, and surveys allows the collection of learning analytics suitable to evaluate learning approaches.

ANTICIPATED OUTCOMES

The proposed activity engages students in a six-steps learning process: modelling of a separation process, hypothesis forming and prediction, process optimization through simulation, design of experiment, results evaluation, and reflection on the original hypothesis. The need to verbalize predictions is expected to improve engagement in the task. It is expected that the sequence of activities encourages students to derive logical conclusions from multiple inputs, question their findings and justify their conclusions. The assessment design allows a longitudinal evaluation of critical thinking and of metacognitive awareness. The combination of students' reflections, summative assessment results (laboratory reports, mid-session exam),

and observations from the teaching team allow for evaluation of dept of learning and skills development.

SUMMARY

An enquiry-based approach has been implemented in a 2nd year chemical engineering laboratory. Such open-ended approach is a closer representation of real-world engineering work that often lack pre-determined solutions. The activity is designed to boost students' engagement with the practical activity and support critical thinking and deep learning. The assessment scheme is an integral part of the learning activity and allows for the observation of students' learning approaches over the duration of the activity and of the knowledge and skills developed.

KEYWORDS

Hypothesis forming, design of experiment, active learning, critical thinking, Chemical Engineering education.

Introduction

Enquiry-based learning and hands-on experimentation provide students with an opportunity to actively construct, process, and communicate their own understanding leading to effective conveyance of concepts (Huet, 2018). Meyers et al. (2009) suggested five principles for effective curriculum design to ensure the attainment of learning outcomes, one of which is to employ authentic, relevant, and real-world teaching and learning resources. It is postulated that students engage more with course content when they feel it is relevant to current real-world practice and necessary to improve their employability. This is particularly true when it comes to engineering students with pragmatic attitude towards knowledge. As such, incorporating unit operations laboratory in chemical engineering curriculum is perceived to be an effective way in exposing students to the real-world application of the theoretical concepts.

Traditional approach in unit operations laboratories is to direct students to carefully follow a laboratory manual to obtain pre-determined and "desired" results (Chandra, 1991; Young et al., 2006). Such an approach fails to inspire students to develop and demonstrate critical thinking, and to make design decisions when dealing with multiple objectives and constraints, the latter being a required graduate attribute by accreditation bodies such as The Institution of Chemical Engineers. Holistic approaches emphasizing the use of design of experiment (DOE) technique and statistical tools in laboratory practicals have been identified as conducive to improved learning outcomes (Doskocil, 2003; Jimenez et al., 2002; Narang et al., 2012; Young et al., 2006). Design of experiment is widely-used in industry to minimise the cost related to experimentation necessary to reach a conclusion while generating results with appropriate levels of accuracy (Doskocil, 2003). Concomitantly, computer simulation and process modelling are being increasingly viewed as safe and cost-effective alternatives to pilot-scale experimentation in chemical industries (Williams et al., 2003). Several educational institutions have applied advancements of information technology to develop virtual laboratories to partially or completely replace bench-scale or pilot-scale unit operations practicals (Brault et al., 2007; Rafael et al., 2007; White et al., 1999; Williams et al., 2003),however, the findings of White and Bodner (1999) suggest that practical laboratory experience is integral to chemical engineering education.

There have been numerous studies suggesting the contribution of hypothesis testing and predictions to active learning and enhancing the students' learning experience (Bertram, 2002; Codella, 2002; Dantas et al., 2008; Modell et al., 2004; Rivers, 2002; Yoder et al., 2005). In a study by Modell et al. (2004) on the effectiveness of hypothesis forming in a physiology laboratory, it was found that students performed better when asked to verbalize their prediction of the outcomes prior to attending the laboratory. This was partly attributed to the fact that students were more likely to engage with the learning task when they had committed to a prediction. However, the literature is limited on the evaluation of the effectiveness of integrated active learning practical labs in promoting critical thinking and independent learning. The latter will be investigated focussing on evidence of metacognition in students' output.

Context of study

The learning and teaching activities included in this study have been designed as part of the educational offer of the Separation Processes courses at School of Chemical and Biomolecular Engineering, University of Sydney. The courses cover the design of separation unit operations commonly used in chemical industries including distillation columns and are offered to second year undergraduate students and to Master of Professional Engineering students. An inquiry-based pedagogy has been adopted articulated in the following main steps: modelling of a separation process, hypothesis forming and prediction, process optimization through simulation, design of experiment (DOE), results evaluation, and reflection on the original hypothesis. Figure 1 presents an overview of the activities.

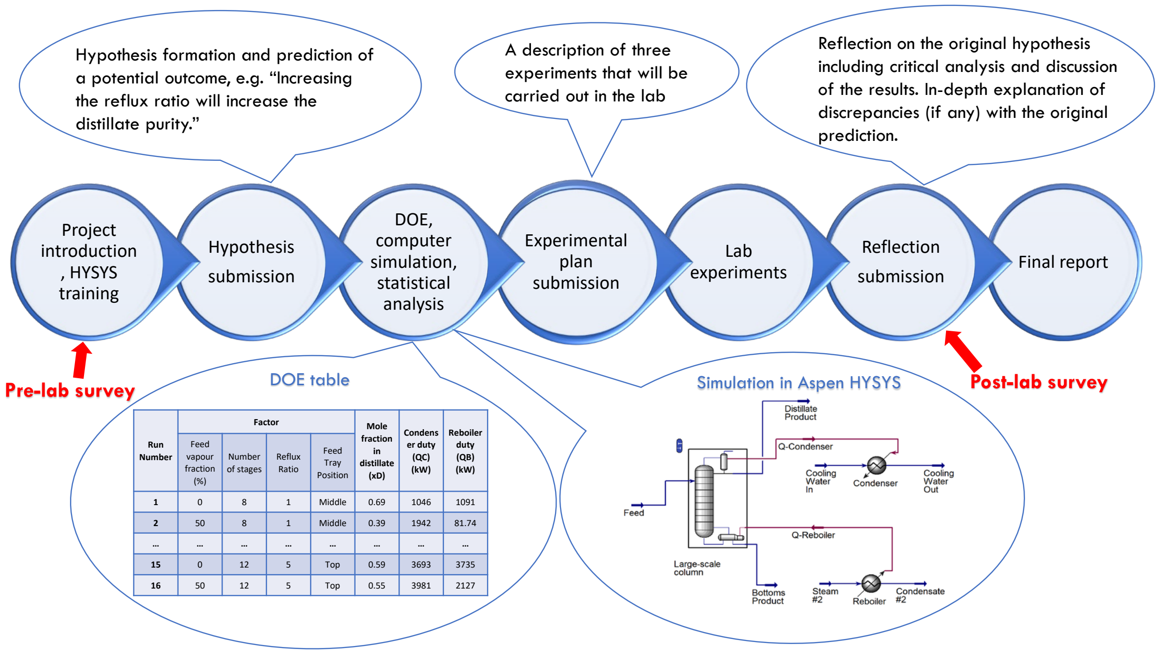
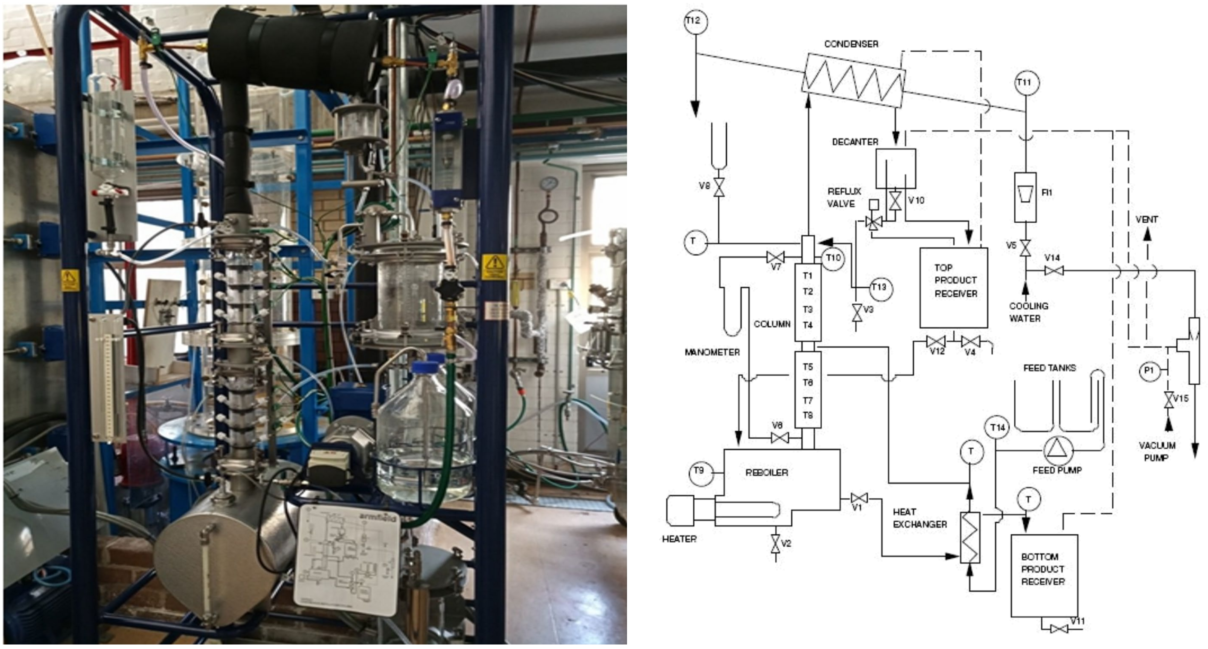


Figure 1. Overview of the teaching and learning activities associated to the distillation laboratory practical.

The hypothesis and reflection submissions are individual tasks and allow for the qualitative longitudinal observation of the students' approach to learning and metacognitive awareness. The assessment scheme of the courses comprises a mid-session individual test that includes conceptual questions. Responses to individual tasks allow an evaluation of student approach with particular attention to evidence of critical thinking and, potentially, to the transformative impact of the intervention.

Students work at the other tasks of the activity in groups of 3 to 4. The activity sets a realistic work scenario in which students are asked to work as chemical engineers in a consulting firm. An ideal client tasks the consulting form to optimise the operation of an industrial-scale distillation column with a specified diameter for the continuous separation of ethanol-water mixtures. The design objective set by the client is to maximise the purity of the distillate with the minimum operating costs: the cost of steam and cooling water consumption in the reboiler and condenser, respectively. The client specifies the pressure at which steam is available. Additional design constrains are that a water-cooled total condenser is used in this column with the cooling water entering the condenser at 30°C and returning to the cooling tower strictly below 40°C. The bottoms from this column are used elsewhere as "process water" and thus cannot contain more than 2 (mole) % ethanol. The client requires the estimation of the total number of sieve trays before proceeding with the procurement and installation of the column internals.

Students carry out a comprehensive experimental study to find optimum operating conditions such as feed temperature, feed tray position, number of theoretical plates, reflux ratio, and reboiler duty using HYSYS. Design of experiment is required to find the minimum number of experiments that maximise the number of variables that could be investigated. Students notice that even after a well-planned DOE, it is unpractical to conduct the experimental study on the industrial-scale column. Hence, the concepts of pilot-scale experimentation and scale-up to large-scale plants is presented, introducing students to a common practice in chemical industries. The distillation equipment available for the practical is a 50 mm diameter sieve plate glass distillation column (UOP3CC, Armfield Limited) containing eight sieve plates. A photograph and a schematic diagram of the equipment are presented in Figure 2. Students are presented with the additional constraint that the session time in the laboratory is sufficient to carry out only three experiments. This leads to the use of simulations to execute the experimental design and investigate the effect of different process variables. The simulation is conducted using Aspen HYSYS simulation software. Subsequently, students perform a statistical analysis of the results and determine the variables that have the most significant impacts on the process. The results inform the selection of the operating variables to be investigated in the practical session when students use the lab-scale experiments to selectively validate the computer simulation data. Students need to estimate the efficiency of the industrial-scale sieve trays to be able to calculate the actual number of sieve trays. This is done by evaluating the tray efficiency in lab-scale column and scaling up the results for large-scale column.



A **B**

Figure 2. A: photograph of experimental rig. B: Schematic diagram of experimental rig

Research Methodology

Enquiry-based pedagogy has been adopted to engage students with the learning process as active learners. Contrary to traditional laboratory approaches that encourage passive learning through prescribing laboratory procedures, the proposed approach provides students with the autonomy to design their own experiments and be actively involved in the learning process. “Autonomy” defined as the willingness to spend time and energy to study is one of the three psychological needs contributing to students' intrinsic motivation towards learning according to Self Determination Theory (SDT) (Niemiec et al., 2009; Trenshaw et al., 2016). Autonomy-supportive teaching practice provides students with the voice and choice in the learning activities thereby increasing their interest in self-learning (Niemiec & Ryan, 2009). The activities start by introducing the project scopes and overview of the tasks. A training session on Aspen HYSYS will be given to prepare students for the process simulation activity. Students are then asked to form a hypothesis and make a prediction of the potential outcome of the optimisation task. For example, they may hypothesis that "increasing the reflux ratio will increase the distillate purity". This gives students the chance to develop an understanding of the theory before entering the laboratory and hence have a better appreciation of the distillation theory in practice. Committing to a prediction, students are more likely to be actively engaged with the activity as suggested by Modell et al. (2004). Students will complete the pre-lab survey (Figure 3) and answer few questions about their attitude to self-directed learning and ability to think critically.

Pre-lab survey

Q1. If you were stranded in a canyon, what would your first move be?

Free text response

Q2. Consider the following skill list.

T - Team work

C - Critical thinking

S - Sourcing information

D - Data analysis

P - Data presentation

Which of these skills are your strong points?

Rank these (TCSDP) from 1 (strongest) to 5 (less strong). You should not have two skills ranked in the same way.

Q3. Experiments should be designed by (please tick the option/s you agree with)

The teaching team

The students

Other (please specify)

Figure 3. Pre-lab survey questions to evaluate students' perceptions of their critical thinking skill and self-directed learning.

To evaluate the validity of their hypothesis, students undertake an experimental campaign including DOE, HYSYS simulation, and statistical analysis of the simulation results to find the most significant factors and their optimum values. Lab-scale experimentation is used to validate the simulation data and estimate the real tray efficiency for scale up purposes. Students commit to three distillation experiments of their choice as part of their experimental plan to be carried out on the lab-scale distillation column. Students individually articulate their predictions of the laboratory and reflect on the assumptions they made considering the experimental results of the lab practicals. Finally, each team submits a laboratory report including recommendations for the ideal client. Students will be asked to answer the post-lab survey questions shown in Figure 4.

Post-test (available any time from the laboratory sessions to the end of the semester)

Please rank the following from 1 (Strongly disagree) to 4 (Strongly agree) or Not Applicable

1. My team decided the scope of the lab practical on our own
2. My team worked out the interpretation of the practical outcomes independently
3. I thought carefully about my predictions
4. I looked at relevant information to interpret the results
5. I thought about what assumptions I made during the project
6. The simulation work and the lab practical together supported my learning
7. I found the project interesting

Each question will also have a free form entry box with the guidance “Please explain your response”.

Figure 4. Post-lab survey questions

The overall experience is designed to support student learning and to provide the opportunity to evaluate student approach to learning at the start of the activity by examining responses to the survey, the hypothesis submission, and the DOE proposed. The first two items are individual and offer the opportunity to evaluate the effectiveness of the experience to shift students learning behaviour toward a more critical approach as opposed to focussing on searching for pre-existing solution algorithms or a memorisation-based approach. This can be achieved by analysing and comparing students' outputs in the early stages of the experience (pre-lab survey, hypothesis submission, DOE) to outputs generated in later stages of the experience (post-lab survey, reflection, response to conceptual questions in mid-session test). Such evaluation of the effectiveness of active learning in chemical engineering labs is novel and the results are likely to be transferable to other contexts in engineering education applying a similar design. The effectiveness of the intervention on the performance of the general cohort will be evaluated based on the examination of the laboratory reports and of the observations of the teaching team that will be collected by semi-structured interviews.

In general, critical thinking is revealed by indicators, for example:

1- Evidence of evaluation
2- Draw of logical conclusions considering all available data
3- Presentation of arguments
4- Practice of critical reflection
5- Evidence of data analysis
6- Suggestion of alternatives
7- Question credibility and accuracy of information and supporting evidence
8- Justification of procedures/recommendations
9- Accurate self-evaluations

Following are some examples of observations from students' outputs indicating a critical approach to the specific activities proposed here.

- Use the temperature profile from the HYSYS model and lab-scale column to estimate the composition of ethanol in the top and bottom products using the theoretical T-xy diagram. Compare differences between the temperature profiles. Discuss possible reasons behind the discrepancies (if any).
- Test the accuracy of the thermodynamic property package used in the HYSYS model by comparing the produced phase equilibria data (T-xy diagram) with literature data.
- Scale up from lab-scale to large-scale column and present conclusion on the real number of plates taking into consideration the column efficiency calculated in lab experiments.

Examples of metacognition can emerge from students' submissions as indications that students identify their abilities in relation to the requirements of the activity and use strategies in response to it. For instance, upon recognising that they cannot explain the results of the experiment, student identifies that linking theory to experimental outcomes is their limiting step and seeks help to improve this skill.

The sample evaluations presented in this work, show that the activities are collectively suitable to highlight the aspects of student learning targeted by this educational intervention. The next iteration will include a larger number of participants and will introduce semi-structured interviews. Both aspects will arguably allow for a more systematic evaluation of the intended outcomes.

Conclusions

To support student learning and experience, enquiry-based pedagogy has been applied in the design of the learning and teaching activities in a chemical engineering laboratory. In particular, the approach aims to support critical thinking and independent learning. Both abilities are recognised as pivotal for university graduates to succeed in the evolving context of the engineering profession. The approach is articulated in multiple steps: design of experiments, computer simulation, hypothesis forming and prediction, results evaluation, and reflection. The study investigates the effectiveness of the approach through analysis of student outputs at different stages of the experience integrated with pre-lab and post lab student surveys and interviews of the teaching team. Results from the work are likely to be transferable to other teaching laboratories in engineering as the approach proposed in generalizable. Moreover, the work contributes a readily applicable framework within engineering practical labs to evaluate critical thinking and the effectiveness of interventions directed to support such skills.

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