A NEW APPROACH TO THE UNIT OPERATIONS LABORATORY AT THE UNIVERSITY OF TORONTO

Graeme Norval, P.Eng., Paul Szabo, P.Eng., Glenn Wilson, Paul Jowlabar
Department of Chemical Engineering and Applied Chemistry
University of Toronto
Graeme.norval@utoronto.ca

Abstract

Unit operations laboratories are a standard feature of most chemical engineering programs. Students spend long hours running distillation columns, gas absorbers, and work with pumps, valves and heat exchangers. This provides much of the hands-on learning that they take into industry after graduation.

Process control laboratories are often integrated into the unit operations laboratory. The most common control laboratory involves heating a tank with a steady inflow of cold water. Our laboratory has all of these features. Our approach can be described as using 20th century technology to control 19th century type processes in an 18th century learning environment while educating engineers for the 21st century. A different way to say it is that our approach is nothing like what a new graduate engineer sees when they arrive at a chemical facility.

Several years ago, our department created a team tasked with upgrading the approach to the unit operations laboratory, and several guiding principles were created. It is important to retain a “hands-on” operational component – students need to open and close valves, read gauges, as well as start and stop pumps. It is equally important to introduce students to a proper distributed control system. It is also important that the DCS is not seen as a “black box” that does everything – the link between the equipment, the P&ID and the DCS needs to be reinforced.

The equipment is now in regular operation, and we continue to expand its capabilities. This submission describes the genesis of the system and the staged approach that has been taken to manage the time and budget pressures.

1 Introduction

It has long been recognized that training in unit operations is central to chemical engineering education. There are a variety of textbooks with variations of this concept in their titles, including the classic “Unit Operations of Chemical Engineering” [1]. The topics include fluid mechanics, heat transfer and mass transfer, with the specific examples of pump performance, fluid flow through pipes and valves, heat exchanger performance, as well as the separation techniques: distillation, absorption, filtration. Our department has a well-equipped Unit Operations Laboratory, and the students perform a variety of half day and full day experiments in the third year.

Early in the last decade we asked the question as to what the Unit Operations lab of the future would look like. This is different than the usual questions “what can be done to make the laboratories better?”, or “what can we do to boost student learning?”. Several of us have extensive experience in industry (specifically polymerizations and inorganic chemicals), both at pilot and full-scale. As a team, we created some guiding principles for change in the unit operations laboratory. This article describes the principles, and the changes we have been implementing, and comments on concepts for future modifications.

2 Some Guiding Principles

The Unit Operations Laboratory has a floor space of 683 m², occupying 2 floors, with an open central space. Figure 1 shows the space. It is used for most of 4 days each week between September and April. The restrictions on change are simple: we can’t expand upwards due to an existing laboratory, and we can’t expand outwards due to the locations of the loading dock and an electrical transformer room. We need to work within the constraints of the current room. In

addition, changes need be limited to the summer months, to avoid conflict with scheduled student activities.

Figure 1: The Unit Operations Laboratory

We reflected on the lab using a SWOT type analysis. The equipment is of reasonable size and quality, but somewhat old. There is a budget available for upgrades, but increasing enrolment places more demands on space and usage, and these labs are space intensive.

There have been various attempts to introduce process control into the laboratory. Some of the equipment has temperature datalogging, and there is a process control experiment. The weakness is that all students perform the same experiment, and there is no challenge as to what the appropriate tuning parameters should be.

After some brain storming, we began to consider the project as one of creating the unit operations laboratory for the 21st century, using 20th century vintage 19th technologies which is part of an institution created in the 18th century. This statement while, to an extent, glib, has a large element of truth in it, and it did help to establish the guiding principles. Regardless of their age, processes such as distillation, gas absorption, filtration will be part of the chemical engineering future; these elements need to be retained, and supported.

At this stage the guiding principles for the experiments became clearer. Four main objectives were targeted for the first step of the redesign of the Unit Operations laboratory:

1. Replacing outdated equipment and process control instrumentation with state of the art equivalents.
2. Designing and building versatile, multipurpose process systems that can be used for teaching a variety of unit operations and as such reducing the equipment acquisition budget and space requirements.

3. Allow the students to experience the connection of various unit operations into an integrated process yielding a finished chemical product instead of studying them in isolation from each other and the reaction engineering.

4. Expose the students to the state of the art realities of Distributed Control Systems (DCS) and their advanced process control computing algorithms.

The students should work with a state of the art control system similar to what one would see in a modern industrial control room. In this environment, multiple student groups could work on different experiments at the same time, much like a team of plant operators.

3 The System

In the first stage of the redesign project, three new systems were designed, built, commissioned and made operational for the undergraduate program:

A Versatile Batch System (VBS) comprised of three cylindrical stirred tank batch reactors (100 liter, 50 liter and 5 liter) equipped with variable speed mixers, reflux and take-off condensers, heating/cooling jackets as well as the full complement of instrumentation and process control components for temperature, pressure, flow and batch sequencing. The three reactors were designed to be geometrically similar such as to allow the students to implement the elementary level principles of scale-up. The versatile design of the system enables students to carry out, without modifications, experiments related to: batch heat transfer, solid/liquid and liquid/liquid mixing, crystallization, solvent exchange, multistep organic syntheses, polymerizations in solution and suspension.

A Continuous Heat Transfer System (CHTS) comprised of two shell and tube heat exchangers that can be run in series, parallel or single configuration for either heating or cooling. The system is equipped with the full complement of process control instrumentation that enables the user to quantify the heat exchange performance of the continuous system in different configurations and in comparison to the corresponding batch systems as well the computation of heat balances, heat transfer coefficients and their relationship the flow parameters.

A closed loop heating/cooling system comprised of two shell and tube heat exchangers (a steam heated heater and a water cooled cooler), a recirculation pump and expansion tank. A glycol/water mixture is continuously circulated in a constant flow variable temperature mode providing the heating/ cooling input to the VBS and CHTS experiments. The heating/cooling system is also equipped with the full

complement of process control elements and integrated through the DeltaV System in a master – slave configuration with the process requirements of the VBS and CHTS.

3.1 Process Control Considerations

The students need to gain sufficient understanding that a process control system is not perceived as a magical black box that does everything for them. In addition, they need to understand how any control system works – essentially, how to read and interpret process, electrical and one-line loop diagrams. One of the key learning objectives was to learn about common instruments (RTDs, pressure transmitters, magnetic flowmeters, solenoid valves, control valves), and how they need to be installed and wired. Figure 2 is one of our Electrical Drawings that is explained to the students in the laboratory. The I/O cabinets (seen in Figure 3) have transparent door panels so that students can see the wiring, components and I/O modules that interface with the field wiring to the control system.

The students should have the ability to adjust parameters as they chose, but in a safe manner. The system was designed to be robust enough to allow for wide variations in process conditions with the added protection of system interlocks developed to protect the system from any unsafe conditions.

Figure 2: An Electrical One-Line Diagram

Within our Faculty, Labview (A National Instruments product) is more widely used; while it is easy for students to program, it is not the interface product that students will see in the workplace. We specifically chose to purchase a robust industrial system

Commercial off the-shelf technologies have provided tremendous increases in functionality and cost advantages to end-users of today's automation systems. The disadvantages are that they also come with expensive administration and life-cycle costs. We selected Emerson's DeltaV system which uses a "Built for Purpose" approach that takes advantage of open standards and adding functionality that allows plug and play, full lifecycle support without upgrades or built in security.

The inherent integration of the DeltaV system extends to batch, advanced control, change management, engineering tools, diagnostics, and event and continuous historian. DeltaV digital automation system harnesses today's predictive technologies (including smart and wireless smart devices) in an easy, intuitive and interoperable manner. A suite of engineering tools handles configuration management both locally and remotely.

Figure 3: Photograph of an I/O Cabinet

3.2 The P&ID

The understanding of any process starts with a P&ID (Figure 4). It shows the arrangement of the pumps and heat exchangers, as well as the location of the solenoid valves, and the temperature control loops. The students are provided the P&ID prior to the laboratory, and need to understand the process logic. They need to trace the process lines as part of the laboratory work; this activity introduces them to what the physical equipment looks like.

Figure 5 is the operations screen of the CHTS experiment – similar in design to any industrial process control screen, and it matches the P&ID.

Figure 6 is a photograph of the CHTS. The solenoid valves, pressure transducers and magnetic flowmeters are clearly visible. More importantly, all devices and valves are tagged for easy identification – just as is done in industry.

Figure 4: P&ID for the CHTS

Figure 5: CHTS Operations Screen

3.3 The CHTS Experiment

The systems are designed to have characteristics of both batch processes as well as continuous processes. The system is activated, and the students choose from a menu of experiments. Once they have selected the experiment, they need to follow several start up steps.

The CHTS can run with either or both heat exchangers, and it can run in either heating or cooling mode. The students are assigned the specific experiment (heating/cooling; # of exchangers, hot fluid temperature) at the start of the experiment. They must identify and open the appropriate solenoid valves. Next, they activate the pumps and fluid begins to move. The heaters are turned on, and come up to temperature.

The students can begin to study the system's response behaviour, and to investigate tuning parameters. Our previous control experiment was a stirred water tank, with a continuous feed of cold water and a steam coil. All students did the same experiment, and all arrived at the same tuning parameters. Indeed, many students arrived at the laboratory, already knowing what the tuning parameter needed to be. With the new system, the multiple variety of flowrates, temperatures and equipment arrangements increases the experimental challenge. Once the system has lined out with one set of tuning parameters, a number of the system variables can be modified. There is a greater range of experiments that can be studied.

Figure 6: Photograph of the CHTS

3.4 The VBS Experiment

Figure 7 is a photograph of the Versatile Batch Reactor (which is not yet completely installed). It shares infrastructure (heating and cooling) systems with the CHTS system; only one of the two can be operated at a time. The VBS has 3 jacketed glass

reactors; the volumes are 5 L, 50 L and 100 L. Each has an air-operated agitator, as well as overhead condensers.

This apparatus has several key goals. The first is to demonstrate the implications of scale-up. For cylindrical reactors, volume and surface area do not scale at the same ratio. The lack of understanding of this fundamental issue has been the root cause of many chemical incidents [2].

A second goal is to study fluid mixing, and the impact of agitator rpm and design on mixing. We use 2 immiscible fluids for the experiment, with one of them dyed. The students can observe the mixing study, and compare their observations with a computer simulation using VISIMIX Turbulent® SV software package [3]. Figure 6 is a photograph of one such mixing experiment involving two immiscible liquids.

Figure 7: Photograph of the VBS Reactor

3.5 Initial Student Results and Comments

The initial work with students was completed during the 2010-2011 academic year. A limited number of 3 person students groups ran experiments with both the VBS and CHTS systems during the fall term. In the winter term, the entire 3rd year class (110 students) performed a process dynamics and control experiment. The system performed as expected – very smoothly.

There were a number of interesting student comments. Many students commented on the solenoid valves – they sat at the computer station, followed the procedure to open a solenoid valve, and heard the click as it activated. They also turned the pump on, and watched the delay as the pressure and flow rate increase to its steady value.

An unexpected observation deals with data analysis. The students build a mathematical model that mimics the system and predicts the results; the quality of the model relates to how closely it mimics the data. Most students tried to get a fit within $\pm 0.1^\circ\text{C}$, without understanding that the accuracy of the RTD is $\pm 0.4^\circ\text{C}$. This is an area that we need to address for next year.

The process control laboratory runs for roughly 2 hours; the temperature response is not quick. This leaves the students with a lot of “sitting around” time. Our goal is to use this time to teach the students about the various devices, and particularly, how they work. Unfortunately, we need to work harder to train the Teaching Assistants do this additional teaching.

The other key weakness was with students not grasping how units are linked together to form a process. For too many students, this was their first exposure to a process with more than one component. We will be adding hands on unit operations experience in our first year chemical engineering course next year to try to start this learning sooner.

4.0 Conclusions

Unit operations remains a key component of the chemical engineering curriculum. It is important that we upgrade the instruction to ensure that students gain a more practical knowledge base. This includes the names and operations of standard measuring devices, what they look like and how they are installed. It is also important that students see the link between the design P&ID and the control system – the control system uses computers, but it is not a computational black box. We have found that we can leverage more learning out of our existing laboratories through a change in the approach to the infrastructure. The initial response of the students has been very positive.

We have opened discussions with other programs within the Faculty. The other programs teach process dynamics and control, and develop mathematical models of systems; response times are always within seconds on the computer simulation. The other programs have an interest in this system for two reasons: a physical event occurs when the system is changed (a valve opens or closes, leading to a change in flow), and the response times are more realistic (than that seen with a computer simulation). As we expand the implementation of this system, we hope to bring in students from other programs to work on future upgrade projects as their capstone design projects.

5.0 Acknowledgements

The financial support for this project has come through the Levy Fund of the University of Toronto Engineering Society. The Levy Fund is a voluntary levy on the undergraduate students, which is matched by each program, and which is to be used to improve the laboratory hardware in the undergraduate teaching laboratories.

We would like to acknowledge Ed Baliat, Ed Pittens and Lakeside Process Controls Ltd. for their support of this project. In particular, we would like to thank Jeremy Sato for his technical assistance to us in resolving several unique programming challenges needed to bring the Delta V system into a teaching mode.

References

[1] McCabe, W.L., J.C. Smith and P. Harriott, "Unit Operations of Chemical Engineering, 7th Ed", McGraw-Hill Book Co., New York, 2005.

[2] U.S. Chemical Safety Board, "T2 Laboratories, Inc. Runaway Reaction", Report 2008-I-FL, September 2009.

[3] Visimix Ltd. P.O. Box 45170, Jerusalem, 91450, Israel.