LAB SCALE PROCESS CONTROL FLOW CART: HEAT EXCHANGE

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ABSTRACT
Lab scale flow carts are commonly used to test processes in the chemical industry. These flow systems are also good tools for educational purposes. They are usually composed of full size process components, such as flow meters and valves, as well as lab scale process units such as pumps and heat exchangers. The small-scale functionality of flow carts provides an opportunity for educational programs to include hands-on plant design in a laboratory setting. The Chemical Engineering Department at RIT currently uses these flow systems to introduce students to components that would commonly be found in manufacturing plants. The existing flow carts only have the capability to generate flow through a system while measuring the results. Working with the chemical engineering department, and in collaboration with Kodak, the multi-disciplinary student group designed and built a flow system that would be used to teach hands-on process control to students in an upper-level lab. This project was completed in parallel with two other projects (P13631 and P13633) in order to develop three similar stations for the lab assignment. The flow cart that was designed incorporates computerized process control with a heat exchange system. The students will be exposed to the basics of building and optimizing a control system by controlling the temperatures of the flow streams.

INTRODUCTION
A flow cart is a self-contained flow system that simulates a larger manufacturing process. All of the components are usually mounted to the cart, making it portable. These systems are used in industry as a prototype stage for new processes as they are a relatively inexpensive way to experimentally optimize a system for scale-up. The chemical engineering department at RIT uses these small-scale systems for educational purposes. The self-contained miniature flow system is the ideal way to expose students to process control systems. The carts currently being used do not have digital process control capability. As a way to expand the student’s educational experience, the chemical engineering department wanted three flow carts to be used for process control laboratory assignments. Three separate design groups worked in tandem to deliver three carts that have similar systems. The cart that was requested from our group required temperature based process control. This was accomplished through the use of a shell and tube heat exchanger flow system. This system is composed of hot and cold flow lines for the heat exchanger, and a
control valve to regulate the flow rate, which in turn will control the process temperature. The cart was only one aspect of the project.

The second aspect of the project was the design of a control system that would be used to analyze the signals from the temperature sensors on the cart and convert that information into an action to change flow rate and effectively control the temperature of the desired stream. This system uses four total temperature sensors. These sensors are used as inputs and feedback in a PID (Proportional Integral Derivative) control loop through a Labview interface. The control output sends a signal through a transducer to a valve that controls the flow rate of the process fluid through the heat exchanger.

Heat exchangers are units used in many manufacturing processes to control the temperature of process lines. These units function by facilitating heat exchange across an interface that prevents the mixing of process fluids and cooling/heating fluids. The most common type of heat exchanger is a shell and tube (Figure 1). A shell and tube heat exchanger cools or heats the process fluid by circulating the exchange fluid around a central tube containing the process fluid.

**Figure 1:**

![Heat Exchanger Diagram](image)

The cart design was based on the requirements of our customer, the chemical engineering department at the Rochester Institute of Technology. These requirements were the baseline for component selection and for the nature of the laboratory objectives.

**Customer Requirements**

- Design modeled after and consistent with existing flow carts
- Design to be modular and adaptable
- Design to be portable, easily moved, easily connected and disconnected to lab utilities
- Robust and durable design
- Minimal maintenance and cleaning
- Interface with Labview
- Utilization can take place in allotted time for lab
- Utilization safe and ergonomic
- Operated by 3 students
- Utilization requires fundamental understanding of Process Control
- Can be operated manually or through Labview interface
- Data can be collected manually
- Automated data collection through Labview
- Means to regulate flow of process fluid
- Means to regulate flow of heating fluid
- Control temperature via regulating temperature or flow
DESIGN PROCESS

Through collaboration with Dr. Christiaan Richter from the chemical engineering department, Steven Possanza from Kodak, and Dr. Michael Sanchez (the adjunct professor for the process controls class), the group considered multiple design options for the flow geometry and control technology. Figure 2 shows the results of this analysis with the design decisions.

Figure 2:

The final design uses portable temperature baths to provide process fluid at set temperature points. The process control component will be accomplished with a control valve placed on the inlet of the cooling flow to affect the outlet temperature of the process fluid. A flow meter was added to the cold flow inlet to measure the flow rate of the controlled stream. In order to decrease the risk of student injury, the heat exchanger was used to cool the process fluid. This prevents the higher temperature flow of the heat exchange from being on the exterior of the design. Figure 3 shows mock ups of the overall cart design.

Figure 3:

The electrical design of the cart includes one RTD and one thermocouple at the input of the heat exchanger and one RTD and one thermocouple at the output of the heat exchanger. This was done in order to compare the effectiveness and response times of various sensors on the heat exchange system (all of the sensor data is sampled by an MSP430G2553 chip, due to its low cost and analog-to-digital converter capabilities). The microcontroller sends this serial data to Labview through a UART (universal asynchronous receiver/transmitter) interface which
allows Labview and the microcontroller to communicate with one another. Using Labview’s available Virtual Instrument Software Architecture, serial data in ASCII format can be written to and from Labview. The software developed in Labview records data from all 4 sensors, but only uses the two RTD sensors to create a PID control loop. The PID variables and set point are modifiable by the user and the resulting output is written to another microcontroller, which, using a serial peripheral interface (SPI), communicates with an MPC4812 digital to analog converter (DAC). This produces an output between 0v and 5v. This is effectively the control signal for the valve. The signal is the input for a current source, with a 24v rail that will convert the 0v to 5v signal to a 4mA to 20mA input signal for the transducer, which will provide a 3 to 15 psi control for the valve. An overview of the electrical system is shown below.

Figure 4:

The cart was constructed using a Rubbermaid wheeled cart with a capacity of up to 250 pounds. The structure was fabricated with aluminum struts, and all of the components were mounted onto the structure. Figure 5 shows images of the constructed cart.

Figure 5:
Once the cart was fully constructed the group performed testing to ensure that it functioned properly within the design parameters, and that it would meet the requirements of the customer for use in a future lab. Figure 6 shows the test plan followed to ensure the final cart was performing to the desired specifications.

Figure 6:

<table>
<thead>
<tr>
<th>Test ID</th>
<th>Test Name</th>
<th>Relevant Specification</th>
<th>Relevant Customer Need</th>
<th>Description</th>
<th>Critical Value</th>
<th>Pass/Fail</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1</td>
<td>Leak Test</td>
<td>Minimal Cleaning</td>
<td>Robust Design</td>
<td>Ensure all connections are tight and no liquid leaks from the system</td>
<td>Pass/Value</td>
<td>Pass</td>
</tr>
<tr>
<td>T2</td>
<td>Accuracy of Rotameter</td>
<td>N/A</td>
<td>Robust design</td>
<td>The measurement the flow meter outputs should be confirmed by experimentally measuring a volume of fluid collected over a set time period</td>
<td>20%</td>
<td>Pass, 8% discrepancy</td>
</tr>
<tr>
<td>T3</td>
<td>Temperature Sensor Accuracy</td>
<td>N/A</td>
<td>Robust Design</td>
<td>The temperature value the temperature sensors return will be confirmed by comparing the readout to known values</td>
<td>Pass/Fail</td>
<td>Pass</td>
</tr>
<tr>
<td>T4</td>
<td>Optimize ΔT</td>
<td>Temperature Control</td>
<td>Teaching</td>
<td>Test heat exchange over a range of inlet temperatures for the hot and cold streams to optimize heat exchange settings</td>
<td>Change in hot stream 10°</td>
<td>15° in 30 minutes</td>
</tr>
<tr>
<td>T5</td>
<td>Labview Runthrough</td>
<td>N/A</td>
<td>Student Use</td>
<td>Full testing of all labview interfaces to ensure communication with the computer</td>
<td>Pass/ Fail</td>
<td>Pass</td>
</tr>
<tr>
<td>T6</td>
<td>Lab Assignment Runthrough</td>
<td>N/A</td>
<td>Student Use</td>
<td>Full testing of lab assignments to confirm the time requirements and results</td>
<td>Pass/Fail</td>
<td></td>
</tr>
</tbody>
</table>
RESULTS AND DISCUSSION

The final product consists of a wheeled cart containing a heat exchanger, air regulator, valve, flow meter, four temperature sensors, and various tubes and fittings. Two water baths can be placed on an adjacent cart or on the countertop to hold the process water, but they can be moved for increased portability. Process air and power are obtained from connections to lab utilities. The cart is integrated with a lab procedure that allows students to gain a hands-on understanding of process control, and has an equipment manual with all relevant data to fix any unforeseen malfunctions.

Due to a mechanical error, the cart was not functional for integrated testing at the time of this report. The mechanical and electrical portions were each tested separately and proved to be effective. No leaks were detected upon start-up and throughout the various other tests performed. The temperature sensors, both the RTD’s and thermocouples, were proven to work correctly and register temperatures in the correct range. Precision of the sensors is more important than degree accuracy for this application as the change is what is analyzed. Effective temperature change was achieved, with a maximum heat exchange possible from the system proven to be fifteen degrees in approximately thirty minutes with a completely open valve. This proved that the cart is capable of teaching heat control in the time provided. The Labview interface was also constructed and shown to work effectively. The integration of the electrical system with the mechanical aspect of the cart was functional before soldering occurred, showing that the design communicated correctly with the cart components.

When the circuits were transferred from the breadboard to the circuit boards all preliminary testing indicated that the transfer of components was successful. After installation, however, problems arose and it was determined that one of the chips was no longer operational. More testing was attempted and yet another component failed. As failure occurred between construction of the circuit boards and integration testing, it was determined that the installation into the electrical box must be at fault. Further investigation determined that the use of washers to stabilize the boards in the box caused the circuits to short, as the metal washers contacted and interfered in the copper circuitry. This short caused multiple components in the circuit to malfunction and resulted in the failure of the circuit boards, preventing integrated testing.

The functionality of the system was determined by the given specifications and guidelines from the customer. These requirements were compiled in the test plan, and systematically assessed. As shown, the cart was fully functional before the circuits were transferred from the breadboard, and most of the specifications given were met. The rest of the requirements are not able to be tested until the cart is operational with the integrated electrical equipment. A path forward to achieve this condition is outlined below. The developed lab procedure in conjunction with the flow cart clearly taught process control in an interesting and innovative manner. The cart performed satisfactorily in both mechanical and electrical aspects, with an equipment manual provided to ensure optimum performance in the future. The portable design requested was achieved with the integration of all components on a wheeled cart with standard fittings for all lab utilities. Manual operation is also possible in the event that Labview is unable to function correctly, while the standard operation involves the use of process control loops in Labview.

CONCLUSIONS AND RECOMMENDATIONS

The overall success of the system is evident in the way in which the specifications were met, and this fact outweighs the failures encountered. There were areas of failure, however, and room for future improvement. The main electrical failure was tied to mechanical sources and was a simple oversight instead of a lack of knowledge or effort. While a Honeywell controller could have been provided from Kodak and would have alleviated this error, the path chosen allowed the electrical engineer on the team to have a meaningful learning experience as well as developing a more efficient system.

The failure of the circuit board prevented the completion of this project by the stated deadline, but a path forward was developed to attain the desired state by the end of the academic term. Although no backup parts had been ordered previously, they will now be ordered with overnight shipping, and the circuit boards re-created. Rubber spacers will be utilized instead of the metal washers, preventing the reoccurrence of the problem. Another electrical engineer is assisting with the re-creation of the circuit boards and double-checking all steps until installation. This plan allows for installation to be achieved in enough time to allow for the rest of the testing to be completed and documented prior to the scheduled poster presentation.

This project fulfilled its purpose as a learning experience as well as providing quality lab equipment for the Rochester Institute of Technology. Important lessons learned from this endeavor include the importance of timely, detailed, and concise communication between all team members and other invested parties such as management. The value of having backup parts on hand for quick replacement in case of malfunction or breakage was shown, as that would have allowed a timely fix to the issue encountered. The need for consistent and detailed documentation was also highlighted. Having only one team member who clearly understood a major component was a drawback for
the team and resulted in a bottleneck of the work, and the mechanical failure preventing integrated operation. Having another team member who understood the electrical system would have resulted in more collaboration and vocal teamwork, which could have prevented the error that caused the system to fail. A second attempt at this project would go more smoothly due to each member having a better understanding of these lessons.

While the final product met the specified guidelines in a robust manner, improvement and enhancement is always possible. The addition of a manual valve actuation system could benefit the project by providing a better hands-on understanding of the effort required in process control and the importance of a quality computer system to handle the actuation portion of process control. Further improvement could come from a software change to a system utilized in industry rather than only in a lab setting. Addition of water baths as a permanent fixture on the bottom of the cart would reduce set up time and ensure dedicated water systems for the cart. These enhancements would improve the cart and potentially help with increased learning, but the system fully meets all requirements and specifications as it stands.

REFERENCES


ACKNOWLEDGMENTS

Many thanks to each of the individuals who contributed their assistance throughout the various stages of this project. Steve Possanza guided the team through each phase from the initial concept to the finished product. Mike Sanchez gave the Chemical Engineering members of the team a strong background in process control, and assisted with the development of the lab procedure for which the cart will be used. Christiaan Richter, as the main customer for the project, helped clarify the project and provide direction where necessary. Paul Gregorious, lab manager, helped in countless ways by providing space to work and odds and ends of parts where needed. Kodak generously supplied most of the cart components as well as loaning us its employees, especially Steve Possanza and the electricians whose expertise and skills helped with assembling the electrical box. Last but not least, Steve Weinstein and the entire Rochester Institute of Technology Chemical Engineering department supported and helped lead to our team’s success.