2006-986: RETROCOMMISSIONING (RCX) MECHANICAL SYSTEMS ON A UNIVERSITY CAMPUS: STUDENT CAPSTONE EXPERIENCE

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Retrocommissioning (RCX) Mechanical Systems on a University Campus: Student Capstone Experience

Abstract
Senior engineering students at Rochester Institute of Technology are required to complete a 22-week culminating project prior to graduating. This multidisciplinary project assembles teams of students in various engineering majors to work together on an engineering design project sponsored by industry or an academic client. There are a wide range of projects available to students, and all stages of the projects are completed from introductory information given by the sponsor, development of possible design concepts, selection of final concept, analysis and completion of final prototype. In the following paper, the capstone design project process is presented from a student perspective, including a breakdown of the twelve-step process used by the design groups, a course assessment from the student team, as well as details of a specific project as it pertains to the various phases of design. The project involves the development of a retrocommissioning (RCX) test plan for evaluating an existing air handling unit (AHU) on a college campus, in order to reduce energy consumption, improve occupant comfort, and prolong equipment operation. The test plan is implemented and test results are analyzed as part of the student's capstone design experience. In addition, a first and second law thermodynamic analysis is conducted. Based on the team findings, a comprehensive RCX test plan is developed for use on air handling units throughout campus and recommendations are made for retrofit design solutions to improve system performance.

Key Words
Retrocommissioning, Air Handling Unit (AHU), Energy, Exergy, Heating, Ventilation, and Air Conditioning (HVAC), Student Capstone Design

Introduction

The multidisciplinary design project brings a group of senior engineering students together for a 22-week project to enhance the principles learned in coursework and expose students to working in multidisciplinary groups in a final culminating project before graduation.

A twelve facet design process is followed for the project. The twelve step process developed in includes the following facet[1]:

1. Needs Assessment
2. Concept Development
3. Feasibility Assessment
4. Tradeoff Assessment
5. Engineering Analysis
6. Preliminary Design Synthesis
7. Engineering Models
8. Detailed Design DFx
9. Production Planning
10. Pilot Production

11. Commercial Production
12. Product Stewardship

Strong emphasis is placed on completing the first ten facets, with the pilot production piece and a final presentation due at the end of the project time period. Eleven weeks into the project, a preliminary design review occurs to measure progress of the project.

Students are encouraged to iterate during various facets of the design process, when necessary. Each project is unique; the requirements and final product differ greatly depending on the needs of the project sponsor, who is typically an industrial or an academic sponsor.

Previously, Stiebitz et al. discussed the Capstone Design Process at the college from an education and administrative perspective[2]. The design process was outlined and learning objectives of the program were discussed. Gannon et al. presented their project on Solid Oxide Fuel Cells at an international fuel cell conference, and described their design process with heavy emphasis on the initial design facets and much less emphasis on engineering analysis and detailed design[3].

In the following paper, one project will be described while pointing out the various design process facets completed. The lead author was a student on the team, and all work performed and described is from the student perspective. The co-author was the project faculty mentor and had constant involvement in the project. Ways in which the project guidelines were tailored to a specific project and how the project was successful and beneficial to the students and the project sponsor will be discussed. All facets of the project will be presented both from a course perspective as well as the perspective of the specific project. Special attention is paid to presenting an actual portion of testing results, analysis results, and details of the final test plan to show the level of engineering involved in the design project and the project process as conducted by the student team.

The project presented is titled *Retrocommissioning (RCX) Building Mechanical Systems in Building 70*. The team consisted of four mechanical and one electrical engineering students. The project sponsor was Facilities Management Services on the college campus.

The following is background information relating to this project. Building commissioning is a term associated with new construction projects as a process of ensuring that new buildings and their heating, ventilation, and air conditioning (HVAC) systems perform as designed. Retrocommissioning (RCX) is somewhat more elusive because it examines existing buildings and HVAC systems that may degrade after periods of extended use. RCX can provide a new beginning to an existing HVAC system. An RCX agent will carry out a methodical effort to uncover inefficiencies and ensure that the specified systems are functioning without any major operating, control, or maintenance problems. This is accomplished by a detailed review of the existing system compared with the original design specifications. RCX offers building owners cost saving opportunities by reducing energy waste, preventing premature equipment failure, maintaining a productive working environment for occupants, reducing risk associated with expensive capital improvements, and increasing the asset value of a facility. In addition, the RCX process will ideally update building documentation, provide appropriate training to the building's operating staff, and organize maintenance and balancing schedules and procedures.

Normal analysis performed during the RCX process includes verifying proper operating conditions and conducting a First Law analysis of the HVAC system components. Exergy analysis is not normally done in commissioning. Exergy analysis, also known as availability analysis, uses the conservation of mass and conservation of energy in combination with the second law of thermodynamics. Like First Law based efficiencies, exergetic efficiency is useful for finding ways to improve energy consumption. It can be used to determine the locations, types, and magnitudes of energy waste and loss.

An outline will be presented for the steps taken in the design process, including a description of what the step entails, as well as the specific description of the RCX project as it fits the design process.

Needs Assessment

The needs assessment facet is the starting point for the project, where team members review existing documents describing their project, and meet with the project sponsor to determine the goals and requirements of the project. It also includes developing a list of needs and desires for both the team members and the sponsor. The team must heavily consider the desires of the project sponsor, but also keep in mind course objectives for senior design to maximize both the benefit to the students and the sponsor. Teams should understand the motivation for their project and collect supporting documents such as relevant publications.

For the RCX project, the sponsor, FMS, is responsible for maintaining building systems across a college campus. A goal was for a retrocommissioning plan to be developed that could be utilized for retrocommissioning building systems on campus, as needed. The RCX plan was to be general enough to apply to many of the buildings throughout the campus, as the systems and equipment can vary. Based on experience, the sponsor suggested that the air handling unit be the primary focus. A budget of $10,000 was allotted for procurement of new equipment as needed for the testing. The student team developed goals for the project, which included that both energy and exergy analyses would be considered in the investigation. The sponsor was primarily interested in reducing energy consumption, improving efficiencies, and maintaining occupant comfort. The project was to include developing the RCX plan, as well as testing and analyzing the system in building 70. The team collected materials such as relevant publications on commissioning, equipment manuals, sequence of operations, building plans, and specifications. By doing this, the students felt they had a more complete understanding of the RCX process as well as how the system operates. Once testing and analysis was complete, retrofit solutions were developed in conjunction with the sponsor recommendations.

Concept Development and Feasibility Assessment

The concept development facet involves using the requirements and goals determined in needs assessment to start generating several concepts to tackle the problem at hand. A majority of projects involve developing a device or object that performs a specified task, while others, like the one described here, develop a process or intangible final product. Several possible project scopes must be considered and chosen from carefully. At the concept development stage the original requirements from the needs assessment are verified for each concept. The concepts are narrowed down to several final concepts for consideration. Concept development can be as informal as sketches on scrap paper, or as technical as a computer drawing. Methods used for concept development, as taught by the multi-disciplinary design course, include brainstorming techniques, synectics, morphological analysis, and empathy methods[2]. The students are responsible to do what is necessary to develop several concepts.

Feasibility assessment is a methodical way to narrow the top concepts down to a robust final concept. There are several methods presented to students to successfully determine their strongest, most feasible concept. The key considerations include schedule, economic, resource, and technical feasibility. The winning concept would be able to be completed in the time frame given, within the allotted budget, all necessary resources would be available, and the students would have the technical capabilities to do so. Students are urged to utilize a methods presented to them, included the Weighted Method and Pugh's Method to determine the importance of several key factors of their projects and help assess feasibility of various designs.

For the RCX project, the students chose the scope of work was chosen as the AHU in the building 70 mechanical system. An air handling unit alone was chosen primarily for time considerations. After the student group weighed the various options, it was not feasible to develop a test plan, conduct tests, and complete an analysis on a larger system, such as all mechanical room components or for the entire building HVAC system. This decision met the sponsor requirements and suggestions. The formats of the tests were also determined. After considering several formats, a combination of documents was chosen. It was decided that the test sheets would be printed copies on which a technician could write values while testing. This document would be modeled in a popular spreadsheet program so that in the future, computerized data entry would be possible. Also, the analysis would be conducted using the program after the data was entered from testing. This option was the most feasible because other software options had licensing issues. The sponsor was in agreement that this was the most practical concept. The sponsor has access to the proposed software and will not need to purchase additional programs.

From a schedule perspective, the feasibility analysis performed by the student group deemed this concept was feasible because it did not require the team members to learn an alternate programming technique, since the chosen program is user friendly and all team members had sufficient knowledge of the software. A preliminary equipment list was developed in parallel with the testing procedure and test points. This was modified based on a list of existing testing equipment already owned by the sponsor. A preliminary test plan was developed by the midpoint of the project, and modifications were made throughout the testing process.

Trade-Off Assessment

It is often the case that the feasibility assessment brings a few final concepts to the forefront, rather than just one. It is then necessary to conduct a trade-off assessment. In this approach, a numbering concept is applied to judge which aspects are more significant than others in order to determine a final concept for the project. This step is not necessary if the feasibility assessment produces a clear idea of the best final concept for the various constraints.

The team determined it was not necessary to conduct a trade-off assessment for the RCX project. An example of a trade-off assessment a team may have to conduct could be deciding between a heavier inexpensive material, and a light weight but more costly material when developing a prototype where both weight of the component and cost to build are essential factors. The team would then have to decide which feature was more important and decide how to proceed.

Engineering Analysis

Engineering analysis is important to create a robust design. The type of analysis conducted varies from project to project, but it is ultimately necessary for all projects. Students will formulate and solve problems to determine the thickness, material types, final temperature, etc. as it relates to their project. For this portion of the project, it is the hope that students will draw from their previous coursework to develop equations and verify parameters. However, the analysis may require them to learn something from a new area not previously learned in classes, or combine new knowledge with previous coursework. The teams have faculty available for assistance throughout the project, and a faculty team mentor to check progress and assist when students need help.

The students on the RCX team developed a spreadsheet containing all of their formulations and calculations. They utilized knowledge from thermodynamics, heat transfer, fluid mechanics, and advanced thermodynamics courses, as well as common equations used in the HVAC field. The analysis was developed before any actual data was acquired. Unlike projects where a prototype is developed, this project needed to conduct testing as a major portion of the project. The test results were then used in the analysis to come to some final conclusions.

The following assumptions were made while conducting the analysis. The system was considered at steady state because the system was allowed to reach equilibrium before collecting data at each set point. The control volume (CV) was taken around the physical boundary of the AHU and was assumed to be adiabatic. The mass flow in and out of this control volume included chilled water, hot water, outside air, exhaust air, return air and supply air. The air flow was assumed to be incompressible, and air was treated as an ideal gas. A constant specific heat at constant pressure (c_p) was assumed for air. Kinetic and potential energy were ignored for air and water flows associated with the AHU.

The analysis developed is presented in the "Results and Retrofit Solutions" section along with the results from this analysis.

Preliminary Design Synthesis

For preliminary design, teams must begin the initial stages of preparation for production, including developing bill of material lists, initial component drawings and selecting possible suppliers for components.

For the RCX team, preliminary design included determining preliminary procedures for testing, compiling existing testing procedures conducted by FMS, and a review of instrumentation. The instrumentation review the students conducted included taking inventory on existing equipment as well as verifying up to date calibration for the instrumentation. No new equipment or calibration certifications were necessary, however if they were it is important to follow through on procuring new equipment and updating certifications at this time so testing can take place on time.

Engineering Models

For most projects it is necessary to complete engineering models using modeling software package. These models compliment the final prototype and may be used when having components made. For some projects, engineering models may be computer program code, a stress analysis model, or a mechanical drawing, depending on the nature of the project. Models are usually created on the component level as well as a final assembly level and are used to show proof of concept[2].

The engineering models for the RCX project consisted of CAD drawings for each component, as well as the system as a whole. An example of one drawing produced by the team can be seen in Figure 1.

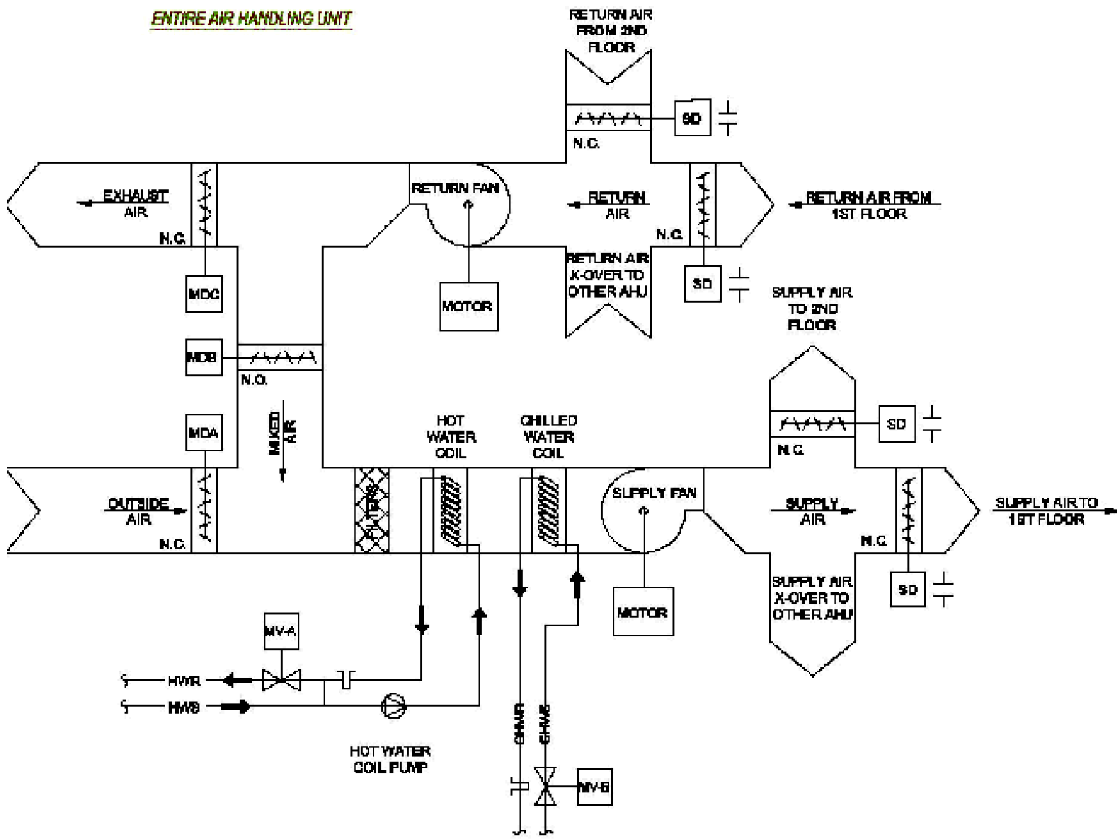

Figure 1: Air handling unit diagram created by RCX team

Detailed Design (DFx) and Production Planning

The detailed design step includes developing and fine-tuning the final design for the project. For projects where a physical prototype is developed, this would be their final design plan and specifications to be followed while fabricating the prototype. Detailed design should include addressing issues of safety, manufacturability, maintenance and quality[2]. If any changes are made while constructing the prototype, those would be incorporated into the DFX for the final project submission.

In the production planning stage, teams develop and review any steps necessary for pre-production. This may include reviewing a bill of materials and ordering components for prototype fabrication, or sending a part to be machined. It could also include tooling design and process flow sheets[2]. This is the final planning stage before construction of the final prototype begins, and is a preparation stage to minimize mistakes during prototype building.

For the RCX team, detailed design included having a test-ready checklist to complete the retrocommissioning testing. They also determined target dates for testing, which were to take place in the following academic quarter. After this step, a preliminary design review took place to verify progress and robust design, and the students proved to a panel consisting of faculty of various engineering disciplines as well as members of industry.

Production planning included reviewing the test check-lists developed in previous stages before proceeding with testing, and verifying that proper instrumentation was available for testing.

Pilot Production

The pilot production phase includes creating a working prototype for the final concept. The usability of the prototype varies depending on the project requirements and budget and range from a scaled model version to a fully functioning device that is immediately put to use. Depending on the project, teams may utilize a machine shop, order components, and assemble a final working prototype based on the detailed design previously completed. The groups are all required to do a prototype demonstration to showcase their work, and prove that it functions properly.

The RCX project didn't involve making a prototype device, but rather a final draft of the testing document, which was the final product requested by the sponsor. The document had undergone several revisions by the team, particularly after the testing phase where procedures and data points were solidified. The testing was an important part of pilot production, because it validated the test procedure and pointed out places where minor adjustments were necessary. In addition to the test plans, final results from the system tested were summarized and presented to the sponsor along with recommended retrofit solutions.

Testing and data collection were completed using the retrocommissioning test plans developed. Testing techniques and practices were verified by a balancing agent. The students conducted all aspects of testing except one circumstance where a safety and liability issue came up. Two to three technicians were available at all times to assist with conducting tests to ensure proper operation of the equipment, as well as offer their expert knowledge of the system and controls necessary to change test parameters. The testing and data collection is described as follows in Sensor Verification, Pre-Functional Tests, and Functional Tests sections.

Verification of the extensive RCX tests developed by the team was one result of the project. A second result of the project includes numerical data obtained from testing and analysis, which is discussed in "Results and Retrofit Design Solutions"

Sensor Verification

The first task for testing was to verify the sensor readings for the web-based control system. This was done by taking hand measurements in the same location as the sensors. Several measurements were taken and averaged to verify that sensors were performing within their published specifications. These sensors included temperature, pressure, and volumetric flow rate. The damper percentage, and voltage and amperage of the Variable Frequency Drive (VFD) were also checked with rough measurements or visual inspection. The validity of the sensor output was assessed, taking into account accuracy of the sensors, accuracy of the measurement devices, and conditions under which the sensors were tested. For example, some temperature sensors are averaging sensors, which obtain and average temperature measurements over a ten foot length, and the temperature probe utilized measured at a single location. In this case, it was likely that the existing sensor would deliver more accurate results than a handheld device. Such factors were taken into account where applicable. With the exception of one, all of the sensors were determined to be accurate, and tests proceeded with using web-based control system values as actual values. The supply air CFM sensor was dirty, and was deemed acceptable after it was wiped clean.

Pre-functional Tests

Pre-functional tests are an important part of the retrocommissioning test plan. These tests check for operational aspects of the components without taking measurements or collecting data. Pre-functional tests check for excess vibration, proper lubrication, and proper installation, among other things.

After researching the subject and brainstorming, the students decided the key things to verify for the fan pre-functional tests are rotation, vibration, cleanliness, lubrication, sheaves, and belts. The fan rotation should be verified—it should rotate easily and in the proper direction. There should not be excessive noise or vibration. The fan and fan blades should have good overall cleanliness. If not, it is a sign that something else may be working improperly. Fan and motor lubrication should be checked. The sheaves should be properly aligned, and the belts should be in good condition.

Important aspects of the coil pre-functional tests include cleanliness, fin damage, insulation, pump operation, leakage, and standing water. A lack of cleanliness on the fins could disrupt proper heat transfer. Fin damage should not be excessive, and the insulation on all pipes should be intact and in good condition. The pump should be operating properly, and the pump, pipes, and fittings should be free from leakage. It is very important that the condensate drain is working properly, and there is no standing water under the coil, as it can lead to fungal growth and pose a health hazard to building occupants.

The function and operation of the dampers should be checked in the economizer pre-functional test. Other aspects such as linkage, lubrication, and proper closure should be verified. Dampers should operate properly when stroked individually or as a unit. They should fully open and close upon command. They should not squeak or otherwise indicate a lack of proper lubrication.

Control pre-functional tests conducted include start/stop hands off auto, and freeze stat. The start/stop hands off auto (S/S H/O/A) will verify that the unit can be properly shut down remotely from the web-based control system. The freeze stat test verifies the system properly reacts to freezing conditions as a safety measure to protect the coils. For the purposes of testing, the freeze stat is tripped with a false temperature as to not damage the coils.

The team decided, with input from the FMS technicians, that the results of pre-functional testing for the building 70 AHU were satisfactory but many items were identified. A majority of pre-functional tests passed. The following are issues encountered in testing:

- A cleanliness issue was encountered in the supply fan. The supply fan blades and the CFM sensor were dirty. The CFM sensor was wiped clean while the fan was left untouched. If dirt is on the CFM sensor, the air flow into the sensor will be obstructed, giving an inaccurate reading. Fan cleaning should be done as part of a preventative maintenance (PM) schedule.

- The fan bearings were over lubricated on the backside of the return fan. There was excess grease in the area that was wiped clean.
- There were fins dented for both coils, but it was not substantial. If too much damage is evident, the fins can be straightened with a combing tool.
- The damper hardware did not appear to be lubricated, although for this particular economizer it may not necessary. However, a squeaking noise was heard when the dampers moved.
- The exhaust air damper was mostly closed when set to 0%. There was a slight gap between the blades. The mixed air damper was not fully closed when set to 0%. The outside air damper closure showed the greatest discrepancy, because there was approximately three eighths of an inch gap between the blades. This may be because the damper is below its normal operating range at 0%. The failure of the dampers to close raises a red flag, and the issue will be assessed after functional testing.

Functional Tests

Functional data was collected for the performance tests, and test modifications were made as the tests were conducted. Several changes were made by the team based on feasibility of their original test plans. Insight to the effectiveness of the original tests was gained through the experience of performing the tests.

The fan test includes varying the supply duct static pressure while obtaining values for frequency, CFM, and horsepower. This is done for duct static pressures above and below normal operation. This will help determine the efficiency of the fan and whether the system is operating at the optimal set point.

The coil test varies both air CFM and valve position while obtaining data for temperature changes. Coil effectiveness formulations are used to obtain a value for coil effectiveness.

The economizer test aims to verify that the system is bringing in minimum outside air when necessary, and utilizing economizer mode when outside conditions apply. The main focus of this test uses trend data over a period of time, which is obtained from web-based control system.

Results/Retrofit Design Solutions

For the RCX project, a deliverable to the project sponsor included results obtained from the testing. This may not be typical for all projects, but it is a verification of the analysis as well as data collection procedures for this project, and thus an important part of the project.

The following analysis was developed by the student team using conventional equations from thermodynamics, heat transfer, and the HVAC industry[4, 5]. Results obtained from the analysis are presented.

The fan efficiency is found from Equation 1, where the fan power is in terms of brake horsepower.

$$\eta = \frac{\dot{V} \times p}{\dot{W}} \qquad \textbf{(1)}$$

where $\dot{V}$ is volumetric flow rate, p is the static pressure across the fan, and $\dot{W}$ is the work into the fan.

The fan efficiencies are shown in Table 1. For the fan efficiencies the first set point of 1" WC static pressure produces better efficiencies for the return fan, but reduces efficiencies for the supply fan. This is due to the fact that the return fan CFM is based on the supply fan CFM.

The design first law efficiency for the supply fan is 70%. Once again, the efficiencies increase as the pressure set point increases. The return fan design first law efficiency is 47.5%, and the efficiencies increase as the pressure set point increases. All efficiencies are with in ten percent of design.

	Design	Static Pressure ("WC)		
		1	**1.25**	**1.5**
Supply Fan Efficiency, η (%)	70.3	60.6	63.7	65.5
Return Fan Efficiency, η (%)	47.5	53.6	40	40

Table 1: Fan efficiencies

To determine coil effectiveness for the heating coil, values for q_c (actual heat) and q_{max} (maximum possible heat) must be determined, as shown in Equations 2 and 3.

$$q_c = C_C \cdot (T_2 - T_1) \qquad \textbf{(2)}$$

$$q_{\max} = C_{\min} \cdot (T_3 - T_1) \qquad \textbf{(3)}$$

Where q_c is the actual heat for the colder flow, q_{max} is the maximum possible heat transfer rate, C_c is the heat capacity rate for the colder flow, C_{min} is equal to C_c or C_h, whichever is smaller (C_c in this case), and T's correspond to temperatures in Figure 2. The ratio of these two values is the coil effectiveness ε, as shown in Equation 4.

$$\varepsilon_c = \frac{q_c}{q_{\max}} \qquad \textbf{(4)}$$

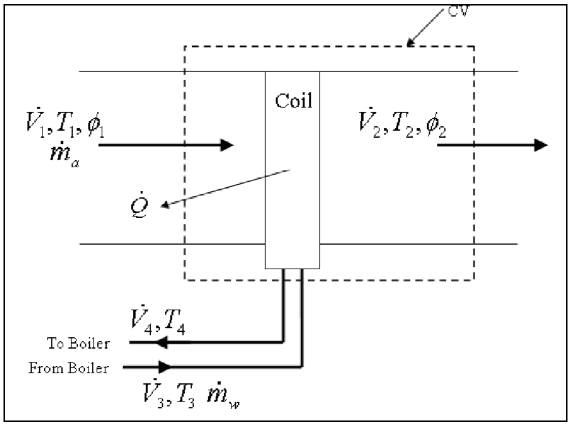

Figure 2: Heating Coil Diagram

Coil effectiveness is shown in Table 2 for the AHU's heating coil. The design conditions have 100% open valves while the test conditions only use 50% maximum valve opening. These lower valve positions raised the air temperature considerably without significantly raising the coil temperature.

	Design	Set Pt 1	Set Pt 2	Set Pt 3
Coil Effectiveness, ε	20.69%	50.99%	38.35%	33.56%

Table 2: Heating coil effectiveness

Flow exergy was calculated for all entering and leaving flows associated with the coil and fans using Equation 5.

$$e_f = (h - h_0) - T_0(s - s_0) \qquad \textbf{(5)}$$

where h = enthalpy
s = entropy
h_0 = dead state enthalpy
s_0 = dead state entropy
T_0 = dead state temperature

The exergy destroyed in the heating coil is found using Equation 6

$$\dot{E}_d = \dot{m}_w\left(e_{f3} - e_{f4}\right) + \dot{m}_a\left(e_{f1} - e_{f2}\right) \qquad \textbf{(6)}$$

The exergetic efficiency, β, that results for the heating coil is calculated using Equation 7

$$\beta = \frac{\dot{m}_a\left(e_{f2} - e_{f1}\right)}{\dot{m}_w\left(e_{f3} - e_{f4}\right)} \qquad \textbf{(7)}$$

Figure 3 shows the mass and energy flows of the fan. The work into the fan is the power supplied to the fan and can be found from the output of the variable drive frequency on the fan. The first law fan efficiency is found from Equation 1. The exergy destroyed in the fan is given in Equation 8.

$$\dot{E}_d = \dot{m}_a\left(e_{f1} - e_{f2}\right) - \dot{W} \qquad \textbf{(8)}$$

Equation 9 is used to determine the exergetic efficiency of the fan.

$$\beta = \frac{\dot{m}_a \left(e_{f2} - e_{f1} \right)}{-\dot{W}} \qquad \textbf{(9)}$$

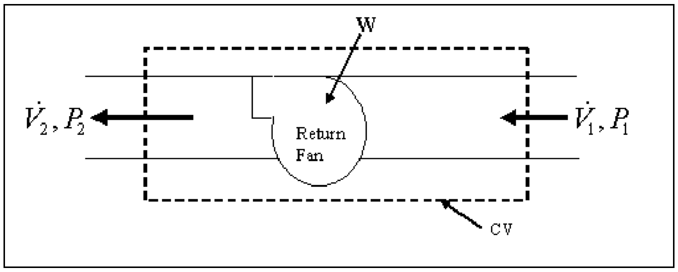

Figure 3: Return Fan Diagram

Using equations 6, 7, 8, and 9, the exergy destroyed and exergetic efficiencies were determined for the supply fan, return fan, and heating coil. These results can be found in Table 3. The first fan set point produces the least amount of exergy destroyed for both fans. The design exergy destroyed is considerably higher than the actual data because the design data is for 40,000 CFM (18.88 m^3/s), while the tests were run at approximately 20,000 CFM (9.44 m^3/s).

		Actual			
Supply Fan	Design	SP1	SP2	SP3	
Exergy Destroyed, E_d	2152.8	159.2	170.2	190.8	Btu/min
Exergy Destroyed, E_d	37.9	2.80	2.99	3.35	kWatts
Exergetic Efficiency, β		58.8	62.0	64.1	
		Actual			
Return Fan	Design	SP1	SP2	SP3	
Exergy Destroyed, E_d	1186.9	50.66	95.85	106.5	Btu/min
Exergy Destroyed, E_d	20.9	0.89	1.68	1.87	kWatts
Exergetic Efficiency, β		55.7	41.5	42.3	%
		Actual			
Heating Coil	Design	SP1	SP2	SP3	
Exergy Destroyed, E_d	3735.2	6741	6926	15615	Btu/min
Exergy Destroyed, E_d	65.7	118.43	129.68	274.33	kWatts

Table 3. Exergy Results

Recommendations

Overall, testing revealed several areas for improvement in the AHU. It is the recommendation that these issues be addressed for improved efficiency and performance. The test plan developed can be used to test additional AHUs on campus for further cost savings. The analysis conducted will be useful for retrocommissioning because it contains the typical first law analysis as well as a more in-depth second law analysis that will provide additional insights without requiring much additional time or money spent. Based on results from the first and second law analysis, and the recommendation of the team, the duct static pressure set point was reduced, thus saving the owner money. Although the best set point value may not have been obvious from the first law analysis, the exergy destroyed analysis from the second law showed the one inch static pressure set point to be the best because the exergy destroyed value was the lowest for both the supply and return fans at this point.

Results show that the heat transfer to the surroundings is more than expected. It is recommended that more insulation be added to the AHU chambers. Pre-functional testing results uncovered the failure of the dampers to fully open and close. This problem should be addressed to minimize energy waste and maximize savings. Air flow sensors should be cleaned and flushed out to remove dirt and debris and ensure proper measurements. The supply duct static pressure set point of 1" WC is recommended for off-peak load seasons to decrease energy consumption while still providing occupant comfort.

Although an exact dollar savings cannot be assigned to all of the proposed suggestions, it is likely that addressing these issues will extend the equipment life and improve occupant comfort.

Problems were encountered with exergy results because conditions were far from design. Data was inconclusive for the design exergetic efficiencies. Experimental flow rates for the coils were lower than design, so there was a better coil effectiveness experimentally. For more accurate results, future testing should be conducted under design conditions. Due to the outdoor air temperatures during data collection (which were a result of only being able to test while the project was taking place), it was not feasible to test design conditions while maintaining occupant comfort in the building. It is recommended that testing be conducted while buildings are vacant to carry out necessary tests.

Conclusion

The capstone project discussed provides students with real world experience by completing a project from industry directed by an industrial sponsor. They must learn to deal with and meet the needs of the sponsor while still maintaining a budget and timeline. Projects are available in a wide range of topics to focus on the interest areas of students in order to generate excitement about their project. Holding the project over two academic quarters (approximately 22 weeks total) allows a significant amount of time to be spent as well as a complete project cycle from start to finish. Students are able to work with other engineering majors, and must learn to work well in a team. This project is a culminating engineering experience to gage the success of skills learned through coursework and co-op employment through their degree program.

The project sponsor has a working prototype for their design problem and necessary documentation at the end of the project term. They benefit from the work the students complete and developing a relationship with the university for future partnerships. The RCX project team gained experience in taking a project from start to finish, dealing with customer requirements and satisfaction, team work, leadership, and work ethic as well as applying their knowledge of thermodynamics, design, and testing gained through coursework and co-op employment experience. The students gained insight from the analysis and testing they conducted as to what engineering processes are like in the 'real world' and they were held accountable for the success or failure of their project from the perspective of their sponsor as well as the course. In addition, students had to successfully explain and present their project to the faculty and industry panel and justify their design process, decisions, and outcomes.

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