Experimental Investigation of Condenser Shading Effects on Residential Air-Conditioning Unit Performance

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Abstract

Condensers are used in chillers and air-conditioning (AC) systems to reject heat from the refrigerant to the outdoor air. Blocking the solar flux radiated from the sun and hitting the condenser is expected to improve the performance of the air-conditioning system. To investigate this concept, a team of three mechanical engineering technology students within the School of Engineering Technology at Purdue University investigated a 3-ton residential AC unit and logged the condenser and evaporator temperatures to evaluate the coefficient of performance (COP) of the cycle under various outdoor temperature conditions. The team logged the temperatures across the condenser pipes and the evaporator while the condenser being shaded and unshaded for 30 days under each condenser state. The evaporator was maintained at three different temperatures: 41° F, 46.4° F, and 50° F. Averages of the COP were grouped for each outdoor temperature and compared for shaded versus unshaded cases. Outdoor temperatures ranged between 65-88° F. The results showed 2-39% improvement in the COP of the cycle under various evaporator and outdoor temperatures. The project was assessed through biweekly progress reports, presentations, final report, and teamwork, which satisfied many of the ABET outcomes.

1. Introduction

Heating, ventilation, and air-conditioning (HVAC) systems have been utilized since 1925 when the first AC system was introduced to the Rivoli Theater in New York City [1]. This newly founded HVAC system was created by the first HVAC company, Carrier. Its founder, Willis Carrier, originally developed this system for a publishing company while he was working as a mechanical engineer [1].

Fast forward to today and HVAC systems are utilized in just about every building in first and second world countries. One of the biggest concerns with HVAC is the amount of energy used across the globe. Not only does it cost consumers money, but it also increases the cost for energy. According to Madison Gas and Electric Company,

> On average, a U.S. office building spends nearly 29 percent of its operating expenses on utilities, and the majority of this expenditure goes toward electricity and natural gas. For the average office building, energy costs can exceed $30,000 per year [2].

According to Madison Gas and Electric Company, the average office building in the US utilizes 14% of its energy specifically for cooling [2]. While this may not be the largest chunk of energy usage in the average office building, it is still the second largest.

Whatever type of refrigerating system is used, it is fundamental to minimize the required heat extraction and to keep the difference between condensing temperature "T_c" and evaporating temperature "T_e" as small as possible [3]. According to the Department of Energy, residential and commercial buildings comprise 40% of the US primary energy of which 75% is electrical. Half this amount of energy consumed is by the ventilation and air conditioning systems [4]. The world equipment demand for HVAC has increased from 50 billion USD in 2004 to more than 90 billion USD in 2014 and for the US almost 11 billion to 19 billion US dollars over the same period [5]. A reduction in the HVAC energy consumption load would reflect a significant reduction in the total energy consumed.

The idea that shading a condenser of an air-conditioning system to increase the performance of the system stems from the basics of heat transfer. The main objective of the condenser unit in an AC system is to reduce the temperature of the refrigerant as it passes through its coils by rejecting heat into the surrounding air. With the condenser being exposed to the solar flux originating from the sun, this process can become impeded. When direct sunlight hits the condenser, it increases the temperature of the condenser, which makes heat transfer more difficult for the system, causing a decrease in performance.

The objective of this project was to investigate the improvement in the performance of an HVAC system in a typical residential house that had its condenser shaded from the direct sun rays. Most condensers are installed outdoors and exposed to sun rays, which increases the refrigerant tubing temperatures in the condenser unit. A shading tool was used to block the solar flux from reaching the condenser unit. The performance of the unit was evaluated for shaded and unshaded cases by measuring and recording the temperatures across the condenser and along the evaporator.

2. Methodology and Experimental Setup

The performance of the HVAC unit in a residential house was investigated by evaluating the coefficient of performance as shown in equation (1), where T_c and T_e are the condenser and evaporator temperatures, respectively. The house AC unit had a capacity of 3-tons refrigerant (TR).

$$COP = \frac{T_e}{T_c - T_e} \qquad (1)$$

Thermocouples were wrapped around the refrigerant pipes at the inlet and exit of the condenser, as shown in Figure 1, and on the evaporator pipes to help in tracking changes in the indoor unit temperature. The average temperature for the inlet and exit temperature of the condenser was used to represent T_c in equation (1). A more representative temperature would be obtained by measuring the temperature along the length of the pipe inside the condenser. A canopy was used to shade the outdoor condenser unit, as shown in Figure 2. The canopy needed to 1) shade the solar flux, 2) provide enough space for the air exiting the condenser fan to be exhaust to the outdoor without being trapped, 3) direct any rain down to the ground and not into the condenser, and 4) be sturdy enough to withstand high winds. The house temperature was varied to maintain the evaporator temperature at approximately 41° F (5° C), 46.4° F (8° C) and 50° F (10° C) during each state of the condenser. The temperature was logged during summer time June until mid-September) from 6:00 am till 9:00 pm. For each evaporator temperature, the condenser temperature was logged under shaded and unshaded days.

The main variable was the outdoor temperature; thus the data were sorted and categorized according to the average outdoor temperature.

The improvement in the COP for the shaded days over unshaded was checked using equation (2),

$$I = \frac{COP_s - COP_u}{COP_u} \qquad (2)$$

where I is the improvement in performance, and the subscripts *s* and *u* stand for shaded and unshaded COP, respectively. Thus, for shaded COP calculations, the recorded data for T_c under shaded testing was used in equation (1) and the same for the unshaded COP.


(a) (b)

Figure 1. Thermocouples wrapped on the refrigerant pipes across the condenser


Figure 2. Canopy used to shade the condenser

3. Results and Analysis

The temperatures were logged in °F, and temperatures are shown in °F in all plots and comparisons. The condenser temperature for both cases, shaded and unshaded, and the reduction in its value when shaded are all plotted in Figure 3. As expected, the condenser surface temperature for shaded cases were lower than the unshaded one for all outdoor temperatures. The temperature for shaded condenser were more uniform than the unshaded case with difference between its maximum and minimum value of 5° F whereas this difference for the unshaded case jumped to approximately 12° F. The temperature difference between the shaded and unshaded cases increased as the outdoor temperature increased except a slight stall at 70° F, which might be due to air "short-circuiting" when being trapped under the shade. Although the vertical distance between the condenser surface and the shading canopy was checked and modified before any testing to ensure no hot air was trapped in between, which is defined as air "short-circuit" that can adversely affect the condenser temperature and cause it to increase, but some discrepancy could have happened during some days and caused this irregularity at 70° F outdoor temperature. The temperature difference between the shaded and unshaded condenser measurements for the range of outdoor temperatures ranged between 3-19° F.

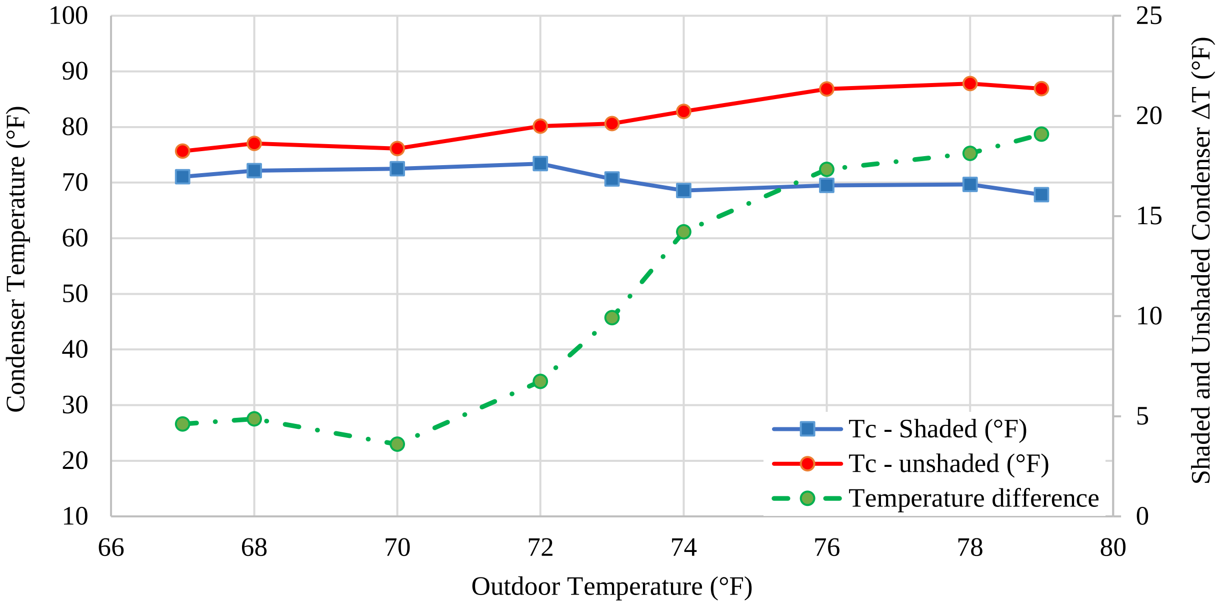

Figure 3. Condenser temperature for shaded and unshaded cases versus outdoor temperatures (left axis) and temperature reduction due to shading (right axis)

The percent improvement in the COP for shaded cases over unshaded are shown in Figure 4. Each point was the average of the COP obtained from the days sharing the same outdoor temperature. The following observations could be made: 1) the COP ranged for all cases between 2-39%, 2) the improvement in the COP was higher with elevated evaporator temperatures, and 3) the improvement in the COP was better for lower outdoor temperatures. Both the second and third observations, when the COP increased with the higher evaporator temperature and lower ambient/outdoor temperatures, were expected since the demand cooling load on the compressor would be less in both cases. Analyzing equation (1) with no experimental data does not give a direct indication whether the COP would increase or decrease with changes in evaporator temperature since the refrigerant temperature would change and thus the condenser temperature, in turn. The relation between the change in evaporator temperature and COP was made possible by conducting this experimental study. A significant drop in the improvement of the COP was recognized for outdoor temperatures higher than 74° F; for outdoor temperature less than 74° F, the improvement ranged between 20-40%, whereas for outdoor temperatures higher than 74° F, it dramatically dropped to below 10% and reaching as low as 2% for outdoor temperatures of 79° F.

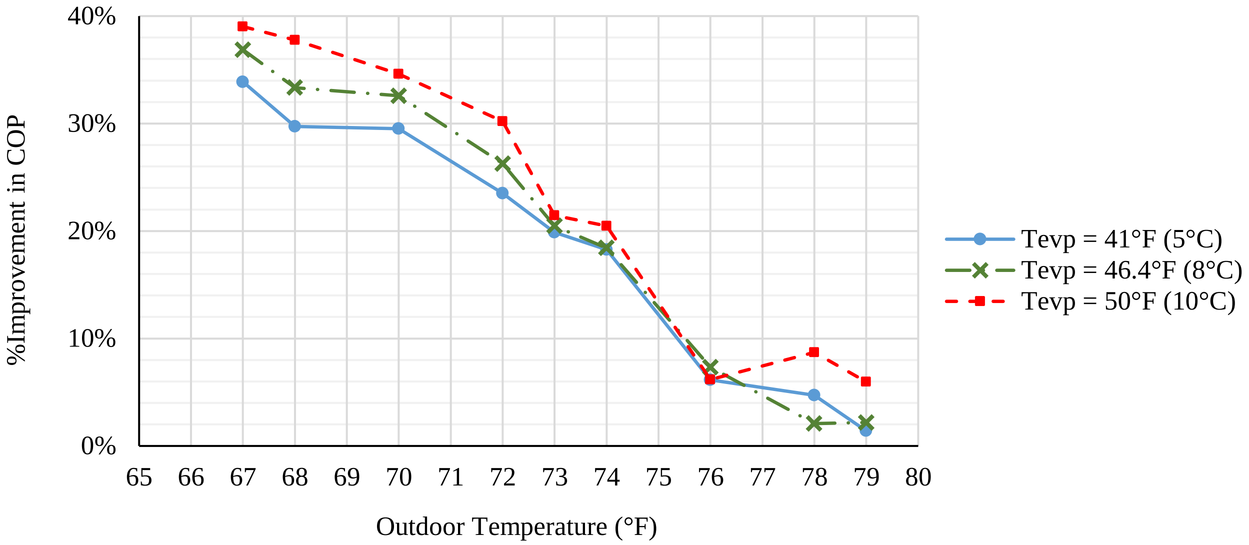

Figure 4. COP improvement due to condenser shading at multiple evaporator temperatures versus outdoor temperature

4. Project Assessment

The project was evaluated using four different categories including biweekly progress reports, presentations, final report, and product and team evaluation as shown in Figure 5. Biweekly reports included submission of logbooks, minutes of meetings, weekly prioritized to-do list, goals achieved in the previous two-weeks, notes from outside research, calculations, graphs, collected data, analyses, conclusions, and challenges. The progress reports were graded and returned to students with feedback and suggestions. The team met with their project advisor after grading the reports to discuss the progress of their project, results, and any outstanding issues. At the end of the project and before the submission of the final report, the students presented their project for a group of faculty members from different disciplines, guests from industry, parents, and other students and staff. The attending faculty and industrial guests filled out evaluation forms scoring different categories based on the presentation and provided any feedback. The instructor collected and summarized the findings and suggestions and forwarded to the students along with his own feedback. The team had to modify their project analysis, findings, and results to reflect these suggestions in the final report. After submitting the final report, the students submitted self-evaluation forms for teamwork contribution hat were kept confidential so each student can evaluate himself and the rest of the team members freely. The other part of the evaluation category included testing the students' knowledge of the project by orally questioning the students.

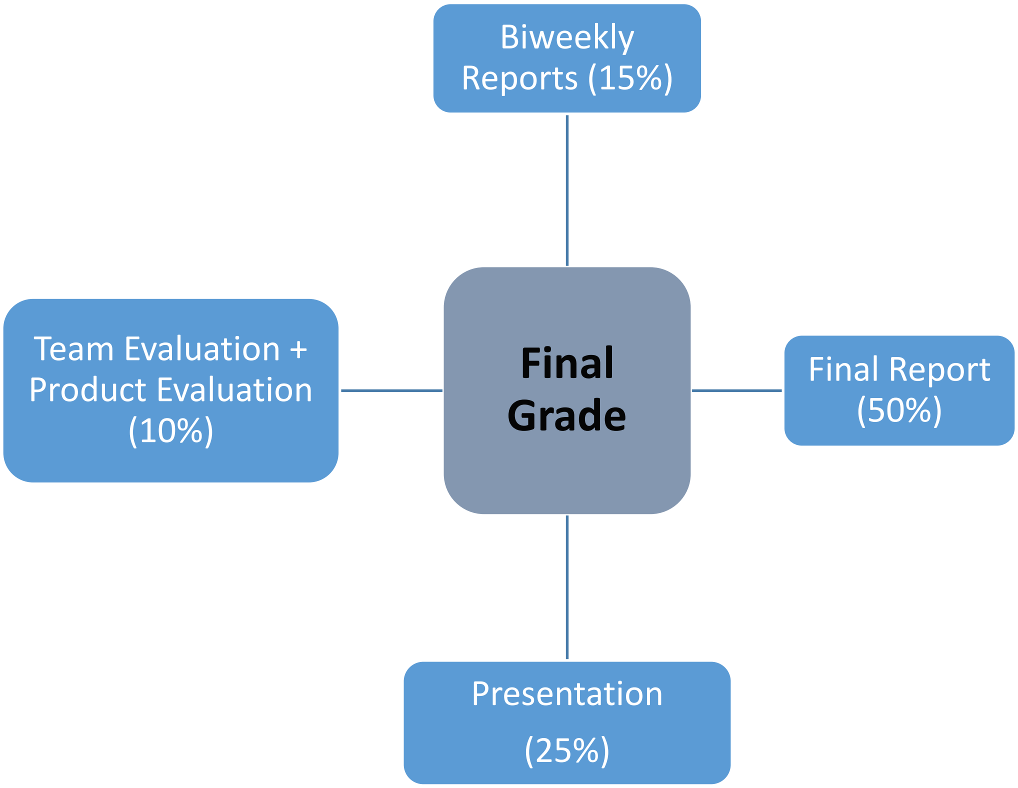

Figure 5. Capstone assessment structure

Through the continuous submission of biweekly progress reports, presentation, and final reports, the students met many of the ABET old outcomes, such as (a) applying knowledge, techniques and skills to engineering technology activities;, (b) applying knowledge of mathematics, science, engineering, and technology to engineering technology problems; (c) conducting tests, measurements, calibration and improving processes; (d) problem solving; and (f) improving written and oral communication skills. The final capstone course grade was based on the elements shown in Figure 5. Table 1 shows assessment methods that reflected the ABET outcomes mapping with the project assessment tools followed.

Table 1. ABET students learning outcomes and assessment methods used

ABET ETAC Outcomes		Assessment Methods
(a)	Apply knowledge, techniques and skills to engineering technology activities	Final Report and biweekly reports
(b)	Apply knowledge of mathematics, science, engineering, and technology to engineering technology problems	Final report and biweekly reports
(c)	Conduct tests, measurements, calibration and improve processes	Biweekly reports, draft report, and final report
(e)	Problem Solving: ability to identify, formulate, and solve engineering problems	Project proposal and biweekly reports
(f)	Effective Communication: ability to communicate effectively	Presentation and biweekly reports

5. Conclusions

A capstone project conducting an experimental investigation of an air-conditioning unit performance was done by a team of mechanical engineering technology students. The effect of shading the condenser of the air-conditioning unit on the unit's performance was done by measuring the condenser temperature during different days and comparing them to the same when the condenser was unshaded. With different evaporator temperatures, the COP was proven to increase between 2-39% when the condenser was shaded. The effect of an increase in the outdoor temperature or an increase in the evaporator temperature were shown to have opposite influences on the COP of the unit. As the evaporator temperature increased, the enhancement in the COP increased, whereas when the outdoor temperature increased, the enhancement in the COP decreased. Analytical reasoning of equation (1) could not provide accurate results for the COP improvement with changes in the evaporator temperature due to lack of information in regards to the actual condenser temperature at different evaporator temperature. This was covered and looked at with the experimental testing done in this study.

The team recommended using sturdier designs if any future testing were to be repeated to prevent pooling of water and recommended measuring the actual power consumed by the compressor which would allow evaluating the efficiency of the cycle rather than just the COP. Throughout this project, the students enhanced their heat transfer knowledge, experimental measurement skills, analysis and critical thinking skills. Many of the ABET outcomes were met through the implementation of this project.

References

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Biographical Information

MAHER SHEHADI, PhD is an assistant professor of MET in the School of Engineering Technology at Purdue University. His academic experiences have focused on learning and discovery in areas related to HVAC, indoor air quality, human thermal comfort, and energy conservation. While working in industry, he oversaw maintenance and management programs for various facilities including industrial plants, high rise residential and commercial buildings, energy audits and condition surveys for various mechanical and electrical and systems. He has conducted several projects to reduce CO_2 fingerprint for buildings by evaluating and improving the energy practices through the integration of sustainable systems with existing systems. Professor Shehadi is currently investigating various ways to reduce energy consumption in office buildings by integrating research and curriculum development.