The Impact of Cool Duct Technology on Energy Use

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Abstract Solar-absorptive surfaces in urban environments cause a temperature increase known as the urban heat island (UHI) effect. Solar reflective coatings mitigate the UHI effect by reducing peak energy demand and increasing energy efficiency. This study examines the effects of “cool” white paint duct coatings on the energy efficiency of rooftop air conditioner units (RTUs). Two RTUs at Cal State University, Sacramento were fitted with sensors that recorded upstream and downstream air temperatures to determine the effect of the installation of the duct coatings. The temperature data were used to graphically analyze the performance of the coating on the RTU and to develop a heat transfer model. The analysis examines how surface temperature, temperature difference between upstream and downstream, and air conditioner usage changed after the coatings were installed. A heat transfer model of convective, conductive and radiative heat flows was developed to evaluate the efficacy of the coatings across a wide array of conditions for different duct systems. The coated ducts reflected a higher proportion of solar radiation than uncoated ducts, which explains an approximate 10-15 °C drop in duct surface temperature post-retrofit. After the coatings were installed, there was approximately a 20 percent reduction in RTU use during peak demand. “Cool” duct coatings reduce the temperature difference between upstream and downstream by approximately 0.05 °C per linear foot of duct.

Introduction

Urbanized society exerts myriad demands on the environment to fulfill its needs. The urban landscape also influences temperatures. The absorption of electromagnetic radiation and release of infrared rays by the urban environments cause an air temperature increase known as the urban heat island (UHI) effect (Bohm 1998). A number of factors contribute to the UHI effect, including surface coloration and thermally radiative materials. Dark asphalt pavements and thermally absorptive roofs coupled with a lack of cooling vegetation cause temperature increases in both the surrounding environment and buildings, which drive up cooling costs.

The reduction of the effects of the UHI is imperative (Baker *et al.* 2002) because the UHI generates numerous problems from the elevated temperatures, including respiratory issues from an increase in photochemical smog (Evans *et al.* 1982), adverse health effects from elevated temperatures for those with weakened immune systems (Armstrong *et al.* 2001), and greater demand for air conditioning. The exposed ducts of rooftop air conditioner units (RTUs) are a source of energy inefficiency. As cool air travels through the ducts, it is warmed by solar radiation. Solar reflective coatings can reduce peak energy demand, increase energy efficiency, and save significant amounts of money if adopted on a large scale. The coatings reduce the heat gain along the length of a RTU duct by reflecting a higher portion of incident solar radiation compared to an uncoated duct. My research examines the effects of "cool" duct coatings on the energy efficiency of RTUs.

Numerous studies, including those of Babawale *et al.* (1993) and Sahin (1998), have examined ways to reduce energy losses as air travels through a duct system. It has been established that entropy gain through duct leakage as tracked by tracer gas is about 45% of the house peak load (Babawale *et al.* 1993). Hourly simulations show an increase of 35% in the energy demand due to duct leakage (Babawale *et al.* 1993). Another source of energy inefficiency in ducts is due to the entropy generated by laminar viscous flow (Sahin 1998). This study looks at how "cool" white paint coatings reduce heat conduction into ducts. According to numerous contractors, coating the exposed ducts with cool coatings that reflect a portion of the solar radiation will yield significant energy savings (Akbari *et al.* 1999). The cool coatings were developed for this study, so there are no previous estimates of their efficiency. However, the current literature and contractor knowledge suggest that cool coatings can reduce energy demand and building energy costs.

I hypothesize that installing the coatings will increase the efficiency of RTUs and reduce the energy demand. There are two components of this project: data collection and analysis, and creating a physical model. Data collection is described in the methods. The data analysis is an evaluation of the effect of the coatings on the performance of the RTUs. The collected data was used to calibrate a mathematical model that describes the interaction between solar heating, atmospheric heating, and other heat transfer mechanisms that operate on the duct system. The model can be used to simulate duct systems in different locations at different times of the year.

Methods

The sites for this study are the Humboldt and Facilities buildings at California State University, Sacramento. The two different sites help control for minute differences in locations and differences in RTU configuration. A system of sensors was installed on the RTUs of the two buildings (Fig. 1). The sensors were configured by my supervisor, Hashem Akbari, an engineer at the Lawrence Berkeley Labs, who documented the entire installation and decommissioning of the project. It is unlikely that the data are inaccurate, or have been collected improperly, since professional mechanical engineers set up the sensors.

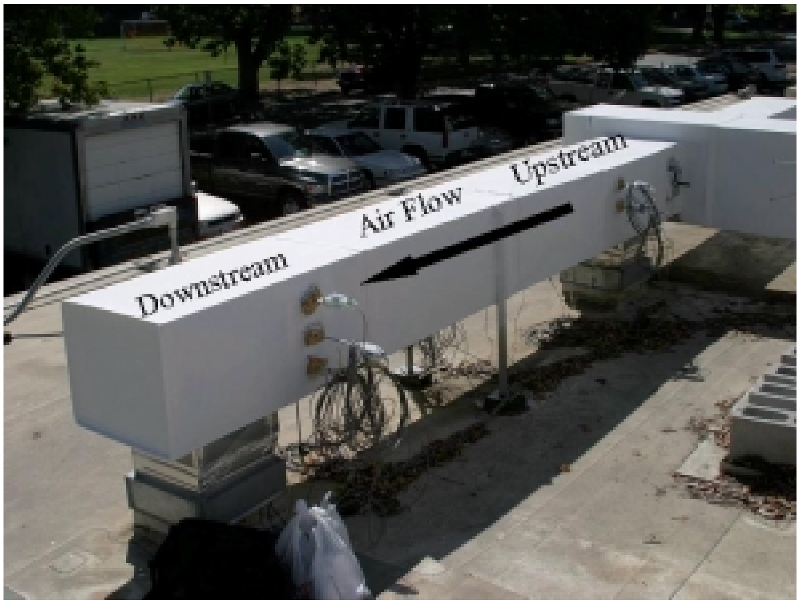

Figure 1: Configuration of sensors on either end of duct

An array of holes was drilled around the outside of each duct at either end. Sensors were inserted into the holes and recorded the duct air temperature, the ambient air temperature, the duct surface temperature, and the time every 15 seconds for the entire test period, from September 14th to October 5th, 2004. The sensors first collected data before the "cool" coatings were added to the ducts from September 14th to the 25th, which were clear, sunny days. The "cool" coatings are simply white paint applied to the duct exterior. The ducts were covered with the coatings and the above parameters were recorded from September 30th to October 10th. The sensors malfunctioned for a few days during the study period, so the data used in this study was from September 14th to the 20th and from September 30th to October 4th.

There are two main cycles that affect the duct system. The incident solar radiation varies diurnally and throughout the day, while the RTU cycles about every 15 minutes. In order to understand important trends, I utilized a running average to condense the data. A running average consists of a number of successive means, each of which incorporates the same number of observations. The surface temperature, ambient temperature, and the temperature difference between the downstream end of the duct and the upstream end were first averaged on an hourly scale. The temperature difference between the downstream end of the duct and the upstream end is hereafter referred to as the "temperature difference." These hourly averages were then averaged again to create a 24 hour average. The averaging condenses the data to a manageable size and highlights the movement of the data with time.

I followed a series of logical steps to determine the relationship between different variables and to evaluate the effectiveness of the cool coatings. First, I reasoned that solar radiation warms the duct surface which heats the cool air inside the duct. I examined how the surface temperature changes over time, and I used the ambient temperature as a benchmark to see if variations in surface temperature could be explained by changes in the ambient temperature. The duct surface should warm the cool air inside the duct through conduction and convection. To test this, I looked at the relationship between the surface temperature and the temperature difference. Then, I examined the variation in the temperature difference over time. If, for example, the temperature difference varied little after the retrofit, it would indicate the coatings are ineffective. Understanding how the temperature difference changes over time would give an indication of changes in RTU use. The RTU runs for as long as it takes to cool the building to a predetermined temperature. If the cool air from the RTU is slightly heated as it travels through the duct, the RTU will have to run longer to compensate for this effect. Finally, I compared the amount of time the RTU runs pre- and post-retrofit in order to understand the effect of coatings on energy usage.

RTU use was not recorded by the sensors, so it was necessary to create a qualitative model of RTU cycling. The RTU cycles predictably on a minutely scale (Fig. 2). The proportion of time the RTU is on in any given period can be found by summing the time between points one and three (Fig. 2).

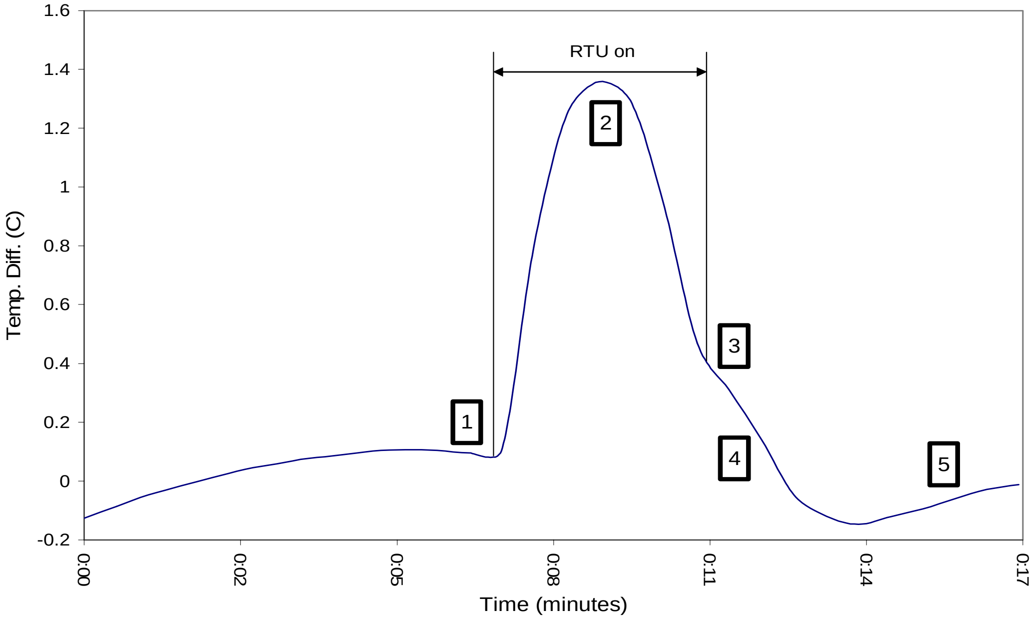

Figure 2: Conceptual Model of a Single RTU Cycle. 1) RTU switches on. 2) RTU reaches full power; maximum temperature difference. 3) RTU switches off. 4) Plug of cool air from RTU reaches downstream end. 5) Sunlight warms duct surface; RTU cools down air near upstream temperature sensor.

Although the data collected from the sites at Cal State Sacramento were analyzed to discover the effects of the coatings, they only represent a specific location during a brief period of the year. I have developed a mathematical model with the help of my mentor to simulate the performance of the duct system for different locations and different times of the year. The model is a system of equations with inputs for the time of day, the day of the year, and the upstream air temperature. The output is the downstream air temperature. There are numerous static parameters in the model that can be adjusted, such as the duct geometry, the convection coefficients, the absorptivity and emissivity of the duct surface, and the duct insulation. All of these parameters were changed multiple times to calibrate the predicted data to fit the actual data (Fig. 3).

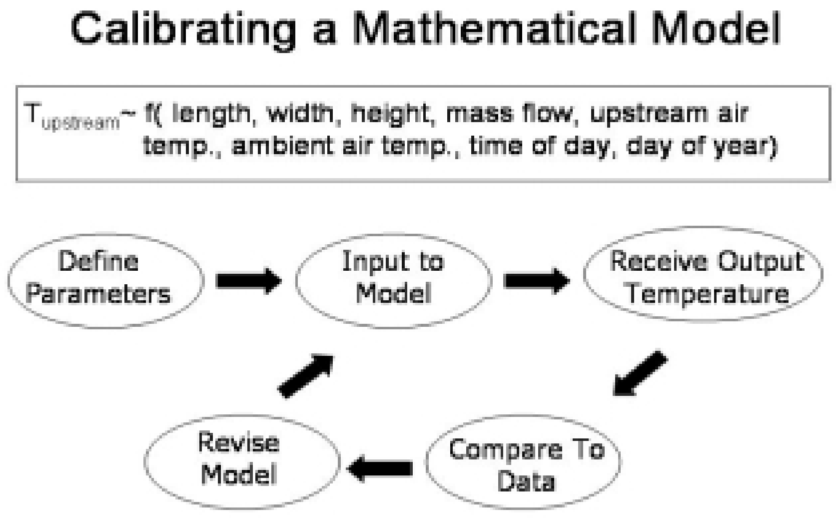

Figure 3: Schematic of calibration of mathematical model

Results

A review of the data collected from the sites in Cal State Sacramento reveals numerous patterns and relationships. Despite the relative continuity in ambient temperature, there is a large drop in the surface temperature of the outside of the duct after the coatings were installed (Fig. 4). There is a strong relationship between surface temperature and the temperature difference (Figs. 5 and 6). The temperature difference falls after coating installation (Fig. 7). RTU use decreases as well (Fig. 8).

Ambient and duct surface temperatures fluctuate throughout the study period (Fig. 4). After the duct retrofit, there is approximately a 10-15 °C drop in the surface temperature, while there is about a two to four °C drop in the ambient temperature.

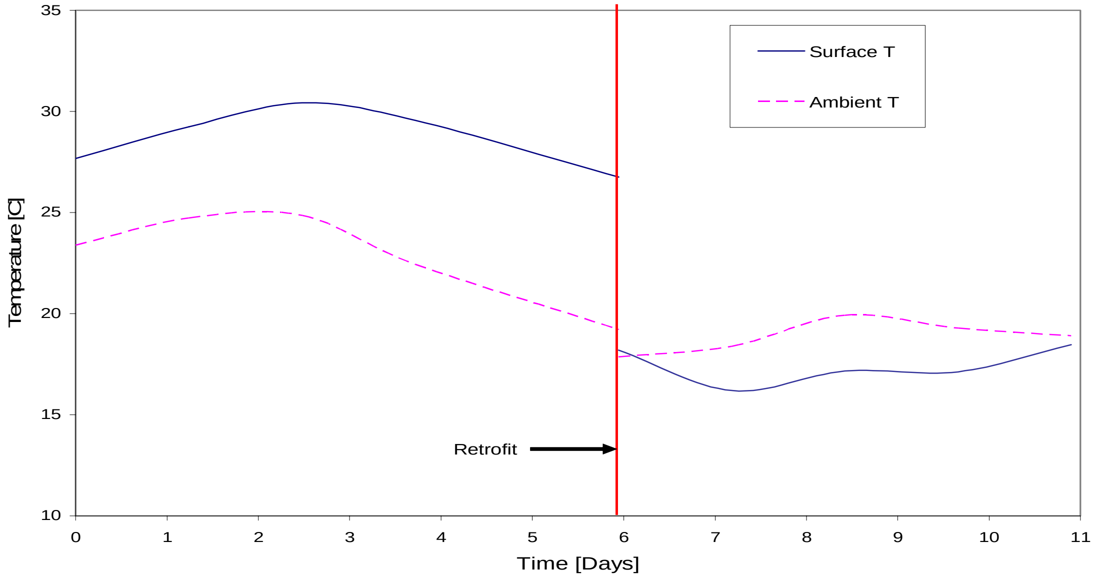

Figure 4: Duct surface temperatures and ambient temperatures averaged over a 24 hour period. There is a gap when the sensors were retrofitted in which no data was recorded that has been removed to assist in clarity of display.

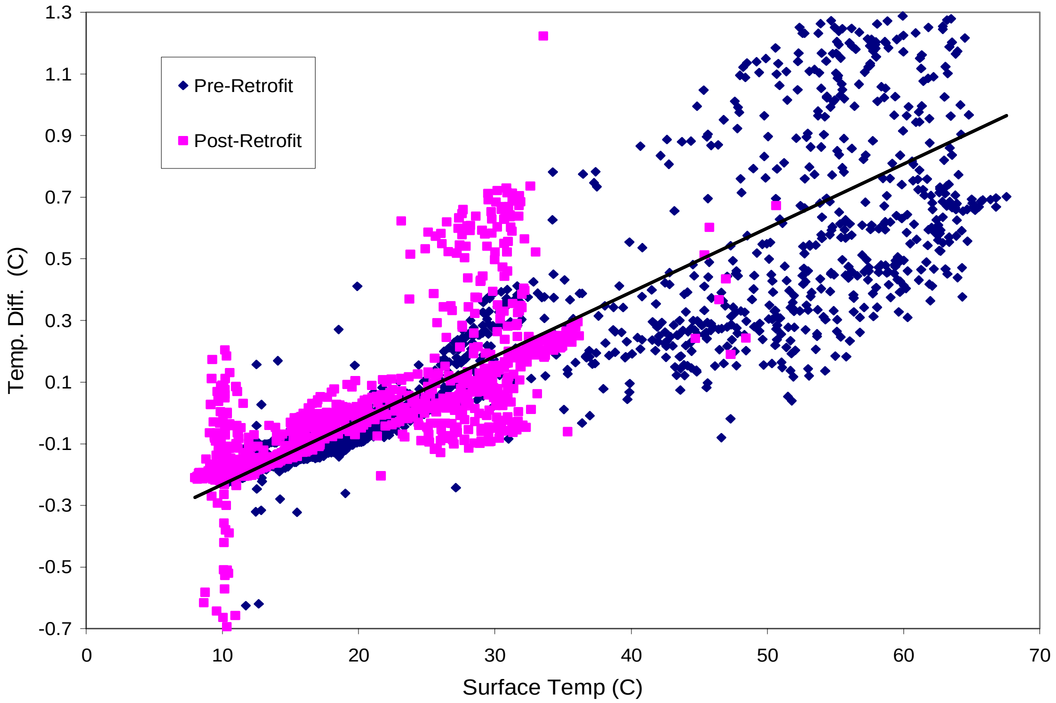

Figure 5: Un-averaged duct surface temperatures matched with corresponding temperature differences. $R^2 = 0.76$, $y = 0.021x - 0.44$, for the entire data set. ($R^2 = 0.7915$, $y = 0.021x - 0.46$, for pre-retrofit, and $R^2 = 0.5497$, $y = 0.021x - 0.43$, for post-retrofit)

There is a strong positive linear relationship between the duct surface temperature and the temperature difference seen in both un-averaged and averaged data (Figs. 5 and 6). There is considerably more scatter seen in the un-averaged data (Fig. 5) than in the averaged data (Fig. 6). In the un-averaged data, the post-retrofit measurements cover a 40 °C range, and the pre-retrofit measurements fall within a 55 °C range. In the averaged data, the post-retrofit measurements are clustered within a five °C range, and the pre-retrofit data, excluding the outlier, falls within a 10 °C range. Both data sets show the same positive linear relationship. In both cases, the pre-retrofit data show considerably more scatter than the post-retrofit data.

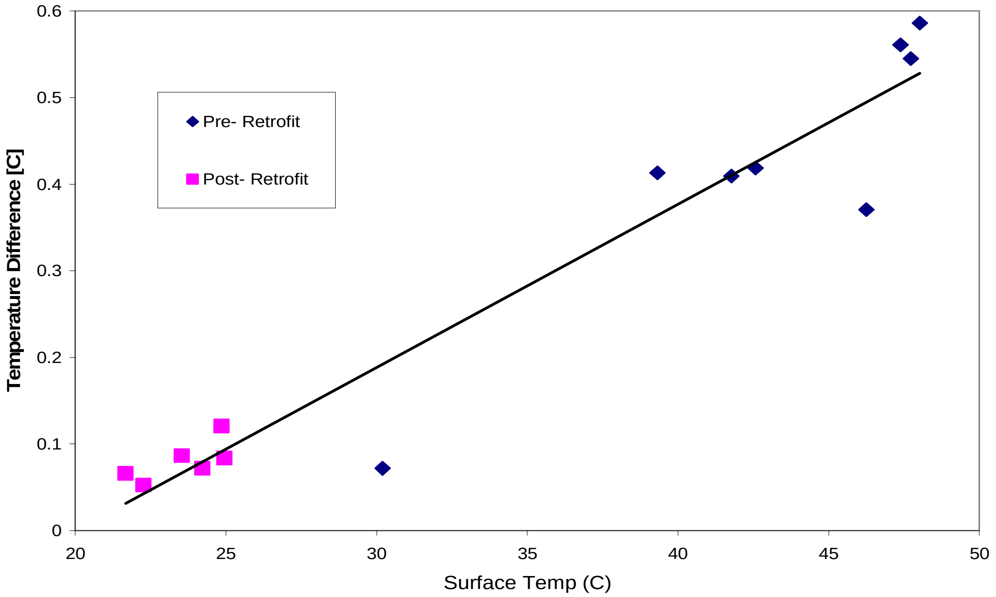

Figure 6: Duct surface temperatures matched with corresponding temperature differences averaged over 24 hours. R^2 = 0.93, y = 0.019x - 0.38, for the entire data set. (R^2 = 0.85, y = 0.025x - 0.65, for pre-retrofit, and R^2 = 0.52, y = 0.012x - 0.21, for post-retrofit)

The averaged temperature difference drops significantly post-retrofit (Fig. 7). The temperature differences are a 24 hour average. The pre-retrofit temperature differences are between about 0.6 °C and 0.4 °C, while the post-retrofit temperature differences are between approximately 0.05 °C and 0.1 °C. There is an approximate drop of 0.4 °C in temperature differences post-retrofit. The drop in temperature differences translates to a reduction in the cooling load of 0.05 °C per linear foot of the duct. A rough calculation (Appendix 1) reveals that there is an approximate 0.03 dollar reduction in cooling costs per duct per day.

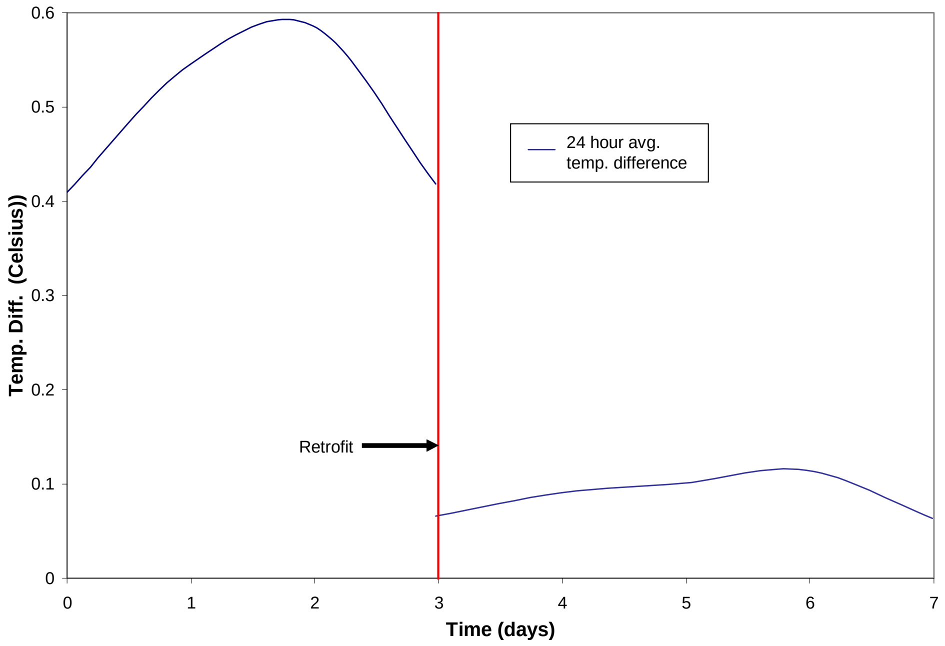

Figure 7: 24 hour average temperature difference over study period. There is a gap when the sensors were retrofitted in which no data was recorded that has been removed to assist in clarity of display.

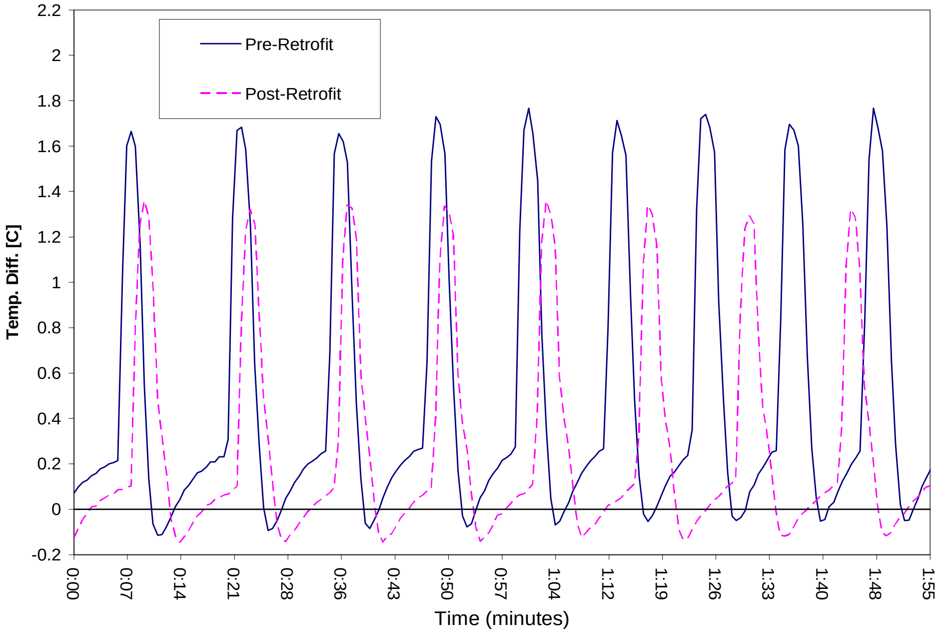

Figure 8: A comparison of the temperature difference in two two-hour time periods with comparable ambient temperatures and solar radiation. Pre-retrofit is from 9/14, 12-2 pm, and post-retrofit is from 10/1, 12-2 pm.

A comparison of the temperature differences from pre-retrofit data and post-retrofit data under similar ambient conditions show that the RTU has an approximately regular cycle throughout the daylight hours (Fig. 8). There is about a 0.3 °C reduction in the maximum temperature difference post-retrofit. The RTU also cycles less frequently post-retrofit, with approximately nine cycles before and eight cycles after in comparable two-hour periods.

Simulated Results The simulated data are generally close to the predicted data (Fig. 9). The predicted data and actual data differ the most pre-retrofit, with a maximum difference of about 0.05 °C. The predicted data is very close to the actual data post-retrofit, and follows the fluctuations of the actual data very closely.

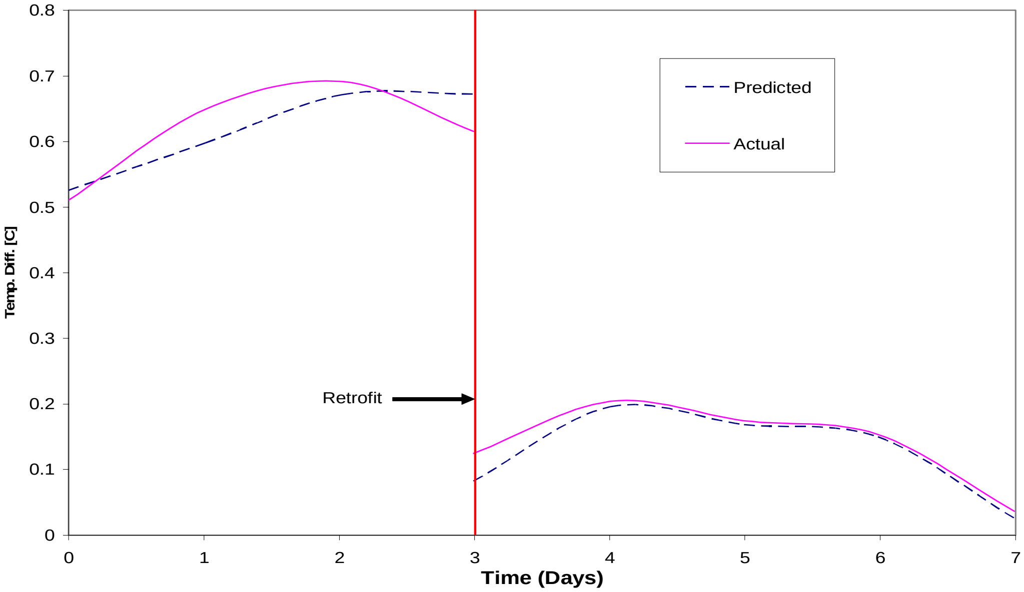

Figure 9: A 24 hour averaged comparison of simulated and actual temperature difference data for the study period

Discussion

The affect of the coatings on the duct surface temperature, the temperature difference, and RTU use conform to the affects predicted by physical laws. The coatings reflected a portion of the solar radiation which lowered the duct surface temperature post-retrofit. The reduction in solar loading caused a decrease in heat conducted through the ducts. The cool air traveling through the duct absorbed less heat because the temperature gradient was reduced. Since the air was heated less, it exhibited a lower temperature difference. As a consequence of the decrease in the temperature difference, the RTU operated less during hours of peak demand. Therefore, the installation of “cool” coatings causes a reduction in RTU use, and an increase in energy efficiency.

In order to substantiate the claim that the installation of duct coatings is associated with decreased energy use, it is essential to examine the effect of the coatings on the duct surface temperature, temperature difference, and RTU use. There was a significant reduction in duct surface temperature after the coatings were installed, while the ambient temperatures fluctuated slightly (Fig. 4). It is unreasonable that the comparatively large dip in surface temperatures can be explained by climatic variation alone.

The strong linear relationship between surface temperature and the duct temperature difference (Figs. 5 and 6) suggests that the drop in surface temperature associated with duct retrofit would result in a corresponding decrease in the temperature difference. The data show that this is the case (Fig. 7) as there is a significant post-retrofit drop in the average temperature difference.

The RTU does not have the same operating frequency or cycle length post-retrofit. In order to estimate energy usage, it is more accurate to measure the amount of time the RTU operates using the conceptual model (Fig. 2), rather than comparing the amount of on/off cycles. According to this model, the RTU is on pre-retrofit for a total of 33 % of the 2-hour period examined above (Fig. 8). After the retrofit, it is on for 26 % of a comparable 2-hour period. This is approximately a 20% reduction in RTU use. However, if the conceptual model inaccurately describes RTU cycling, it could introduce error into the evaluation of the time the RTU operates.

A more thorough calculation of the change in RTU use due to the coatings can provide evidence for the use of the coatings. A number of conditions need to be met in order to calculate the improvement in energy efficiency. Two data sets of pre-retrofit and post-retrofit temperature differences that experience similar ambient temperatures and solar radiation need to be compared to draw any valuable conclusions. There are no data that fits these criteria closely, in which case the mathematical model would be useful to compare different idealized conditions. The model can simulate the performance of the coatings under many different conditions, including different locations and different times of the year.

"Cool" duct coatings show promise to increase the energy efficiency of RTUs. The performance of the coatings can be explained by a heat transfer analysis. If the coatings provide significant savings and improve efficiency, one of the future goals beyond the scope of this project is to prepare a code change proposal for the California Title 24, which gives energy efficiency standards for residential and nonresidential buildings. If the coatings are successful in reducing energy demand, the next goal is to develop incentive programs, such as building subsidies. Regardless of the effectiveness of the cool coatings, it will be important to inform professional contractors of the results.

Appendix 1

In order to estimate energy savings per day, I made a number of assumptions. I assumed the average daylight length is 6 hours. Then, I assumed that electricity costs about 0.10 dollars per kilowatt-hour. All other values are measured, conversions, or constants.

Average Energy Savings = (0.05 °C/ duct- foot) * (7.5 duct- feet/ duct) * (21600 sec/ daylight time) * (0.14 kg Air/ sec) * (1.007 kJ/ kg Air/K) * (1 kWh/ 3.6*10^3 kJ) * (0.10 dollars/kWh) = 0.03 dollars/duct/day

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