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Ultraviolet germicidal coil cleaning: Impact on heat transfer effectiveness and static pressure drop

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ABSTRACT

Cooling coil surfaces are ideal sites for biofilm formation due to the presence of adequate nutrients (deposited particles) and moisture (condensate), causing adverse impacts on heating, ventilation and air-conditioning (HVAC) energy usage and performance. In this study, an HVAC test apparatus was built in our laboratory to investigate the hypothesis that ultraviolet germicidal coil cleaning (UVG-CC) of heat exchanger surfaces improves heat transfer effectiveness and reduces the static pressure drop across the coil. The test apparatus consisted of two parallel ducts, each with its own cooling coil. One coil was treated with UVG-CC while the other was the control and left untreated. Thermodynamic properties of the air and water flowing through both heat exchangers were monitored over the course of two years with sensors and a data acquisition system. Differences in static pressure drop and coil effectiveness between the UV-treated and control coil were compared across multiple modes of coil operation (defined by presence of condensate). The effectiveness of UVG-CC was drastically affected by the presence of condensation on coil fins. We observed a statistically significant difference in the heat transfer effectiveness between the UV-treated and control coils in wetted conditions while no difference was observed in dry conditions. Sensor accuracy, however, contributed to large uncertainty in our result. The average heat transfer of the UV-treated coil was 3.0–6.4% higher compared to the control coil, with an uncertainty of ±2.7%. UVG-CC, however, did not significantly reduce static pressure drop.

1. Introduction

Ultraviolet germicidal irradiation (UVGI) has a long history of being used for the disinfection of both water and air streams, primarily in environments with higher risk of airborne pathogen transmission such as water treatment plants, healthcare facilities, schools, and prisons [1]. UVGI systems use low-pressure mercury vapor lamps that emit shortwave ultraviolet-C, peaking at 253.7 nm. Using ultraviolet germicidal coil cleaning (UVG-CC) technology in heating, ventilation, and air-conditioning (HVAC) systems has recently gained popularity [2]. While air disinfection may still occur as air passes by the UVG-CC system, the primary focus of UVG-CC is surface disinfection and, in turn, maintenance cost savings, and increased or prolonged system capacity due to cleaner heat exchanger surfaces, resulting in an overall system energy savings due to better heat transfer and reduced load on the chiller, pump, and/or fan. Life cycle cost simulations of UVGI in HVAC systems for air disinfection (requiring higher levels of irradiance than UVG-CC) found the annual energy cost of a UVGI system to be relatively small compared to a typical whole-building energy cost and, for comparison, found UVGI to be significantly more cost effective than the equivalent high efficiency filtration for removing microbial air contaminants [3]. The buildings sector accounted for 41% of primary energy consumption in the US in 2010 [4]. More than half of the energy used in buildings is for heating, ventilating and/or air-conditioning the indoor environment [5], so energy savings for HVAC systems could have large implications for total building energy consumption.

In many climates where the outdoor air must be dehumidified prior to entering the building space, air is cooled below the dew point to condense moisture out of the air. This moisture can linger within the densely packed fins of a cooling coil and eventually form biofilms from deposited environmental bacteria and fungi present in the air. Heat exchanger surfaces are an ideal site for biofilms due

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to the presence of adequate nutrients (i.e., debris inherent on coil surfaces) and moisture [6]. High bacterial and fungal concentrations have been documented within HVAC systems, specifically on cooling coils and drain pans [7–9].

Biological fouling of heat exchangers can affect HVAC system energy efficiency and usage in a variety of ways. Two direct effects are a loss in heat transfer effectiveness due to lower thermal conductivity of heat exchange surfaces and an increase in pressure drop across the heat exchanger due to increased fin thickness, both caused by biofilm covering the fins. Increased energy usage occurs when subsequent actions are taken to maintain the same system performance with fouled equipment. One such action may be to lower the temperature of the cooling fluid to maintain the desired supply air temperature, causing the chiller to work harder to provide additional cooling, and thus use more energy. Alternatively if the cooling fluid temperature is not lowered, higher flow rates needed to meet the load would result in an increase in pump energy usage. Additionally, an increased pressure drop may lead to increased fan energy usage by a variable speed fan to maintain the desired air flow rate or meet the cooling load. Although a constant speed fan would result in reduced fan power due to increased flow resistance, the system would no longer be achieving design airflow.

While health benefits of UVG-CC have been shown in the literature [9,10], little evidence exists of the potential energy efficiency benefits of this technology. Anecdotal evidence describes "visibly cleaner" cooling coils and energy savings after the installation of a UVG-CC system [11]. An increase in energy efficiency of 10–15% from coil cleaning has also been reported, but not specifically using UVG-CC [12]. A recent paper reported on a field study applying UVG-CC to an air handling unit in a building in Singapore. Results show that the coil overall thermal conductance increased by 10%, the pressure drop decreased by 13% and the fan energy used fell by 9% [13].

The objective of this study was to investigate the hypothesis that UVG-CC increases heat transfer effectiveness and decreases static pressure drop across the coil. We built a lab-based test apparatus consisting of two identical heat exchangers, one being irradiated with UV and the other not; detailed thermodynamic measurements were collected. This study was conducted over the course of two years and was able to discern how slight changes in inlet air properties due to outdoor air variations affected heat exchanger performance. The results presented in this study allow us to provide recommendations for effective installation and operation of UVG-CC technology for reducing coil fouling and increasing or prolonging HVAC heat exchanger effectiveness.

2. Materials and methods

2.1. Test facility

A custom HVAC test apparatus was built in the Air Quality Laboratory at the University of Colorado Boulder, consisting of two parallel ducts, each with its own cooling coil, but supplied by the same temperature and relative humidity controlled airstream (Fig. 1). Similar custom testing ducts have been used to investigate heat exchanger performance [14–16]. The coils were steam cleaned prior to starting the tests. The test apparatus was equipped with sensors to measure duct velocities using pitot tubes (BAPI ZPS-ACC12, ±1% on 0–1 psi range, www.bapihvac.com) connected to differential pressure sensors (OMEGA PX2650, ±1% best fit straight line (BFSL), www.omega.com), static pressure drops (OMEGA PX2650), entering and exiting water temperatures (OMEGA TH-44000-NPT, ±0.1 °C, www.omega.com), and entering and exiting air temperatures (OMEGA ON-405, ±0.1 °C, www.omega.com) and relative humidity (OMEGA HX71, ±4%, www.omega.com) for each branch. Voltage output from the sensors was fed into a data acquisition system (NI cDAQ-9171 with NI 9205 module, www.ni.com) and processed with LabView to export data for analysis in MATLAB. Both coils were TRANE light commercial tube and fin coils (Type P2) with aluminum fins (Prima-flo H) and copper tubes, one-ft^2 face area, 12 fins/inch, and were four rows deep. One UVC lamp (ALTRU-V V-Ray Model 23-1100, 25 W) was installed ten inches away from the coil on the downstream side. The lamp was burned in for 100 h prior to use. The lamp was shielded with mesh to achieve the desired level of surface irradiance.

The test apparatus used indoor air from the room as the inlet air. The room HVAC system supplied 100% outdoor air filtered with MERV 14 filters. Air entered each cooling coil, on average, at 24 °C (75 °F) and 44% relative humidity and chilled water entered at 10 °C (50 °F), satisfying conditions for condensation onto the coils. The system mimicked a constant volume HVAC system, meaning the volumetric flow rate is held constant at 350 CFM. The flow rates through each coil were held equal to one another using dampers since the static pressure drop across the coils may not be equal given equivalent flow rates. The dampers were positioned fully open at the start of the experiment and were only closed by a few degrees to equilibrate flow rates throughout the experiment. Pitot tubes were placed four feet downstream of the coils in a six foot section of straight ductwork to allow for uniform flow at the location of measurement. Air and water inlet temperatures, inlet relative humidity, and water flow rate were held as constant as possible (see Table 1 for mean values). Fluctuations in outdoor air conditions slightly affected conditions within the apparatus. During summer months, both coils had water actively condensing onto fin surfaces at nearly all times and drain pans were wet. In the winter months when outdoor air became very dry (~10% RH), the apparatus was unable to humidify the air sufficiently to continue condensing water onto the cooling coils. These test periods of desiccation revealed interesting results, described in the Results section.

The system ran undisturbed for four months without UVG-CC on either coil to ensure that both coils fouled at an equivalent rate and to establish a robust baseline dataset. After four months of operation, the UV lamp was turned on, irradiating the downstream side of one of the cooling coils (called the *treatment* coil). The *control* coil was never irradiated. The irradiance at the surface of the treatment coil was on average 200 μW/cm^2, being roughly 280 μW/cm^2 at the center but 180 μW/cm^2 at the corners, just above levels referenced as "typical" in the ASHRAE HVAC Applications Handbook [17] at 50–100 μW/cm^2. A factory calibrated radiometer (model 1400 International Light Inc., Newburyport, MA) was used to measure UV irradiance. Measurements were made in a grid vertically across the ducting at 0.3 m way from the UV lamp, on the surface of the coil.

2.2. Coil effectiveness

One of the main challenges in assessing changes in flow characteristics and effectiveness in two heat exchangers over time is that all variables affecting these qualities are never exactly the same and cannot be held completely constant. For this reason, small fluctuations in temperature, relative humidity, or flow rate affected static pressure drop and the calculated value of heat transfer, making it difficult to compare. To remedy this, comparisons between the control and UV-treated coils were only made with dimensionless quantities, including heat exchanger effectiveness and the coefficient of an assumed quadratic relationship between static pressure drop and velocity.

Heat exchanger effectiveness compares the actual airside heat transfer to the maximum heat transfer theoretically possible. The equation for calculating heat transfer effectiveness is different for a