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Ventilation Benefits when Using Radiative Cooling Material in High Ambient Temperature Countries

Walid Chakroun, PhD
Fellow ASHRAE

Sorour Alotaibi, PhD
Member ASHRAE

Kamel Ghali, PhD
Member ASHRAE

Nesreen Ghaddar, PhD
Member ASHRAE

ABSTRACT

Cooling in high ambient temperature (HAT) countries is a major energy consumer. In Kuwait, 70% of the electricity generated is consumed on cooling residential and commercial buildings. Because of the extreme temperatures in the summer, which can reach 50℃, outdoor fresh air vents are closed because AC units are incapable of cooling air at such elevated temperatures. Consequently, this has significantly reduced indoor air quality (IAQ) in residential and commercial buildings for indoor occupants. Recently, several researchers have shown that radiative cooling (RC) materials have huge potential in providing suitable daytime and nighttime pre-cooling for outdoor fresh air to indoor spaces. The objective of this study is to investigate the effect of radiative cooling materials on reducing the energy consumed on cooling in a typical house in a HAT country. This is done mainly by connecting a water pre-cooler heat exchanger to fresh air ducts to cool the outdoor ventilation air before entering the cooling coil. The water will be cooled via radiative cooling panels installed on the roof. A mathematical model of the hydronic RC panel is developed to predict the system operation and the RC power in Kuwait's climate that can be utilized in the pre-cooling of fresh air. Hence, the effect of installed RC panels on reducing the cooling load of a typical two-story Kuwaiti house is evaluated by integrating the RC system to the house thermal model to determine its energy performance with and without RC panels' installation. The energy savings are estimated over the cooling season. It has been shown that substantial savings are achieved during night and day operations in the months of hot and dry weather.

INTRODUCTION

Outdoor ventilation air or fresh air is a key component in providing suitable indoor air quality to residential and commercial buildings. The flow rate of outdoor air to be supplied to an indoor space is specified in ASHRAE Standard 62.1, depending on the number of occupants, the floor surface area, and the human activity level of individuals in indoor spaces or zones. Outdoor ventilation air maintains an acceptable IAQ by diluting pollutants in indoor spaces. The higher the ventilation rate the more dilution there is for pollutants, the healthier indoor air is for occupants (Dimitroulopoulou, 2012).

In high ambient temperature (HAT) countries, it is common practice to either close outdoor ventilation ducts or

Walid Chakroun is a professor in the Mechanical Engineering Department, Kuwaint University, Kuwait City, Kuwait. **Soroor Alotaibi** is an associate professor in the Mechanical Engineering Department, Kuwait University, Kuwait City, Kuwait. **Nesreen Ghaddar** is a professor in the Mechanical Engineering Department, American University of Beirut, Beirut, Lebanon. **Kamel Ghali** is a professor in the Mechanical Engineering Department, Ameican University of Beirut, Beirut, Lebanon.

not include the ventilation load within the design to decrease the coil load. These practices negatively affect the IAQ in buildings and can cause building de-pressurization allowing for outdoor pollutants to penetrate the building envelope (Chan, 2002). As most HAT countries are in desert regions, indoor climates are more prone to particulate matter resulting from sandstorms (Sangiorgi et al. 2013).

In recent years, several researchers (Bao et al. 2017, Huang et al. 2016, Zhai et al. 2017) developed several radiative cooling (RC) surfaces. These surfaces consist of materials that include Titanium dioxide, Silicon dioxide, Silicon Carbide, silver, and aluminum layers. RC technology rejects heat to outer space at the atmospheric window corresponding to thermal infrared rays of wavelengths of 8 to 13 µm, without needing or demanding any electrical input. These materials have shown promising results in providing cooling with average cooling powers around 100 W/m2 during the day at an outdoor ambient temperature of 300 K. Such materials can be used to reduce the overall cooling load of a building or reduce the portion of the energy consumed by the building cooling system annually.

Radiative cooling materials can be used to cool down the water. Hosseinzadeh and Taherian (2012) analyzed numerically and experimentally a 4 m^2 radiative cooling surface was able to cool the water temperature by around 8℃, for water mass flow rates between 0.01 to 0.05 kg/s, which corresponds to a maximum cooling capacity of 52 W/m^2. Aili et al. (2019) studied the effect of radiative cooling materials on cooling water at different flow rates. It was found that the cooling power of these materials was reduced at higher water flow rates greater than 0.1 $L/(min{\cdot}m^2)$. Nonetheless, a 4℃ drop in water temperature can be achieved at a water flow rate of 0.227 $L/(min{\cdot}m^2)$. Water cooling via radiative materials is achievable, and the cooled water can be utilized for different HVAC applications in HAT countries.

The objective of this study is to reduce the load on the cooling coil when the fresh air vents are open in a residential building in Kuwait, which is a HAT country. For a typical villa, the roof was covered by panels of RC material. These panels consist of water pipes, which are underneath the radiative surface, where water flows to cool down. An air-water counter-flow heat exchanger is placed in the fresh air ducts, to cool that fresh air using the water, before entering the cooling coil. The degree of reduction of the coil load during peak and part-load conditions were studied during the day using an analytical model.

METHODOLOGY

A 2-story above the ground floor residence in Kuwait was studied as the typical villa. Using modeling software, each room's dimensions and properties were entered to estimate the cooling load. The building envelope properties and peak weather conditions were in accordance with the Kuwaiti Ministry of Electricity and Water (MEW) Code of Practice 2018. The peak summer conditions were taken as $48℃$ for the dry-bulb temperature and $27.1℃$ for the wet-bulb temperature. The lighting loads were assumed to be $5\ W/m^2$ for each room. The electrical loads were assumed to be $5\ W/m^2$ for bedrooms, and $10\ W/m^2$ for living spaces. Occupancy, electrical, and lighting schedules were entered depending on the type of room and accounting for weekdays and weekends. The number of people was taken depending on indoor furniture. The assumed sensible and latent loads per person are $75\ W$ and $55\ W$, respectively.

The simulations were run without the radiative cooling material to obtain the peak and part loads during the day. Weather data provided from Kuwait's Meteorological Center were used to evaluate the part loads on different summer days. For simplicity, the villa was taken as a single zone with one package unit cooling the entire building.

An RC panel was placed to cover 70% of the roof area for the above-mentioned villa, covering $350\ m^2$ of the roof. The remaining area of the roof is reserved for building services. The RC panel consisted of an emissive layer of silicon dioxide S_iO_2, topped by a reflective layer of Titanium dioxide T_iO_2 (see Figure 1). The optical properties of these layers were experimentally measured and reported by Bao et al. (2017).

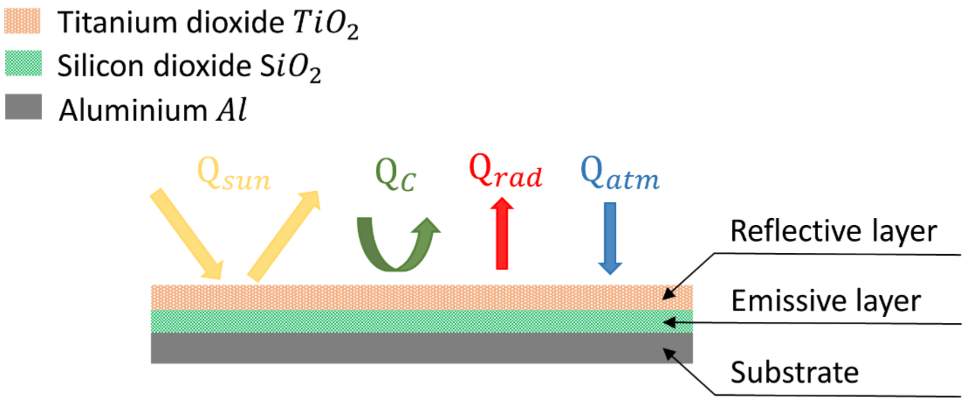


Figure 1 Radiative cooling panel layer schematic

A water piping network was placed below the RC panel, with a water flow rate of $0.18\ L/s$. It is assumed that the RC panel is only cooling down the water and not the indoor air of the villa. The cooled water exits the RC panel to enter a fresh air/water heat exchanger. The water cools the fresh air before it is mixed with the recirculated air. The water is circulated back to the RC panel to be cooled again. Figure 2 shows the water loop of the hydronic system.

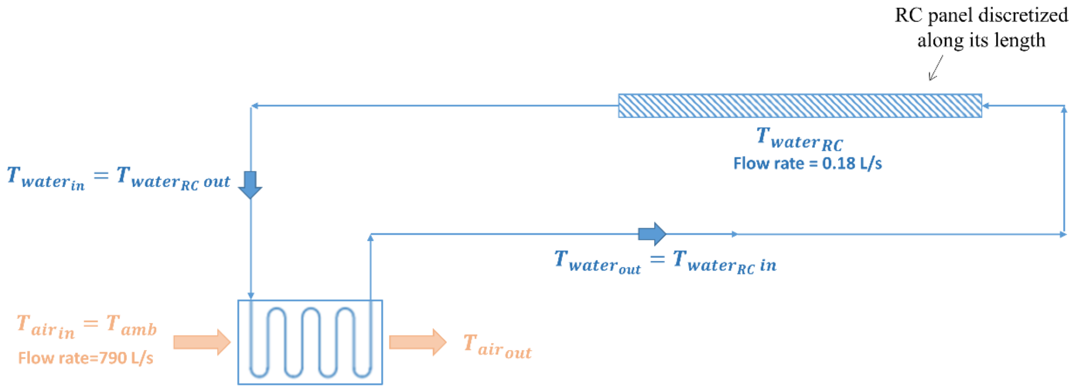


Figure 2 Water Loop or Hydronic System with the radiative cooling material

The model of the hydronic radiative cooler of Wang et al. (2016) was adopted to predict the temperature of the water flowing in the pipes underneath the RC panel. The latter was discretized into multiple sections along its length since the variation of the water temperature in the pipes was assumed unidirectional. Each panel segment was considered to have a constant surface temperature. The water temperature in segment j of the panel was given by:

$$\rho_w V_j\, C_{p_w} \frac{dT_{w,RC_{(j)}}}{dt} = \dot{m}_{w,RC}\, C_{p_w} \left(T_{w,RC}(t,j-1) - T_{w,RC}(t,j)\right) - Q_{net}(\mathrm{t,j})\, A_j \tag{1}$$

Where the left term represents the transient storage term, the first term to the right is the convective heat flow and the second term to the right is the net cooling power of the panel. ρ_w and C_{p_w} are the density and the specific heat capacity of the water respectively,V_j and $\dot{m}_{w,RC}$ are the volume and mass flow rate of the water in the considered segment, $T_{w,RC}(t,j-1)$ and $T_{w,RC}(t,j)$ are the inlet and outlet water temperature of segment j at time t, and A_j is the area of the considered segment of the panel. $Q_{net}(\mathrm{t,j})$ is the time-dependent net cooling power per unit area of segment j of the radiative panel, and it is obtained by the following equation (see Figure 1):

$$Q_{net}(t,j) = Q_{rad}(t,j) - Q_{atm}(t) - Q_{sun}(t) - Q_c(t,j) \tag{2}$$

Where $Q_{rad}(t,j)$ represents the longwave radiative power emitted by the surface of segment j $Q_{atm}(t)$ is the absorbed power due to the incident atmospheric thermal radiation, $Q_{sun}(t)$ represents the absorbed power due to the incident solar radiation and $Q_c(t,j)$ is the power lost/gained due to convection with the ambient air at the upper side of the panel. All of the mentioned powers are expressed per unit area of the panel. Note that the roof is considered insulated, so no heat exchange is assessed from the lower side of the hydronic panel.

The emitted longwave radiation Q_{rad} is depending on the radiative surface temperature $T_S(t,j)$, and is given by:

$$Q_{rad}(t,j) \;=\; 2\,\pi \int_0^{\frac{\pi}{2}} sin\,\theta\, cos\,\theta\; d\theta \;\int_0^{\infty} I_{BB}(T_S(t,j)\,,\lambda)\;\epsilon(\lambda,\theta)\;\; d\lambda \tag{3}$$

Where $I_{BB}(T\,,\lambda)$ is the blackbody spectral intensity (Duffie et al. (1991)), $\epsilon(\lambda,\theta)$ is the emissivity of the surface, considered independent of the zenith angle θ. $T_S(t,j)$ is taken to be equal to the average temperature of water flowing across each segment (Zhang et al. (2012)).

The absorbed atmospheric radiation Q_{atm} depends on the ambient temperature T_{amb} as follows:

$$Q_{atm}(t) = \;2\,\pi \int_0^{\frac{\pi}{2}} sin\,\theta\, cos\,\theta\; d\theta \;\int_0^{\infty} I_{BB}(T_{amb}(t),\lambda)\;\epsilon(\lambda,\theta)\;\epsilon_{atm}(\lambda,\theta)\; d\lambda \tag{4}$$

$\epsilon_{atm}(\lambda,\theta)$ is the emissivity of the atmosphere, and it depends on the RH and cloud coverage (Berger (1988)). However, it is considered independent of the zenith angle θ.

As for the absorbed solar radiation Q_{sun}, it is expressed as:

$$Q_{sun}(t) \;= q_{solar}(t)\;\alpha_{solar} \tag{5}$$

Where α_{solar} is the surface's solar absorptivity and $q_{solar}(t)$ is the solar radiation on a horizontal surface in (W/m^2).

Regarding the fresh air/water heat exchanger, it was assumed to be a counter-flow heat exchanger, and only sensible cooling was applied to the fresh air. Once the exiting fresh air temperature $T_{air_{out}}$ was obtained, this cooled fresh air was mixed with the recirculated air. All supply, indoor, and return conditions were the same as the case of no RC panel or fresh air/water heat exchanger. The only difference is in the pre-coil air temperatures. The reductions in the coil load due to the pre-cooled fresh air were estimated at peak and part-load conditions.

RESULTS AND DISCCUSION

The first step was to analyze the coil load at peak conditions. The total calculated coil load was 72.9 kW. Upon calculating the loads, an assessment of the effect of the reduction in the coil load when the fresh air is pre-cooled by the air/water heat exchanger was achieved. Initially, the effect of radiative cooling material in reducing the coil load at peak summer conditions was studied. These conditions were assumed to be constant throughout the day. The pre-cooled fresh air reduced the coil load by 11% during the afternoon, with a maximum reduction of 19% at no sunlight (Figure 3). Such reduction in the coil loads can decrease the energy consumption during peak conditions, and smaller air conditioning units can be used. In accordance with the MEW code of practice 2018, the required cooling capacity is 1.5 kW/tons or (8 EER) at 48°C for non-inverter or VRF direct expansion units. The RC panels will reduce the theoretical compressor work input from 31.2 kW to 27.7 kW at the highest coil load during the day with this material. Note that the increase of the coil load during the daytime is due to the reduction of the net cooling radiative power (see Figure 3). This reduction resulted in lower water cooling, which resulted in a lower reduction in the fresh air temperature during the daytime.

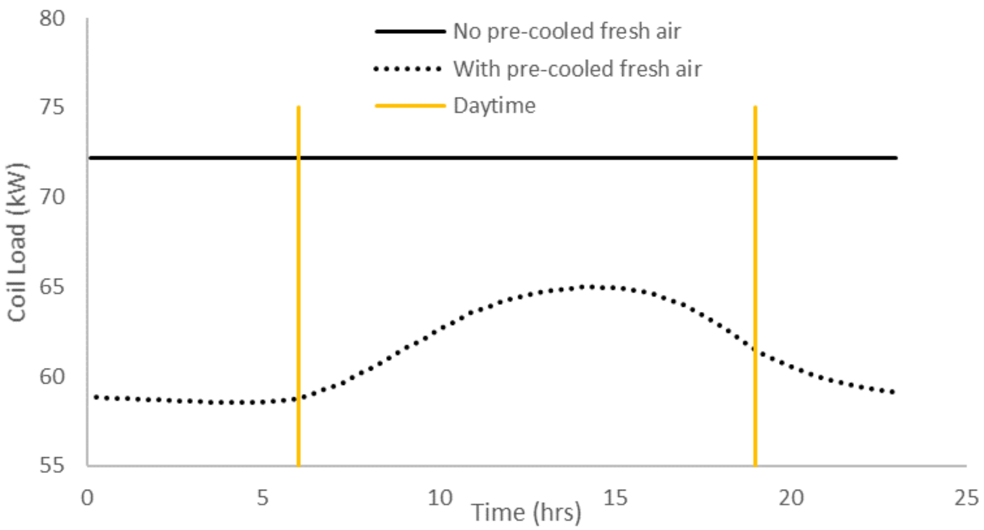
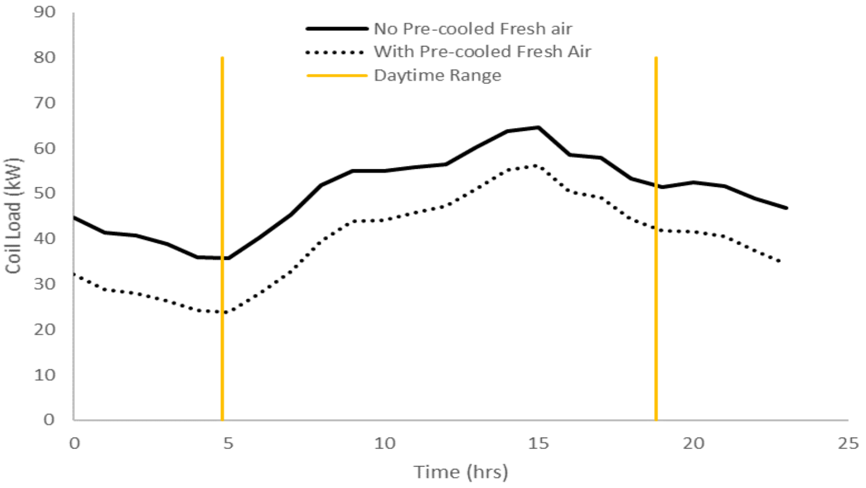


Figure 3 Reduction of the coil load due to pre-cooling the fresh air using the RC panels at peak conditions

Part Loads During the Summer

As the peak conditions occur at 1% of the time annually, it was important to investigate the part-load effect during the year on reducing the coil loads. As the outdoor weather conditions during the year were provided by Kuwait Meteorological Center, we can provide an estimate on the reduction in the part loads on a daily basis. The selected days were the 15th of June, July, and August. The hourly coil loads for the three months are shown in Figures 4(a-c). The coil load reductions for the months of June, July, and August are close to each other as the weather conditions in Kuwait are close during these months. The reduction in the coil loads during the day is around 13% and can reach up to 25% during nighttime.

(a)



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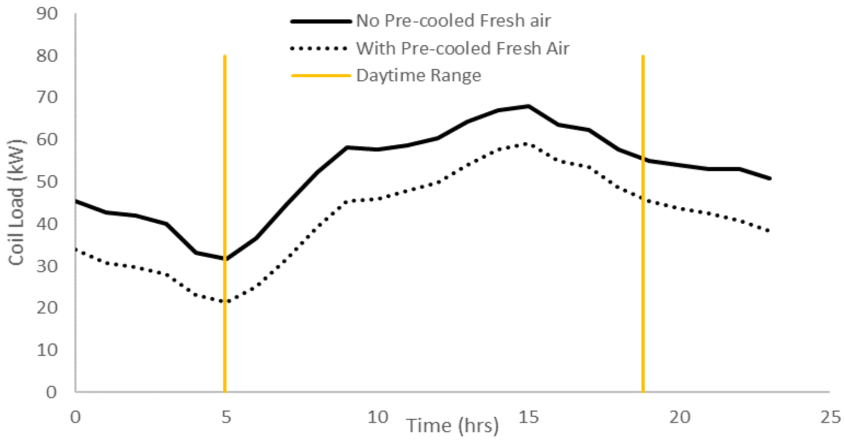

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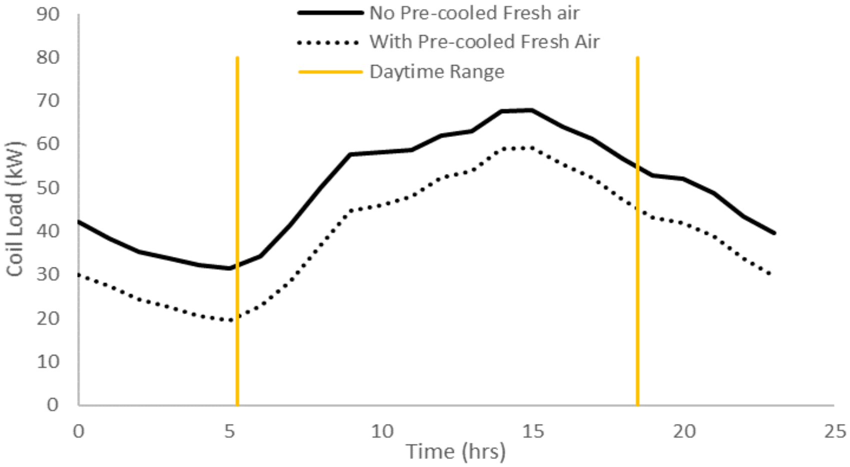

Figure 4 Reduction of the coil load due to pre-cooling the fresh air using the RC panels on the 15th of (a) June, (b) July and (c) August

Improvement of IAQ

As it is possible to reduce the coil load by pre-cooling fresh air, the indoor air quality of the typical villa can be further improved by increasing the fresh air flow rate. To set the increase in the fresh air flow rate, the carbon dioxide (CO2) levels were controlled in the indoor space. The fresh air CO_2 concentration was set to 400 ppm, while the maximum acceptable indoor CO_2 level was set to be at 1000 ppm. This increased the amount of fresh air than in the previous sections, where the reported indoor CO_2 concentration was reported to be 1588 PPM. For a day in a weekend in the month of July, Figures 5(a) and (b) show the fresh air flow rates and the indoor CO_2 ppm by the hour, respectively. Notice that the fresh air rates at nighttime are lower than the after as the occupancy in the kitchens, living spaces, dining a and reception areas are assumed to be zero. The occupancy schedules were assumed based on the local Kuwaiti traditions. Usually, in the weekend afternoons, Kuwaiti families tend to meet in living areas, and receptions for family visits, hence explaining the elevated ventilation flow rates in the afternoon till the evening. The elevation in ventilation rate in kitchens and dining areas area due to cooking activities occurring, and combined family meals that occur during the visits. As the occupancy levels increase, the amount of ventilation air available for all indoor occupants will decrease, therefore increasing the CO_2 levels indoors.

(a)

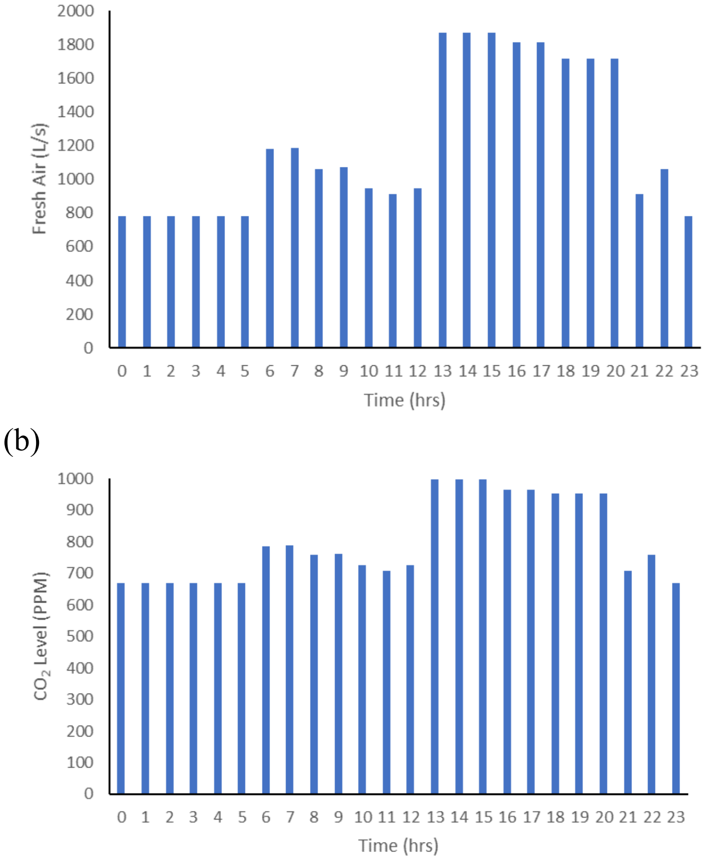

Figure 5 (a) Fresh airflow rate in (L/s) and (b) indoor CO2 concentration by the hour for July

As the fresh air flow rate increases during the day, the coil load will consequently increase. If the fresh air is not precooled, this will result in severe increases in the electrical consumptions during the day, as the coil load will exceed 100 kW (Figure 6). When the fresh air is precooled, a 12% reduction in coil load is achieved. This shows that the radiative cooling materials can further cool down the fresh air, thus, reducing the coil loads.

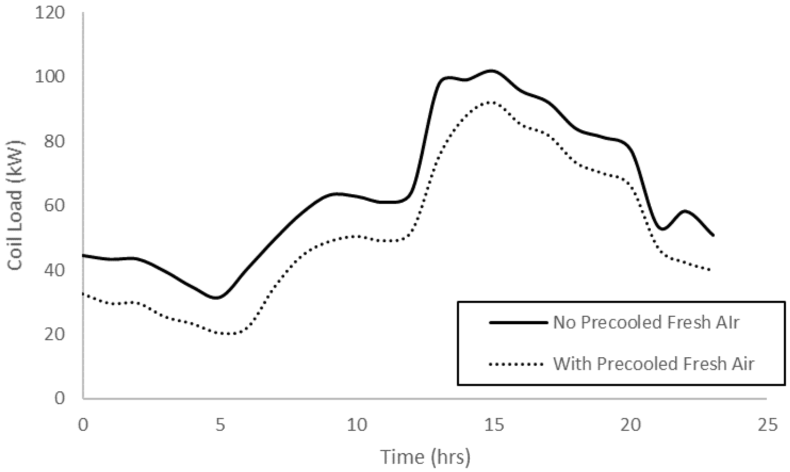

Figure 6 Reduction of the coil load due to pre-cooling the fresh air using the RC panels on the 15th of July

The reduction in the coil load can be further improved if heat exchangers of higher performances are used. For simplicity, the heat exchanger assumed here was a counter-flow heat exchanger. Future research work will include air/water heat exchanger systems that are used commercially.

CONCLUSION

A study on the reduction of the coil load was conducted when the fresh air is precooled via an air/water counterflow heat exchanger. The water was cooled via radiative cooling panels covering 70% of a typical villa in Kuwait. The results show that the use of radiative cooling panels in a HAT country, like Kuwait, has good potential to reduce the overall coil load at peak conditions and by the hour. This can encourage end-users to go for higher fresh air flow rates to achieve high IAQ at their residences. The reported reductions in the coil loads were 13% at peak conditions during the day, and 25% during the nighttime. Improvement of the pre-cooler heat exchanger design conditions can further reduce the coil loads during the day, which will be addressed in the future.

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