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Impact of integrating desiccant dehumidification processes to conventional AC system on urban microclimate and energy use in Beirut city

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ABSTRACT

This study investigates the anthropogenic heating of the urban environment of Beirut city due to air conditioning (AC) when integrating a desiccant dehumidification wheel into the conventional vapor compression (VC) system to reduce the high electricity consumption during the summer. Two hybrid system configurations with integrated heat exchanger (HE) and indirect evaporative cooler (IEC) are studied. The hot humid microclimate of Beirut is simulated assuming the use of conventional VC systems. The results were validated by comparing measured and predicted temperatures in four locations of the city. Simulations were then performed using the proposed interventions of the two hybrid systems.

The results show that conventional VC systems resulted in an average increase in the ambient temperature in Beirut of 1.3 °C in day-time and 2.2 °C in night-time in the simulated period in the month of August. The electrical energy consumption of hybrid systems with IEC and HE systems was lower by 53% and 38% than VC systems, respectively. Compared to VC, HE systems increased the sensible waste heat by 10% while IEC systems decreased it by 2%. Compared to VC systems, IEC systems resulted in decrease of ambient temperature by 0.1–0.3 °C and HE systems increased the ambient temperature by 0.1–0.3 °C. The IEC system is recommended due to its high electricity savings and lower impact on the urban heat island compared to the conventional system.

1. Introduction

Artificial modifications by humans of the natural ecosystem changed the heat balance in urban regions causing urban regions to become warmer than their rural surroundings and resulting in what is identified as Urban Heat Island (UHI) [1]. One feature of UHI is the replacement of the vegetation cover with new construction materials, such as concrete and asphalt, which absorb and store more heat. This caused an increase in the outdoor temperature and in a less comfortable the local climate to the urban inhabitants [2,3]. In addition, higher outdoor temperature significantly increases the cooling loads in buildings during the summer, and consequently increases the buildings energy consumption for air conditioning (AC). Furthermore, the performance of the conventional Vapor Compression (VC) systems is reduced due to condensers operating at higher outdoor temperature. In Athens, the mean heat island intensity exceeded 10 °C, the cooling load of urban buildings was doubled, and the peak electricity load for cooling tripled, while the minimum coefficient of performance (COP) of air-conditioners decreased up to 25% [4].

Cities worldwide consume more electrical energy in the summer to meet the cooling requirements that are mainly provided by the conventional vapor compression AC systems. For ventilation loads characterized by high latent loads, a possible measure to reduce the electrical energy consumption is the integration of a desiccant dehumidification wheel to the vapor compression system [5–7]. The fresh air is directed to the desiccant wheel to decrease its humidity. However, the latent load removal by the desiccant system imposes additional sensible load on the VC unit. One of the methods of reducing the load is to exchange the heat carried by the process air leaving the desiccant wheel with the cooler exhausted room space air. Ghali found that this configuration of hybrid desiccant system could reduce the size of VC unit by 35% [5]. Another method allowing to achieve further reduction of the additional load is to cool the process air leaving the desiccant wheel by indirect evaporative cooling, and thus further electrical energy savings up to 55% can be obtained [8–10].

Even though the hybrid desiccant systems reduce the electricity consumption, they have adverse effect on the outdoor climate. The hybrid systems release more sensible and latent waste heat to the urban environment than the conventional VC systems due to the desiccant regeneration process. In hot humid climate, the regeneration

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Nomenclature

A	area [m^2]
C	volumetric heat capacity [$MJ/m^3 K$]
d	thickness [m]
f	fraction [–]
H	height [m]
h	enthalpy [kJ/kg]
k	thermal conductivity [W/m K]
$\dot{m}$	mass flow rate per unit area [$kg/s\,m^2$]
q	heat rate [W/m^2]
T	temperature [°C]
V	volumetric flow rate per unit area [$l/s\,m^2$]
α	albedo [–]
ε	emissivity [–]
λ	roughness length [m]

Abbreviations

AC	Air Conditioning
ACH	Air Change per Hour
ADP	Apparatus Dew Point
BEM	Building Energy Model
CAS	Central Administration of Statistics
COP	Coefficient of Performance
ECMWF	European Centre for Medium-Range Weather Forecasts
HE	Heat Exchanger
IEC	Indirect Evaporative Cooler
MAE	Mean Absolute Error
OEA	Order of Engineers and Architects
PLF	Part Load Factor
RCREEE	Regional Center for Renewable Energy and Energy Efficiency
RH	Relative Humidity
RMSE	Root Mean Square Error
SHGC	Solar Heat Gain Coefficient
TEB	Town Energy Balance
TMY	Typical Meteorological Year
TSBL	Thermal Standard for Buildings in Lebanon
UBL	Urban Boundary Layer
UHI	Urban Heat Island
VC	Vapor Compression

temperature could exceed 80 °C [11], implying that an air stream of high temperature and humidity is exhausted to the outdoor. The collective use of the hybrid systems in a city may therefore result in the increase of the contribution of AC system to the anthropogenic sensible and latent heat, thus aggravate the urban heat islands. The ambient temperature and humidity in the city may increase, as well as the buildings' sensible and latent loads which may prevent the achievement of the desired benefit of reduced electrical energy consumption in buildings. In literature, the hybrid desiccant system was recommended as it achieves electrical energy savings, without taking into consideration its impact on the urban microclimate [6,7,12].

It is important to assess the implication of the hybrid desiccant systems, not only on the electrical energy consumption, but also on the urban microclimate. A method of assessment by researchers has been by performing simulations using coupled models for air conditioning systems in buildings and the outdoor microclimate [13,14]. Meso- and micro-scale climate numerical models have been used to simulate the local climate for cities [13,14]. Meso-scale models solve for the atmospheric variables such as temperature, moisture, velocity, and winds in large 3-D domains above the urban canopy level, defined as the height slightly above the level of the buildings roofs [13]. Meso-scale models ignore the complexity of the urban canopy and assume it as an aerodynamic roughness. However, micro-scale models use the surface energy balance equation proposed by Oke [14] to solve for the heat fluxes in the urban canopy layer. Micro-scale models represent the urban geometry by one building and road, and compute the temperature and the humidity in the canopy layer at street level [13]. A coupling between meso- and micro-scale models may be done at a forcing level above the canopy [15,16]. In this case, the micro-scale model uses the atmospheric variables, called atmospheric forcing, at the top-canopy level computed by the meso-scale model to compute the temperature and humidity in the surface layer at street level, and the momentum and heat fluxes of the surface layer. The meso-scale model uses the values of these surface fluxes to compute the atmospheric variables in the open space above the surface layer that becomes the atmospheric forcing of the micro-scale model in the next iteration [15]. Several researchers integrated a building energy model to the microscale model coupled to the meso-scale model to simulate buildings' AC systems, their thermal loads and power consumption [17–20]. For example, De Munck et al. [17] investigated the impact of various AC scenarios on the UHI during heat waves. Kikegawa et al. [19] predicted, using the same approach, the increase in cooling energy demands and evaluated the urban warming countermeasures. Similarly, Salamanca and Martilli [20] evaluated the impact of AC systems on the air temperature and their energy consumption.

The present study focuses on the impact of the hybrid desiccant AC systems on UHI in Beirut city. Beirut is characterized by a hot and humid climate during the summer where the UHI intensity reaches its peak. In Beirut city, the cooling is mainly provided by traditional vapor compression AC systems using the electricity as energy source [21]. Integrating a desiccant wheel to the conventional AC system in Beirut is proposed as a hybrid AC system to reduce the energy consumption [5]. However, such hybrid system may have an adverse effect on the outdoor temperature and humidity due to the large amount of waste heat releases by the desiccant wheel. The amount of waste heat releases to the environment depends on whether the hybrid system uses heat exchanger or indirect evaporative cooler.

In this study, the conventional VC system and the two configurations of the hybrid AC dehumidification system using heat exchange (HE) and indirect evaporative cooling (IEC) are evaluated in terms of energy savings and impact on the urban microclimate. The objectives are first to assess the impact of the operation of AC systems in a large scale in Beirut city on the urban microclimate; and second to evaluate the effect of the integration of the two hybrid AC systems configurations that save electrical energy but may increase the outdoor air temperature and humidity. The purpose is to make recommendations on the appropriate choice of cooling systems that not only reduce the electrical energy consumption but also do not adversely compound the urban heat island.

2. Research methods

The study domain is Beirut city (Lat. 33° 52′ N, Lon. 35° 30′ E), the capital of Lebanon. It is situated in the Mediterranean coast and it has a cold and short winter, and a hot and humid summer. The summer is usually rainless with a monthly average high temperature of 32 °C. Beirut is the largest city of Lebanon with a population of about 1.8 million [22]. The land cover of Beirut consists of densely built areas in majority, with the presence of some vegetation covers.

To study the effect of the use of AC systems on the city microclimate, the numerical approach of using coupled meso-scale, microscale and building energy model is followed [17–20] where simulations