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Investigation of a hybrid system of nocturnal radiative cooling and direct evaporative cooling

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ABSTRACT

In this paper, the results of a study on a hybrid system of nocturnal radiative cooling, cooling coil, and direct evaporative cooling in Tehran have been discussed. During a night, the nocturnal radiative cooling provides required chilled water for a cooling coil unit. The cold water is stored in a storage tank. During eight working hours of the next day, hot outdoor air is pre-cooled by means of the cooling coil unit and then it enters a direct evaporative cooling unit. In this period, temperature variation of the conditioned air is investigated. This hybrid system complements direct evaporative cooling as if it consumes low energy to provide cold water and is able to fulfill the comfort condition whereas direct evaporative alone is not able to provide summer comfort condition. The results obtained demonstrate that overall effectiveness of hybrid system is more than 100%. Thus, this environmentally clean and energy efficient system can be considered as an alternative to the mechanical vapor compression systems.

1. Introduction

Cooling is an essential issue in air conditioning of most buildings in warm and humid climates. In fact, due to great consumption of energy in buildings, there are increasing demands to design building heating, ventilation, and air conditioning (HVAC) equipments and systems energy efficiently. Among the HVAC components and systems, cooling systems consume the largest amount of electrical energy. The issues of climatic change caused by global warming, the consumption of fossil fuels, the resources depletion, and demand for reducing pollutant particles have led to a growth use of natural resources instead of conventional energy resources or partly replacement of active cooling system. The usage of passive cooling has been considered to drive cooling cycles to provide comfort cooling. In addition, evaporative cooling system can be an economical alternative, or as a pre-cooler in the conventional systems. Also, it is known due to its zero pollution, easy maintenance, low energy consumption, simplicity, and good indoor air quality [1–8].

Passive cooling resources are the natural heat sinks of the planet in order that understanding their parameters is worthwhile for all varieties of cooling methods. Three heat sinks of nature are the sky, atmosphere, and the earth. Energy transfer to sky is entirely done by radiation in the wave-length interval from approximately 8–14 μm. In fact, the only means which the earth can lose heat is radiative cooling [1,3].

Significant thermal comfort can be achieved during summer by passive cooling in buildings with a great reduction of cooling loads. A black object at ambient temperature interacts with all temperature range of atmospheric layers and causes cool down beneath of ambient temperature in optimum situations. Heat dissipation techniques are based on the transfer of excess heat to a lower temperature natural sinks. Regarding sky, heat dissipation is carried out by long-wave radiation from a building to the sky that is called radiative cooling. The sky equivalent temperature is usually lower than the temperature of the most bodies on the earth, therefore, any ordinary surface that interact with the sky has a net long-wave radiant loss [2,3].

Direct evaporative cooling (DEC) is the oldest, and the most widespread form of air conditioning. The underlying principle of DEC is the conversion of sensible heat to latent heat. Through a direct evaporative cooling system, hot outside air passes a porous wetted medium. Heat is absorbed by the water as it evaporates from the porous wetting medium, so the air leaves the system at a lower temperature. In fact, this is an adiabatic saturation process in which dry bulb temperature of the air reduces as its humidity increase (constant enthalpy). Some of the sensible heat of the air is transferred to the water and become latent heat by evaporating some of the water. The latent heat follows the water vapor and diffuses into the air. The minimum temperature that can be obtained is the wet bulb temperature of the entering air [8–11].

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In HVAC systems, cooling coils unit (CCU) perform an essential function by exchanging the cooling load from the hot air to the chilled water loop by pushing air flow through the coil. Also, CCU can be utilized as pre-cooler systems to decrease temperature of hot air. Totally, utilization of cooling coils affects performance of HVAC systems increasingly [12,13].

Several research papers were dedicated to explore issues about nocturnal cooling such as, Berdhal and Fromberg (1982) [14], Argiriou et al. (1994) [15], Ali et al. (1995) [16], Mihalakakou et al. (1998) [17], Al-Nimr et al. (1998, 1999) [18], Spronken-smith (1999) [19], Erell and Etzion (1999, 2000) [20–23], Meir et al. (2003) [3], Bagiorgas and Mihalakakou (2007) [2], Bassindowa et al. (2007) [24], Salim Shirazy et al. (2008) [25,26], and Farmahini Farahani et al. (2009) [27]. Aforementioned research studied experimental and theoretical investigation of long-wave radiance, nocturnal radiative cooling and its potential in different conditions, and effects of different parameters on it. Regarding direct evaporative cooling, Lueng (1995) [28], Halaz (1998) [29], Camargo et al. (2000–2005) [8,30], Dai and Sumathy (2002) [31], Liao and Chiu (2002) [32], and Al-Sulaiman (2002) [33] have proposed mathematical modeling and done experimental in order to analyze efficiency or simulate direct evaporative cooling. Furthermore, Scoldfield and DesChamps (1984) [34], Al-Juwayhel et al. (1997) [35], El-Dessouky et al. (2004) [36], and Heidarinejad et al. (2009) [37] have studied two-stage evaporative cooling to examine its efficacy on performance.

To the best knowledge of the authors of this paper, no significant investigation has been performed on combining nocturnal cooling and evaporative cooling. Thus, lack of information about feasibility of this new combination is the motivation of this study.

In this research, the water in a storage tank is cooled by means of circulating the water through a flat-plate radiator throughout a night (nocturnal radiative cooling). During the next day, the cold water in the storage tank is used in a cooling coil unit as chilled water to decrease temperature of outdoor air (pre-cooling). Then, the pre-cooled air with lower wet bulb temperature passes through a direct evaporative pad (See Fig. 1). By this way, the hot outdoor air is pre-cooled through the CCU which augments efficacy of whole cooling system. The chilled water is obtained from a renewable and pollutant-free process which consumes low energy in comparison with conventional mechanical vapor compression systems. The performance and feasibility of such cooling system have been analyzed in this paper.

2. Modeling and formulations

This system consists of four parts 1 – Radiator, 2 – Storage tank, 3 – Cooling coil, and 4 – Direct evaporative cooling. Formulations and modeling of each part have been described in the following subsections.

2.1. Formulation of the flat-plate radiator

The flat-plate collector as heat exchanger is studied and temperature distribution in any desirable point along flat-plate is proposed by equation (1) [4,20]. If time interval is kept reasonably small, this steady state expression predicts accurate outlet temperature.

$$\frac{T_f - T_a + S/U_L}{T_{fi} - T_a + S/U_L} = \exp\left(\frac{-U_L nwFy}{\dot{m}C_p}\right) \tag{1}$$

Where, T_f is the outlet fluid temperature, T_a is the ambient air temperature, T_{fi} is the fluid temperature at the collector inlet, S is the emitted radiative energy to sky from surface of the collector, U_L is the overall heat loss coefficient of the collector, n is the number of parallel tubes in the collector structure, w is distance between the tubes, y is the tubes length, F is the collector efficiency factor, $\dot{m}$ is the mass flow rate through the collector, and C_p is the specific heat of the fluid.

The flat-plate collector efficiency factor denotes the proportion of the factual real gain rate per tube per unit length to the gain which would occur if the collector absorber plate were at the temperature T_f [38]. The flat-plate collector efficiency factor depends on structure of the collector, character and thermal conductivity of the adhesive material between tubes and absorber plate, and heat transfer coefficient of heat carrier inside of tube. The flat-plate collector efficiency factor value varies between 0.85 and 0.95.

The overall heat loss coefficient U_L is sum of heat losses around the collector such as, convection on top of the collector and conduction under and on sides of the collector. The heat loss due to conduction beneath of the collector is the proportion of thermal conductivity of the insulation to thickness of the insulation. Because the sides' loss is less than 5%, it is negligible. The top loss coefficient U_t is assessed by considering convection losses from the upward surface of the collector. The highest amount of heat loss takes place at the top of the collector. Equation (2) estimates top loss.

$$U_t = 1.8 + 3.8v \quad 1.35 < v < 4.5 \tag{2}$$

where v is wind velocity. If the wind velocity is less than 1.35 m/s, this expression overestimates the heat loss [39], but it does not interfere calculation.

2.2. Modeling of sky equivalent temperature

Ambient temperature and sky equivalent temperature are two effective measures of the surrounding conditions. These two measures affect the cooling performance and outlet temperature of the collector exposed to the night sky. The difference between ambient temperature and sky equivalent temperature demonstrates the potential of the nocturnal cooling [25]. The wind speed

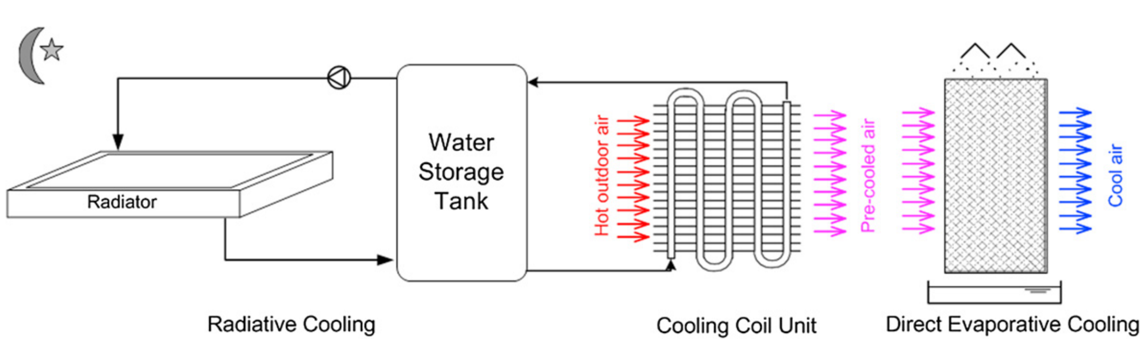

Fig. 1. A Schematic diagram of the hybrid system of radiative cooling, cooling coil, and direct evaporative cooling.