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An Experimental and Analytical Study of a Radiative Cooling System with Flat Plate Collectors

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Abstract

A nocturnal radiative cooling system with flat plate solar collectors in Beijing, is assessed both experimentally and numerically. A cooling loop, including a radiator, a storage tank, pump, radiant floor and connecting pipes has been studied experimentally. The heat loss of an uncovered night-sky radiator was analysed according to radiation and convection theory. The water is circulated through the flat-plate radiator having 2 m^2 of collector area at night to be cooled by convection and radiation to sky. The results indicate that the minimum temperature of the floor surface is 19.5 °C. Vertical temperature field is uniform. Design temperature can increase 1 °C compared with conventional heat convection. The average net cooling reached 26 W/m^2, as condensation does not occur. It is possible to increase the total cooling capacity while maintaining a low pressure drop. It demonstrates the feasibility of cooling using fluid medium through nocturnal radiation.

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Keywords: Nocturnal cooling, Flat-plate collector, Radiative cooling;

1. Introduction

On an average about 40% of world energy is used in residential buildings and the largest energy consumption is allocated to the cooling and air-conditioning systems. The energy consumption related to cooling of buildings is steadily increasing as a consequence of the world-wide industrialisation and increasing living standard. The debate on global warming and the demand of reducing CO_2 emissions suggests alternative cooling methods with the potential

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Nomenclature

RH	relative humidity (%)	T_a	ambient air temperature (°C)
T_{indoor}	indoor air temperature (°C)	T_o	operation temperature (°C)
T_f	floor surface temperature (°C)	T_r	mean radiant temperature (°C)
A_i	surface area (m^2)	$P_{c,exp}$	cooling power (W/m^2)
T_{sys}	system temperature (°C)	C_{sys}	heat capacity (kJ/K)
P_{pump}	heat pump power (W/m^2)	P_{conv}	total cooling power (W/m^2)
ε_r	emittance	t_i	temperature of corresponding surface (°C)

to substitute or partly replace traditional (active) air conditioning systems. So every attempt to economize energy consumption is very valuable.

Radiative cooling is based on the heat loss by long-wave radiation emission towards the sky. Sky temperature during summer nights can be less than 0 °C, under clear summer night sky conditions sky temperatures of -10 °C are possible. This corresponds to relative temperature depressions between of 20–30 K. The long-wave radiation is mainly dependent on the water content of the atmosphere, with 90% of the sky radiation originating from the first kilometre above ground and 40% from only 10 m above ground [1]. Therefore the radiation strongly varies from site to site. The radiators are twin-wall sheets made of a modified polyphenylenoxid resin, which are proposed as low cost roof integrated modules.

The thermal performance of a system with a radiator aperture area of 5.3 m^2 and reservoir volume of 280 l has been investigated in experiments for Oslo climate [2]. Different radiative cooling applications have been investigated, such as movable insulation, air based systems and open or closed water-based systems. The specific cooling power measured ranges from 20 to 80 W/m^2 [3]. A numerical and experimental study in Namibia [4] with 48 m^2 of collectors, resulted in 60.8 W of cooling per square meter of collector area. In another study of nocturnal cooling radiators[5]reported results of experiments on a concrete roof component where 3/4" steel pipes were installed on a steel plate and painted white to minimize heat gain during the day. One of the first applications of radiative cooling tested about 50 years ago was the movable insulation. The roof insulation is removed during the night in order to cool down the building through radiation towards the sky. The major drawback of such system is the motoroperated system to remove and replace the insulation panels [6]. Radiative cooling of buildings has attracted considerable research over the years, much of it focused on evaluating the magnitude of the resource and the variations in cooling potential for different locations [7]. Experimental and analytical study of a radiative cooling system is presented [8]. The results indicate that water temperature decreases 7–8 °C and the average net cooling will be ranged from 23 to 52 W/m^2, as the mass flow rate increases from 0.01 to 0.05 kg/s. Experimental studies of uncovered PVT collectors were carried out in Stuttgart to validate a simulation model, which calculates the night radiative heat exchange with the sky [9]. Measured cooling power levels were between 60 and 65 W/m^2, when the PVT collector was used to cool a warm storage tank and 40–45 W/m^2, when the energy was directly used to cool a ceiling.

Nocturnal radiation cooling is one of the natural cooling techniques which can draw away the heat accumulated during the day to the cool night sky via the radiator. In this research a nocturnal radiative cooling system with flat plate solar collectors in Beijing, is assessed both experimentally and numerically.

2. System description

Figure 1 illustrates the experimental set-up and the parameters, which were recorded. This close system consists of flat plate solar collectors made of a galvanized iron radiative plate with the back insulation, small diameter copper tubes painted matte white, a radial piston pump and a storage tank. The radiators are mounted as integrated modules on the roof of a building, normally under a small tilt angle, and replace conventional roof cover materials. The heat carrier is lifted by pump power in the upper part of the radiator. Driven by the force of gravity the liquid trickles through the radiator intrinsic channels, releases heat and returns to the reservoir. The system is a drain-back system and the store represents the drain-back reservoir for the heat carrier when the system is not operative. The heat carrier circulates freely between the radiator loop and the storage tank without intermediate heat exchangers. When no net cooling power is obtained, the circulation is stopped by the controller, the water drains back in the reservoir and unwanted heat gains are avoided.

The surface area of collector is 2 m^2. The copper tubes outer diameter is 10 mm and they were installed on the top of the unglazed collector surface at a distance of 2-3 cm from each other. The insulated cylindrical storage tank of 300 litre-capacity. During the night, the water drawn from the top layer of the storage tank was circulated through the copper tubes and delivered to the bottom of the storage tank, after being cooled. The base of cooling system's function is the radiation heat exchange of the radiator with the sky. Convection heat transfer with the ambient air could be efficient if the radiator is warmer than the environment. So, the sky temperature is a key parameter for determining whether or not the radiative cooling system is practical.

The experiments were carried out at a small free-standing outdoor test laboratory in BeiJing. In order to obtain a good cooling performance and secure the drain-back of the heat carrier, a tilt angle of approximately 10° would be more optimal. The present experiments have been carried out with the tilt angle of 32° given by the existing roof. Relative to horizontal placement, the cooling power at 10° tilt angle is reduced by approximately 1% and by 7% with a tilt angle of 32°. The cooling reservoir which is placed inside the test house, is a modified domestic hot water store. The temperatures were monitored by Agilent (HP) 34972A LXI Data Acquisiton Unit with 1 Gbit LAN and USB 2.0 Model Details 3-slot LXI mainframe with 6 ½ digit DMM and built-in signal conditioning measures temperature (RTDs, thermocouples, thermistors), AC/DC V, 2/4 wire resistance, frequency/period, AC/DC current.

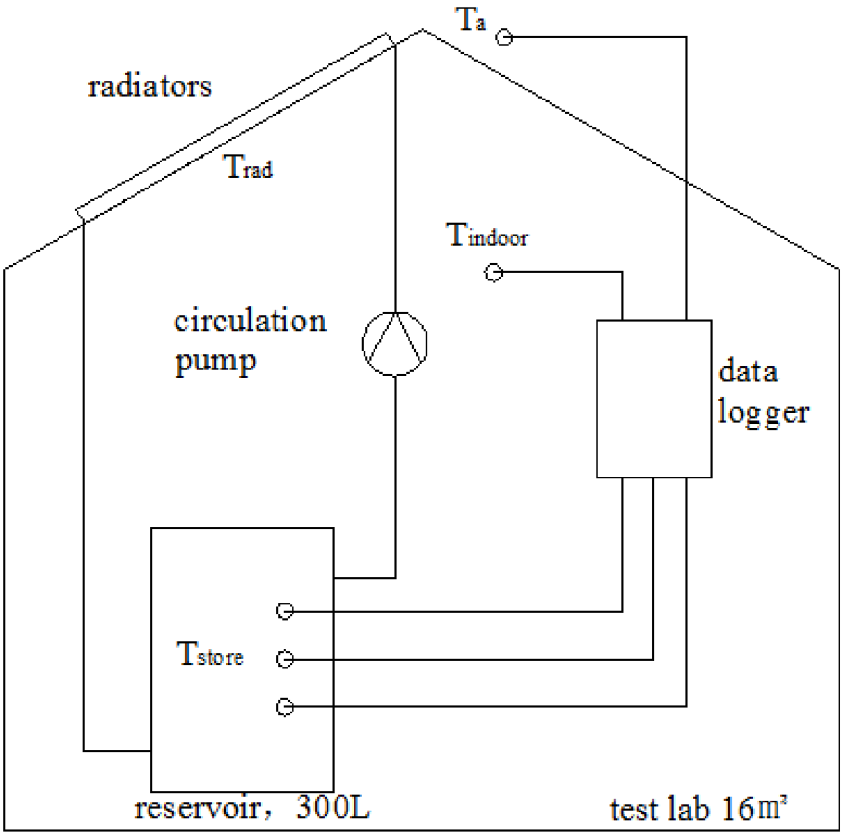

Fig. 1. Experimental set-up for the radiative cooling measurements and recorded parameters

3. Experimental

3.1. Experimental data

Experiments began to test in September. The plots show the ambient air temperature T_a, the relative humidity *RH*, the indoor lab temperature T_{indoor}, the Operation Temperature T_o, the floor surface temperature T_f, the supply water temperature and the returning temperature.

Experimental test began after system running three days. For the analysis, only the periods from 18:00 to next day 7:00 were considered. The nocturnal ambient air temperature was between 23.2 °C and 29.5 °C, the relative humidity between 21% and 74%.

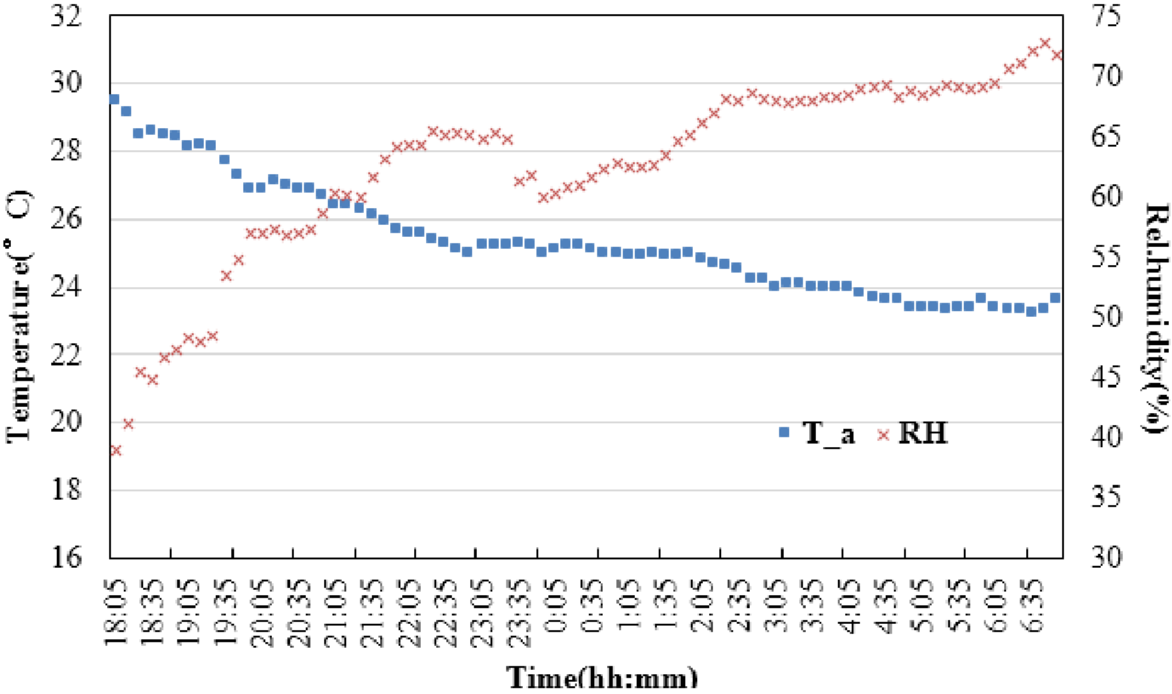

Fig. 2. Shown are the temperature of the ambient air temperature T_a, the relative humidity *RH*

Radiation cooling energy can spread in a straight line. It is absorbed by the solid surface and allowed to cool. As air is the transparent body of radiation, it cannot be directly heated by radiant energy. It relies on convection to cool with cold source and room interior surface. There is a continuous exchange of radiant energy between surfaces. For the human body, reduction in temperature of envelope inner surface is more conducive to the body eliminate excess heat by radiation. Heat dissipation of evaporation reduces while thermal comfort can be improved. Operation Temperature is used to represent thermal comfort. It was compared with indoor air temperature.

$$T_o = 0.52T_{indoor} + 0.48T_r \quad (1)$$

$$T_r = \frac{\sum A_i t_i}{\sum A_i} \tag{2}$$

Where T_r is the mean value of Mean Radiant Temperature. A_i is the surface area of inner surface, and t_i is the temperature of corresponding surface.

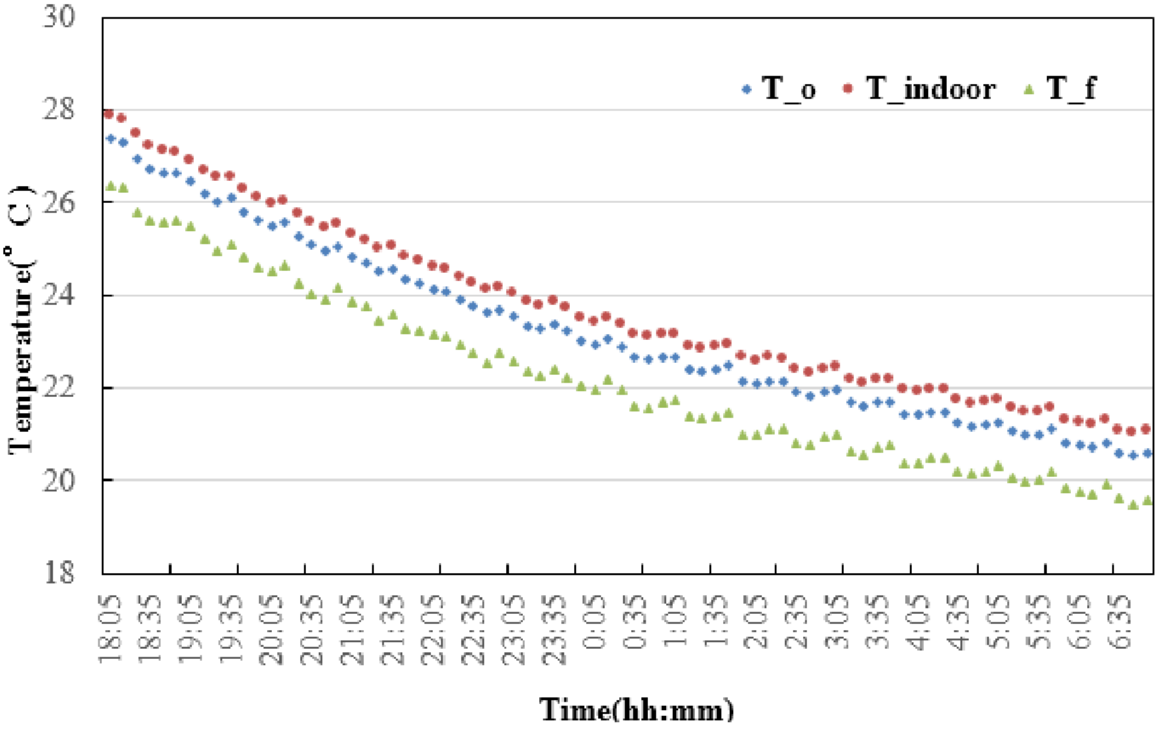

Fig. 3. Shown are the temperature of the operation temperature T_o, inside the test lab T_{indoor}, floor surface temperature T_f

Fig. 3 shows temperature trend of Operation Temperature and indoor lab temperature is same. There exists 1 °C difference between the two. Average temperature of indoor envelope surface is lower than indoor lab temperature. Then it can absorb heat in air together with the floor surface, and indoor lab temperature decreased. Design temperature can increase 1 °C compared with conventional heat convection. According to a large number of actual research, most people are not satisfied when the floor temperature is below 18 °C. Surface temperature controlled at 19 °C as the limitation of condensation. Therefore, the importance of the floor surface temperature that affects not only the thermal comfort but also the floor surface condensation. Minimum temperature of the floor surface during the test was 19.5 °C. During operation, supply water temperature decreases less than 1 °C per hour. Hence the local temperature differences in the complete system are small at a given time.

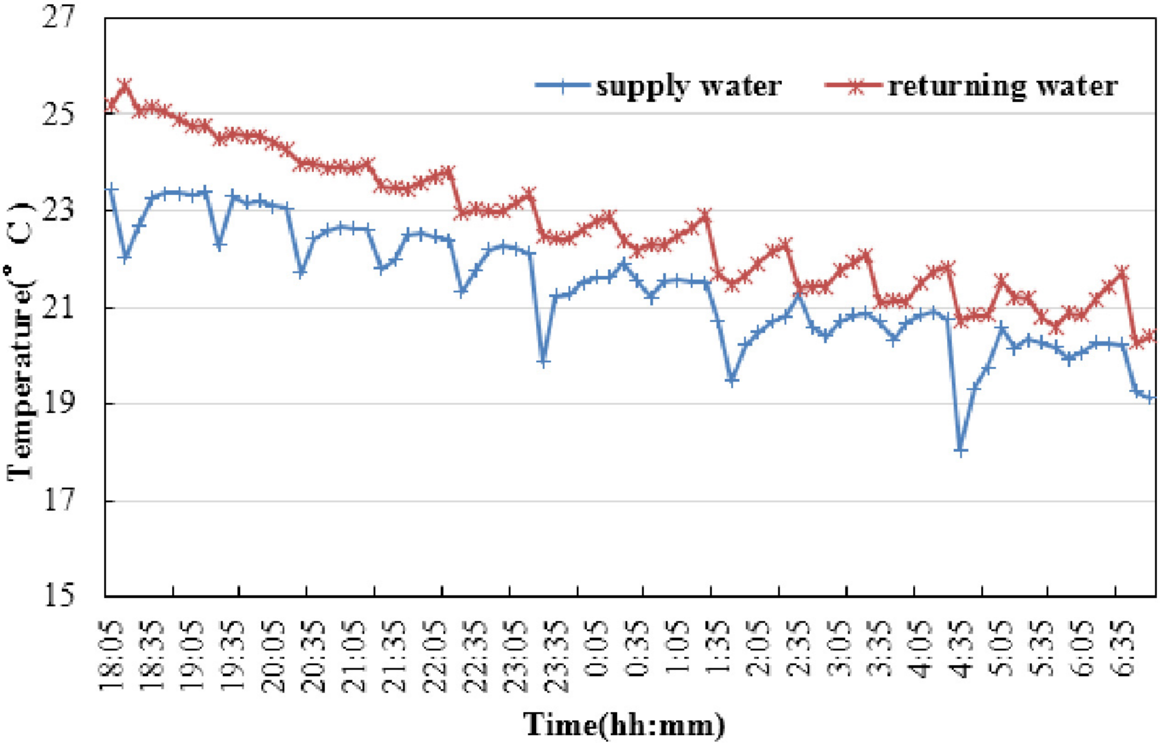

Fig. 4. Shown are the temperature of supply water and returning water

The cooling power $P_{c,exp}$ of the radiators is determined from the change of the system temperature T_{sys} per time unit dt(dT/dt) and is corrected for the heat losses/gains from the reservoir, the pipes and the surrounding.

$$P_{c,\exp} = -C_{sys}\left(\frac{dT}{dt}\right)_{sys} - k_{sys}\left(T_{sys} - T_a\right) + P_{pump} \tag{3}$$

Where C_{sys} is the heat capacity of the cooling system and P_{pump} is the heat which transferred by the circulation pump to the system water, corresponding to approximately 75% of the electric power consumption in the pump (here: P_{pump}=60W). In practice are T_{sys} and hence T_{rad}, the mean temperature of the radiator, at a given time equal to T_{store} because of the high mass flow and the negligible thermal stratification.

3.2. Theoretical analysis

The heat loss of an uncovered night-sky radiator is caused by radiation and convection. The heat loss related to conductive heat transfer between radiator and surrounding can be neglected.

$$P_c = P_{rad} + P_{conv} \tag{4}$$

Where P_c is the total cooling power and P_{conv} the convective cooling power of the radiator. The long-wave radiative cooling power, P_{rad}, of a radiator with aperture area A and an emittance ε_r is given.

$$P_{rad} = A \cdot \varepsilon_r \left(\sigma T_{rad}^4 - R \right) \tag{5}$$

R is the long-wave radiation incident on the radiator's surface. For a horizontal surface, the down welling long-wave radiation originates mainly from a few hundred meters thick atmospheric layer near the ground (R=R_A). The air temperature near the ground, T_a, is fairly representative for this layer In order to describe the radiant heat transfer of the atmosphere R_A, the term 'sky temperature' T_{sky} is introduced. It is defined as the temperature of a black body radiator emitting the same amount of radiative power as the sky according to the equation.

$$R_A = \sigma \cdot T_{sky}^4 = \sigma \cdot \varepsilon \cdot T_a^4 \tag{6}$$

Where the sky emittance ε is independent on wavelength and σ is the Stefan–Boltzmann constant. In the present experiments the effective sky temperature has not directly been measured. It can be calculated according to research [10] which expresses the emittance of the night sky as a function of the temperature and the relative air humidity for cloudless atmospheres. Cooling power $P_{c,exp}$ as a function of the temperature difference ΔT=T_{rad}-T_a, $P_{c,exp}$ is 26W/m^2 approximately during the test.

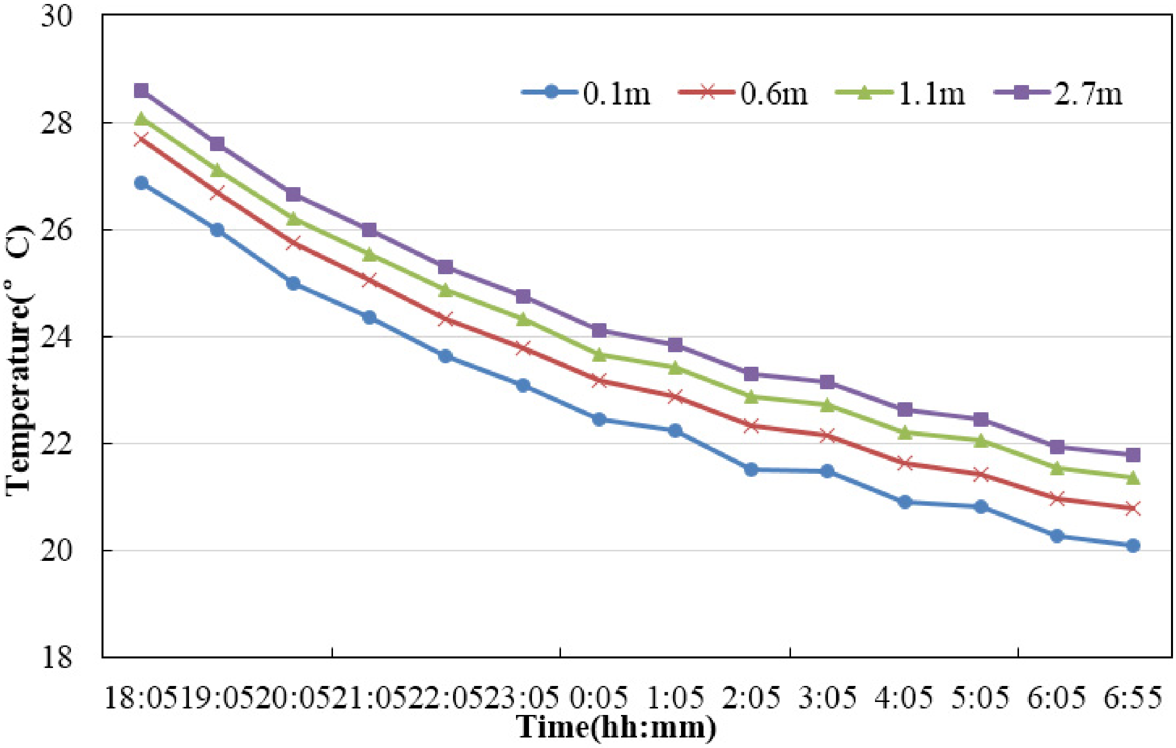

Fig. 5. Shown are the temperature of inside the test lab at different set

Uniform temperature distribution is to investigate thermal comfort of radiant floor cooling room (Figure 5). Multiple measuring points were arranged at vertical direction 0.1 m, 0.6 m, 1.1 m, 2.7 m, respectively to study the indoor temperature gradient radiant of floor cooling system room. During operation, temperature gradient was 0.72 °C. It was very small within 0.1-2.7 m. The maximum temperature difference was 1.89 °C. Vertical temperature field was uniform within the scope of the work area at the vertical direction maximum temperature difference 1.42 °C. It complies the recommended value of thermal comfort. Furthermore, condensation does not occur.

4. Conclusions

This paper has evaluated the performance of a flat-plate collector radiative cooling system from experiments and theoretical analysis. A cooling loop, including a radiator, a storage tank, pump, radiant floor and connecting pipes has been studied experimentally. The heat loss of an uncovered night-sky radiator was analysed according to radiation and convection theory.

The water is circulated through the flat-plate radiator having 2 m^2 of collector area at night to be cooled by convection and radiation to sky. The results indicate that the minimum temperature of the floor surface is 19.5 °C. Vertical temperature field is uniform. Design temperature can increase 1 °C compared with conventional heat convection. The average net cooling reached 26 W/m^2, as condensation does not occur. The design and operating characteristics of a night radiator and their effect on the system efficiency have been considered.

It is possible to increase the total cooling capacity while maintaining a low pressure drop. It demonstrates the feasibility of cooling using fluid medium through nocturnal radiation.

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