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A Novel Nocturnal Cooling Radiator Used for Supplemental Heat Sink of Active Cooling System

Yi Man[a,**], HongxingYang[b], Yunxia Qu[a], and Zhaohong Fang[a]

[a]*Shandong Key Laboratory of Building Energy Saving Technique, Ministry of Education Key Laboratory of Building Renewable Energy Utilization Technologies, Thermal Engineering School, Shandong Jianzhu University, Jinan 250101, Shandong, China*
[b]*The Hong Kong Polytechnic University, Hong Kong, China*

Abstract

Nocturnal cooling radiation is one of the effective natural passive cooling technologies by infrared radiation exchange between terrestrial surfaces and the sky. Although the application of nocturnal cooling radiation technology as the exclusive heat sink in active cooling systems is inherently limited, it can be used as an excellent supplemental heat sink and to be activated under ideal meteorological conditions to reduce system energy consumption. A novel nocturnal cooling radiator (NCR) works as supplemental heat rejecter of active cooling system is designed in this study. A practical analytical model of the NCR is developed. A computer program based on this developed model is plotted and verified by experiment. Based on performance simulation results of a NCR operated in humid subtropical climate, the novel NCRis found to be feasible as the supplemental heat sink of active cooling system.

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*Keywords:*Nocturnal cooling radiator;supplemental heat sink;passive cooling;active cooling system

1. Introduction

It is well known that, nocturnal cooling radiation is one of the effective natural passive cooling technologies

* Corresponding author. Tel.: +86-182-5315-6650 .
E-mail address: manyilaura@163.com

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caused by infrared radiation between the terrestrial surfaces and the sky [1]. The sky far away from atmosphere is a great free radiation heat sink, whose temperature is about 4K [2]. Since the temperatures of the skyward terrestrial surfaces are always higher than 4K, these surfaces experience heat loss by infrared radiation to sky. Although the atmosphere forms a screen between terrestrial surfaces and space to prevent the excessive heat loss of earth, the screen function is weak for radiation between infrared wavelengths of 8 to 13μm, which is called "atmospheric window". The nocturnal cooling radiation is enhanced if the terrestrial surface has a high emissivity in the wavelength region matched to the "atmospheric window". Then the terrestrial surface can effectively utilize the space as free heat sink and reach the low equilibrium temperature.

The nocturnal cooling radiation phenomenon was first explored by Arago [3] for dwellings climatization since 19th century. Following the energy crisis of the 1970's, the nocturnal cooling radiation technology for buildings received increasing attentions from researchers. Both flat plate solar collectors and other specially designed radiators were investigated for nocturnal cooling mainly in five topics: the performance investigation of the passive cooing and heating systems in which flat plate solar collectors were used [4-8], the simulation model and experimental results of the flat plate solar collectors as the nocturnal cooling radiator (NCR) [9], the performance of a passive cooling system with other specially designed radiators [10-14], and the simulation model and experimental results of the other specially designed radiators [15, 16]. From literature review, the existing researches mainly concentrated on the performances investigation of passive cooling systems mainly consisting of nocturnal cooling radiators and their accessories.

In fact, application of the nocturnal cooling radiation technology for normal heat pump applications in active cooling systems is inherently limited. First, the cooling capacity of NCR system can not match the building cooling loads. The NCR can not be used at daytime when the peak building cooling load exists, additionally, the NCR giving better performance during winter but more cooling capacity is required in summer. Second, the cooling capacity of the NCR is significantly affected by relative humidity of ambient air and cloud cover conditions of a nocturnal sky. However, its inherent feature determined that, the NCR can be used as supplemental heat rejecter and to be activated under ideal meteorological conditions. Therefore, it is more suitable to be utilized as efficient supplemental heat sink to assist other stable heat sinks in an active cooling system. There are some additional advantages to employ NCR works as supplemental heat rejecter. First, the NCR can be installed horizontally against on the roof of buildings, which does not affect the building appearance. Second, there is no rotating part in the NCR so that it has a long operation life with no noise and nearly no maintenance. Third, the NCR is easy to be controlled by the circulating pump. Fourth, the NCR is usually cheaper than other common heat rejecters, such as cooling tower.

To the best knowledge, the study on the NCR as the supplemental heat rejecter of the active cooling systems still does not exist due to its complexity in design and simulation. Therefore, the aims of this study are to propose a novel NCR suit for practical engineering application, to develop a practical short time step simulation model of the novel NCR, to simulate the operation performance of the novel NCR, and to validate the model accuracy. In this study, the proper designed active cooling system with novel NCR possesses high operation energy efficiency, and the optimal sized novel NCR used for supplemental heat sink of active cooling system is explored to be feasible.

Nomenclature

A	effective area of radiator (m^{-2})
c_p	specific heat capacity ($J\ kg^{-1}\ K^{-1}$)
h	convective heat transfer coefficient ($W\ m^{-2}\ K^{-1}$)
k	heat conductivity ($W\ m^{-1}\ K^{-1}$)
m	water mass flow rate (kg/s)
q_C	convective heat transfer with ambient air ($W\ m^{-2}$)
q_L	radiator heat loss capacity ($W\ m^{-2}$)
q_R	radiation heat loss to sky ($W\ m^{-2}$)
T_a	temperature of ambient air (K)
T_{fi}	inlet water temperature of radiator (K)
T_{fo}	outlet water temperature of radiator (K)

T_m	mean temperature of water in the radiator (K)
T_s	equivalent sky temperature (K)
T_w	wall temperature of radiator (K)
δ	thickness of radiator's skyward wall (m)
ε	emissivity of the radiator
σ	Stefan Boltzmann constant

2. Methods

According to Yair Etzion[17], the NCR with simple metal surface is inexpensive, and is easy for installation and maintenance, but it has comparative nocturnal cooling performance compared with other radiators with complex configurations. Therefore, a simple rigid radiator as shown in Fig.1 is selected in this study, which consists of double-walled galvanized steel panels welded at the edges and stamped by many regular spot depressions at intervals. The circulation water flows in the interstices between these two panels. The space between the two galvanized steel panels is 0.006m and each panel has a thickness of 0.001m. The galvanized steel panel is selected because it has a high emissivity in the "atmospheric window" and it is economical as well. Dimensions of galvanized steel panel are depended on the radiation cooling load and the available roof area of specific project.

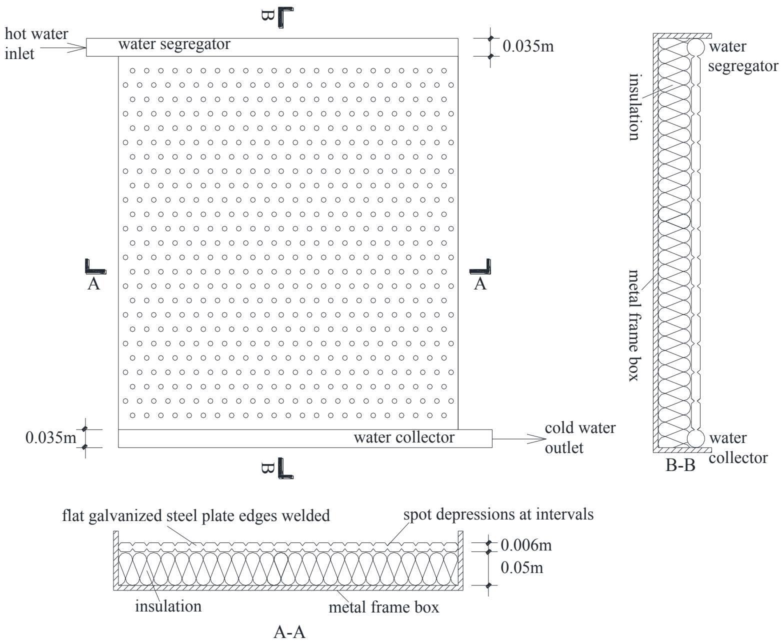

Fig.1. Axonometric plan of the NCR.

2.1. Model development of NCR

The analytical model of NCR is developed to simulate its outlet water temperature and effective cooling capacity according to the inlet water temperature, the mass flow rate and the Typical Meteorological Year (TMY) weather data. In order to incorporate the NCR model into the model of the comprehensive whole active cooling system and to simulate its operation performance for long periods, a compromise must be taken between the model precision and simulation efficiency. A relative concise analytical model is established based on the following assumptions:

(1) The operation of the NCR is assumed to be a steady state process.

(2) Heat loss from the back and edges of the NCR panel can be negligible.

(3) The water and heat flow inside the NCR is one-dimensional along its length direction.

(4) The front galvanized steel panel is gray body with constant emissivity of 0.9.

(5) The front galvanized steel panel is assumed to be an isothermal wall due to its large thermal diffusivity coefficient and limited size in its length dimension.

According to these assumptions, the heat transfer principle of the NCR is plotted in figure 2. The heat transfer between the NCR and ambient environment at night mainly includes radiation heat transfer and convection heat transfer. Its overall energy balance is shown in equation (1).

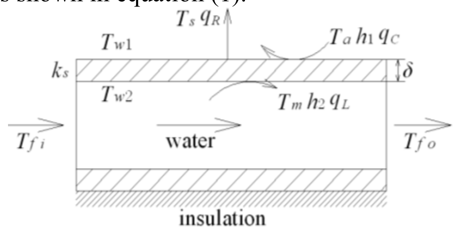

Fig. 2.Heat transfer process of the NCR.

$$q_L = q_R - q_C \quad (1)$$

2.2. Radiator heat loss capacity q_L

Heat conduction from the interior wall to exterior wall of the front panel can be found from:

$$q_{L1} = \frac{k_s}{\delta} \cdot (T_{w2} - T_{w1}) \qquad (2)$$

Heat convection from the fluid water to interior wall of the front panel can be written as:

$$q_{L2} = h_2 \cdot (T_m - T_{w2}) \qquad (3)$$

where T_m is the mean temperature of the fluid water, which can be calculated by equation (4).

$$T_m = \frac{1}{2} \cdot (T_{fi} + T_{fo}) \qquad (4)$$

Since $q_{L1} = q_{L2} = q_L$, according to equations (2) and (3), we have:

$$\frac{k_s}{\delta} \cdot (T_{w2} - T_{w1}) = h_2 \cdot (T_m - T_{w2}) \qquad (5)$$

T_{w2} can be deduced from equation (5), i.e. $T_{w2} = \dfrac{\frac{\delta}{k_s} \cdot h_2 \cdot T_m + T_{w1}}{1 + \frac{\delta}{k_s} \cdot h_2}$ (6)

Combining equation (6) and (3), q_L can be found as $q_L = h_2 \cdot \left(T_m - \frac{\frac{\delta}{k_s} \cdot h_2 \cdot T_m + T_{w1}}{1 + \frac{\delta}{k_s} \cdot h_2} \right)$ (7)

2.3. Radiation heat loss to the sky q_R

$$q_R = \varepsilon \cdot \sigma \cdot \left(T_{w1}^4 - T_s^4 \right) \quad (8)$$

An equivalent sky temperature T_s is defined as the temperature of a black body radiator which emitting the same amount of radiation power as the sky, which can be calculated according to the infrared radiation intensity from the sky R_{is} based on the Stefan Boltzmann Law:

$$T_s = \left(R_{is} / \sigma \right)^{0.25} \quad (9)$$

The infrared radiation intensity from the sky R_{is} can be found in the TMY2 weather data sources of the Energy Plus commercial software.

2.4. Convention heat loss with ambient air q_C

$$q_C = h_1 \cdot \left(T_a - T_{w1} \right) \quad (10)$$

2.5. Calculation of exterior wall temperature of front panel T_{w1}

Based on the energy balance equation (1), the following equation can be deduced:

$$h_2 \cdot \left(T_m - \frac{\frac{\delta}{k_s} \cdot h_2 \cdot T_m + T_{w1}}{1 + \frac{\delta}{k_s} \cdot h_2} \right) = \varepsilon \cdot \sigma \cdot \left(T_{w1}^4 - T_s^4 \right) - h_1 \cdot \left(T_a - T_{w1} \right) \quad (11)$$

i.e.

$$\varepsilon \cdot \sigma \cdot T_{w1}^4 + \left(h_1 + \frac{h_2}{1 + \frac{\delta}{k_s} \cdot h_2} \right) \cdot T_{w1} = \varepsilon \cdot \sigma \cdot T_s^4 + h_1 \cdot T_a + \left(h_2 - \frac{\frac{\delta}{k_s} \cdot h_2^2}{1 + \frac{\delta}{k_s} \cdot h_2} \right) \cdot T_m \quad (12)$$

Equation (12) is equivalent to:

$$A \cdot T_{w1}^4 + B \cdot T_{w1} = C \quad (13)$$

where: $A = \varepsilon \cdot \sigma$, $B = h_1 + \dfrac{h_2}{1 + \dfrac{\delta}{k_s} \cdot h_2}$, $C = \varepsilon \cdot \sigma \cdot T_s^4 + h_1 \cdot T_a + \left(h_2 - \dfrac{\dfrac{\delta}{k_s} \cdot h_2^2}{1 + \dfrac{\delta}{k_s} \cdot h_2} \right) \cdot T_m$

Using the undetermined coefficients to solve this equation, the solution of the exterior wall temperature of the front panel can be obtained:

$$T_{w1} = \frac{-k + \sqrt{k^2 - 4l}}{2}, \text{where } k = \left[\frac{4r}{3} \left(\frac{q^2 + \sqrt{q^4 - \frac{256}{27} r^3}}{2} \right)^{-\frac{1}{3}} + \left(\frac{q^2 + \sqrt{q^4 - \frac{256}{27} r^3}}{2} \right)^{\frac{1}{3}} \right]^{\frac{1}{2}} \quad (14)$$

$$l = \left(k^3 - q\right) / 2k, \; q = B/A, \; r = -C/A$$

2.6. The NCR outlet water temperature T_{fo} and cooling capacity

T_{w1} is calculated by the assumptive value of the outlet water temperature T_{fo}. After $T_{w1}$is obtained, the interior wall temperature T_{w2}can be calculated according to equation (6). On the other hand, since the front galvanized steel panel is assumed to be an isothermal wall, the Newton's law of cooling is utilized to calculate the outlet water temperature T_{fo}. The heat loss from the circulating water inside the NCR can thus be calculated by equation (15):

$$Q = A \cdot h_2 \cdot \Delta T_m, \qquad \text{where } \Delta T_m = \left(T_{fi} - T_{fo}\right) / \ln\left(\frac{T_{fi} - T_{w2}}{T_{fo} - T_{w2}}\right) \quad (15)$$

According to the overall heat balance, the above equation can be re-written as:

$$Q = A \cdot h_2 \cdot \left(T_{fi} - T_{fo}\right) / \ln\left(\frac{T_{fi} - T_{w2}}{T_{fo} - T_{w2}}\right) = m \cdot c_p \cdot \left(T_{fi} - T_{fo}\right) \quad (16)$$

Therefore, the outlet water temperature T_{fo} of NCR can be found:

$$T_{fo} = T_{w2} + \left(T_{fi} - T_{w2}\right) / \exp\left(\frac{A \cdot h_2}{m \cdot c_p}\right) \quad (17)$$

By comparing the calculated and assumptive values of T_{fo}, an iterative method is utilized to calculate the accurate outlet water temperature T_{fo} of the NCR. The cooling capacity of the NCR can then be calculated with equation (18). The whole NCR calculation program based on this proposed model is compiled with FORTRAN language.

$$Q = m \cdot c_p \cdot \left(T_{fi} - T_{fo}\right) \quad (18)$$

3. Simulation Results

3.1. Experimental verification of the established NCR calculation model

The cooling radiator tested by Yair Etzion et al. (1999) are found to be very similar with the NCR investigated, therefore, their test results are used to verify the NCR calculation model developed in this study. The radiator investigated by Yair Etzion et al.'s test was constructed of double glazed polycarbonate sheets. This test was conducted in the Center for Desert Architecture and Urban Planning at Sede-Boqer of Israel. The test results are compared with the analytical results from the simulation model developed in this paper in Fig. 3.

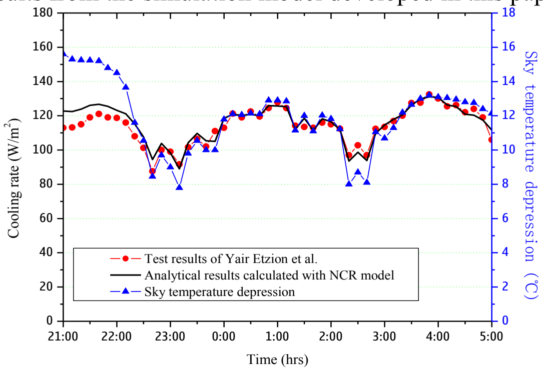

Fig.3. Comparison between the simulation results and YairEtzion et al.'s test results.

It is shown that the calculation results based on the NCR model agree well with the test data except the results recorded in the first hour which might be caused by the remaining heat stored in the NCR absorbed from solar radiation during daytime. By experimental verification, the established NCR model is found to be accurate enough to simulate the operation performance of the NCR for engineering applications.

3.2. Simulation of the NCR operation performance

Hong Kong (22.23^{o}N, 114.06^{o}E) belongs to humid subtropical climate, and has a high annual average air temperature both in dry bulb and wet bulb. In order to investigate the feasibility of this novel NCR works as supplemental heat rejecter, a case study is analyzed for a NCR located in Hong Kong, where the worst meteorological condition is provided for the novel NCR. The outlet water temperature, exterior wall temperature and cooling capacity of the NCR for different mass flow rates, constant inlet water temperature of 35℃ and the annual average TMY weather conditions of Hong Kong are plotted in Fig. 4.

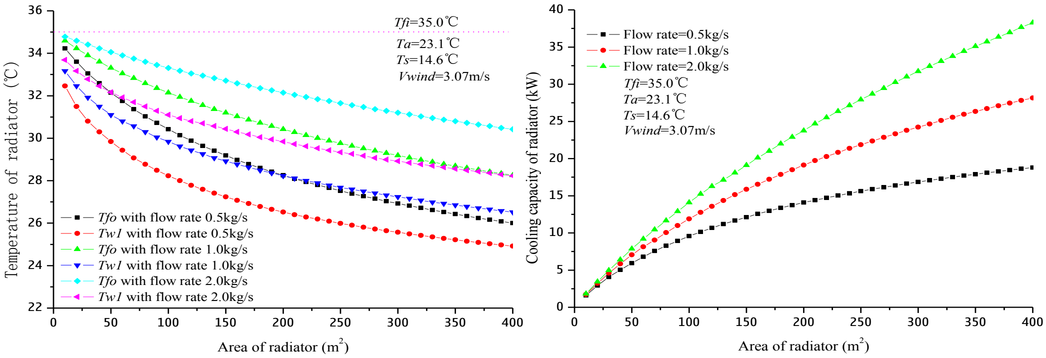

Fig. 4.Simulated operation performance of NCR.

4. Discussion

As shown in Fig. 4, sizable cooling capacity can be provided by the novel NCR even operated in humid subtropical climate. It is feasible to use novel NCR as supplemental heat sink of active cooling system. Based on simulation results plotted in figure 4, the outlet water temperature and exterior wall temperature of the NRC decrease, but its cooling capacity increases accordingly with increasing surface area. However, these variation tendencies turn to plain with continuous increase of the size, which demonstrate that optimal sizing of the NRC exists when the energy and economical performances are analyzed together. The optimal size of novel NRC should be selected according to the operation simulation of the specific active cooling system utilizing the novel NRC as supplemental heat rejecter.

5. Conclusions

In order to utilize the nocturnal sky as an excellent supplemental heat sink of the heat pump system and to reduce system energy consumption, a novel NCR used for supplemental heat rejecter is proposed. Based on simulation, it is feasible to use novel nocturnal cooling radiator as supplemental heat sink of active cooling system. The proper designed active cooling system with novel nocturnal cooling radiator possesses high operation energy efficiency.

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