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COMPARISON BETWEEN NOCTURNAL COOLING OF WATER IN A CLOSED LOOP FORCED CIRCULATION AND OPEN LOOP SYSTEMS

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Abstract

Experimental measurements have been done in order to clarify the perfomance of both the closed loop (forced circulation) and the open loop (gravity flow) night sky radiation cooling systems used for cooling flowing water through a radiator unit in both systems. The net cooling power obtained from the closed loop system was 82 W (55 W m^{-2}) and 65 W (43.3 W m^{-2}) for water flow rates of 0.00822 and 0.02075 kgs^{-1}(19.68 and 49.66 kg h^{-1} m^{-2}) respectively, Whereas electric power input to the circulation pump motor in both cases was about 70 W In the open loop system, the average cooling power was about (45 W m^{-2}) for average water mass flow rate of about 0.008548kg s^{-1}(20.7 kg h^{-1} m^{-2}). For the closed loop system, it the found that both the outlet water temperature from the radiator unit and the average was temperature in the sky tank at the end of the night were a little higher than was ambielnt air temperature. However it was less than that of the ambient air temperature in the open loop system. This led to the conclusion that the forced circulation system is less efficient in energy perfomance as compared to the open loop system(gravity system) regardless of the mass flow rate of water in the systems.

Key Words : Nocturnal Cooling, Experiment, Sky, Radiation Cooling. Water Cooling

1. INTRODUCTION

Cooling by nocturnal radiation is one method of passive utilization of nature. The temperature of the upper atmosphere is close to absolute zero, approximately 4 K[1] and thus it can be utilized as a heat sink for heat loss by radiation from any surface on the ground in the absence of solar radiation. Nocturnal radiation cooling of a surface exposed to the sky can be used to lower the temperature of fluid flowing underneath a radiator plate to a temperature lower than that of the surroundings. Since the nocturnal cooling system is effective during night time, a storage system is essential to keep the cold fluid for utilization during the following daytime when cooling is appreciated. Cold fluid produced by nocturnal cooling systems in air comfort applications could be working simultaneously with other convective and/or evaporative cooling system(s). Extensive work has been done to utilize nocturnal cooling either directly[2] or indirectly to cool stagnant water[3] or to cool flowing air[3]-[5] or flowing water[6]-[10]. Most of the previous studies have been done to cool flowing water by nocturnal radiation cooling in a forced flow circulation system using a pump such as [6]-[9]. Also, some studies have been carried out using a natural circulation system as[9] or using an open loop system as[10]

In this study experimental work for nocturnal radiation cooling of flowing water by using both closed loop (forced flow circulation) and open loop systems (gravity flow) has been done to compare and to clarify the performance of both systems in nocturnal radiation cooling of flowing water. For the closed loop system, a night sky radiator unit and a water storage tank were constructed. A pump was used to draw water from the storage tank and move it through the radiator unit to investigate the effects of forced circulation of water on the performance of both the radiator unit and the whole system. The results thus obtained will be compared with the results of the open loop system in which water flows between two tanks through a radiator unit using the effect of gravity. One of the tanks was located at a higher level than the radiator unit and used to keep the warm water, while the other tank was used to store

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the cooled water flowing out of the radiator unit and located at a lower level than the outlet of the radiator unit, as presented in[10]. In this study the performance of both systems was studied by comparing the outlet water temperature from the radiator unit and the final average water temperature in the cold storage tank at the end of the night with the ambient air temperature. Also, the cooling power in both systems was defined as the net rate of heat lost from the flowing water and emitted by the unit area of the radiator plate in (Wm^{-2}).

2. MATERIAL AND METHODS

Figures 1 and 2 show a schematic drawing of the closed loop (forced flow circulation system) and the open loop systems (gravity flow system) respectively.

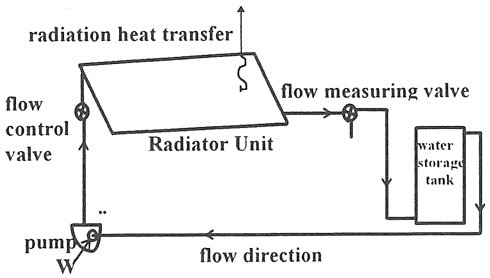

Fig. 1 Schematic drawing of the closed loop nocturnal radiation cooling of water by forced circulation system.

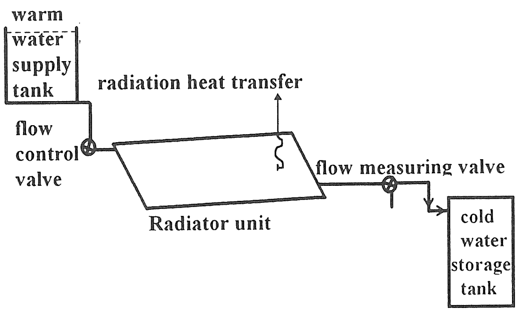

Fig. 2 Schematic drawing of the open loop nocturnal radiation cooling of water by gravity flow system.

As seen in the figures, both of the systems have the following common elements; (a) a nocturnal sky radiator unit, (b) a flow rate measuring valve (three way {3/4 inch} 19.05 mm in mean diameter), and (c) a flow rate control valve ({3/4 inch} 19.05 mm in mean diameter). For the closed loop system shown in Fig. 1, a pump was added to move water through the system. Two water tanks were used for the open loop system shown in Fig. 2. The upper tank was not insulated, had a movable wooden cover, and was used to keep warm water. The lower tank was insulated and was used to store the cold water flowing out from the radiator unit. All these elements were connected as indicated in Figs. 1 and 2 by reinforced rubber hose of (1 inch) 25.4 mm in mean diameter and insulated by 3 mm thick foam insulation tape ($k=0.4324\ W\ m^{-1}\ K^{-1}$) colored black. The radiator unit consisted of a radiator plate, a windscreen cover, thermal insulation, and steel housing. Dimensions of the radiator plate are as follows; 2.6 m in length, 0.74 m in width, 2 mm in thickness, net radiating area 1.504 m^2. The radiator plate was made of aluminum painted with commercial black paint. The spectral reflectance of the coated plate was presented in [10]. A colorless transparent polyethylene film with thickness of 50 μm was used as a windscreen cover. Its monochromatic transmittance was presented in [10]. Other detailed information of the radiator unit is available in [10]. The water storage tank had a capacity of 255 ℓ and was made from galvanized steel of 1 mm thickness with inner dimensions of 570 mm in diameter and 1m in height and outer dimensions of 780 mm in diameter and 1.2 m in height. The 50 mm annuls between the inner tank and outer shell were filled with polystyrene boards. In the case of the closed loop system, to obtain stratification in the water storage tank, it was so designed that the inlet pipe was located near the bottom of the tank and the outlet pipe was fixed near the top. The pump was used to circulate water from the tank to the radiator unit through the outlet as shown in Fig. 1. The pump was driven by a 100 W maximum capacity electric motor, the input power of which was measured by a watt-meter. Both closed loop and open loop systems were painted white to minimize heat storage by thermal capacity of the systems' components from solar radiation during the day time. For the closed loop system, the water flow rate was measured at the beginning of the experiment. The time required to collect 3 liters of water was measured. Hourly values of flow rate for the open loop system were taken as the average of three measurements per hour by measuring the time required for collecting 0.5 ℓ of water. All temperatures were measured by shielded iron-constantan thermocouples. The reading of each thermocouple sensors were calibrated before fixation in the experiment set-up, using four reference points. These were boiling point and a mixture of (ice + water) pure water, boiling points of diethyle-ether2, and acetone at atmospheric pressure. The difference in the sensors readings with those four standard points ranged from +0.3 to +0.8 K respectively. Thermocouples were used to measure the water temperatures of inlet and outlet from the radiator unit, six locations in the (cold) water storage tank, at a height of 150, 280, 410, 540, 670, and 800 mm from the bottom of the tank respectively, and ambient air dry and wet bulb temperatures. In the case of the open loop system, temperature measurements in the cold water storage tank were recorded only once at the end of the night. The temperatures were recorded by a multi -point digital recorder type Speedomax 2500 TC/EMf (manufactured by Leeds and Northrup Co., U.S.A). The wind speed was measured using a portable digital anemometer Model 1717 (Power Instrument Inc., U.S.A). The radiator unit was tilted in both systems 3° to the horizontal against the gravity to ensure good contact of water with the radiator plate. The experimental measurements were carried out at Assiut University, Egypt, latitude 27° 8¥ N and longitude 31° 12¥ E, during the summer season of 1990. The sky condition during the experimental measurements was clear from clouds except for suspended dust in the air. This is characteristic of upper Egypt all year.

3. RESULTS AND DISCUSSION

3.1 Closed loop system

The experiments to clarify the performance of the closed loop (forced circulation) system as shown in Fig. 1 were conducted for two different mass flow rates of water i.e., 0.00822 and 0.02075 kg s^{-1} (29.6 and 74.7 kg h^{-1}) corresponding to a mass flux - 19.68 and 49.66 kg h^{-1} m^{-2} of radiator plate respectively. Figure 3 shows the performance of the radiator unit with the measured meteorological data in the case of mass flow rate of 0.00822 kg s^{-1} (29.6 kg h^{-1}) while Fig. 4 shows the temperature distribution along the vertical axis of the water storage tank during the same night. Stratification in the tank was enhanced by locating the inlet pipe to the tank near its bottom and locating the outlet pipe near its top. As shown in Fig. 4 stratification can be observed in the tank. Also, the water was delivered from the tank at almost the same height as the top thermocouple. The water was passed through a 7 m long rubber hose to the pump and then, pumped into the radiator unit. The measured temperature at the inlet and outlet from the radiator unit as well as the cooling power and the meteorological data are shown in Fig. 3. As seen from Figs. 3 and 4, at the beginning of the night (experiments) the ambient air temperature is higher than the water temperature in the system.

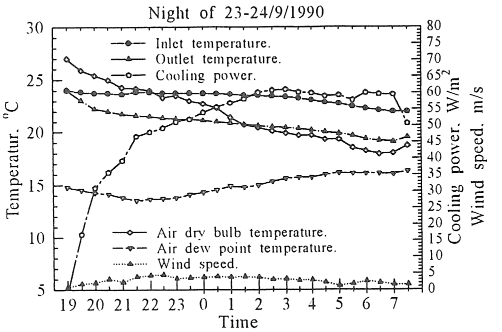

Fig. 3 Performance of the radiator unit in closed loop system for water mass flow of (19.68 kg/h m^2) and the measured meteorological data.

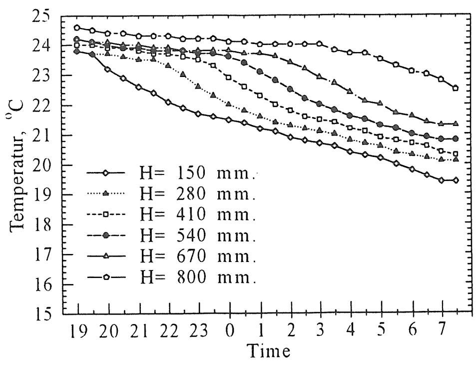

Fig. 4 Temperature distribution inside the water storage tank in closed loop system for water mass flow rate (19.68 kg/h m^2).

As time elapsed the rate of decrease in the ambient air was high while the cooling rate of the water was very low. This is due to a part nocturnal radiation cooling used to cool the structure of the radiator unit that has heat in the form of thermal capacitance from the day time. At about 21:00 hrs. the ambient air dry bulb temperature was lower than the inlet water temperature of the radiator unit. Also, at that time stratification in the tank was taking place, and the inlet water of the radiator unit was pumped from the upper layer in the storage tank. As can be expected from nocturnal cooling systems warmer radiator plate temperature leads to an increase in cooling power. Also, the rate of cooling power (radiation losses to the sky) is limited by the meteorological conditions as well as the radiative properties of the radiator element. The rate of cooling of water was found to be much more than the rate of decrease in the ambient air. This was clear at 2:00 a.m. when the ambient air temperature becomes less than the whole water in the system. So, for this system the only way for heat loss is through radiation from the radiator unit and a very small amount is lost through the rubber hose. As seen from Fig. 3, the average value of the cooling power during the night was about 55 W/ m^2 (82 W) while the electric power consumed by the pump was about 70 W. A part of the power required to drive the pump must be added to the water before it enters the radiator unit as thermal energy. An investigation of the temperature of the water at the inlet to the radiator unit showed that it was lower than at the top of the tank by about 0.3 to 0.8 K during the night. This is contrary to what would be expected with the existence of the pump due to higher water temperature in the hose than the ambient air temperature. The only reasonable explanation for this is that there was larger heat dissipation from the water in the reinforced rubber hose than that gained from the pump. One sink for this heat dissipation is the net loss to the sky by radiation and the other to the ambient air by convection. This can also be noticed from Figs. 3 and 4. These figures show that the temperatures of water at the top of the tank were higher than that of the ambient air. So, when the water flowing out from the tank to the radiator has a low mass flow rate and a temperature higher than that of the ambient air, heat can flow out from the parts between the outlet pipe of the tank and the inlet of the radiator unit. To find out the order of the magnitude of those values some simplified calculations were made to check the energy balance from the available measurements as presented in[11].The calculation of the heat losses from the closed loop system shows that other sources of heat gains and losses also exist in the closed loop system beside the radiator unit. These factors should be taken into consideration seriously when designing such systems. In Fig. 4, it can be noticed that the average temperature in the tank at the end of the night was about 20.8 °C and the minimum temperature inside the tank was 19.4 °C whereas the average temperature of the ambient air during the night was about 22.5 °C.

The results for the relatively high water mass flow rate of 0.02075 kg s^{-1} (74.7 kg h^{-1}) -49.66 kg h^{-1} m^{-2}- are shown in Figs. 5 and 6. Fig. 5 shows the performance of the radiator unit with the measured meteorological data, while Fig. 6 shows the axial temperature distribution in the water storage tank during the same night and which temperatures between the top and bottom thermocouples are less than 1K.

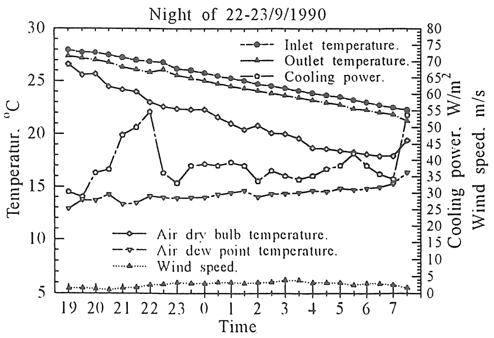

Fig. 5 Performance of the radiator unit in closed loop system for water mass flow of (49.66 kg/h m^2) and the measured meteorological data.

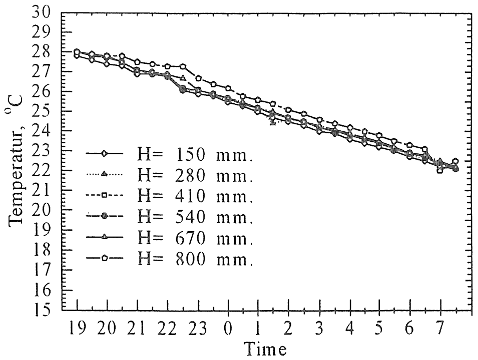

Fig. 6 Temperature distribution inside the water storage tank in closed loop system for water mass flow rate 49.66 kg/h m^2.

As expected, a high mass flow rate leads to a decline in the radiator unit performance. Also, it is clear from Fig. 5 that the outlet water temperature from the radiator unit was always higher than the ambient air temperature. The electric power supplied to the pump in this case was approximately 70 W and the average cooling power during the night was about 65 W (43 W m^{-2}). The same discussion as in the case of a low flow rate will be applicable here in addition to the effect of thermal energy added to the water flowing from the pump. Details of a simple method examining for the energy balance for this case appeared in[11]. The average temperature in the tank at the end of the night which can be calculated from Fig. 6 was about 22.2 °C and the minimum temperature inside the tank was 22.0 °C.

3.2 Open loop system

The results of the experiments for the open loop system (Fig. 2) are shown in Fig. 7, including the inlet and outlet water temperature the mass flow rate, cooling power, and the meteorological data.

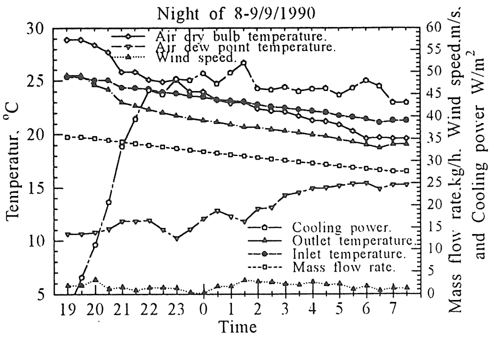

Fig. 7 Performance of the radiator unit in open loop system for average water mass flow of (20.7 kg/h m^2) and the measured meteorological data.

As shown in Fig. 7, at the beginning of the night (experiment) the temperature of the water in the warm water supply tank was equal to the inlet temperature to the radiator unit which was about 25.3 °C, while the ambient air temperature was about 29.0 °C. As time passed the water in the warm water supply tank was cooled by combined convective and radiation cooling effects during the whole night. At the end of the night the water temperature in the tank was about 21.2 °C. The temperature of the water inlet to the radiator unit was less or slightly higher than that of the ambient air throughout the night. This leads to the conclusion that the outlet water temperature from the radiator unit will be less than that of the ambient air, as seen in Fig. 7. One of the main purposes of using the nocturnal cooling system is to cool water for air comfort applications because this system was designed as a part of a unit which can use this cold water in air comfort applications during the day time. The warm water will be required to be pumped once at the beginning of the night to the upper warm water supply tank. Thus, the amount of power in this case will be less than that needed to circulate the water through the closed loop system during the whole night. As seen from Fig. 7 the average water mass flow rate throughout the night was about 0.008648 kg s^{-1} (20.7 kg h^{-1} m^{-2}) and the average cooling power during the night was 45 W m^{-2}. At the end of the night the average water temperature in the cold storage tank was about 20.6 °C while the coldest temperature inside the tank was 19.0 °C and the average ambient air temperature about 25.5 °C.

As seen in Figs. 3 and 7, the water mass flow rate is almost the same and changes in meteorological conditions are not so great. Although the average cooling power along the night for the closed loop system (Fig. 3) is even higher as compared to that of the open loop system (Fig. 7), the outlet water temperatures are still higher than the ambient air temperature from 1:00 a.m. to the end of the night. This situation is not always desirable for nocturnal cooling. In the open loop system (Fig. 7) the outlet temperature of water from the radiator unit is always lower than the ambient air temperature. The difference in the performance between the two systems can be attributed to the following. The only way for heat losses to occur in from the closed loop system is by radiation to the sky from the radiator unit, while the open loop system has heat losses by radiation to the sky from the radiator unit plus convective cooling and radiation to the sky from the warm water supply tank, before it enters the radiator unit. In the normal case of actual utilization of cooling produced by night sky radiation, the outlet water temperature is less than the ambient air dry bulb temperature, ranging from 3 to 5 K without the addition of any pump power. Therefore, using a closed loop system for cooling of water by nocturnal cooling for such climatic conditions does not have any advantage for air-comfort applications. This disadvantage is due to the fact that the outlet water temperature from this system becomes higher than that of the ambient air and is also due to the this consumption of clean energy to produce a small amount of thermal energy. Electrical power of 70 W was used to produce 82 W of thermal power and this is a waste use of clean energy.

4. CONCLUSIONS

The results obtained by comparing the performance of the closed and the open loop systems, can be summarized as follows,

- The total temperature drop through the closed loop system is smaller than that of the open loop unit. Also, the outlet water temperature from the radiator unit and the average water temperature in the water storage tank are equal to/or higher than the ambient air temperature in the case of the closed loop system, while in the open loop system it is always less than the ambient air temperature.
- The closed loop system consumes 70 W clean energy to produce 82 W or less of thermal energy, and this is a waste use of clean energy.
- The open loop system of night sky radiation is better in energy performance than the forced circulation system since no power is required to drive a circulation pump and in general there is no temperature rise as a pump is not used.

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