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Radiative water-cooling in maritime and moderate continental climatic conditions

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Abstract

In this paper, the analysis of a flat-plate radiative panels operation, using average hourly weather data, was conducted. Radiative panels, with high-emittance surface cover, were integrated in the space-ventilation system with air-cooling by means of a cold-water coil. The panels should prepare a sufficient quantity of cold water that is collected in a cold-water tank during the nighttime operation. The collected cold water is used for cooling of the air during daytime.

A simulation model for the parametric analysis of the system in summer operating conditions and the influence of its components on the system's operation was developed. The model includes the control of the system's operation, which prevents water circulation in the periods without cooling contributions.

The purpose of the research was to predict the system behaviour in the Irish and the continental Croatian climatic conditions, to enable sizing and design of the test rig that is to be built for experimental validation of the system. The results of simulation were obtained for the small cooling system with a total panel aperture area of 6 m^2 and a volume of tanks of 300 l.

The results were presented in the charts, where the influence of the main parameters on the system's operation was illustrated. The results showed that the radiative cooling system is more efficient in maritime than in moderate continental climatic conditions during summer.

Introduction

Passive, hybrid and low energy cooling, heating and ventilation techniques are being researched and implemented in a number of countries throughout the world. There are also ongoing collaborative efforts in this area, including the European Union Fifth Framework / Energy sub-programme "Evapcool" and the International Energy Agency Solar Heating and Cooling programme. There is currently a research project underway in the area of low energy cooling, heating and ventilation of buildings in Irish (maritime) climatic conditions.

Solar heating and radiative cooling systems have been studied in particular for the last 30 years. An extensive research of a radiative cooling system, consisting of unglazed flat plate radiators, water as a heat carrier, and storage tank was presented by Meir et al. [1-2]. The radiators were twin-wall sheets made of a modified PPO (polyphenylenoxid). The impact of a tilt angle, the aperture area and the reservoir volume on the system performance was simulated. The system performance has been investigated with a radiator aperture 5.3 m^2 and tank volume of 280 l in experiments for Norwegian (Oslo) climate. Argiriou et al. [3] have analyzed the combined effects of climate and radiator characteristics on cooling potential. Twelve years weather data set was used to assess radiative cooling potential in Athens. The dynamic performance of a radiative cooling system for buildings, using a metallic panels with covered by a polyethylene windscreen, for a location in northern Italy, has been analyzed by Mihalakakou et al. in [4]. Saenkhomvong [5] has developed the water heating system using flat-plate solar collectors. This author also developed a radiative cooling system. To use the same device, additional equipment for cooling water was designed and installed. This newly developed device, fixed to the flat-plate solar collector, was used to cool-off flat-plate surfaces in the night by self-radiation. The performance of a

Nomenclature

A_C	collector area	m^2
A_{TOT}	total panels area	m^2
c_p	specific heat capacity	J/(kgK)
F_R	collector heat removal factor	-
h_c	convection heat transfer coefficient	$W/(m^2K)$
I	global solar irradiation	W/m^2
m	mass of water in storage tank	kg
Q_C	heating capacity	W
Q_L	heating/cooling load	W
Q_{l-g}	heat loss/gain	W
Q_R	cooling capacity	W
U_L	overall heat loss coefficient	$W/(m^2K)$
t	time	s, h
T_a	ambient temperature	K
T_{dp}	dew point temperature	K
T_r	radiation panel temperature	K
T_s	water temperature in storage tank	K
T_{sky}	sky temperature	K
V	volume of water in storage tank	m^3
w	wind velocity	m/s
α	absorbtance	-
γ	panel tilt angle	°
ε_r	panel emissivity	-
ε_{sky}	sky emissivity	-
ϑ_{in}	temperature of water entering collector	°C
ϑ_a	ambient temperature	°C
τ	transmittance	-
σ	Stefan-Boltzmann constant	$5.67\ 10^{-8}\ W/(m^2K^4)$

thermosyphon water cooler with a parallel, flat-plate radiator has been studied theoretically and experimentally by Yeh and Tseng in [6]. Some theoretical predictions of water temperatures in the storage tank and of the cooling intensity have been obtained from energy and momentum balances. The results were used in assessing the combination of solar heating and radiative cooling with a single device. A radiator system using an infrared transparent windscreen that doubles as the structural envelope was proposed and supporting experimental results were presented in [7]. Analysis of flat-plate solar collectors, converted into cooling radiators, was performed by Erell and Etzion in [8, 9]. Primary factors determining the heat output were the global solar irradiation, wind velocity and temperature difference between the water and the air. An expression was derived linking these parameters to predict the system's performance with accuracy. Theoretical and experimental analysis of a radiative cooling system for Jordan climate was presented in [10, 11]. The results for the proposed models showed an acceptable qualitative agreement between simulations and measurements.

The purpose of the research, presented in this paper, was to develop and design the sustainable energy system that uses solar energy (solar panels) for the supply air-conditioning during the whole year for maritime climate. It was also necessary to compare the system operation in different climatic conditions in order to get more information about the system performance.

The panels are integrated in the space-ventilation system with air-cooling by means of a water coil. Their primary function is to prepare sufficient quantity of cold water, integrating radiative and convective cooling, that is collected in the cold-water tank during nighttime operation. That cold water is used for cooling of the air during daytime. The research objectives include analysis of solar system performance in cooling operating mode. The impact of the panel surface area, tank volume and panel surface emissivity on the cooling performance was studied in simulations. Hence, thermal analysis of water-cooling, including weather data analysis (temperatures, wind velocities, solar irradiation), together with design of the experimental rig were performed.

By small modification, solar panels could be turned into collectors and used to produce the hot water during daytime.

The aim of the research was to predict the system behaviour, to enable sizing and design of the test rig that is to be built for experimental investigation.

Mathematical model

The solar irradiation data presented in [12, 13] were used to estimate how much energy is likely to be available for the water heating at the observed location.

In the heating operating mode, the collector plates absorb as much of the irradiation as possible through the glazing, while losing as little heat as possible upward to the atmosphere and downward through the back of the casing. Collected heat is then transferred to the water. The performance of collectors was analyzed by Whillier's procedure [14-16]. The basic equation is:

$$\dot{Q}_C = A_C F_R [(\tau\alpha) I - U_L (\vartheta_{in} - \vartheta_a)] \tag{1}$$

where the collector heat removal factor F_R is the ratio of the heat actually delivered to that delivered if the collector plates were at uniform temperature equal to that of the entering water. F_R is affected by the collector characteristics, the fluid type and the flow rate thorough the collector, having a value less than 1.0.

The data of global solar irradiation on a horizontal surface, presented in [13], had to be converted into values for a tilted surface I. Determination of solar angles that describe the direction of incidence of the solar beams on a tilted surface was performed with the model that was developed and tested earlier [17].

Heat exchange between the panel and the surroundings, in the cooling operating mode during the night, is described with the following expression:

$$\dot{Q}_R = A_C [\varepsilon_r \sigma (T_r^4 - T_{sky}^4) + h_c (T_r - T_a)] \tag{2}$$

where the first term refers to radiation from the panel towards the atmosphere and the second term refers to convection between the panel and the ambient air. Because the radiation effect is the most obvious at night, it is often termed nocturnal radiation.

The most useful parameter for characterising the radiative heat transfer is the sky temperature, defined as the temperature of a black body radiator emitting the same amount of radiative flux as the sky. It is defined as:

$$T_{sky}^4 = \varepsilon_{sky} T_a^4 \tag{3}$$

Many correlations are reported in the literature for calculating the sky emissivity ε_{sky}. In this paper, the following relation [16] is used:

$$\varepsilon_{sky} = 0.8 + \frac{T_{dp} - 273.15}{250} \tag{4}$$

with the dew point temperature T_{dp} calculated from the psychrometric chart for moist air by the analytical procedure presented in [1-3].

Convective heat transfer depends on the ambient air temperature and wind velocity, which is expressed through the convection heat transfer coefficient h_c. In engineering practice, h_c is often represented by the simplified expression, as the first order linear function of the wind velocity [15]:

$$h_c = 2.8 + 3.0w \tag{5}$$

Sizing of water storage tanks is performed by using a simulation model developed for this purpose, that includes the heat balance between the charging energy Q_C (or Q_R) from the heat source/sink on one side and the heat removal by the load Q_L and the heat losses/gains (radiation + convection) $Q_{l\text{-}g}$ to/from the environment on the other side (Fig. 1):

$$(mc_p)_S \frac{dT_S}{dt} = \dot{Q}_C - \dot{Q}_L - \dot{Q}_{l-g} \tag{6}$$

where $(mc_p)_s$ is the heat capacity of the water in storage and dT_s is the change of water temperature in time t. Q_C (Q_R) is determined from Eqs. (1) or (2) when charging the water tank.

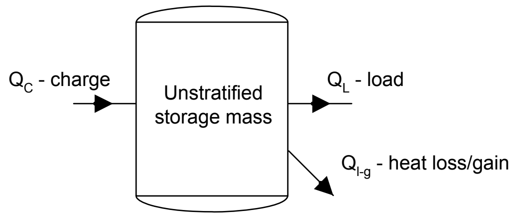

Fig.1 Schematic of the storage energy balance

After integration of Eq. (6) for a selected time interval, the change of storage temperature is calculated as a function of time. In Eq. (6) it is obvious that the storage mass and the water temperature in storage are indivisibly connected. Therefore, the storage mass (or volume) can be adjusted to the desired water temperature at the end of the heating/cooling process.

Solar thermal system (Fig. 2) is designed in order to supply the required amounts of energy for the heat exchanger, which is used for cooling of the supply air. The system is designed to satisfy completely cooling energy requirements.

Radiative panels are used for cooling of water by means of radiation towards sky (and convection to the outside air) during nighttime. Since the requirements on collectors and radiators operation are opposite to each other, it would be difficult to achieve good performance in both heat collection and heat dissipation with only one panel type (except, perhaps, in a warm climate – [18]). Therefore, the best approach would be to use one panel type for solar heat collection (i.e. standard flat-plate collectors) and to use different type for a nighttime water-cooling (could be done by using modified swimming pool absorbers [1, 2]). If the required total panels area is large, then the solution with two panel types becomes expensive. In this case, both operation modes could be covered with one panel type, but the adjustments of standard panel designs are required. The easiest way to adjust a flat-plate collector for cooling operation is to substitute it's glazing with a high-radiative cover (i.e. PE/PPO) [10].

Results and discussion

Results presented in the following charts are based on average Irish and continental Croatian weather data for summer – solar irradiation, temperatures and wind velocities.

In Fig. 3, simulation of the change of water temperature in the cold storage tank during nighttime is presented.

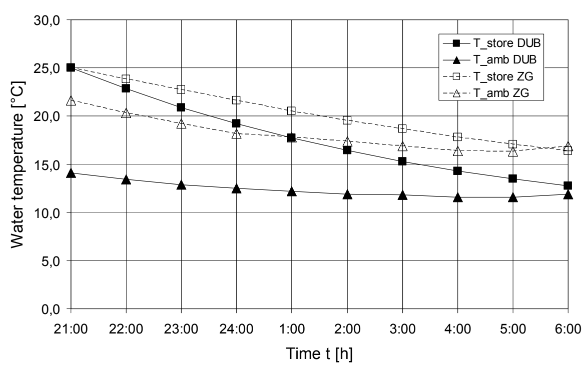

Fig.3 Water-cooling in the tank during the night

Continuous line presents the results for the Dublin climate (DUB). It can be seen that the end temperature in the tank can reach about 12°C in clear sky conditions in average outside temperature and wind conditions. Dashed line presents the results for the Zagreb climate (ZG). The end temperature in the tank can only reach about 16°C. The different outside weather conditions influence performance of the panels and change the temperature curve of water-cooling. Increase of the end temperature in continental climate conditions for about 4°C implicates that the radiative system would be more efficient in maritime climate. The reason is in significantly different wind velocities and the sky temperatures during the night that are about 5.5°C higher in Zagreb compared to Dublin, in the average. The selection of initial water temperature 25°C is based on predicted summer room conditions. Placing the tank outside would cause heating of the water by the sun during the day. If the initial temperature were, for example, 30°C, the end water temperature would be about 1°C higher.

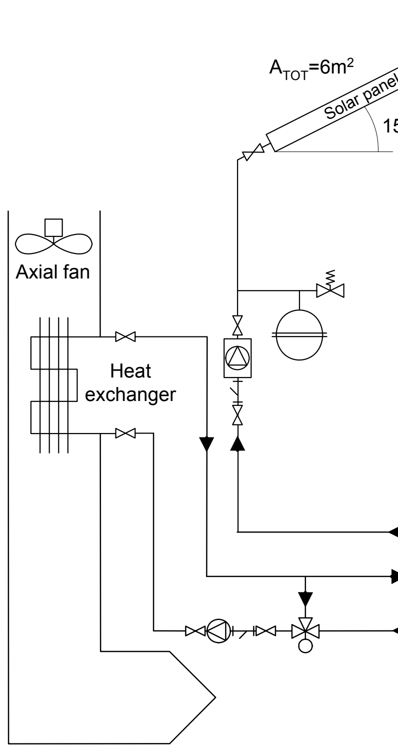

Fig.2 Radiative water-cooling system schematic

The temperature change in the tank, presented in Fig. 3, is calculated for the following design parameters:

- aperture area of the panels A_{TOT}=6m^2
- volume of the tank V_S=300l
- tilt angle γ=15°
- panel emissivity ε_r=0.85

Presented parameters were also used for the experimental rig design (Fig. 2).

In Fig. 4, the change of water temperature in the tank for different emissivities of the panel surface is presented. This chart shows that the emissivity of panel surface ε_r has large impact on the cooling effect. In case when standard selective absorber plate is used (ε_r = 0.10), the end temperature in the tank rises significantly. This implies that standard absorbers used in solar collectors could not provide good cooling performance without the increase of their surface emissivity. The results for continental climate (dashed line) again show increased values of the water temperatures, compared to the maritime climate (continuous line).

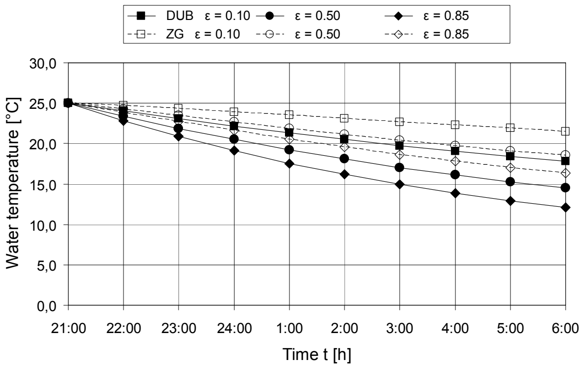

Fig.4 Water-cooling as function of panel emissivity

In Fig. 5, dependence of the change of water temperature in the tank for different sizes of panel surface area is presented. If the initial panel area is 6m^2, then decreasing of total panel area for 2m^2 causes about 2.8°C and 2.1°C higher water temperature in Dublin and Zagreb, respectively.

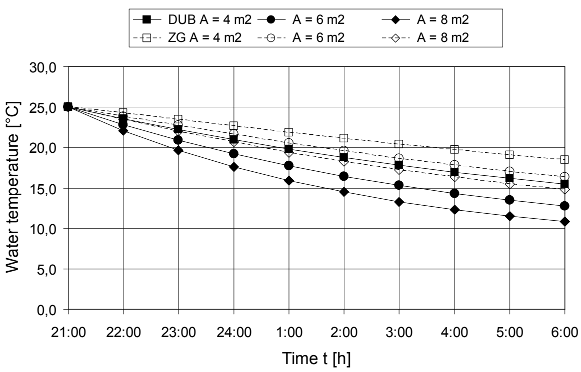

Fig.5 Water-cooling as function of panels' aperture area

On the other hand, increasing total area for 2m^2 would cause the temperature decrease for 1.8°C and 1.6°C, respectively. Further increasing of panel area would contribute even less in lowering the water temperature. Theoretically, with panel area of 12m^2 or more it would be possible to reach the water temperature in the tank equal to the dew point temperature of outside air.

The change of water temperature for different sizes of water storage is presented in Fig. 6. Increasing or decreasing the storage volume for 50 litres, would change the water temperature in the tank for about 1 °C in both climatic conditions.

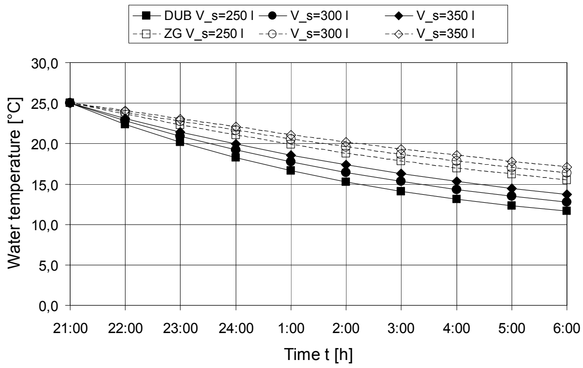

Fig.6 Water-cooling as function of tank volume

Conclusions

In this research, the mathematical model that describes the dynamic thermal performance of a radiative cooling system was developed and the test rig for the system experimental analysis was designed. Radiator panels are used for cooling of water by means of radiation towards the sky and convection to outside air during nighttime.

The results were obtained for a small solar cooling system with the total aperture area of 6 m^2 and tank volume of 300 litres (Fig.2).

The water temperature in the tank decreases for higher panel emissivity, which should be considered by panel design and material selection. Also, the temperature decreases for greater panels' area and smaller tank volume, which should be considered by system design in order to gain the optimal system sizing.

The radiative system is more efficient in maritime climatic conditions than in moderate continental climatic conditions. This is because, during summer, the sky temperatures are lower and wind velocities are higher in maritime climate, compared to continental climate. Hence, the cooling effect is more distinctive.

Future research will include analysis of parameters' influence on the system operation in more details, in different operating conditions and development of the experimental rig in order to validate the mathematical model.

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