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Analysis of cooling and heating of water with flat-plate solar radiators

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ABSTRACT

Extensive analysis of flat-plate radiative panels operation using average hourly weather data for a maritime climate region was performed. The panels are integrated in the space-ventilation system with air-cooling by means of a cold-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 the nighttime operation. That cold water is used for cooling of the air during daytime. By small modification during daytime, solar panels could be turned into collectors and used to produce the hot water that is collected in a separate tank. A simulation model for the parametric analysis of the system in summer operating conditions and 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/heating contributions. The purpose of the research was to predict the system behaviour in Irish climatic conditions, to enable sizing and design of the test rig that is to be built for experimental validation as part of a current large research project. The results were presented in the appropriate charts, where the influence of the main parameters on the system's operation was illustrated. The results showed that the same system, with small modifications to the physical set-up, could provide a significant proportion of the hot water heating requirements in the daytime operation.

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 current 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 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

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experiments for Norwegian (Oslo) climate. Argiriou *et al.* [3] have analysed the combined effects of climate and radiator characteristics on cooling potential. 12 years weather data set was used to assess radiative cooling potential in Athens. Saenkhomvong [4] has developed the water heating system using flat-plate solar collectors. This author also developed 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 thermosyphon water cooler with a parallel, flat-plate radiator has been studied theoretically and experimentally in [5]. 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 in 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 [6]. Analysis of flat-plate solar collectors, converted into cooling radiators, was performed by Erell and Etzion [7-9]. 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]. The results for the proposed model 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 is using solar energy (solar panels) for the supply air-conditioning during the whole year for maritime climate. The panels are integrated in the space-ventilation system with air-heating/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 the nighttime operation. That cold water is used for cooling of the air during daytime. By small modification, solar panels could be turned into collectors and used to produce the hot water during daytime that is collected in a separate hot-water tank. The research objectives include analysis of solar system performance in cooling and heating operating mode. Hence, thermal analysis of cooling and heating of water, including weather data analysis (temperatures, wind velocities, solar irradiation), together with design of the experimental rig were performed.

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.

DESIGN OF THE EXPERIMENTAL RIG

Solar thermal system (Fig. 1) is designed in order to supply the required amounts of energy for the heat exchanger, which is used for heating/cooling of the supply air. Because heating demands are significantly larger than cooling demands in their absolute values, it is decided to design a system that will completely satisfy cooling energy requirements, and will satisfy only a part of heating energy requirements. The second reason for that decision is that solar energy gains in winter are very small, and because of that it is not technically justified to produce total heating energy for a system only by means of solar collectors. That is why the auxiliary heater has to be immersed into a hot-water tank (Fig. 1).

Solar panels are used for heating of water by means of collection of solar irradiation during daytime and also for cooling of water by means of radiation towards sky (and convection to outside air) during nighttime. Since the requirements on collectors and radiators operation are opposite to each other, it is very difficult to achieve good performance in both heat collection and heat dissipation with only one panel type. Therefore, the best would be to use one panel type for solar heat collection (i.e. standard flat-plate collectors) and to use the other panel 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, than the solution with two panel types becomes very expensive. In this case, both operation modes could be covered with one panel type, but the adjustments of standard panel design are required. The easiest way to adjust a flat-plate collector for cooling operation is to substitute it's glazing with high-radiative cover (i.e. PE/PPO) [10].

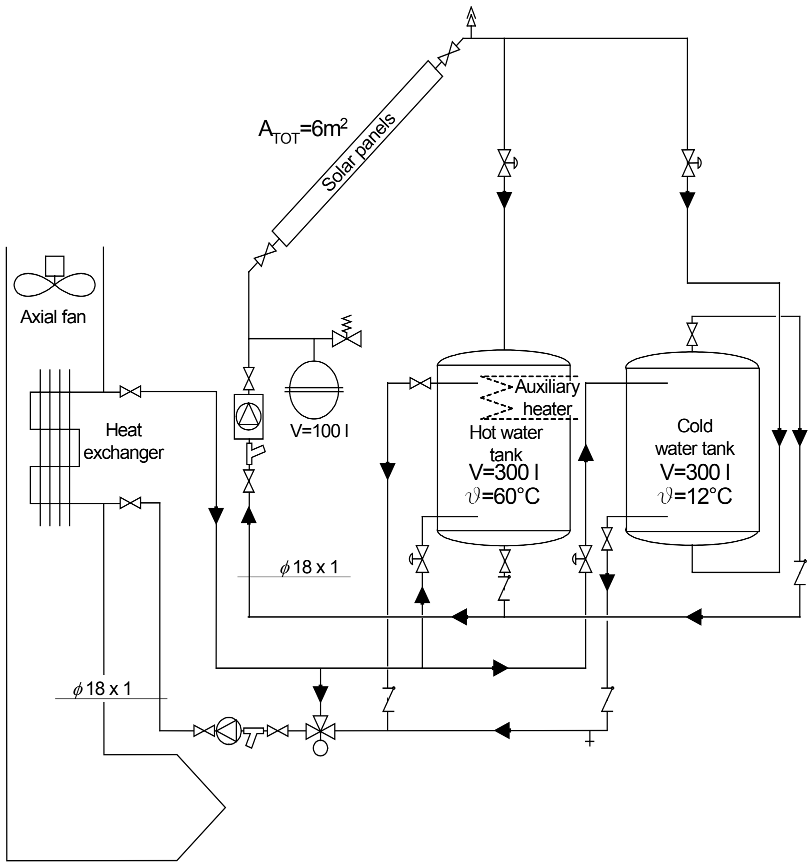

Fig. 1. Experimental rig schematic

The sizes of the equipment stated in Fig. 1 were determined by using well known calculation models for solar and HVAC applications [11-14].

MATHEMATICAL MODEL

The solar irradiation data presented in [15-16] were used to estimate how much energy is likely to be available at the observed location.

In the water heating mode, the collector plate absorbs 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 analysed by Whillier's procedure [12-14]. The basic equation is:

$$Q_C = A_C F_R [(\tau\alpha) I(t) - U_L (\vartheta_{wi}(t) - \vartheta_a(t))] \quad (1)$$

where the collector heat removal factor F_R is considered the ratio of the heat actually delivered to that delivered if the collector plate 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. It was determined from the equation:

$$F_R = \frac{\dot{m}c}{U_L A_C}\left(1 - e^{\frac{U_L A_C F'}{\dot{m}c}}\right) \quad (2)$$

The data of global solar irradiation on horizontal surface [16] had to be converted into values for a tilted surface $I(t)$ (Eq. 1). Determination of solar angles that describe 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 surrounding, in the water cooling mode during the night, is described with the following expression:

$$Q_R = A_C[\varepsilon_r \sigma (T_r^4(t) - T_{sky}^4(t)) + h_c(T_r(t) - T_a(t))] \quad (3)$$

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 characterizing 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:

$$T_{sky}^4 = \varepsilon_{sky} T_a^4 \quad (4)$$

Many correlations are reported in the literature for calculating the *sky* emissivity. In this paper, the following relation is used [14]:

$$\varepsilon_{sky} = 0.8 + \frac{T_{dp} - 273.15}{250} \quad (5)$$

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 [13]:

$$h_c = 2.8 + 3.0w \quad (6)$$

Most of time during the night, convection is complementary with the radiation for the observed geographic location, because the panel temperature is generally higher in summer than the air temperature [18].

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 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_{loss} to/from the environment on other side:

$$(mc)_S \frac{dT_S}{dt} = Q_C - Q_L - Q_{loss} \qquad [\text{W}] \qquad (7)$$

where $(mc)_s$ is heat capacity of the water in storage and dT_s is the change of water temperature. Q_C is determined from Eq. (1) when charging the hot water tank or from Eq. (3) when charging the cold water tank.

After integration of Eq. (7) for selected time interval, the change of storage temperature is calculated as a function of time. In Eq. (7) 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 heating/cooling process.

RESULTS AND DISCUSSION

Results presented in the following charts are based on Irish weather data in summer and winter – average solar irradiation, temperatures and wind velocities [15-16, 18].

The results in Figs. 2 - 4 are based on the following input data:

- total panel area $A_{TOT} = 6$ m^2
- hot water tank volume $V = 300$ l.

Water cooling

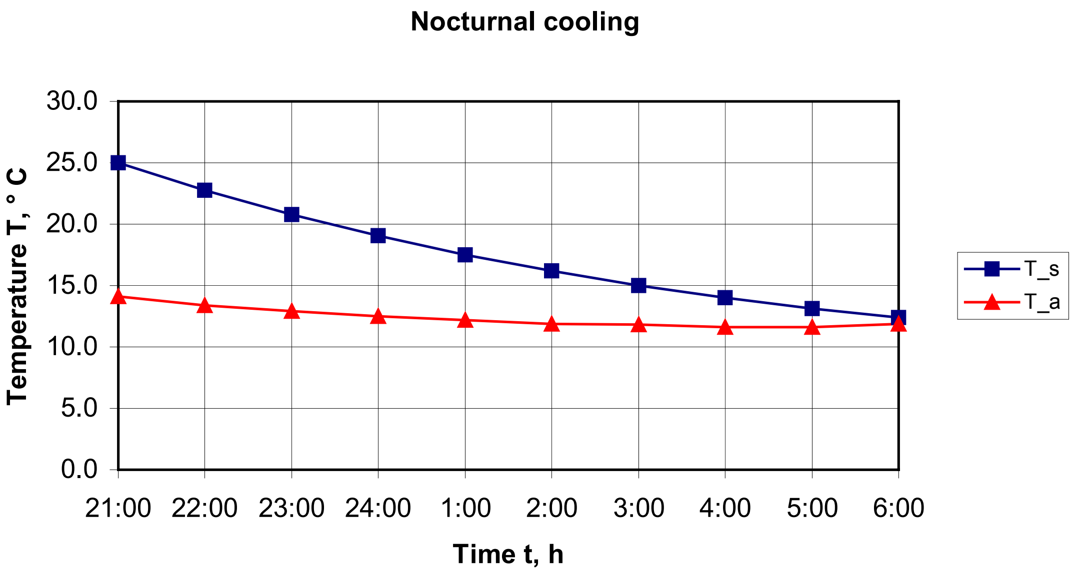

Fig. 2. Water-cooling in cold storage tank in average Irish summer night

In Fig. 2, simulation of the change of water temperature in the cold storage tank during nighttime is presented. It can be seen that the end temperature in the tank can reach around 12°C in clear sky conditions in Irish outside temperature and wind conditions [18]. Selection of start temperature 25°C is based on average summer room conditions. Placing the tank outside would cause heating of water by sun. If the start temperature would be 30°C, end temperature would be about 1°C higher and if the start temperature would be 20°C, end temperature would be about 1°C lower than 12°C. Of course, change of outside weather conditions would influence performance of the radiators and that would also change the end temperature in the cold storage tank.

Water heating

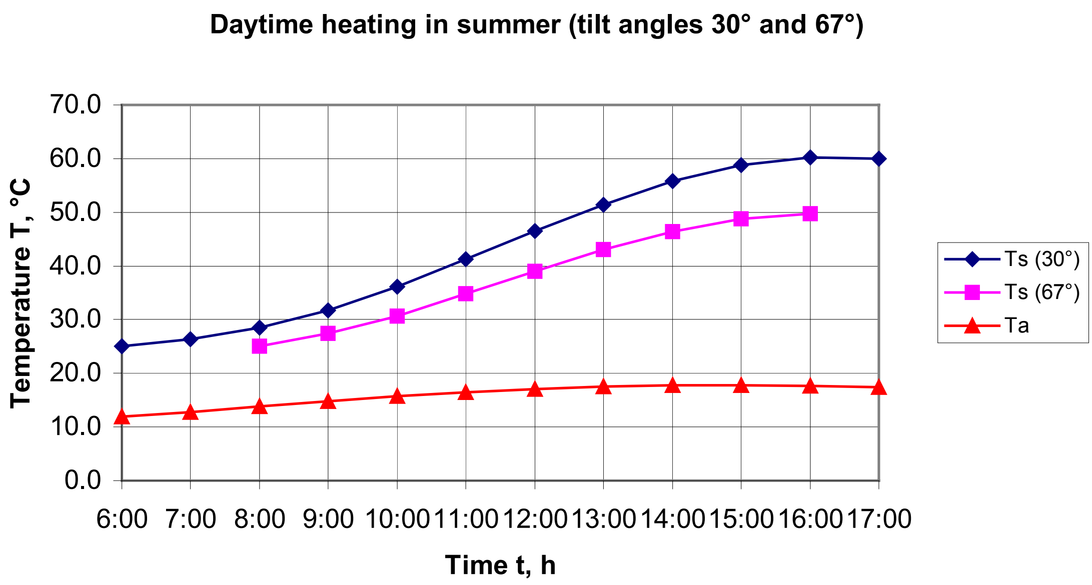

Fig. 3 Water heating in hot storage tank in average Irish sunny summer day

In Fig. 3, the change of water temperature in the hot storage tank during summer day is presented. It can be seen that the end temperature in the tank can reach around 60°C in clear sky conditions with 30°-tilt, average solar irradiation, outside temperature and wind conditions. Selection of start temperature 25°C is based on average summer room conditions. Placing of the tank outside would cause cooling of water by cold outside air during winter. If the start temperature would be 20°C, end temperature would be around 58°C and if the start temperature would be 30°C, end temperature would be around 62°C.

In Fig. 3, the influence of tilt angle on the system heating operation in summer is presented. If collectors would be tilted from horizontal plane for 67°, the end temperature is about 10°C lower than for 30°-tilt, with other parameters unchanged.

In winter operating conditions, system will not be able to heat the water on wanted temperature without support of an auxiliary heater. In Fig. 4 is presented that water temperature could be increased only for 4-5 °C during a sunny winter day. The result in cloudy conditions would be even worse. It is obvious that this is not sufficient for supply air heating.

Calculation presented in Fig. 4, performed with 67° tilt angle, gives better results for winter operation than 30° angle, because the incidence of a solar beam is closer to the normal on the tilted plane [13], [14].

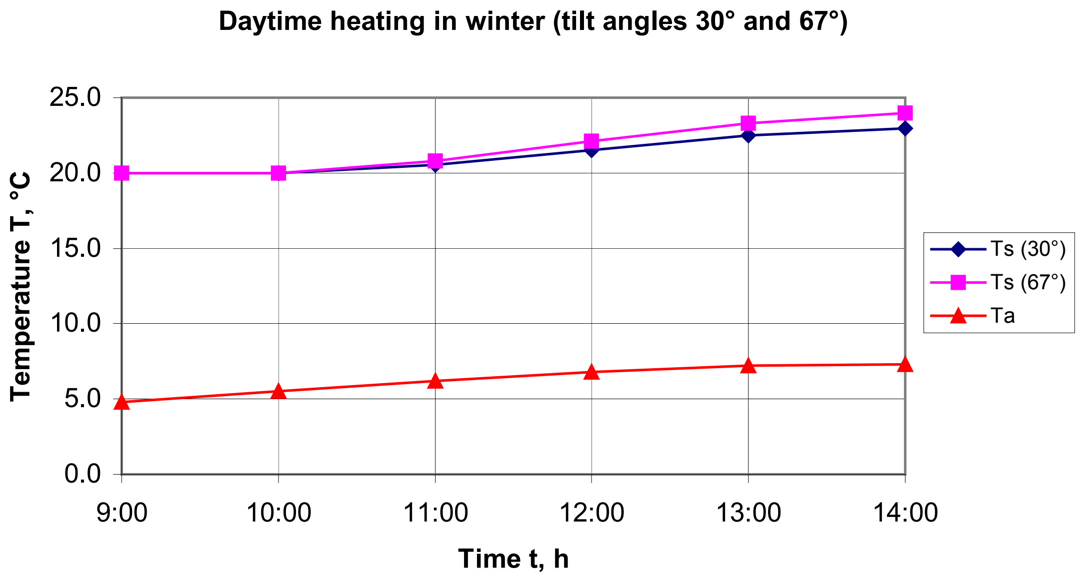

Fig. 4 Water heating in hot storage tank in average Irish sunny winter day

Performed analysis shows that many parameters have influence on system behaviour in both heating and cooling mode. The selection of equipment sizes, considering performed analysis, is considered to be optimal. Eventual change of some equipment size or properties would cause the change of performance of the system components.

CONCLUSION

In this research, the mathematical model, that describes the dynamic thermal behaviour of a solar heating system and a radiative cooling system, was developed and the experimental rig for the system analysis was designed. Solar collectors are used for heating of water by means of collection of solar irradiation during daytime and radiator panels are used for cooling of water by means of radiation towards sky and convection to outside air during nighttime. The results were obtained for the small cooling/heating system with a total aperture area of 6 m^2 and volume of tanks of 300 l, for both circulation loops (Fig.1).

The system in heating operation mode does not produce sufficient heating energy during winter; therefore the auxiliary heater is used in the hot water tank.

The simulation results indicate that sufficient radiative cooling is obtained and the system of the selected size covers full cooling energy demands during summer.

The future research will include the analysis of parameters' influence on the system behaviour in different operating conditions and set-up of the experimental rig in order to validate the mathematical model.

NOMENCLATURE

A_C	collector area	[m^2]
A_{TOT}	total panel area	[m^2]
c	specific heat capacity	[J/(kgK)]

F_R	collector heat removal factor	[-]
F'	collector geometry factor	[-]
h_c	convection heat transfer coefficient	[W/(m^{2}K)]
I	global solar irradiation	[W/m^2]
m	mass of water in storage tank	[kg]
$\dot{m}$	mass flow of water	[kg/s]
Q_C	heating capacity	[W]
Q_L	heating/cooling load	[W]
Q_{loss}	heat loss/gain	[W]
Q_R	cooling capacity	[W]
U_L	overall heat loss coefficient	[W/(m^{2}K)]
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	[l]
w	wind velocity	[m/s]
α	absorbtance	[-]
ε_r	panel emissivity	[-]
ε_{sky}	sky emissivity	[-]
σ	Stefan-Boltzmann constant	[5.67 10^{-8} W/(m^{2}K^4)]
ϑ_{wi}	temperature of water entering collector	[°C]
ϑ_a	ambient temperature	[°C]
τ	transmittance	[-]

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