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Hybrid roof panels for night cooling and solar energy utilization in buildings

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Abstract

The aim of this contribution is to evaluate the usability of solar hybrid panels, which were originally optimized for heat load removal from buildings by radiation against the night sky, for water preheating. First we created a surrogate model based on CFD simulations defining performance of the panel dependent on changing boundary conditions. This model was then implemented to the water heating model created in TRNSYS software. Estimated hot water usage would suffice for operation of 2 restaurant facilities in a building of our interest. Subsequent simulations were carried out using reference year climate data for Brno (Central Europe). Results demonstrated that in the given conditions, the average annual efficiency of solar energy usage is 55 %. The results also showed that the system is able to cover approximately 7 % of the heat demand for water heating.

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Keywords: Night sky cooling; Solar hot water heating; Surrogate model; Numerical simulation; CFD simulation; TRNSYS;

1. Introduction

Night sky cooling represents a method of passive cooling of buildings. It is based on the principle of heat radiation from hot surface of a solar panel against the cold night sky. Temperature of the night sky on the atmospheric boundary layer reaches 4 K [1]. This method of cooling is preferably applicable in dry climatic conditions because high air humidity absorbs heat radiated from the ground and therefore this heat is partially emitted back. According to previous studies [2,3], the efficiency of cooling collectors is affected not only by relative

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humidity, but also by other climatic conditions. Therefore, the evaluation of passive solar cooling efficiency against the night sky is primarily based on local climate data [4].

This paper builds on previous article [5], in which the applicability of the night sky cooling in context of climatic conditions in the Czech Republic was assessed by simulation method. The research was applied on a specific office building with varying occupancy parameters, settings of natural ventilation, different heat sources from lights etc. This model examined the effect of climatic conditions on energy performance of the panel throughout the year. The assessed model of the whole system employed heat activation of concrete floor system (TACC) used for storage of cold in reinforced concrete slabs. Results showed that the night sky cooling has favourable impact on interior temperature leading to decrease of the temperature to optimal value. These results were supported by calculated PMV and PPD parameters.

The aim of this paper is to evaluate usability of these hybrid roof panels during daytime. These panels might serve during daytime as solar collectors for pre-heating of hot water. Daily heat demand for restaurants is set as 0.389 MWh. Article [6] deals with optimization of water heaters. Article [7] presents design of a suitable water heating system of water heating using solar and heat pumps in six different ways. Literature [8] provides a life cycle assessment of solar systems used for heating of hot water. Article [9] presents a comparative study between solar and conventional heating of water and [11] presents analyses of combined solar systems. Study [12] deals with comparison of the design methods of hot water storage tanks. Article [13] provides an overview of technology and installation and summarizes behavior of the photovoltaics used for hot water heating. Economic analysis of solar hot water heating system is described in [14]. Different types of water heating systems are analyzed in terms of economic characteristics and impacts on global warming in article [15]. Study [16] investigates the efficiency of different types of home heating system in terms of energy use. Articles [17] and [18] deal with Legionella pneumophila in hot water systems and its negative impact on human health.

Nomenclature

c	specific heat capacity [J/(kg·K)]
I	specific solar irradiation [W/m^2]
m	mass flow [kg/s]
Q_{2D}	performance of hybrid panel in 2D model [W/m]
Q	performance of hybrid panel [W]
q	densitiy of heat flux [W/m^2]
t	temperature [°C]
w	wind velocity [m/s]
TACC	thermal activation of concrete ceiling

Subscripts

e	external
m	heat transfer medium in panel
in	enters
out	leaving
2D	two dimensional

2. Methods

Thermal performance of panels is dependent on both climatic and operating conditions. The most important parameters influencing the panel heat gains are solar radiation intensity I, outside air temperature t_e, wind velocity w as climatic parameters and mean temperature of the medium in the panel t_m as an operating parameter.

2.1 CFD simulations

Nine combinations of boundary conditions (variant A to I) were suggested for determination of performance characteristic of the panels. Heat accumulation of the panels was neglected. Performance of one hybrid panel in W/m was calculated by CFD method using ANSYS Fluent software. Geometry of the simulated panel was identical to the panel used in [5] and it is displayed in Fig. 1a.

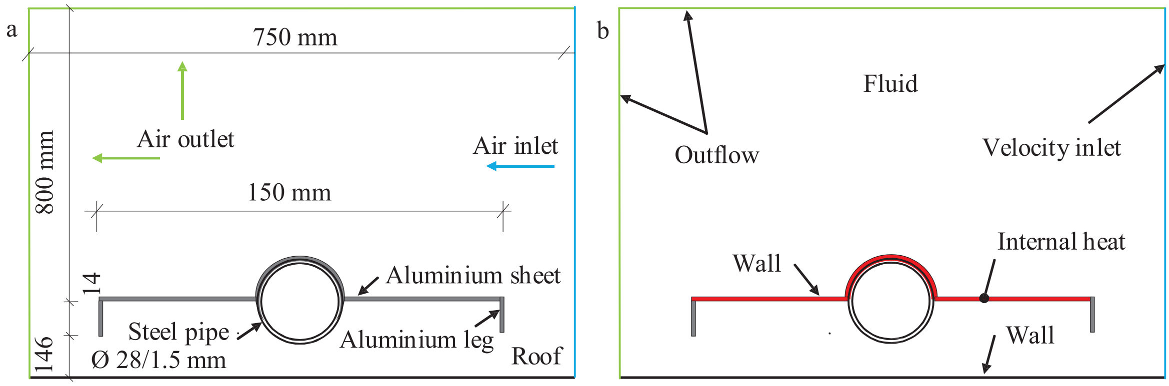

Fig. 1. (a) Geometry of the panel; (b) Boundary conditions used in ANSYS Fluent.

Climate data used in simulation represent typical climatic conditions of the given location. Energy absorbed into volume heat source was determined from intensity of solar radiation incident on the surface of aluminum coating of the plate. This energy was inserted into our model as internal energy source. A set of simulations was created for each parameter – the solar radiation intensity I, the wind velocity w and the temperature difference Δt between outside air temperature te and the mean temperature of medium tm. Only one examined parameter was changed in each set of simulations, other parameters remained constant.

Air in our model was considered as incompressible. Realisable k-ε turbulence model with the standard wall function was selected. Turbulence intensity was defined as 10% and with hydraulic diameter 0.5 m. All the simulations were fully converged by iterative solver.

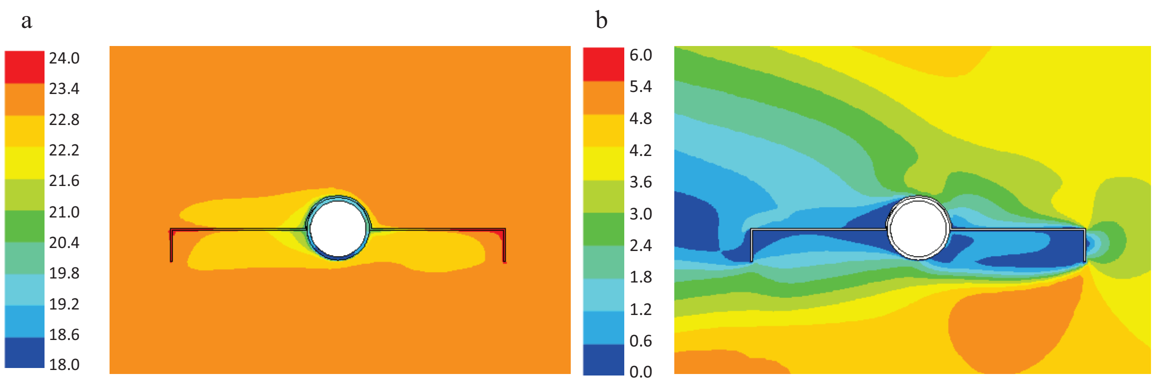

Fig. 2. ANSYS Fluent results – case E – (a) Static temperatures [°C]; (b) Velocity [m/s].

Functional dependence of the intensity of solar radiation I, the wind velocity w and the temperature difference Δt on the heat performance of 1 m of the panel was defined using composed least squares method. This surrogate model of usable panel performance [W/m] is based on Equation 1.

$$Q_{2D} = 47.95 \cdot [(0.001503823057804 \cdot I + 0.216773256103872) \cdot (1.17155948187826 \cdot w^{-0.1087456324933307}) + (-0.00025123664 \cdot (t_e - t_m)^4 + 0.00264445004 \cdot (t_e - t_m)^3 - 0.02184781074 \cdot (t_e - t_m)^2 + 0.29250805389 \cdot (t_e - t_m) - 0.222326595)] \quad (1)$$

Then we created a testing set of simulations – see Table 1 – on which we verified results from CFD method and results from approximation equation. Figure 2 displays a graphical comparison of outputs from CFD simulation and results from surrogate model. Figure 3 shows the outputs from variant E.

Table 1. Variants and boundary conditions for CFD simulations.

Simulation	Δt [°C]	t_e [°C]	t_m [°C]	w [m/s]	I_{TOT} [W/m^2]
Simulation A	1	15	14	7,4	200
Simulation B	2	17	15	6,6	280
Simulation C	3	19	16	5,8	360
Simulation D	4	21	17	5	440
Simulation E	5	23	18	4,2	520
Simulation F	6	25	19	3,4	600
Simulation G	7	27	20	2,6	680
Simulation H	8	29	21	1,8	760
Simulation I	9	31	22	1	840

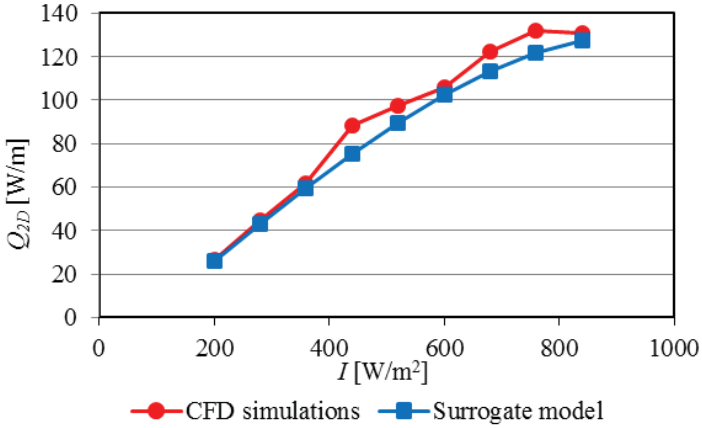

Fig. 3. Thermal performenace Q_{2D} of the panel depending on solar intensity I.

2.2 Surrogate model of solar panel

This study is focused on hybrid solar panels. In this contribution they are studied mainly as an alternative method of decreasing building's thermal load – cooling by radiation against the night sky [5]. Two parallel connected panel fields are considered, each field containing 50 lamellae with length 1 m. Geometry of the lamella is shown in Figure 1a.

Surrogate model was designed in EXCEL application. Thermal performance of panel fields is calculated from equation [1] derived from 2D model of one lamella. The panel model considers constant temperature of fluid in each lamella tube. Thermal capacity of panels was neglected. The outlet water temperature of the sub-panels is calculated in 1 meter step from the calorimetric equation [2]. The outlet water temperature is used as inlet temperature to the next lamella – the panels are connected in series . The water mass flow in the primary circuit is contemplated as 0.14 kg/s, thus in one panel field the water mass flow is equal to 0.07 kg/s.

$$Q = m \cdot c \cdot (t_{out} - t_{in}) \tag{2}$$

Than we applied following restrictive conditions into the model that ensure the operation of solar panels only at suitable climatic and operating conditions:

- temperature of external air must be higher than 10 °C,
- outlet water temperature tout must be higher than 17 °C.,
- solar radiation intensity I must be higher than 50 W/m^2.

2.3 Simulations in TRNSYS

Thermal performance of the hybrid panels was evaluated using building energy simulation software TRNSYS. This software allows calculating hour by hour desired quantities of a modeled system. Software works with pre-defined device components, while the model itself was inserted using programmed EXCEL application. Climate data used for the software calculation represent typical meteorological year [TMY] commonly used in simulation software; in this case we used data for Brno (Central Europe).

A connection diagram of the hybrid panels in switch mode between night and day operation is shown in Figure 4. The cooled water from the panels flows directly to activated concrete TACC core and reduces thermal load of the office spaces during nightime, but during daytime water may be heated and used for pre-heating of water for restaurants. Primary panel circuit transfers the heat through heat exchanger surfaces, which preheat the cold water pipeline of 14 °C. Than the pre-heated water flows into a storage tank, where this water is heated on desired temperature by gas boiler. Amount of the hot water consumption is presumed for 2 restaurant facilities located in lower floors of the building. These canteens manage to serve food for up to 3000 diners per day. The restaurant facilities are in service only during weekdays. Chart of predicted hot water demands is shown in Fig 5.

This study considers only model with daytime operation of the facilities. Pre cooling of the primary circuit water due to radiation against the night sky is not considered. This would further increase the efficiency of the panels.

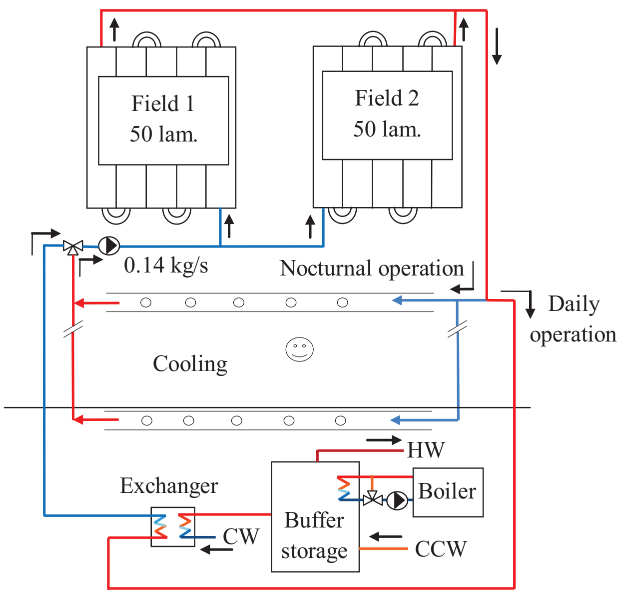

Fig. 4. A connection diagram.

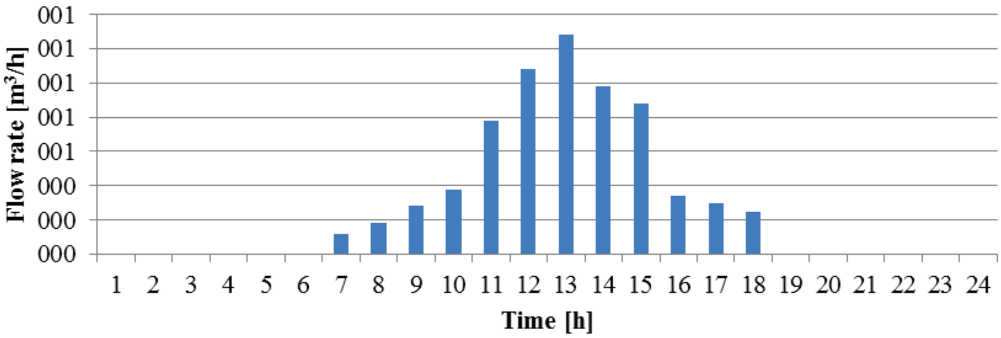

Fig. 5. Predicted hot water demands during a typical day.

3. Results and discussion

Our simulations were carried out for the whole reference year. Thermal performance of the hybrid panel fields, the heat exchanger and the gas boiler were determined from results of our simulations. Results show that these panels could be used for pre-heating of water with annual year efficiency 55 % in climatic conditions of Central Europe. At certain time during the reference year effectiveness higher than 100 % was achieved. This occurs when there is low intensity of solar radiation and the outside air temperature is higher than the temperature of fluid entering the panels. The average efficiency of the heat exchanger was calculated as 90.2 %

Figure 6 discusses combined coverage of heat demand by the solar panel, which transfers heat through the walls of the heat exchanger to cold water, and by the gas boiler, which heats this water in storage tank. Usage of the solar panel during the summer time – from early May to late September – supplies in total 2.83 MWh for this period into the storage tank, which makes 7.1% of the total energy demand for heating of water. The highest thermal performance of the panels was recorded in July, when the solar device covered 10% of energy demand and daily average supply was 0.026 MWh. Furthermore it was shown that the solar panels are ineffective for pre-heating of hot water outside the summer season.

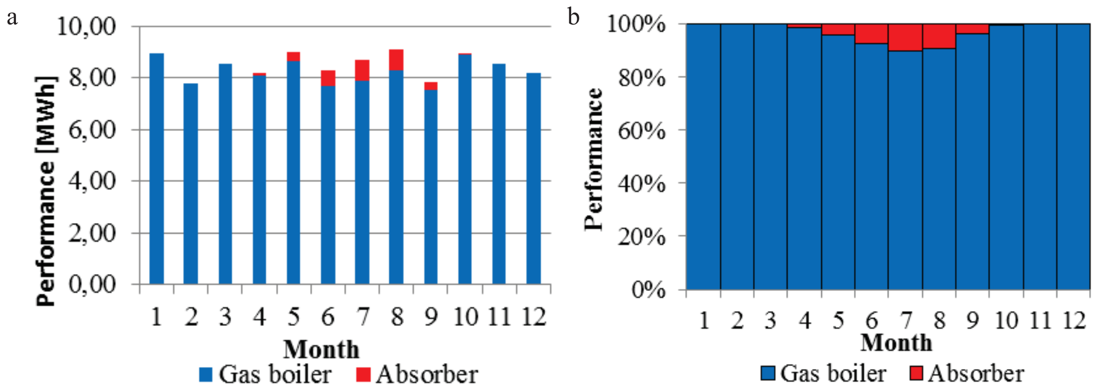

Fig. 6. (a) Coverage of heat demand Q [MWh] during the year; (b) Relative coverage of heat demand Q [%]

4. Conclusions

This contribution dealt with determination of efficiency of the hybrid solar panel designed and optimized for heat load removal of the building using radiation against the cold night sky and possibility of usage of the panel for pre-heating of water. Fluid in the primary circuit of the panels is cooled during nighttime and removes accumulated thermal load by cooling floor slabs. During daytime the hybrid solar panels utilize solar energy for pre-heating of hot water.

To perform simulations we used ANSYS Fluent and TRNSYS software. The results revealed minor but not negligible effect of the hybrid solar panels on hot water heating during daytime.

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