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Solar concrete collectors for heating of domestic hot water

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Scientific paper

Abstract: In this paper, the performance of a domestic hot water heating system with solar concrete collector is studied. The principal components of this system are a serpentine pipe, a storage tank and an auxiliary heating source, e.g. a gas burner or an electric resistance heater. The serpentine pipe can be placed inside roof slabs, concrete pavements or walls. A numerical code based on the finite volume method has been developed in order to solve transient three-dimensional heat conduction in the concrete element with the serpentine pipe inside. Heat transfer at the exposed surface of the concrete element is described with a mixed convection-radiation boundary condition. The numerical simulations gave the following results: water temperatures throughout the serpentine pipe, storage tank temperatures and efficiency of the solar concrete collector heating system. It has been seen that the serpentine pipe can heat water up to 40-50 °C while the heat storage tank reaches temperatures of 30-40 °C during the summer period. The average May to September efficiency (i.e. solar fraction) is 50-70% in Rijeka (Croatia), meaning that less than half the energy demand is supplied by the auxiliary heating source. Several parameters influencing the efficiency of solar concrete collector systems are studied: pipe spacing, pipe length, pipe depth, solar absorptance and tilt angle of the concrete element. For example, the spacing between pipe bends should be at least 15 cm to avoid pipe-to-pipe thermal influence.

Keywords

Solar concrete collector
Solar energy
Domestic hot water
Finite volume method

Betonski solarni kolektori za grijanje potrošne tople vode

Izvornoznanstveni članak

Sažetak: U ovom je radu analizirana učinkovitost sustava grijanja potrošne tople vode s betonskim solarnim kolektorom. Glavne komponente ovoga sustava su cijevna zavojnica, spremnik tople vode i pomoćni izvor topline, npr. plinski ili elektrotporni grijač. Cijevna zavojnica može se postaviti unutar krovnih ploča, betonskih podova ili zidova. Nestacionarno trodimenzionalno provođenje topline u betonskom elementu u kojem je postavljena cijevna zavojnica rješeno je pomoću računalnog programa koji se temelji na metodi kontrolnih volumena. Izmjena topline na izloženoj površini betonskog elementa je opisana prirodnim rubnim uvjetom koji uzima u obzir konvekciju i zračenje topline. Numeričke simulacije dale su sljedeće rezultate: temperatura vode duž cijevne zavojnice, temperatura spremnika tople vode i učinkovitosti sustava grijanja s betonskim solarnim kolektorom. Utvrđeno je da cijevna zavojnica može zagrijati vodu na 40-50 °C, dok spremnik tople vode dostiže temperature od 30-40 °C u ljetnom razdoblju. Prosječna učinkovitost (tj. stupanj solarne pokrivenosti) je 50-70% u Rijeci, što znači da se manje od polovice potrebne energije osigurava iz pomoćnog izvora topline. Ispitan je utjecaj različitih parametara koji utječu na učinkovitost sustava s betonskim solarnim kolektorom: razmak između susjednih cijevi, duljina cijevi, dubina cijevi, koeficijent apsorpcije i kut nagiba betonskog elementa. Npr., razmak između susjednih cijevi mora biti veći od 15 cm, kako bi se izbjegao njihov međusobni toplinski utjecaj.

Ključne riječi

Betonski solarni kolektor
Sunčeva energija
Potrošna topla voda
Metoda kontrolnih volumena

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1. Introduction

Solar collectors are by far the most reliable, efficient and financially viable equipment for the conversion of solar radiation into thermal energy. In Rijeka (Croatia), the annual global solar irradiation on a south-oriented, 45° tilted surface is 1460 kWh m^{-2} of which 500-700 kWhm^{-2} can be used for domestic hot water (DHW) heating in households. Despite their advantages, solar collectors may not be mounted on protected buildings. The EU Directive on energy efficiency of buildings [1] leaves to Member States to decide whether to or not to

Symbols/Oznake

A	- surface area, m^2 - površina
c	- specific heat capacity, J $kg^{-1}K^{-1}$ - specifični toplinski kapacitet
d	- pipe depth, m - dubina cijevi
e	- system efficiency, - - učinkovitost sustava
$\dot{G}$	- solar irradiance, W m^{-2} - sunčevo ozračenje
h	- heat transfer coefficient, W $m^{-2}K^{-1}$ - koeficijent prijelaza topline
k	- heat conductivity, W $m^{-1}K^{-1}$ - toplinska provodnost
l	- pipe spacing, m - razmak između cijevi
T	- temperature, K - temperatura
t	- time, s - vrijeme
V	- volume, m^3, L - volumen
w	- wind speed, m s^{-1} - brzina vjetra

Greek letters/Grčka slova

α	- absorptance, - - koeficijent apsorpcije
β	- tilt angle, ° - kut nagiba
ε	- emissivity, - - emisivnost
ρ	- density, kg m^{-3} - gustoća

Subscripts/Indeksi

c	- concrete - beton
DHW	- domestic hot water - potrošna topla voda
dp	- dew point - točka rosišta
hst	- heat storage tank - spremnik topline
s	- surface - površina
∞	- ambient air - vanjski zrak
0	- mains water - voda iz vodovoda

apply the Directive on buildings of special architectural or historic merit. In Croatia and especially along the Adriatic coast which enjoys plenty of sun, installation of solar energy systems is not allowed on cultural heritage buildings and on buildings within protected cultural and historic urban areas, unless they are invisible to all intents and purposes and comply with rigid conservation requirements [2]. Indeed, the character and appearance of those buildings could be unacceptably altered by energy efficiency measures and renewable energy systems. For example, only in Rijeka the protected urban area encompasses different historical sites and several hundred buildings over an area of about 2.5 km^2.

Solar concrete collectors can be used alternatively to roof-mounted solar collectors. In a solar concrete collector, water is heated in copper pipes which are placed inside roofs, concrete pavements or walls having their surfaces exposed to sunlight. These surfaces can reach temperatures of 60 °C or more during the summer period as shown with the infrared image in Figure 1. In this way the solar concrete collector is hidden but a significantly larger surface needs to be employed to match the heating output of a solar thermal collector.

Solar concrete collectors have been investigated by a smaller number of researchers. The slab solar collection process of a road hydronic ice-snow melting system was experimentally studied in [3]. The investigators determined that the heat collecting rate of the road slab is 150-250 W m^{-2} when the solar irradiance is 300-1000 W m^{-2}, yielding an efficiency of about 30%. The performance of a solar concrete collector with a surface area of 2 m^2, a thickness of 40 mm and a serpentine pipe long 20 m was measured in [4]. It was found that the solar concrete collector was capable of producing 140-180 liters of hot water per day at a temperature of 42-46 °C, with an average efficiency of 32%. The performance of a roof-integrated solar concrete collector with a surface area of 5.8 m^2 for DHW preparation was measured in [5]. The authors determined that the solar concrete collector can supply 40 liters of water per day at temperatures of 40-50 °C. The thermal response of small-scale asphalt solar collectors was experimentally studied in [6]. The influence of water flow rate, initial temperature and time of operation start-up on the heat collection process was studied. The paper concluded that water pipes can cool down asphalt pavements to a rate capable of reducing the heat island effect in cities.

In this paper, the performance of a domestic hot water heating system with solar concrete collector is investigated numerically. The solar concrete collector consists of a serpentine pipe placed inside a concrete slab which can be a pavement or a house roof. The performance of the solar concrete collector system is studied through the variation of different parameters: pipe spacing, pipe depth, pipe length, tilt angle and solar absorptance of the concrete slab.

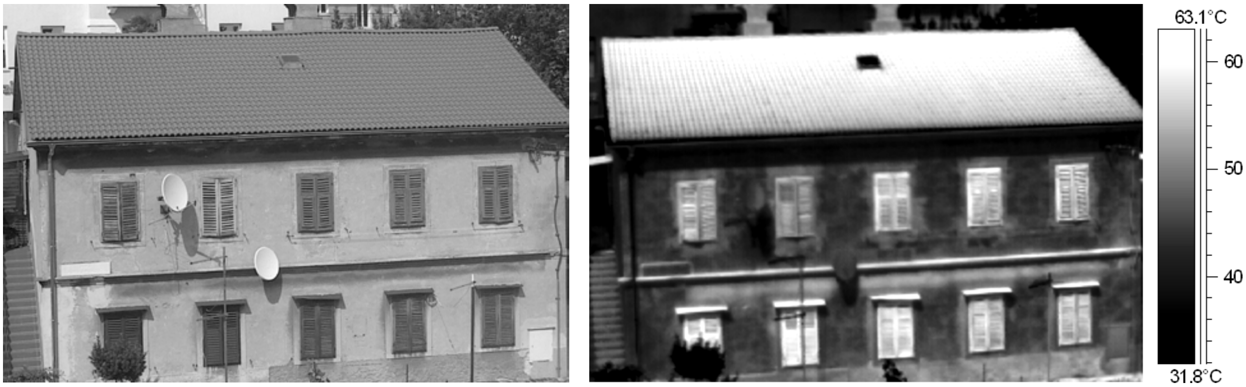

Figure 1. Infrared photo of a building located in the Rijeka's protected urban area (photo taken at 15:30, June 21, 2012)

Slika 1. Infracrveni snimak zgrade unutar zaštićene gradske jezgre u Rijeci (snimak napravljen u 15:30, 21. lipnja, 2012.)

2. Mathematical model

2.1. Energy conservation equation

The performance of the solar concrete collector system for domestic hot water heating is studied by means of a computer code developed in Visual Basic. Three-dimensional transient heat conduction is used to determine the rate of heat transfer to the serpentine pipe inside the concrete slab. The heat exchange mechanism at the concrete slab surface consists of shortwave (solar) and longwave (infrared) heat radiation as well as of heat convection. The energy conservation equation for the concrete slab reads

$$\rho_\mathrm{c}\, c_\mathrm{c}\, V \frac{\partial T}{\partial t} = k_\mathrm{c}\, V \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) + \alpha_\mathrm{s} A \dot{G} + \\ + hA\left(T_\infty - T\right) + \varepsilon_\mathrm{r}\, \sigma A \left(T_\mathrm{sky}^4 - T^4\right) \quad , \quad (1)$$

Equation (1) represents the three-dimensional transient heat conduction equation for isotropic solids extended by a source term which includes the heat flux mechanisms at the concrete slab surface: solar radiation, heat convection and longwave heat radiation. In other words, the temperature of the concrete slab surface (left-hand side) changes because of heat conduction inside the concrete slab (first term on right-hand side), solar radiation gains (second term), convection and longwave radiation heat transfer at the concrete slab surface (third and fourth term). The volume of the concrete slab is V (m^3) and its exposed surface area is A (m^2). The physical properties of concrete are given with mass density ρ_c ($\mathrm{kg m^{-3}}$), thermal conductivity k_c ($\mathrm{W\, m^{-1}\, K^{-1}}$) and heat capacity c_c ($\mathrm{J kg^{-1} K^{-1}}$).

The incident global solar irradiance $\dot{G}$ ($\mathrm{W\, m^{-2}}$) is partially absorbed and partially reflected from the concrete slab surface. The solar absorptance α_s depends on the color and surface roughness of the concrete slab as well as on the radiation source temperature [7]. An unfinished concrete slab has solar absorptance of 0.65 (source temperature of 5780 K) while the absorptance for longwave atmospheric radiation α_r is 0.90 (source temperature of 300 K). If the concrete slab is covered with roofing elements such as tiles or shingles, the solar absorptance could be: 0.82 for red concrete tiles, 0.75 for unpainted cement tiles, 0.27 for white concrete tiles, 0.88 for ocean grey and desert tan asphalt shingles, and so on, according to one experimental investigation [8].

Besides absorbing solar radiation, the concrete slab surface emits energy into the sky aperture by longwave heat radiation. The atmosphere is assumed to be a blackbody having a fictitious sky temperature and emitting the same amount of energy of the real atmosphere. This fictitious sky temperature T_sky (K) can be determined if knowing the air dew point temperature T_dp (K) and the air dry bulb temperature T_∞ (K) with the expression presented in [9]

$$T_\mathrm{sky} = \left[T_\infty^4 \left(0.754 + 0.0044\, T_\mathrm{dp} \right) \right]^{1/4} , \quad (2)$$

Since there is no considerable difference between sky temperature and concrete slab surface temperature, in view of Kirchhoff's law of radiation, it can be taken that the concrete slab surface emittance is equal to the longwave absorptance of the same surface ($\varepsilon_\mathrm{r} = \alpha_\mathrm{r} = 0.90$). The Stefan-Boltzmann constant of heat radiation is denoted with σ ($= 5.67 \cdot 10^{-8}\ \mathrm{W m^{-2} K^{-4}}$).

The convection heat transfer coefficient h ($\mathrm{W m^{-2} K^{-1}}$) of the surface is determined in relation to the wind speed w ($\mathrm{m s^{-1}}$), from the equation suggested in [10]

$$h = 6.22 + 4.41\, w^{0.861} , \quad (3)$$

The weather data necessary for closure of equation (1) is collected from the typical meteorological year for Rijeka (Croatia) which consists of average hourly values of global solar irradiance $\dot{G}$ ($\mathrm{W m^{-2}}$), diffuse solar irradiance $\dot{G}_\mathrm{d}$ ($\mathrm{W m^{-2}}$), air dry bulb temperature T_∞ (K), absolute air humidity x ($\mathrm{g kg^{-1}}$) and wind speed w ($\mathrm{m s^{-1}}$).

2.2. Physical properties of concrete and water

The mass density of concrete is $\rho_c = 2200$ kg m^{-3}, the thermal conductivity is $k_c = 0.75$ W m^{-1} K^{-1} and the specific heat capacity is $c_c = 920$ J kg^{-1} K^{-1}. The physical properties of concrete are constant throughout the whole domain and temperature independent. The specific heat capacity of water c_w (J kg^{-1} K^{-1}) is defined with a temperature-dependent polynomial that approximates table data from ASHRAE-2009 Handbook [11].

3. Numerical solution

3.1. The finite volume method

The energy conservation equation (1) needs to be discretized in order to be solved numerically. Spatial discretization is performed using the finite volume method (FVM) and involves integration of space terms over finite steps Δx, Δy and Δz. The mesh consists of hexahedral control volumes arranged in a structured grid. Temporal discretization is performed using the fully implicit method where time is divided into discrete time steps equal to $\Delta t = 3600$ s (which correspond to the one-hour time step of weather data in the TMY).

The discretized form of the heat conduction equation with mixed convection-radiation boundary condition is not given here but the reader may refer to [12]. In simple words, discretization of the energy conservation equation produces a system of algebraic equations which contains unknown node temperatures in the direction perpendicular to the concrete slab surface (the direction of dominant heat conduction). The system of algebraic equations is solved using the tridiagonal matrix algorithm (TDMA). In the first step of the TDMA, elementary row operations are used to place zeros below the main diagonal (forward elimination). In the second step, the solution of the resulting upper triangular matrix is found by back substitution. Once the system of algebraic equations is solved, the TDMA moves forward in pipe-wise direction to the next set of equations until all the node temperatures in the domain are found. The procedure repeats until a convergence criterion is satisfied. Thereafter, the code proceeds to the next time step $t + \Delta t$ to calculate new temperatures until all time steps are solved. The flowchart of the numerical algorithm is given in Figure 2.

In the concrete slab, the serpentine pipe is heated by heat conduction. The serpentine pipe is divided into a finite number of control sections where water temperatures can be determined knowing the rate of heat conduction to the pipe section, the mass flow rate and the specific heat capacity of water. The inlet water temperature of the observed control section of the serpentine pipe is equal to the exit water temperature of the preceding pipe control section.

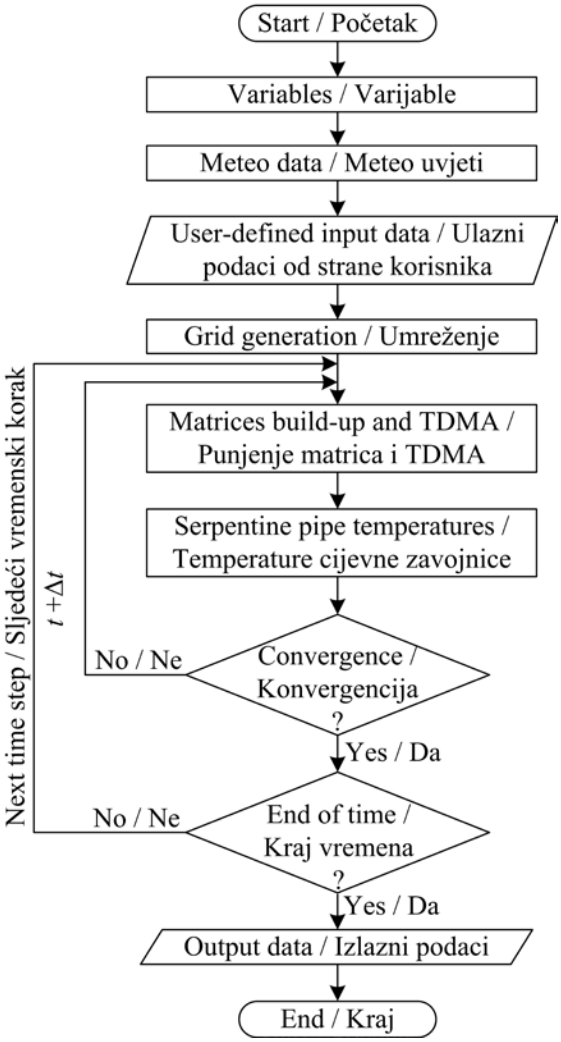

Figure 2. The flowchart of the numerical algorithm

Slika 2. Dijagram toka numeričkog algoritma

3.2. Validation of the numerical model

The temperatures of the concrete slab, resulting from the presented numerical model, are validated against temperature measurements taken at different depths in a concrete pavement without serpentine pipes. Heat conduction is supposed to be one-dimensional and with dominant heat conduction in the direction perpendicular to the concrete slab surface which is exposed to the heat transfer mechanisms previously explained. The weather data necessary for describing these heat transfer mechanisms was retrieved from the weather station in Rijeka. Temperature measurements were taken at depths of 1 cm and 10 cm over a period of 8 days, from August 6 to 13, 2011. Very good accordance between measured and simulated temperatures is achieved as it can be seen in Figure 3.

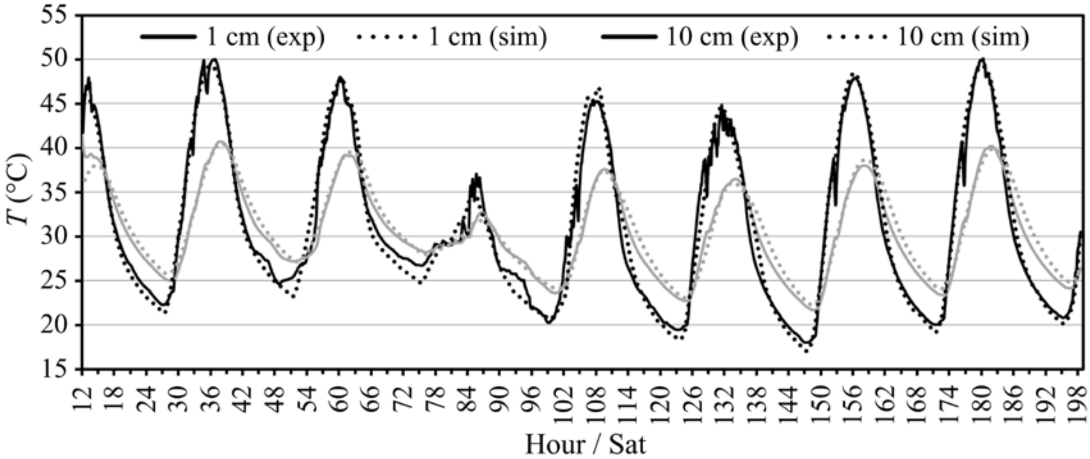

Figure 3. Comparison between measured (exp) and simulated temperatures for depths of 1 cm and 10 cm in the concrete slab

Slika 3. Usporedba između izmjerenih (exp) i izračunatih (sim) temperatura za dubine od 1 cm i 10 cm u betonskoj ploči

3.3. The temperatures of the concrete slab

The numerical model combined with the weather data from the TMY can be used to determine the temperatures in the concrete slab throughout a year. Figure 4 plots monthly values of maximum and average surface temperatures of the concrete slab as well as maximum and average air temperatures in Rijeka. As it can be seen, the solar absorptance of the concrete slab surface has a major influence on the temperatures of the concrete slab. The solar absorptance of concrete can range between values of 0.65 and 0.95, depending on material composition, surface color and texture. In June, for example, concrete surfaces having solar absorptance of 0.95 (black-painted surface) achieve a maximum temperature of 66.8 °C. But, this maximum temperature is reduced to 59.4 °C or 52.6 °C if the solar absorptance of the concrete slab is 0.80 or 0.65, instead. Generally, the higher the solar absorptance of the surface the higher the temperature of the surface. High solar absorptances are not desired in urban environment, though. Buildings, roads and other manmade structures perform as heat traps, absorbing large amounts of solar irradiation while reflecting only smaller portions [13]. The absorbed heat is returned to the air through convection and as a consequence the air temperature increases. This effect is called urban heat island (UHI) effect and its main consequence is an increase of air temperature by several degrees in urban areas when compared to the air temperature in surrounding rural areas. Therefore, solar concrete collectors could present multiple advantages in urban areas: 1) collecting of free solar energy while 2) mitigating the urban heat island effect and 3) being unnoticeable.

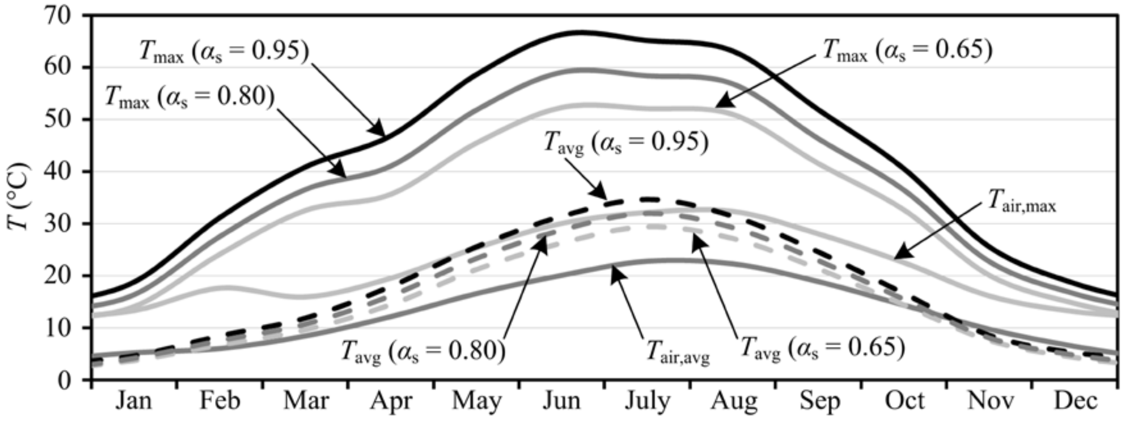

Figure 4. Average (T_{avg}) and maximum (T_{max}) concrete slab surface temperature and ambient air temperature (T_{air}) in Rijeka

Slika 4. Prosječna (T_{avg}) i maksimalna (T_{max}) temperatura površine betonske ploče i temperatura zraka (T_{air}) u Rijeci

3.4. Influence of grid size on numerical results

The influence of grid size on numerical results is examined by comparing three different levels of grid refinement. The compared results are the temperatures of the heat storage tank, which in the end, determine the efficiency of the solar concrete collector system. Figure 5 plots the heat storage temperatures produced by a fine grid consisting of 550 000 finite volumes (18 control sections per pipe bend), a medium size grid with 360 000 finite volumes (14 control sections per pipe bend) and a coarse grid with 140 000 finite volumes (8 pipe sections per pipe bend). The fine and the medium size grid produced results within 2% difference but the coarse grid overestimates them by up to 5%. The medium size grid is chosen for further analysis as it seems to be a good compromise between accuracy and computer processing time. The domestic hot water (DHW) consumption profile of the household with the solar concrete collector system is generated using *DHWcalc* [14] and shown in Figure 5 over 10 days.

4. Performance of the solar concrete collector system

4.1. The hydraulic scheme

The principal components of the solar concrete collector system are: serpentine pipe, heat storage tank, auxiliary heating source, controller, sensors, pumps, valves, expansion vessel and piping, as shown in Figure 6. The controller turns on the pump in the solar loop when the weather conditions are favorable, i.e. when the water temperature at the serpentine pipe outlet is higher than the heat storage temperature. An immersed spiral pipe heat exchanger transfers heat from the heat storage tank to DHW. The auxiliary heating source turns on and supplies additional heat if the temperature of DHW leaving the heat storage tank drops below 45 °C.

On average, the solar concrete collector system supplies 200 liters of DHW per day with maximum draw-off volumes during morning and evening hours.

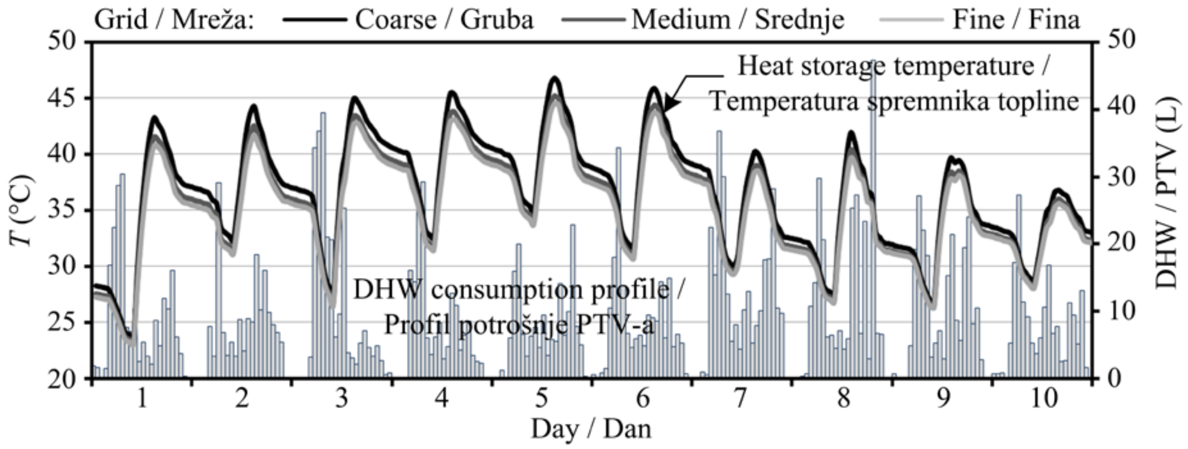

Figure 5. Influence of grid size on heat storage temperatures – a comparison between three levels of grid refinement

Slika 5. Utjecaj veličine mreže na temperature spremnika topline – usporedba između tri razine gustoće umreženja

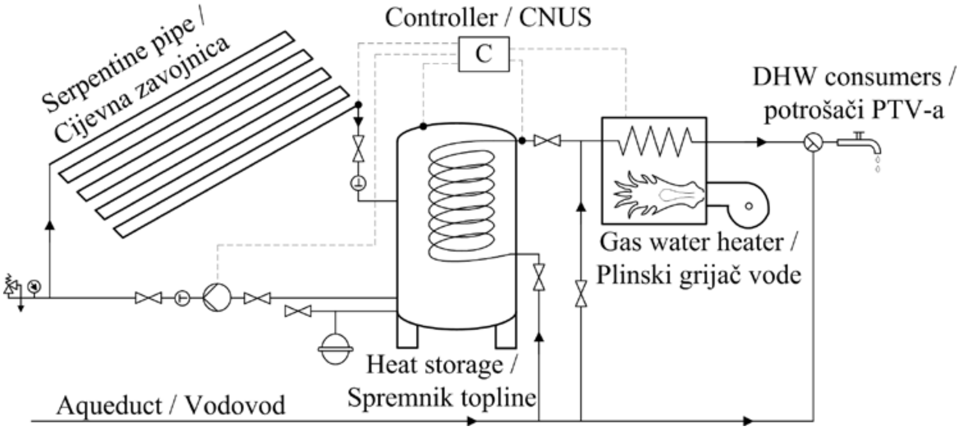

Figure 6. Hydraulic scheme of the solar concrete collector system for domestic hot water heating

Slika 6. Shema spajanja sustava grijanja potrošne tople vode s betonskim solarnim kolektorom

The serpentine pipe is embedded into a concrete slab with a surface area of 50 m^2. The thickness of the concrete slab is 20 cm and it is adiabatic at the bottom side while the top side is completely exposed to weather conditions. The concrete slab tilt angle is denoted with β and the solar absorptance of the surface is α_s. The dimensions of the serpentine pipe are: total pipe length L, pipe diameter D, number of pipe bends n, spacing between pipe bends l and pipe depth d.

4.2. System efficiency

The system efficiency e (%) is specified as the ratio between the saved energy in the solar concrete collector system and the energy consumed in a conventional (non-solar) system which supplies the entire amount of energy for DHW heating, i.e.

$$e = 1 - \frac{V_{\mathrm{DHW}} \rho c \left(T_{\mathrm{DHW}} - T_{\mathrm{hst}}\right)}{V_{\mathrm{DHW}} \rho c \left(T_{\mathrm{DHW}} - T_{\mathrm{w}_0}\right)} = 1 - \frac{T_{\mathrm{DHW}} - T_{\mathrm{hst}}}{T_{\mathrm{DHW}} - T_0}, \quad (4)$$

The DHW temperature (T_{DHW}) which has to be achieved both in the solar and in the conventional system is 45 °C. The heat storage temperature is denoted with T_{hst} while the mains water temperature is denoted with T_0. The mains water temperature for an hour in the year n_{h} is calculated from

$$T_0 = T_{0,\mathrm{m}} - \frac{\Delta T_0}{2} \cos\left\{ \frac{n_{\mathrm{h}} + 24\left(n_{\mathrm{d,max}} - 273.5\right)}{8760/360} \right\}, \quad (5)$$

The average mains water temperature is $T_{0,\mathrm{m}}$ and the temperature amplitude is half the difference between maximum and minimum mains water temperature in the year, i.e. $\Delta T_0/2 = (T_{0,\max} - T_{0,\min})/2$.

From the author's experience these temperatures in Rijeka are: $T_{0,\min} = 7$ °C, $T_{0,\mathrm{m}} = 12$ °C and $T_{0,\max} = 17$ °C. The ordinal number of hour in the year (1 to 8760) is denoted with n_{h} and the ordinal number of day in the year with maximum mains water temperature is $n_{\mathrm{d,max}}$ which is taken to be August 15 (i.e. $n_{\mathrm{d,max}} = 227$).

4.3. Results and discussion

Figure 7 gives the numerically obtained temperature distribution in one possible serpentine pipe geometry. The serpentine pipe in Figure 7 has the following geometry: pipe depth 5 cm, pipe spacing 45 cm, pipe diameter 10 mm and 11 pipe bends giving a total pipe length of 109 m. Water from the heat storage tank enters the serpentine pipe with 33 °C and exits with 42 °C while the temperature of the surrounding concrete is 44 °C. The temperature distribution in Figure 6 happens on July 30 at 15:00 hours when the TMY data reads: solar irradiance 670 W m^{-2}, air temperature 31.4 °C, relative air humidity 46% and wind velocity 1.6 ms^{-1}.

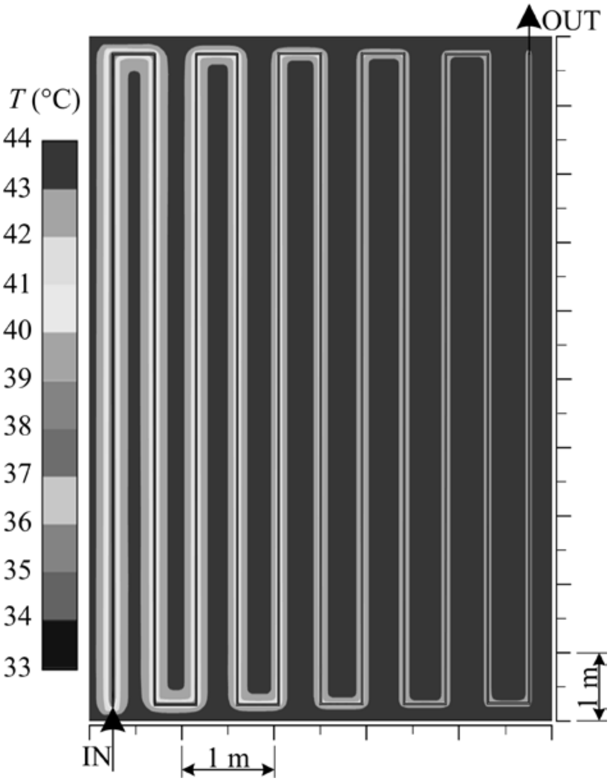

Figure 7. Temperature distribution in serpentine pipe plane

Slika 7. Raspodjela temperatura u ravnini cijevne zavojnice

The influence of pipe depth (d) and concrete solar absorptance (α_s) on the efficiency (e) of the solar concrete collector system is studied next. As it can be seen from Figure 8, both pipe depth and concrete solar absorptance strongly influence the system efficiency. For a given concrete solar absorptance, the system efficiency can be increased from 10 to 25% if placing the serpentine pipe closer to the surface, i.e. reducing the pipe depth from 5 cm to 3 cm and 1 cm. On the other hand, for a given pipe depth, the system efficiency can be improved from 15% to 40% if increasing the concrete solar absorptance from 0.65 to 0.80 and 0.95. The solar absorptance of an unfinished concrete slab ($\alpha_s = 0.65$) can be increased painting the slab surface into a darker color. The characteristics of the studied solar concrete collector studied are: pipe spacing 45 cm, number of pipe bends 11, total pipe length 109 m, pipe diameter 10 mm, heat storage tank volume 300 L, DHW set point temperature 45 °C and horizontally placed concrete slab (tilt angle β = 0°). A solar concrete collector having the same characteristics is also studied in the next paragraphs but taking a pipe depth of 1 cm and a concrete solar absorptance of 0.80.

The influence of concrete slab inclination on the system efficiency and heat storage temperatures is shown in Figure 9. Solar concrete collectors with tilt angles from 15° to 45° achieve best system efficiencies in the period from May to September. And, tilt angles from 15° to 45° correspond to the inclinations of roofs in single- and multi-family houses which could have had one part of their hot water energy demand supplied from solar concrete collector systems. Solar concrete collectors with horizontal slabs perform less, especially in September, when the sun elevation is gradually declining. Vertical concrete surfaces and surfaces with big tilt angles are not favorable for collecting heating energy with solar concrete collectors.

The relationship between pipe spacing l(cm) and solar concrete collector efficiency is shown in Figure 10. The pipe spacing in the serpentine pipe has been varied between 5 cm and 45 cm. As it can be seen, the pipe spacing, i.e. the distance between neighboring pipe bends, presents a major influencing factor on the system efficiency. Generally, the system efficiency deteriorates as the pipe spacing shortens. For example, a serpentine pipe with narrow pipe spacing (e.g. l = 5 cm) results with 40% diminished system efficiency compared to serpentine pipes with pipe spacing of 15 cm or more. As a rule of thumb, the pipe spacing should be at least 20 cm in the serpentine pipes of solar concrete collectors to avoid pipe-to-pipe thermal influence.

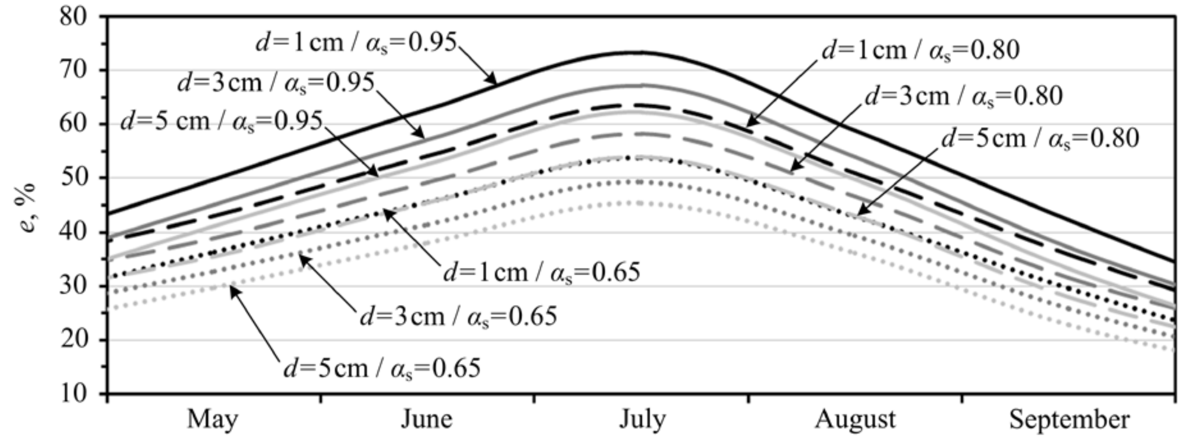

Figure 8. Influence of pipe depth (d) and concrete solar absorptance (α_s) on the efficiency of the solar concrete collector (e)

Slika 8. Utjecaj dubine cijevi (d) i koeficijenta apsorpcije betona (α_s) na učinkovitost betonskog solarnog kolektora (e)

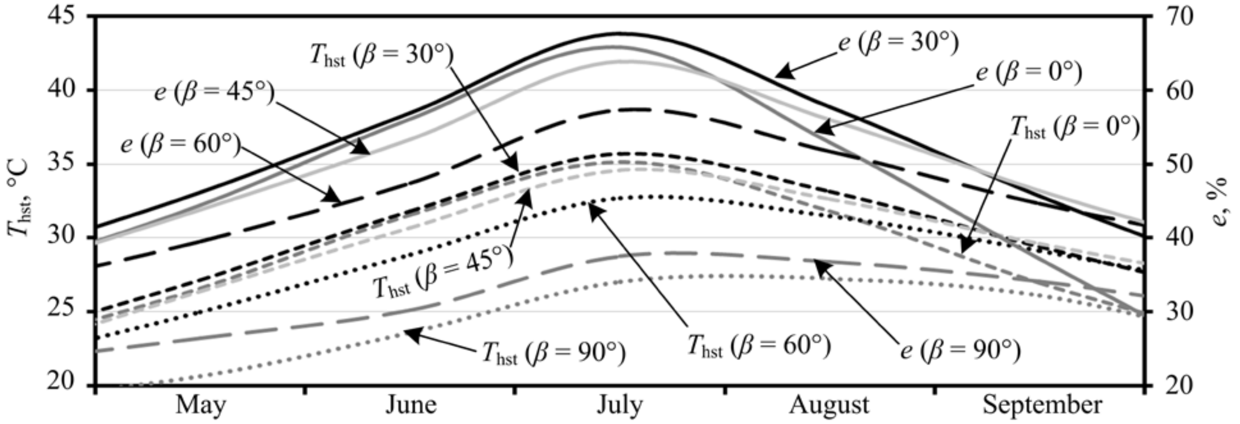

Figure 9. Influence of concrete slab tilt angle (β) on heat storage temperature (T_{hst}) and solar concrete collector efficiency (e).

Slika 9. Utjecaj kuta betonske ploče (β) na temperaturu u spremniku (T_{hst}) i učinkovitost betonskog solarnog kolektora (e)

Figure 11 shows the temperatures achieved by the solar concrete collector system with the following characteristics: pipe spacing 45 cm, pipe depth 1 cm, number of pipe bends 11, total pipe length 109 m, pipe diameter 10 mm, heat storage tank 300 L, concrete solar absorptance 0.80 and horizontally placed concrete slab.

In the summer period from May to September, water leaves the serpentine pipe with temperatures between 30 °C and 50 °C most of the time while the average temperature of the heat storage tank ranges mostly between 20 °C and 40 °C which is also the temperature of water at the serpentine pipe inlet. These temperatures yield an average seasonal efficiency of about 50% in the solar concrete collector system. In other words, in the summer period alone, the solar concrete collector system supplies 540 kWh of solar energy and saves €60 through electricity bills (average price of electricity in Rijeka €0.11/kWh).

5. Conclusion

The performance of solar concrete collector systems for heating of domestic hot water has been studied in this paper. During sunny summer days, concrete surfaces offer a large heat collecting potential as they can easily reach temperatures of 65 °C or more. Although solar concrete collectors cannot compete to solar thermal collectors, they have the advantage of being invisible. Solar concrete collectors can be installed inside manmade structures such as: walls, roofs, pavements, streets, parking surfaces and so on. From the present study, it has been seen that solar concrete collector systems can supply from 40% to 70% of the energy demand for DHW heating in the summer months. The exact value of this solar fraction or system efficiency depends on the characteristics of the concrete slab and on the geometry of the serpentine pipe.

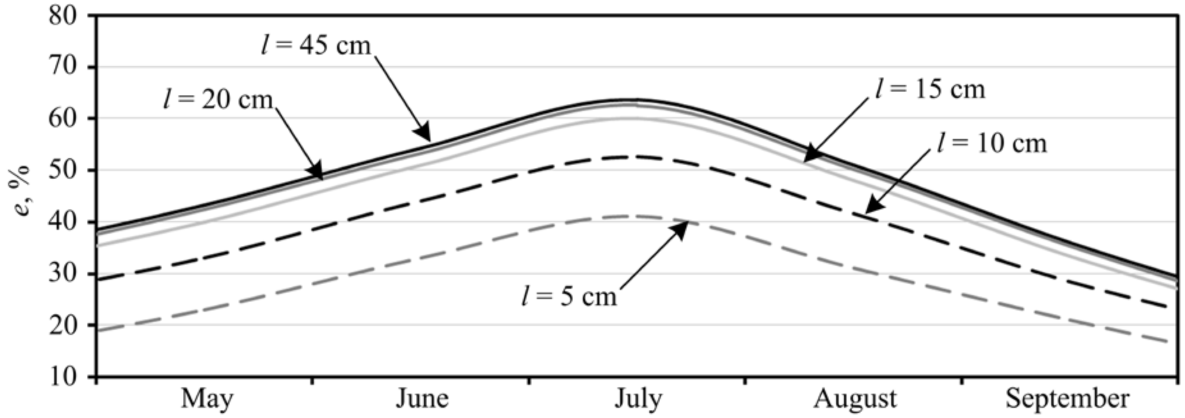

Figure 10. Influence of pipe spacing (l) on the efficiency (e) of the solar concrete collector system

Slika 10. Utjecaj razmaka između cijevi (l) na učinkovitost sustava grijanja (e) betonskog solarnog kolektora

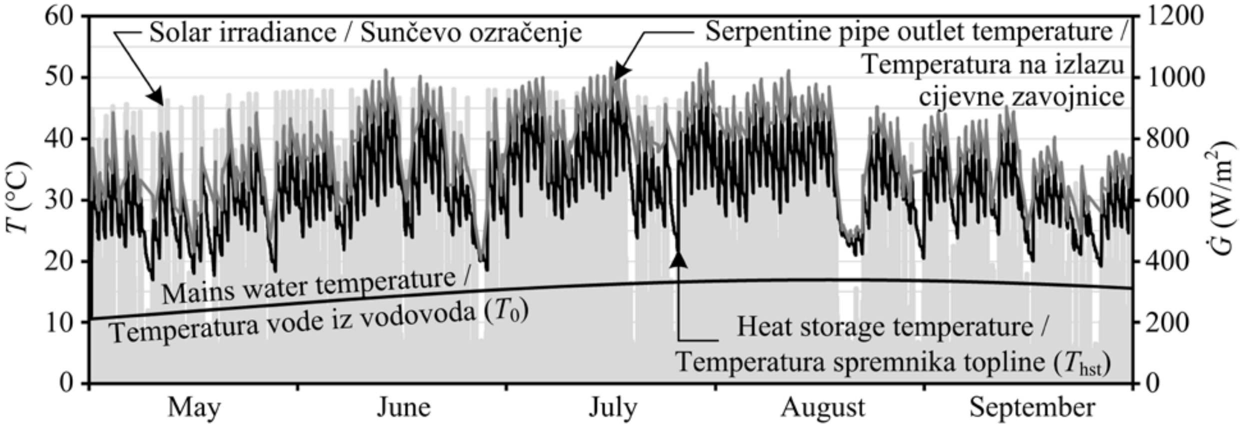

Figure 11. Heat storage temperatures and serpentine pipe outlet temperatures in the solar concrete collector system

Slika 11. Temperature u spremniku topline i na izlazu cijevne zavojnice u sustavu grijanja betonskog solarnog kolektora

Outside the summer period, solar concrete collectors are not capable of supplying larger amounts of heat due to low temperatures in the concrete slab. Nevertheless, during the winter period, hot water could be pumped through the serpentine pipe of solar concrete collectors in order to de-ice the surface of concrete sideways, streets and pavements.

Due to the relatively weak heat conduction flux density reaching the serpentine pipe from the concrete surface, the serpentine pipe has to be quite long – about 100 m while the flow velocity of water has to be quite slow – under 0.3 m/s. To ensure a high efficiency of the solar concrete collector system, the serpentine pipes of solar concrete collectors should be placed as close as possible to the exposed surface. Also, neighboring pipe bends should be placed with spacing in between of at least 15 cm to avoid mutual thermal influence. The optimum inclination of the concrete slab for maximum efficiency in the summer period is 30°. Smaller or bigger inclinations would result with reduced efficiency of the solar concrete collector system due to reduced solar irradiation on the concrete slab surface.

Taking into account the above-mentioned design guidelines for serpentine pipes of solar concrete collectors, the water temperature at the serpentine pipe outlet could be between 40 and 50 °C and the heat storage temperature between 30 and 40 °C while the mains water temperature is between 10 and 17 °C. In Rijeka (1340 kWh/m^2 of solar irradiation on horizontal surface per year), such a solar concrete collector system could supply 50% of the DHW heating demand to a single-family in the summer period. The resulting energy saving would be 540 kWh which is worth €60 in electricity for the period from May to September.

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REFERENCES

[1] …: *Directive 2010/31/EU on the Energy Performance of Buildings (recast)*, European Parliament and the Council of the EU, Official Journal of the European Union (18.6.2010) L153/13-35. 2011.

[2] …: *Special requirements for the protection of cultural property with regard to the installation of solar collectors and photovoltaic cells on cultural heritage buildings in Rijeka*, Conservation Department in Rijeka Directorate for the Protection of Cultural Heritage, Ministry of Culture, authors' communication, Rijeka 2011.

[3] GAO, Q., HUANG, Y., LI, M., LIU, Y., YAN, Y.: *Experimental study of slab solar collection on the hydronic system of road*, Solar Energy 84 (2010), 2096-2102

[4] HAZAMI, M., KOOLI, S., LAZÂAR, M., FARHAT, A., BELGHITH, A.: *Energetic and exergetic performances of an economical and available integrated solar storage collector based on concrete matrix*, Energy Conversion and Management 51 (2010), 1210-1218

[5] SARACHITTI, R., CHOTETANORM, C., LERTSATITTHANAKORN, C., RUNGSIYOPAS, M.: *Thermal performance analysis and economic evaluation of roof-integrated solar concrete collector*, Energy and Buildings 43 (2011), 1403-1408

[6] SHAOPENG, W., MINGYU, C., JIZHE, Z.: Laboratory investigation into thermal response of asphalt pavements as solar collector by application of small-scale slabs, Applied Thermal Engineering 31 (2011) 10, 1582-1587

[7] ÇENGEL, Y.A.: *Heat transfer: a practical approach, 2nd ed.*, McGraw-Hills Science, New York, 2003

[8] PARKER, D.S., MCILVAINE, J.E.R., BARKASZI, S.F., BEAL, D.J., ANELLO, M.T.: *Laboratory testing of the reflectance properties of roofing material*, FSEC-CR-670-00, Florida Solar Energy Center, Cocoa (FL) 2000 http://www.fsec.ucf.edu/en/publications/html/FSEC-CR-670-00/

[9] TANG, R., ETZION, Y., MEIR, I.A.: *Estimates of clear night sky emissivity in the Negev Highlands*, Israel. Energy Conversion & Management 45 (2004), 1831-1843

[10] SMITH, J.O.: *Determination of the convective heat transfer coefficients from the surfaces of buildings within urban street canyons*, PhD thesis, University of Bath 2010

[11] ...: *ASHRAE Handbook – Fundamentals,* American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., Atlanta 2009

[12] VERSTEEG, J.K., MALALASEKERA, W.: *An introduction to computational fluid dynamics, The finite volume method, 2nd edition,* Pearson Education Limited, Essex 2007

[13] AKBARI, H., ROSENFELD, A. H., TAHA, H.: *Summer heat islands, urban trees and white surfaces*, ASHRAE Transactions 96 (1990) 1, 1381-1388

[14] JORDAN, U., VAJEN, K.: *DHWcalc, tool for generating domestic hot water consumption profiles on a statistical basis v1.10*, IEA SHC Task 26, Kassel 2003