MAXIMIZING PERFORMANCES OF A SOLAR DOMESTIC HOT WATER SYSTEM THROUGH OPTIMUM SOLAR COLLECTOR SLOPE AND AZIMUTH ANGLES USING THE HOOKE JEEVES ALGORITHM

OPTIMIZACIJA PERFORMANSI SOLARNIH PRIJEMNIKA KORIŠĆENJEM SOFTVERA ENERGYPLUS I ALGORITMA HOOKE JEVEES

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In Serbia, it is customary to use electrical energy for heating of domestic hot water (DHW). As around 70% of electrical energy is produced by using coal with high greenhouse emission, it is beneficial to environment to use solar energy for heating of DHW in solar DHW system (SDHWS). It is very important to maximize the value of solar fraction during a SDHWS operation. In this paper, a use of Hooke-Jeeves algorithm is reported to obtain the optimum slope and surface azimuth angles for solar collectors that is a part of the SDHWS that give the maximum value of solar fraction for the SDHWS. Different values of optimum slope and azimuth angles of solar collectors due to south and the collected solar energy are calculated for each month during entire year that enable the maximum amount of the solar energy and the solar fraction for SDHWS.

Keywords: *Optimization, SDHWS, Solar Fraction, Simulation, Solar collector*

U Srbiji je uobičajeno da se za grejanje sanitarne tople vode koristi električna energija. S obzirom da se 70% električne energije proizvodi korišćenjem uglja pri čemu dolazi velikih emisija gasova staklene bašte, za životnu sredinu je korisnija upotreba solarne energije za zagrevanje vode koja se koristi u domaćinstvu. Veoma je važno postići maksimalnu vrednost solarnog udela u toku rada sistema za grejanje sanitarne tople vode (STV). U ovom radu, korišćenjem Hooke algoritma dati su optimalni uglovi (nagiba i azimuta) za solarni prijemnik koji je deo solarnog sistema za grejanje sanitarne tople vode pri čemu dobijamo maksimalne vrednosti solarnog udela za taj sistem. Različite vrednosti optimalnog ugla (nagiba i azimuta) solarnog prijemnika usmerenog ka jugu i prikupljene solarne energije izračunavane su za svaki mesec u toku godine pri čemu dobijamo maksimalne vrednosti solarnog udela za solarni sistem za grejanje sanitarne tople vode.

Ključne reči: *Optimizacija, STV, Solarni udeo, Simulacija, Solarni prijemnik*

1. INTRODUCTION

During the first years of the twenty-first century, extensive efforts have been undertaken to alleviate global warming of the earth caused by emission of CO_2 in atmosphere. These emissions are generated by intensive burning of fossil fuels to satisfy the growing energy needs of humanity. The emissions may be mitigated when part of energy needs is satisfied by using non-polluting energy sources such as solar energy, instead of fossil fuels. Also, another important advantage of the usage of solar energy is that it does not pollute the environment with nitrogen oxides and sulfur dioxide.

In Serbian households, the high amount of DHW is used for shower, tap, cloths-washing machines, and dish-washing (machines). It is customary to use electricity for heating of DHW. As around 70% of electricity is produced by using coal with high greenhouse emission, it is important and the most rewarding to use solar energy for DHW heating instead of electrical energy. Accordingly, in Serbia and worldwide, the most rewarding application of solar energy is when it replaces electrical energy for heating of DHW in households [1]. In addition it is important to have a high efficiency of conversion of solar energy to heat. Then, the highest amount of avoided primary energy, avoided electrical energy, avoided exergy, and decrease in CO_2 emissions may be expected.

To use SDHWS with the greatest benefit, SDHWS must have adequate design, installation, and operation. During its operation, the applied solar collector has to take the optimal position that will guarantee the highest generation of heat. The solar collector takes the north-south direction and the objective of this paper is to find the optimum solar collector slope and azimuth angle. In literature, there is a lot of research with this objective. By using the equations for the global solar radiation by an empirical model, Nijegorodov and Jain calculated optimum slope of a north-south aligned absorber plate from the north to the south poles [4]. By determining the sunshine duration, Chang roughly estimated the optimal tilt angle of a solar collector in the northern hemisphere [3]. Based on the incident angles of the direct solar radiation, Skeiker calculated the optimum tilt angle and orientation for solar collectors in Syria [5]. By taking into account position of the sun at the sky and using the model of ASHRAE, Bari calculated the optimum orientation of domestic solar collectors for the low latitude countries [6]. By using the measured values of the global solar radiation, Ibrahim calculated the optimum tilt angle for solar collectors used in Cyprus [7]. Based on the measured data for solar radiation by meteorological station, Shariah et al optimized the tilt angle of solar collectors for the SDHW system where maximum solar fraction was used as an indicator for the optimum tilt angle [2] which is the case in the repoted investigations. Talebizadeh, reported investigation, the optimum slope and azimuth angles for hourly, daily, monthly, seasonally and yearly bases were found using the Genetic Algorithm (GA) respectively. The percentages of heat gain of a solar collector under these optimum angles were obtained.[8]

In this paper, a use of Hooke-Jeeves algorithm is reported to obtain the optimum slope and azimuth angles of solar collectors due to south and the collected solar energy are calculated for each month during entire year that enable the maximum amount of the solar energy and the solar fraction for SDHWS . The solar collectors of the SDHWSs are placed in north-south direction at roofs of houses. The used weather data were from the meteorological stations and software Meteonorm. These investigations use the computer codes: EnergyPlus and GenOpt and HJ search algorithm.

2. MODELLING AND SIMULATION

In this investigation, simulation, and optimization are performed by using two separate software packages. The research of these installations was performed by using simulation by EnergyPlus and optimization by using Hooke-Jevees method. In this investigation, the Hooke-Jevees method was used to optimize energy flows in SDHWS. In this investigation, the solar collector slope and azimuth angle is optimized to obtain the highest solar fraction.

Simulation Software – EnergyPlus: In this study, the building energy simulation software EnergyPlus (Version 7.0) was used to predict solar energy and electrical energy use in solar installation for heating of DHW in several cities in Serbia. Then, the solar fraction was determined for its different design, installation and operation parameters. EnergyPlus is made available by the Lawrence Berkley Laboratory in USA [9]. Its development began in 1996 on the basis of two widely used programs: DOE-2 and BLAST. The software serves to simulate building energy behavior and use of renewable energy in buildings [10]. The renewable energy simulation capabilities include solar thermal and photovoltaic simulation. Other simulation features of EnergyPlus include: variable time steps, user-configurable modular systems, and user defined input and output data structures. The software has been tested using the IEA HVAC BESTEST E100-E200 series of tests [11]. Modeling of the SDHWS in EnergyPlus environment required models of different components embedded in EnergyPlus such as that of flat-plate solar collector, storage tank, tempering valve, and instantaneous water heater [12]. Water in the storage tank was heated by solar energy and water in the instantaneous water heater by electricity.

Genopt Software: GenOpt is an optimization program for the minimization of a cost function that is evaluated by an external simulation program [13]. It has been developed for optimization problems where the cost function is computationally expensive and its derivatives are not available or may not even exist. GenOpt can be coupled to any simulation program that reads its input from text files and writes its output to text files. The independent variables can be continuous variables (possibly with lower and upper bounds), discrete variables, or both, continuous and discrete variables. Constraints on dependent variables can be implemented using penalty or barrier functions. GenOpt has a library with local and global multi-dimensional and one dimensional optimization algorithms, and algorithms for doing parametric runs [14]. An algorithm interface allows adding new minimization algorithms without knowing the details of the program structure. GenOpt is written in Java so that it is platform independent. The platform independence and the general interface make GenOpt applicable to a wide range of optimization problems. GenOpt has not been designed for linear programming problems, quadratic programming problems, and problems where the gradient of the cost function is available. For such problems, as well as for other problems, special tailored software exists that is more efficient.

Optimization Algorithm: For optimization, the Hooke–Jeeves algorithm is used together with EnergyPlus simulation. These two programs are connected together by using Genopt software [13]. In this research, the adaptive precision Hooke-Jeeves algorithm is used. Hooke-Jeeves algorithm is derivative free optimization algorithms [15, 16]. Hooke Jeeves algorithm is a direct search algorithm [17]. In direct search methods, only the objective functions and the constraint values are used to guide the search strategy. The methodology of search is given in [16,17] in sufficient details. The used Hooke Jeeves algorithm is the adaptive precision algorithm. This algorithm progressively increase the precision of the approximating cost functions as the sequence of iterates approaches a stationary point. In addition, the algorithm only accepts iterates that reduces the cost sufficiently. It reduces the computation time up to a factor of four compared to the standard Hooke–Jeeves algorithm.

3. MATHEMATICAL MODEL

To obtain performance of SDHWS, the operation of the SDHWS was investigated by using simulation and optimization. The mathematical model was developed in EnergyPlus simulation environment and the optimization was performed by using Hooke-Jeeves search algorithm.

This part of the paper provides the mathematical model used to simulate the energy behavior of SDHWS and different parts of its installation: solar collector, thermal tanks (storage & heaters), tempering valve, and SDHWS-control devices.

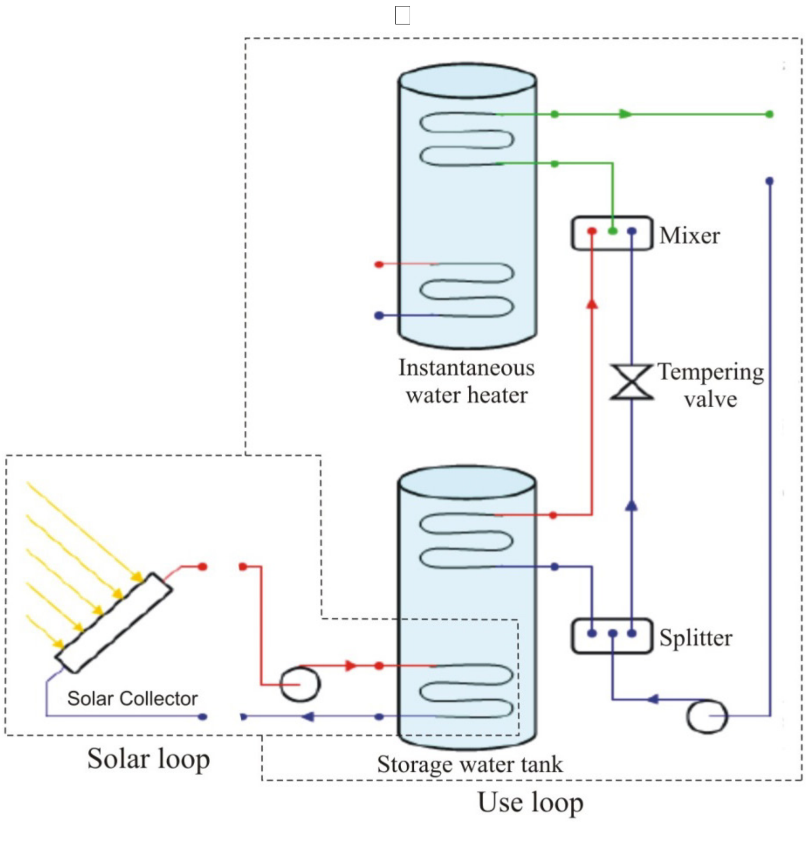

Fig.1 Schematics of SDHWS for heating of DHW (adapted from [12])

EnergyPlus Model for SDHWS: The SDHWS heats DHW by using solar and electric energy. The DHW is used as water for sink, bath, shower, dish washing and cloth washing. The SDHWS is schematically shown in Fig.1 in EnergyPlus environment. The SDHWS consists of the following main elements explained separately in the text below: the solar collector, storage water tank, instantaneous water heater, tempering valve, and temperature controls. These elements are located in two inner loops of the SDHWS: the solar loop and the use loop. The solar loop is a loop through the solar collector. The use loop is a loop for DHW consumption. The solar loop consists of the solar collector, water pump, and spiral pipe heat exchanger (inside the hot water storage tank). The use loop consists of the splitter, storage water tank, instantaneous water heater, tempering valve, and mixer. Inside the solar loop, the solar collector captures solar energy. This energy heats water that flows through the solar collector. Furthermore, the hot water heats DHW in the storage water tank. In the use loop, the cold DW reaches the splitter. From the splitter, the DW may go to the storage water tank or to the tempering valve. In the storage water tank, DW is heated from the solar loop via the spiral pipe heat exchanger. From the storage water tank, the hot water goes to the instantaneous water heater where can be additionally heated. Then the hot water from the instantaneous water heater and the cold water from the tempering valve go to the mixer and after that as DHW to the consumers. The water temperature in the storage tank may be higher or lower than the needed (hot-water set-up) DHW temperature. If this water temperature is higher than the needed DHW temperature, then this water temperature is lowered in the mixer by using the cold DW through the tempering valve. If this water temperature is lower than the needed DHW temperature, this water is heated by electric energy in the instantaneous water heater to the needed DHW temperature.

The investigated solar collector is of flat plate type.

Surface geometry. Calculations require that the solar collector surface is described geometrically. Here, the solar collector is placed to the building roof. The solar collector is rectangular in shape (see Fig.2) with its length designated as (*a*) and its width as (*b*). The building height is designated as h. Finally, the solar collector surface is described by the coordinates of their vertices 1, 2, 3, and 4 in a three dimensional Cartesian coordinate system. This right-hand coordinate system has the *X* axis pointing east, the *Y* axis pointing north, and the *Z* axis pointing up that is characteristics of EnergyPlus Cartesian coordinate system. The vertices are recorded in counter-clockwise sequence (as the surface is viewed from outside its zone).

The solar collector is south facing. Its tilt angle (β) is the angle between the *Z*-axis and the normal to the surface of the solar collector (or between the solar collector surface and the horizontal). The convention assumed here is that $-90^0<\beta<90^0$. The surfaces with positive β face south and with negative β face north. Its azimuth angle (γ) is defined as the displacement angle between the projection on a horizontal plane of the normal to the collector surface and due north. The convention assumed here is that $-180^0 < \gamma < 180^0$.

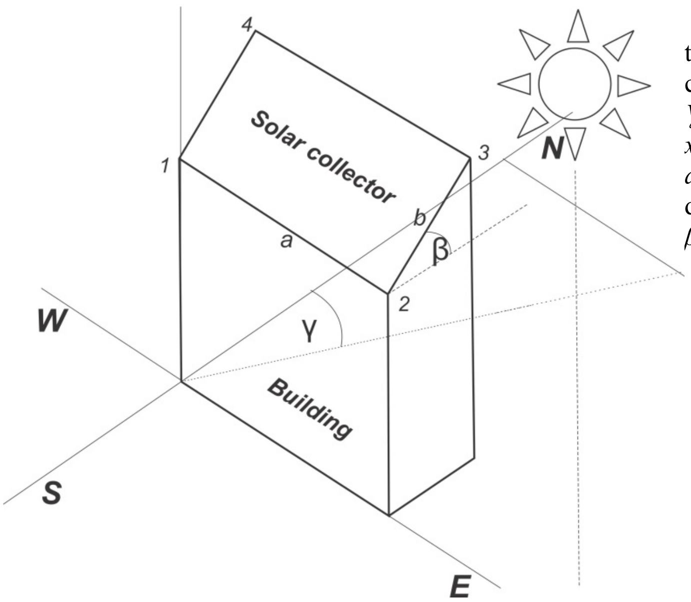

Fig.2. The buiding with the solar collector at its roof. The surface area of the solar collector 1234 is equal to that of the building roof.

The surface of the solar collector is rectangular and defined by 4 vertices. Vertex 1 has coordinates: $x_1 = b \cos\beta \sin\gamma$, $y_1 = b \cos\beta \cos\gamma$, $z_1 = b \sin\beta + h_{12}$. Vertex 2 has coordinates $x_2=0$, $y_2=0$, $z_2=h_{12}$. Vertex 3 has coordinates: $x_3= a \cos\gamma$, $y_3= b \sin\gamma$, $z_3 = h_{12}$. Vertex 4 has coordinates: $x_4 = b \cos\beta \sin\gamma + a \cos\gamma$, $y_4 = b \cos\beta \cos\gamma + a \sin\gamma$, $z_4 = h_{12} + b \sin\beta$.

Calculation of energy consumption : Calculation of energy consumption during the calculation period gives two electrical energies *E* and *R* consumed for DHW production. The energy *E* is consumed by the electric heater when the solar collector is present and operating, and energy *R* is consumed when no solar collector is employed. The objective function is the performance of the installation is evaluated by calculating the solar fraction (*f*) by:

$$f = 100\ (R-E)/R \qquad (1)$$

Solar Collector (Thermal Performance): Solar Collector is of Flat Plate type produced by, Alternate Energy Technologies (AE-32) with length of 3.66m and width of 2.43m. The thermal efficiency of a collector is defined as

$$\eta=(q/A)/I_{solar} \qquad (2)$$

where q = useful heat gain, A = 8.89m^2 gross area of the collector, and I_{solar} = total incident solar radiation. Note that the efficiency η is only defined for $I_{solar} > 0$.

For η, the following quadratic correlation is used

$$\eta = c_0 + c_1 \frac{(T_{in} - T_{air})}{I_{solar}} + c_2 \frac{(T_{in} - T_{air})^2}{I_{solar}} \qquad (3)$$

Both first- and second-order efficiency equation coefficients from [12] are given as c_0 = 0.691, c_0 = 3.396 W/m2-K, and c_0 = 0.00193 W/m^2K^2.

Solar Collector (Incident Angle Modifiers): As with regular windows the transmittance of the collector glazing varies with the incidence angle of radiation. Usually the transmittance is highest when the incident radiation is normal to the glazing surface. Test conditions determine the efficiency coefficients for normal incidence. For off-normal angles, the transmittance of the glazing is modified by incident angle modifier coefficients by the equation:

$$K_{\tau\alpha} = (\tau\alpha)/(\tau\alpha)_n = 1+b_0(-1+\cos\theta)+ b_1 (-1+\cos\theta)^2 \quad (4)$$

The incident angle modifier coefficients b_0= -0.1939 and b_1= -0.0055 are usually negative [12]. and only valid for incident angles of 60 degrees or less. Because these curves can be valid yet behave poorly for angles greater than 60 degree, the EnergyPlus model cuts off collector gains for incident angles greater than 60 degrees.

Thermal tanks (storage & heaters): Water thermal tanks are devices for storing thermal energy in water from the SDHWS. The input object of EnergyPlus (WaterHeater:Mixed) provides a model that simulates a storage water tank (well-mixed water tank), and also instantaneous water tank (tankless water heater). The storage water tank has volume of 0.75 m^3.

Tempering Valve: In certain solar hot water and heat recovery situations, a thermal storage tank may become warmer than is necessary or allowable for safe use of the hot water. The tempering valve acts to divert flow through the branch it is on in order to adjust the temperature at the outlet of the mixer.

SDHWS-Control temperatures for solar loop: To control use of this installation, several temperatures will be supported in the solar loop by using the control equipment inside this installation. Its maximum flow rate is 0.00006 m^3/s. Main parameters of solar heating installation for water loop through the solar collector are the following Loop temperature (T_L=60^{0}C), High temperature turn off in solar loop (60^{0}C), High temperature turn on in solar loop (0^{0}C), Temperature difference on limit (differential thermostat) (10^{0}C), Temperature difference off limit (differential thermostat) (2^{0}C).

SDHWS-Control temperatures for use loop: To control use of this installation, several temperatures will be supported in the use loop by using the control equipment inside this installation. Main supported temperatures are are the hot water setpoint temperature (T_H=50^{0}C) and the maximum temperature limit for storage tank (82.2 ^{0}C).

4. SIMULATION AND OPTIMIZATION

For simulation and optimization to run, it is necessary to know the hot water consumption and climate.

Hot Water Consumption: This installation generates four different types of hot water: that of tap, shower, dish-washer, and cloth-washer. Fig.3 provide hot water characteristics: temperatures, maximum flow rates and daily schedules that may be valid for family of four in Serbia. Regarding its application, the water would be heated to two temperatures: 43.3 (tap and shower with the maximum flow rate of 0.0000945 m^3/s) and 50^{0}C (dish and clothes washer with the maximum flow rate of (0.000063 m^3/s). For water with lower temperature and for water with higher temperature used in dish washer, the daily schedule is the same for each day throughout entire summer. The cloth washer operates only on Sunday. For water with higher temperature used in the cloth washer, the daily schedule is the same for each Sunday throughout the entire summer.

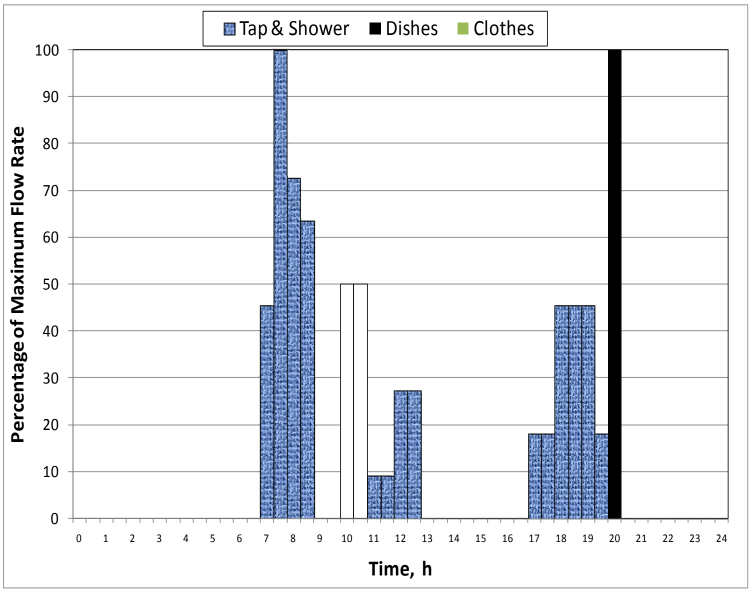

Fig. 3 Schedule of hot water use for (a) tap and shower, (b) dish and clothes washer.

Weather: The location of the facility under analysis is critical for the determination of energy consumption. In EnergyPlus, both external (i.e, weather files supplied from others) and internal weather data is used during simulations. The “Site:Location” input object includes parameters that allow EnergyPlus to calculate the solar position (using Latitude, Longitude and Timezone) for any day of the year as well as supply the standard barometric pressure (using elevation). Weather files have hourly or sub-hourly data for each of the critical elements needed during the calculations (i.e., Dry-Bulb Temperature, Dew-Point Temperature, Relative Humidity, Barometric Pressure, Direct Normal Radiation, Diffuse Horizontal Radiation, Total & Opaque Sky Cover, Wind Direction, Wind Speed) as well as some auxiliary data such as Rain or Snow.

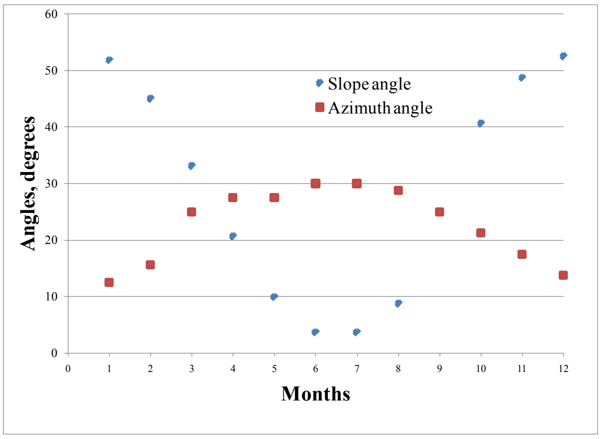

Fig.4 Optimal collector slope and azimuth angle for different months for the collector located in Belgrade, Serbia

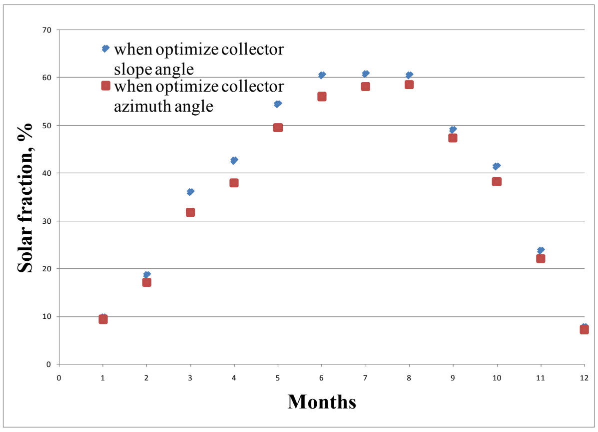

Fig.5 Solar fraction for different months for the collector located in Belgrade, Serbia

5. RESULTS AND DISCUSSION

To use SDHWS adequately, it must be satisfactory designed, installed, and operated. In this paper, we report how the optimal installation of the SDHWS can be achieved by using EnergyPlus software with the modified Hooke Jeeves direct search algorithm. As an example, these software tools are applied to SDHWS in Belgrade, Serbia. Figure 4 shows the optimal collector slope and azimuth angle for different months for the collector located in Belgrade, Serbia. Figure 5 shows the solar fraction of solar collector due to south, calculated for each month during entire year. The first curve shows the maximum values of solar fraction when only the slope angle of the solar collector is optimized. The second curve shows the maximum values of solar fraction when the slope and azimuth angles are optimized for different months for the collector located in Belgrade, Serbia.

6. CONCLUSION

To use SDHWS with benefit, it has to be optimally designed, installed, and operated. In this paper, we report how the SDHWS can be optimally installation achieved by using EnergyPlus software with the modified Hooke Jeeves direct search methodology. As an example, the optimum slopes and azimuth angles of solar collector due to south and the collected solar energy are calculated for each month during entire year that enable the maximum amount of the solar energy and the solar fraction for SDHWS in Belgrade, Serbia.

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