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OPTIMIZATION PERFORMANCES OF A SOLAR DOMESTIC HOT WATER SYSTEM USING TAGUCHI METHOD

ABSTRACT
In Serbia, it is usually to use electrical energy for domestic hot water (DHW) heating. About 70% of electrical energy is produced by using coal with high greenhouse emission, so it is beneficial to environment to use solar energy for heating of DHW in solar DHW system (SDHWS). In addition, it is important to have the highest possible efficiency of this use that may be obtained for the solar collector placed at its optimal position. It is very important to maximize the value of the solar fraction during a SDHWS operation. With computer software EnegyPlus and Hooke-Jeeves algorithm, it was obtained the limit values of the slope and azimuth angle of the solar collector in SDHWS during year for Belgrade, Serbia. The used weather data are from the meteorological station. In this paper, it is stated that Taguchi design is suitable for analyzing in a systematic and simple way the maximum values of the solar fraction of the output parameters for various SDHWSs in the function of numerous optimal positions of the solar collector in the SDHWS, as well as which parameters have the greatest influence on the solar fraction, for Belgrade, Serbia.
Keywords: Optimization; SDHWS; Solar Fraction; Solar collector; Taguchi method

Optimizacija performansi sistema za zagrevanje sanitarne tople vode korišćenjem taguči metode

SAŽETAK
U Srbiji se najčešće električna energija koristi za zagrevanje sanitarne vode (SV). Kako se oko 70% električne energije dobija korišćenjem uglja koji oslobađa veliki broj gasova sa efektom staklene bašte, korišćenje solarne energije za zagrevanje sanitarne vode u solarnim sistemima za zagrevanje sanitarne vode (STV) ima povoljan uticaj na očuvanje životne sredine.Pored toga, važno je postići najveću moguću efikasnost koja se može dobiti za solarni kolektor postavljen u optimalni položaj. Vrlo je važno maksimizirati vrednosti solarnog udela tokom rada STV-a. Korišćenjem softvera EnegyPlus i Hooke-Jeeves algoritma dobijene su granične vrednosti ugla nagiba i ugla azimuta solarnog kolektora u STVu u toku godine za Beograd, Srbija. Korišćeni vremenski podaci su iz ovlašćenih meteoroloških stanica. U ovom radu Taguči metodom su na jednostavan i sistematičan način analizirane dobijene maksimalne vrednosti solarnog udela, kao izlaznog parametra. Korišćeneni su različiti STV u funkciji broja optimalnih položaja solarnog prijemnika. Takođe je analiziran i uticaj ulaznih parametra (ugla nagiba i ugla azimuta) na solarni udeo, za Beograd, Srbija.
Ključne reči: Optimizacija; STV; Solarni udeo; Solarni prijemni; Taguči metod

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 nonpolluting energy sources such as solar energy, instead of fossil fuels. Also, another im-portant advantage of the usage of solar energy is that it does not pollute the environment with nitrogen oxides and sulfur dioxide.

In Serbia, it is customary to use electricity for operation of solar domestic hot water systems (SDHWS). As around 70% of electricity is produced by using coal with high greenhouse emission, it is important to use solar energy for domestic water heating. In addition it is important to have a high efficiency of this use.

In households, the high amount of domestic hot water (DHW) is used for shower, tap, cloth-washing (machines), and dish-washing (machines). If this water is heated by electricity which is generated by coal burning, then the highest amount of CO_2 is released to atmosphere. Accordingly, the most rewarding application of solar energy is when it replac-es this type of electrical energy for heating of hot water in households. Then, the highest decrease in CO_2 emissions may be expected. In renewable energy field, SDHWS have arisen a great research interest [1,2,3]. To use SDHWS with the greatest benefit, SDHWS must have adequate design, installation, and operation.

In this paper, it is stated that Taguchi design is suitable for analyzing in a systematic and simple way the maxi-mum values of the solar fraction of the output parameters for various SDHWSs in the function of numerous optimal positions of the solar collector in the SDHWS, as well as which parameters have the greatest influence on the solar frac-tion, for Belgrade, Serbia. The mathematical model was developed in EnergyPlus simulation environment and the op-timization was performed by using Hooke-Jeeves search algorithm. When forming the Taguchi matrix as the output parameter, the solar fraction is observed. The solar fraction was calculated by simulation and optimization routines, using the Hooke Javes algorithm and observed for two different months (July and August), three different angles tilt (5^o, 10^o and 15^o) and three different angles azimuth (20^o, $30^o$and 40^o) [4-9].

2 MATHEMATICAL MODEL

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.

SDHWS serves to heat domestic hot water. The system heats the water by using solar energy and electric energy. The domestic hot water is used for heating of sink water, bath and shower water, and water for dish washing and cloth washing machines. Schematic of the solar hot-water system for heating of domestic hot water in is shown in Fig.1. The system

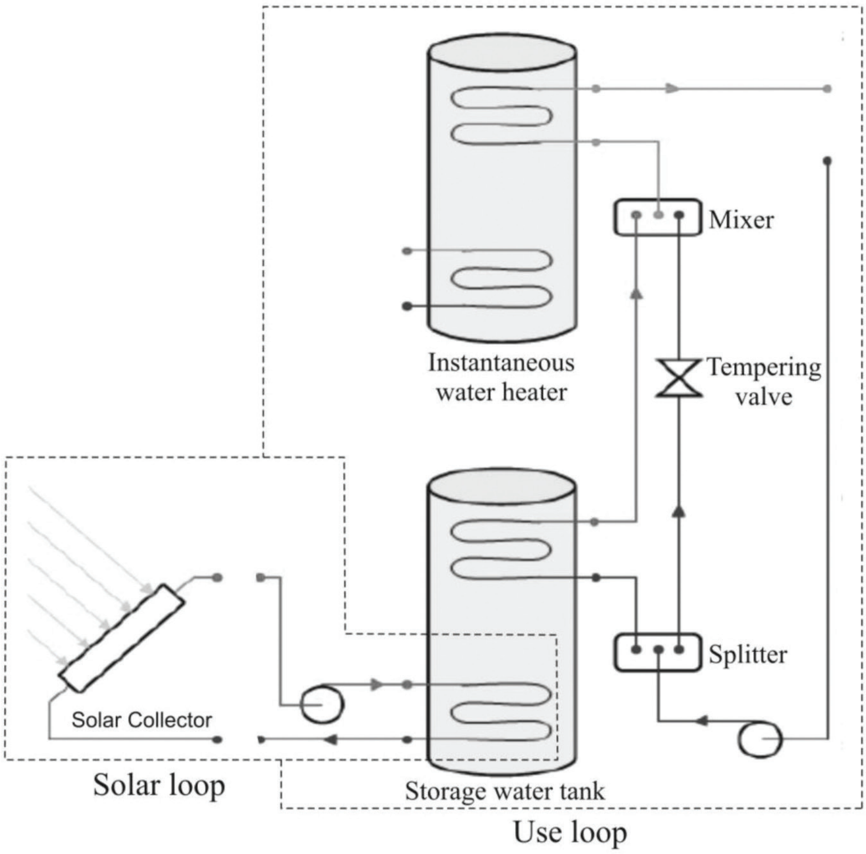

Fig.1 *Schematics of the solar hot-water system for heating of domestic hot water (taken from* [8])

consists of the solar collector, storage tank, instantaneous heating tank, and tempering valve. Solar energy is captured by using solar collector. This energy heats water that flows through the collector. Furthermore, the water from collector heats water in the storage tank to some temperature that may be higher or lower than the needed (hot-water set-up) temperature. If this temperature is higher than the needed temperature, then this temperature is lowered by using cold water through the tempering valve. If this temperature is lower than the needed temperature, this water is heated by electric energy in the instantaneous water heater.

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 objec-tive function is the performance of the installation is evaluated by calculating the solar fraction (*f*) by:

$$f=100(R-E)/R=f(\beta_i, \gamma_i) \quad (1)$$

If $f=f_i$ is larger, the SDHWS better protects the environment. Variable f_i is a function of tilt β_i and azimuth angle γ_i. It should be maximized in the constrained region of β_i and γ_i. As a result of the optimization, we obtain the maxi-mum solar fraction $f_{i,max}$, and the optimum tilt $\beta_{i,opt}$, and optimum azimuth angle $\gamma_{i,opt}$.

Each solar collector that stays at optimal position generates the highest amount of heat from the incident solar energy. Then, the SDHWS uses this heat for the DHW heating instead of the electrical energy from the electricity net-work. This means that such a SDHWS avoids use of the highest amount of electrical energy from the electricity grid for the DHW heating. In addition, this avoids the highest amount of electrical energy generation by the national power plants [7].

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.

Thermal tanks (storage & heaters): Water thermal tanks are devices for storing thermal energy in water from solar hot water systems. The input object of Energy Plus (Water Heater: Mixed) provides a model that simulates a well-mixed water tank (the thermal tank) with volume of 0.75 m^3, and also instantaneous, tank less water heater.

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 (TL=60ºC), High temperature turn off in solar loop (60ºC), High temperature turn on in solar loop (0ºC), Temperature difference on limit (differential thermostat) (10ºC), Temperature difference off limit (differential thermostat) (2ºC).

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=50ºC) and the maximum temperature limit for storage tank (82.2ºC).

Hot Water Consumption: This installation generates four different types of hot water: that of tap, shower, dish-washer, and cloth-washer. 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 50ºC (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.

Climate Calculations: Weather data: The investigated SDHWS is located in the city of Belgrade. These are ei-ther measured by the meteorological stations or calculated by the software Meteonorm for sites where data from me-teorological stations are not available. Belgrade has the average height above sea-level of 99 m. Its latitude is 44.82ºN, longitude 20.27ºE, and time zone GMT +1.0 Hours. To familiarize with the Belgrade climate, Figs.2 and 3 are given by using monthly statistics for the Belgrade weather file.

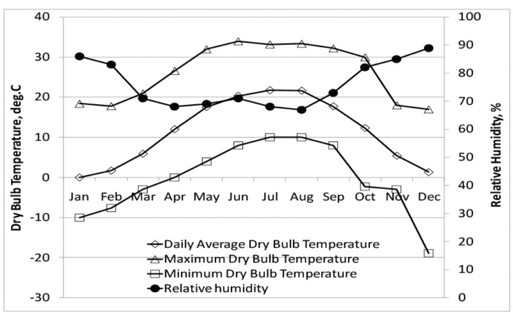

Fig.2 *Relative humidity and dry bulb temperature (minimum, daily average and maximum) from the monthly statistics for Belgrade, Serbia from Belgrade weather file.*

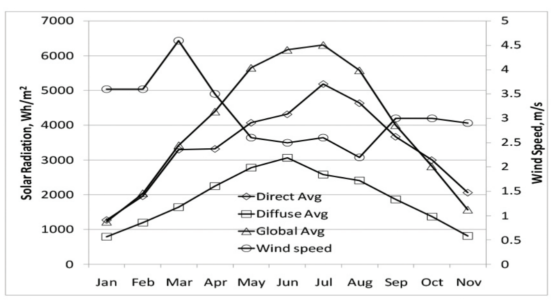

Fig.3 *Direct, diffuse, and global average solar radia-tion, and daily average wind speed from the monthly statistics for Belgrade, Serbia from Belgrade weather file.*

3 EXPERIMENTAL DESIGN

When forming the Taguchi matrix as the output parameter, the solar fraction is observed. The solar fraction was calculated by simulation and optimization routines, using the Hooke Javes algorithm and observed for two different months (July and August), three different tilt angles (5o, 10o and 15o) and three different azimuth angles (20o, 30o and 40o). Factors which have an influence on solar fraction are given in Table 1 [8].

Control factors	Units	Level I	Level II	Level III
(A) month	-	1	2	
(B) Angle tilt		5	10	15
(C) Azimuth angle		20	30	40

Table 1. *Levels for various control factors*

For the experimental design, the orthogonal matrix L18 (Table 3) was obtained using the Taguchi design [9-13]. In order to obtain an orthogonal matrix, the Minitab 16 statistical tool was used. In this paper, the S/N ratio ("greater is better") is used in the analysis of the solar fraction. The equation for calculating the S/N ratio is " greater is better" is:

$$S / N = -10 \log \frac{1}{n} \left(\sum y_i^{\,2} \right) \quad (2)$$

Where:
- S/N is the signal-to-noise ratio,
- n is the repetition number of each trial and
- y_i is the result of the i-th experiment for each trial.

The S/N ratio for each level of control parameters is calculated on the basis of S/N analysis of the solar fraction. In our case, the S/N ratio is obtained using the Minitab 16 statistical tool for all combinations of input parameters.

Experimental results for the solar fraction are shown in Table 2, obtained using the orthogonal matrix L18. Solar fractions are given for all input parameter values. Table 2 also shows S/N relations for the solar fraction.

4 RESULTS AND DISCUSSION

The average values of the S/N ratio are calculated for each level of the discussed input parameters in relation to the solar fraction (Table 3). Based on the results of the S/N ratio (Table 3, Figure 4, 5), it can be determined which of the above factors has the greatest influence on the solar fraction. In the case under consideration, the most significant effect on the solar fraction is the month in which the calculation is made, then the azimuth angle and the tilt angle.

Level	Month	Angletilt	Azimuth angle
1	35.56	35.64	35.66
2	35.72	35.66	35.69
3		35.63	35.58
Delta	0.16	0.03	0.11
Rank	1	3	2

Table 3. *Response Table for Signal to Noise Ratios for better is better*

Figure 4 shows the influence of the parameters under consideration on the solar fraction. The analysis of the experimental values of the solar fraction over S/N ratio gives the optimum value of the solar fraction. The optimum value of the solar fraction is obtained when the influential factors are at the next level (A2, B2 and C2) (Figure 4). Figure 4 shows that the solar fraction is higher in the second month, i.e. in August, than in July. Solar fraction grows when tilt angle

L18	Month	Angle tilt	Azimuth angle	Solar fraction	S/N ratio for solar fraction
1	1	5	20	60.2563	35.6001
2	1	5	30	60.414	35.6228
3	1	5	40	59.6751	35.5159
4	1	10	20	60.1722	35.5879
5	1	10	30	60.5242	35.6386
6	1	10	40	59.6909	35.5182
7	1	15	20	59.9493	35.5557
8	1	15	30	60.1312	35.582
9	1	15	40	59.3066	35.4621
10	2	5	20	61.0952	35.7201
11	2	5	30	61.1627	35.7297
12	2	5	40	60.6702	35.6595
13	2	10	20	61.3863	35.7614
14	2	10	30	61.6131	35.7935
15	2	10	40	60.7411	35.6697
16	2	15	20	61.1994	35.7349
17	2	15	30	61.4872	35.7757
18	2	15	40	60.6397	35.6551

Table 2. *Experimental design using L18 orthogonal array*

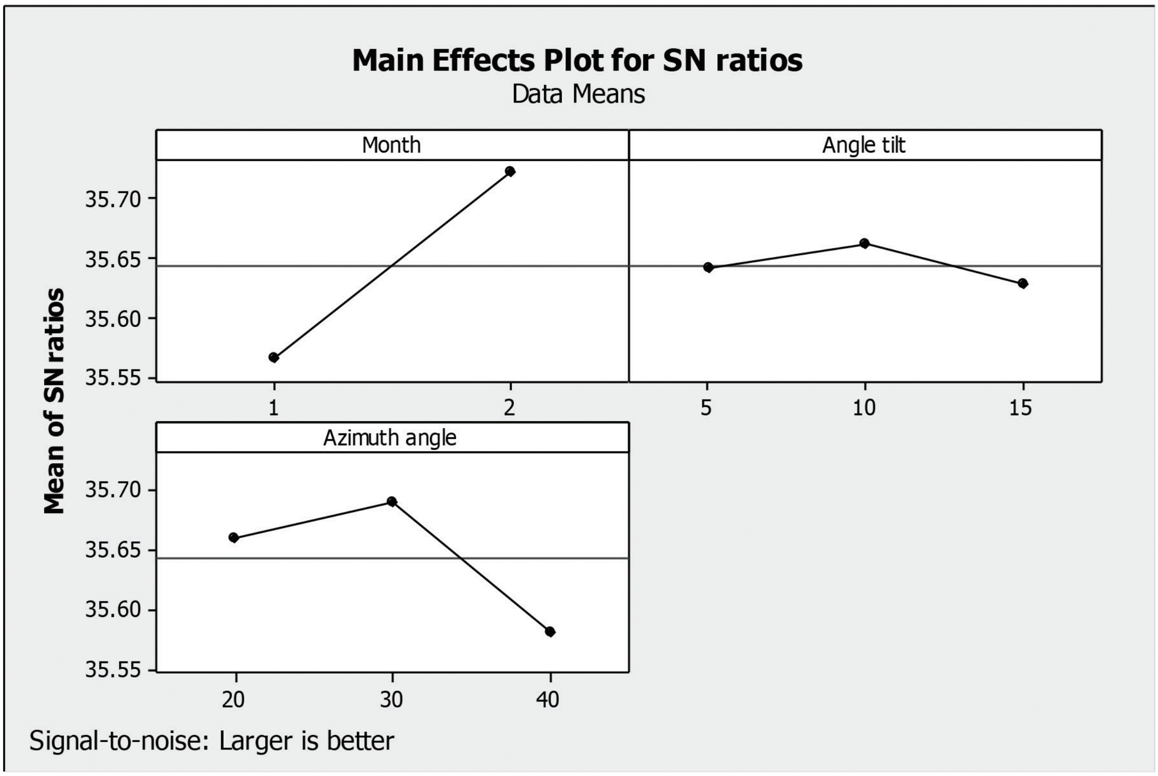

Fig. 4. *Main effects plot for S/N ratio for the solar fraction*

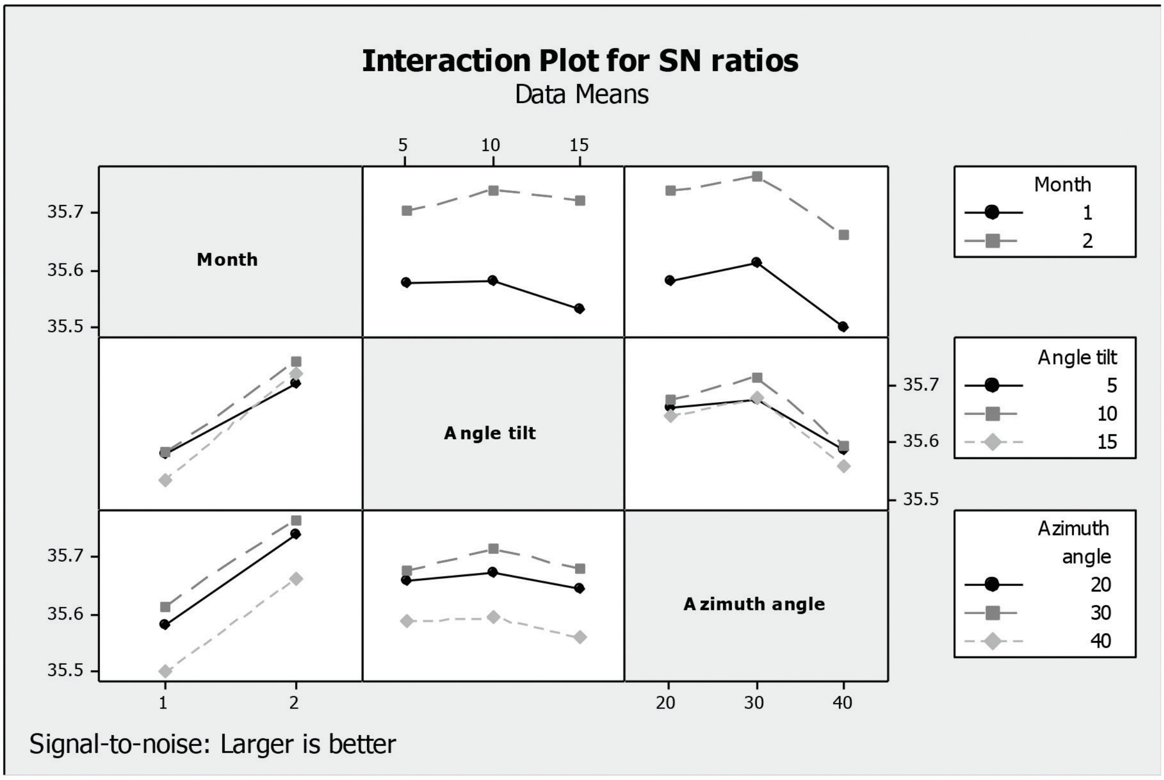

Fig. 5. *Interaction plot for S/N ratio for the solar fraction*

increase from 5^0 to 10^0, and then solar fraction decreases. Also, the solar fraction increases with increasing azi-muth angle from 20^0 to 30^0, and then decreases.

Figure 5 shows the interactions between individual parameters and their mutual influence on the solar fraction.

4.1 Analysis Of Variance

Analysis of the influence of the input parameters on the solar fraction was done using the ANOVA analysis, us-ing the Minitab 16 software. The influences of certain factors and their interaction on solar fraction are shown in Table 4. The last column shows the percentage impact of certain factors as well as their interactions. This analysis was done for the level of significance of α=0.05, ie. for a level of confidence of 95%. Sources with a P-value less than 0.05 were considered to have a statistically significant contribution to performance measures.

In the last column of Table 4 it can be seen that the month in which the solar fraction is measured has the great-est impact of 70.36%. A much smaller impact on the solar fraction has a change in angle azimuth (24.59%) and tilt angle (2.21%). The interaction of the Month* Angle tilt interaction is only relevant (2.02%). The influence of other interactions can be ignored.

On the basis of obtained factores in Figures 6 and 7 are given 2D and 3D diagrams of relation of angle tilt and angle azimuth on solar fraction, respectively.

4.2 Multiple Regression Model

The multi-linear regression model was developed using the Minitab 16 statistical software. This model shows the relationship between the influencing parameters and it can be represented by a linear equation. The regression equation in this way creates a connection between the influence parameters obtained by ANOVA analysis. The sign in front of an influential parameter shows its impact. The regression equation shown in expression 2 confirms the ANOVA analy-sis, ie. It confirms that the solar fraction is larger in the second month (plus sign). Otherwise the solar fraction decreases with increasing angle tilt and angle azimuth (sign minus).

The regression equation is

Solar fraction = 59.8 + 1.10 Month - 0.0093 Angle tilt - 0.0278 Azimuth angle

S = 0.307293 R-Sq = 82.8% (3)

Figure 8 shows a comparison between the actual test results and the predicted values obtained by the linear re-gression model.

5 CONCLUSION

The Taguchi design can be successfully used to analyze the problem of the solar fraction as described in the pa-per. From this analysis, the following general conclusions can be drawn:

The solar fraction is higher in the second month. It decreases with increasing angle of inclination and azimuth.

The largest solar fraction occurs in the second month, i.e. In August, at the angle of inclination of 10^0 and at az-imuth of 30^0.

Taguchi design is suitable for analyzing the problem of solar fraction as described in the paper. This method provides a systematic, efficient and very simple methodology for optimizing parameters that affect the value of the solar fraction

The largest impact on the solar fraction is the month in which the measurement is carried out and amounts to 70.36%. A much smaller impact on the solar fraction has a change in the angle of the azimuth (24.59%) and the angle of inclination (2.21%). The interaction of the Month* Angle tilt interaction is only relevant (2.02%). The influence of other interactions can be ignored.

Using the statistical software MINITAB 16, the linear regression equation of the dependence of the solar frac-tion on the month, angle of inclination and azimuth has been developed.

The estimated S/N ratio for the wear could be calculated using the optimal testing parameters rate, and a good agreement between the predicted and actual solar fraction was observed for a confidence level of 99.5%.

ACKNOWLEDGMENT

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Source	DF	Seq SS	Adj SS	Adj MS	F	P	Pr
Month	1	0.111490	0.111490	0.111490	962.10	0.000	70.36
Angle tilt	2	0.003499	0.003499	0.001750	15.10	0.014	2.21
Azimuth angle	2	0.038964	0.038964	0.019482	168.12	0.000	24.59
Month*Angle tilt	2	0.003194	0.003194	0.001597	13.78	0.016	2.02
Month*Azimuth angle	2	0.000089	0.000089	0.000044	0.38	0.704	0.06
Angle tilt*Azimuth angle	4	0.000765	0.000765	0.000191	1.65	0.320	0.48
Residual Error	4	0.000464	0.000464	0.000116			0.29
Total	17	0.158465					100

Table4. *Analysis of Variance for SN ratios for solar fraction*

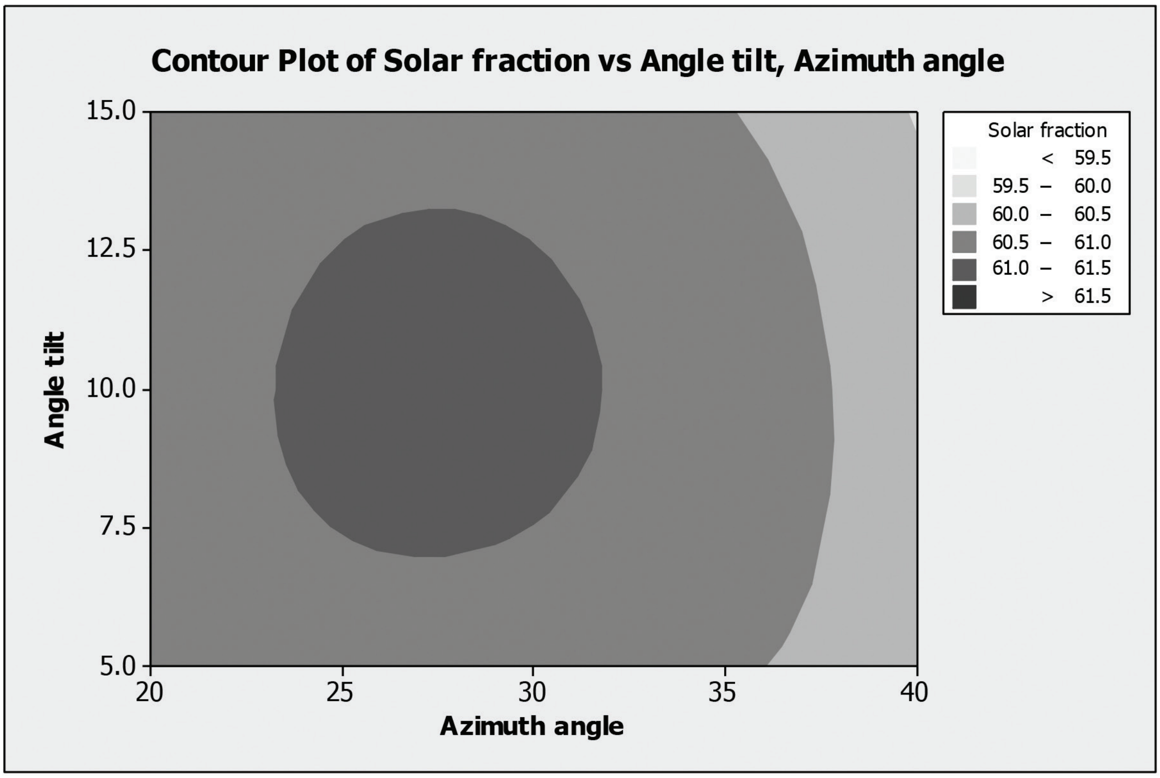

Fig. 6. *Contour plot for dependence between solar fraction of the angle tilt and azimuth angle*

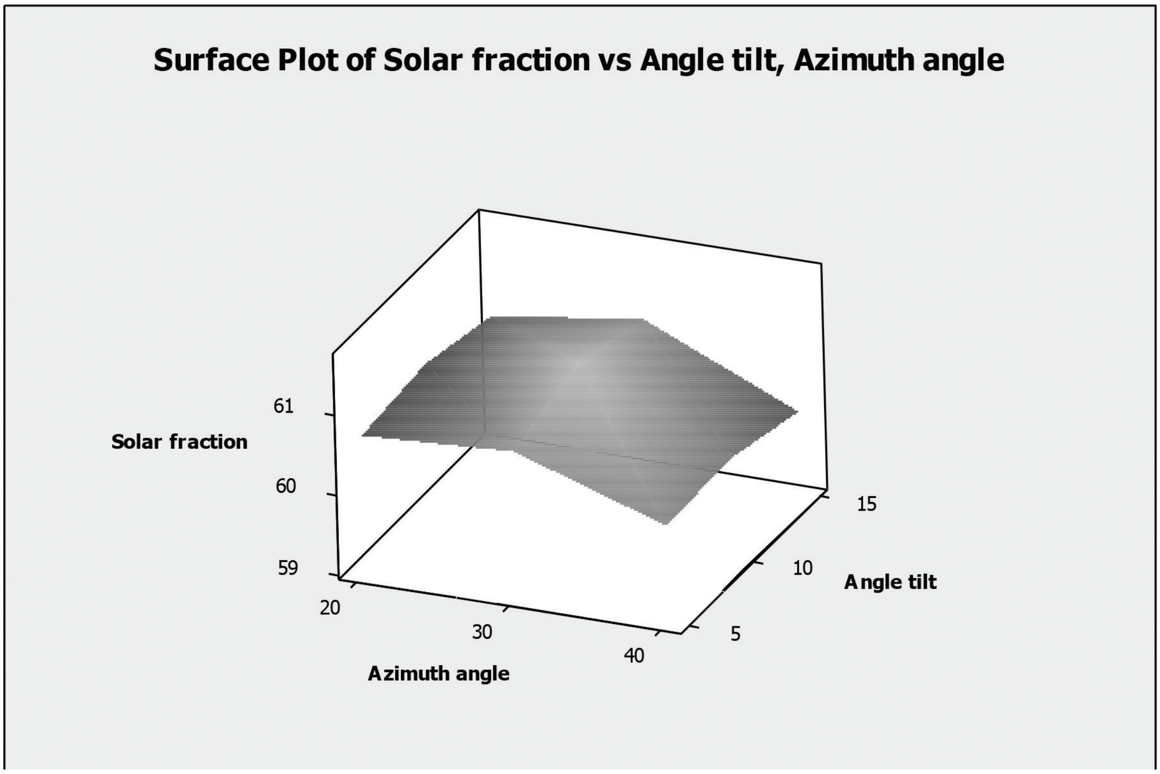

Fig. 7. *Surface plot for dependence between solar fraction of the angle tilt and azimuth angle*

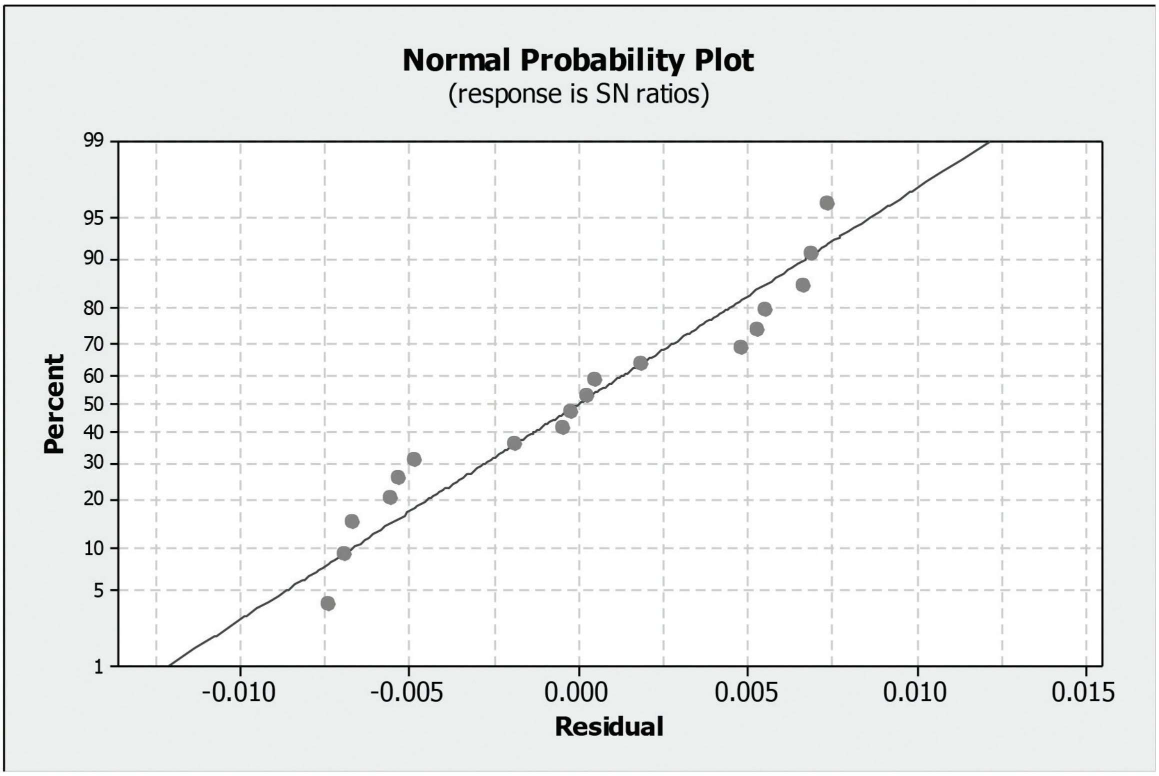

Fig. 8. *Comparison of the linear regression model with experimental results for the solar fraction*

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