OPTIMIZACIJA GEOMETRIJSKIH PARAMETARA RADI AUTOMATIZACIJE PROJEKTOVANJA SOLARNIH KOLEKTORA

OPTIMIZATION OF GEOMETRIC PARAMETERS TO AUTOMATE SOLAR COLLECTOR DESIGN

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U ovom radu izvršeno je određivanje geometrijskih parametara solarnih kolektora optimizacionim metodama. Razvijen je matematički model za određivanje povoljnih geometrijskih karakteristika solarnih kolektora u cilju maksimizacije njihovog iskorišćenja. Optimalno rešenje kreirano je za geometrijske karakteristike kolektora sa cevima kruznog poprečnog preseka i kolektora sa cevima pravougaonog poprečnog preseka. Izvršena je uporedna analiza iskorišćenja oba tipa kolektora. Rezultatima ovog istraživanja predstavljen je značaj primene optimizacije i parametarskog modeliranja u projektovanju kolektora. Ova rešenja mogu se mogu jednostavno primeniti u praksi. Na kraju rada je izvršena diskusija rezultata i date su smernice daljih istraživanja.

Ključne reči: *solarni kolektori, faktor iskorićenja, optimizacija, parametarsko modeliranje.*

In this paper the determination of geometric parameters for solar collectors using optimization methods. A mathematical model has been developed for determining beneficial geometric characteristics of solar collectors with a goal to maximize their utilization. An optimal solution was created for geometric characteristics of a collector with circular pipes and a collector with rectangular pipes. A comparative utilization analysis was performed for both types of collectors. Results of this research present the importance of using optimization and parametric modeling in designing collectors. These solutions can be simply be used in practice. The paper concludes with a discussion of results and directions for possible further research.

Key words: *solar collectors, utilization factor, optimization, parametric modeling.*

I. Introduction

Direct sunlight energy can be used in practice for its transformation into heat, electric, or chemical energy. The most widespread use of solar energy is an application of solar collectors for heating water. Solar collectors are devices which by absorbing solar rays turn radiation energy into heat for fluids which flow through the collector. The fluids found in most uses in solar collectors for converting solar into heat energy are air and water. Regarding construction, solar collectors are divided into flat and focusing. Flat collectors absorb global solar radiation and convert it into heat up to 100^0 C, while focusing collectors using optical systems can achieve temperatures up to 3000^0 C. Optimization of solar collectors presents very attractive research field. The development of construction and technology of flat solar collectors was done in order to increase their level of efficiency, and decrease their price and other side effects.

Farahat et al. [1] optimized solar collectors based on influential parameters to improve their performance. Many of the collector parameters were included in this research, such as: absorber plate area, overall collector dimensions, circular pipes diameter, input and output temperature, heat losses and many others. Badache et al. [2] optimized thermal characteristics of solar collector based on influential parameters and experimental results. The authors determined how to choose optimal performance to improve collector efficiency. In the research [3] Vargas et al. maximized solar collector performance based on their real-time application. Szargut & Stanek [4] optimized the solar collectors from thermo-ecological side. This research does not consider inner installation parameters. Optimization of collector types against climate conditions was performed by Luminosu and Fara [5]. Ghoneim [6] researched optimal collector performance from the side of the collector inside elements with square-celled honeycomb positions. The multidisciplinary optimization with experimental and numerical results was presented in [7]. Kalogirou [8] applied artificial intelligence and genetic algorithm optimization in this research area. In [9], authors developed mathematical model for determination of optimal characteristic of solar collectors with one or two collector glass cover with air space inside the collector. Kundu [10] conducted optimization to increase performance of the absorber plate. Morawietz & Hermann [11] used method of multidisciplinary optimal design for optimization of the solar collector pipes. The previous optimization research did not yield to automation of the collector design.

This paper presents research to optimize and automate the collector design by optimization the absorber with pipes. To achieve this, a mathematical model was created for calculation of the optimal dimensions of the absorber plate with pipes. Then, a comparative analysis of circular and rectangular piped collectors was performed. The diagrams of all solutions were given and discussed. Paper concludes with parametric CAD model of optimal collector to automate a design of the solar collector.

II. Problem formulation

To choose optimal geometric parameters, it was necessary to prepare an appropriate mathematical model, for the case of circular and rectangular pipes. For both cases as an objective function, the efficiency factor *F'* of a flat solar collector was taken into account. To compare use of collectors with circular and rectangular pipes, the following assumptions were made such as: 1) the inner section area through which the fluid flows must be equal for both circular and rectangular pipes, 2) the total heat loss coefficient U_L must be equal for both cases, 3) the absorber thickness δ must be equal for both cases, 4) the pipe wall thickness *t* must be equal for both cases, and 5) the distance between pipes in the collector W_f must be equal for both cases.

The equation for *F'* for both collectors is taken from [1], and is given as

$$F' = \frac{\dfrac{1}{U_L}}{W_f\left[\dfrac{1}{U_L\left[\left(W_f - D_o\right)F + D_o\right]} + \dfrac{1}{C_b} + \dfrac{1}{\pi D_i H_{fi}}\right]}. \tag{1}$$

Here, C_b stands for the bond conductance, D_i, stands for the circular pipe inside diameter, D_o, stands for the circular pipe outside diameter, *F*, stands for the standard fin efficiency, *F'*, stands for the solar collector efficiency factor, H_{fi}, stands for the heat-transfer coefficient in the conduits, U_L, stands for the overall heat loss coefficient and W_f, stands for the fin width.

The equation for *F* for circular pipes is taken from [1].

$$F = \frac{\tanh\left[M\dfrac{W_f - D_o}{2}\right]}{M\dfrac{W_f - D_o}{2}}. \tag{2}$$

In equation (2) the variable *M* is given for:

$$M = \sqrt{\frac{U_L}{k\delta}} \tag{3}$$

Variables given are k, thermal conductivity of absorber plate (W/m K) and δ, absorber plate thickness (m).

Section view of a collector fin with circular pipes is shown in figure 1.

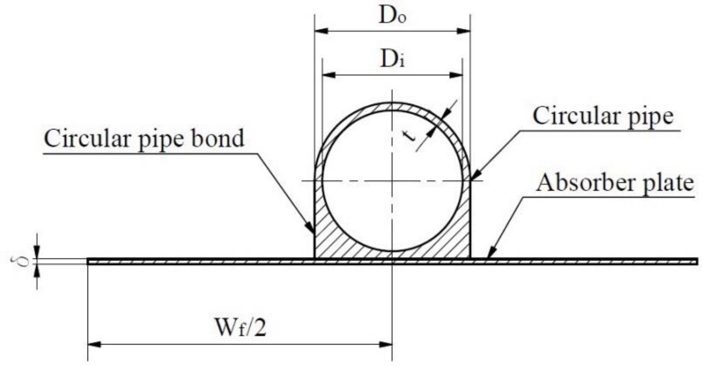

Figure 1 – Collector fin cross-section with circular pipe

A similar equation is used for determining the collector efficiency factor with rectangular pipes:

$$F' = \frac{\dfrac{1}{U_L}}{W_f\left[\dfrac{1}{U_L\left[\left(W_f - W_o\right)F + W_o\right]} + \dfrac{1}{C_b} + \dfrac{1}{2\left(W_i + H_i\right)H_{fi}}\right]} \quad (4).$$

Variables given are W_i, rectangular pipe inside width (m) and W_o, rectangular pipe outside width (m).

Solar collector fin efficiency factor F for collectors with circular pipes is taken from [1]:

$$F = \frac{\tanh\left[M\dfrac{W_f - W_o}{2}\right]}{M\dfrac{W_f - W_o}{2}} \quad (5).$$

Variable M, for collectors with rectangular pipes are also calculated using equation (3). A cross-section view of the collector fin with rectangular pies is shown in figure 2.

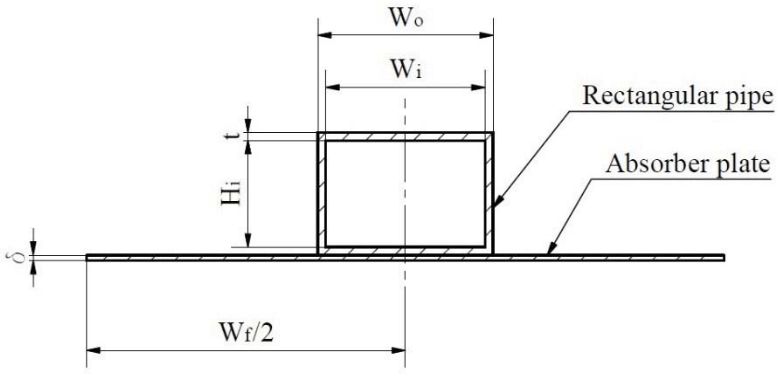

Figure 2 – Collector fin cross-section with rectangular pipe

The ratio of inner width of the rectangular pipe W_i and inner height H_i is 1.5. This ratio is frequent with rectangular cross-section pipes used in collectors.

III. Problem solving methods and discussion of results

To find an optimal solution for both cases, it is necessary to set the objective function and its constraints. Equation (1) was used as the objective function for circular pipe collectors, while equation (4) was used for rectangular pipe collectors. The constraints for values used in the objective functions are taken from suggestions in [2-6], and given in Table 1.

Table 1 – Input parameter (constraints and constants)

Input parameters – Variable constraints				
Symbol	Range	Qty	Unit	Name
W_f	Upper	250	[mm]	Fin width
	Lower	120		
Rectangular cross-section				
W_i	Upper	30	[mm]	Inside width of rectangular pipe
	Lower	5		
H_i	Upper	20	[mm]	Inside height of rectangular pipe
	Lower	3.33		
Circular cross-section				
*D*i	Upper	27.64	[mm]	Inside diameter of circular pipe
	Lower	4.61		
Input parameters – Constants				
t	1.5		[mm]	Pipe wall thickness
δ	1		[mm]	Absorber plate thickness
U_L	4		[W/m^{2}K]	Overall heat loss coefficient
H_{fi}	300		[W/m^{2}K]	Heat transfer coefficient in the conduits
k	400		[W/mK]	Thermal conductivity of the absorber plate
Absorber				
L	1200		[mm]	Absorber length

Values dependent on W_i are labeled yellow. The inner height of the rectangle pipe H_i is calculated from the previously mentioned ratio, while the inner diameter of the circular pipe is calculated by equating its area with the cross section surface area of the rectangular pipe. The coefficient of heat transfer k depends on the choice material of absorber and pipe. The length of solar collector is set according to standard. The calculation was done by using MS Excel.

The optimal solutions for both, rectangular and circular pipes are determined by using the method of random search [14, 15] through 400 iterations to cover all possible cases of variable changes. The random search interval was narrowed four times to get a higher precision of the results as possible. The narrowing of the random search interval was performed after every 100 iterations. The initial interval was given by the variable constraints in Table 1. Parameter W_f was searched from 120 to 250 mm. Parameter W_i was searched from 5 to 30 mm. Parameter D_i was simultaneously calculated for all iterations from the rectangular pipe cross-section area, by formula

$$D_i = \sqrt{\frac{W_i \cdot H_i \cdot \pi}{4}} . \qquad (6).$$

The other parameters in the objective functions (3) and (5), were set as constant. The collector efficiency surface obtained by the random search method for the solar collector with circular pipes is shown in Figure 3.

From figure 3, it can be seen that the collectors with circular pipes had the optimal solution where the W_f was the smallest and D_i the biggest. The collector efficiency factor F' for the optimal solution was 0.977.

The collector efficiency surface for the solar collector with rectangular pipes is shown in Fig.4. This surface is similar to that for the collector with circular pipes, because the areas of both cross sections are connected with expression (6). The optimal results of the solar collector with rectangular pipes are slightly greater than that for the solar collector with circular pipes. The collector efficiency factor F' for the optimal solution in this case is 0.980.

The comparative diagram of the objective functions (3) and (5) is shown in Fig.5. The comparative diagram is given through all of the 400 iterations.

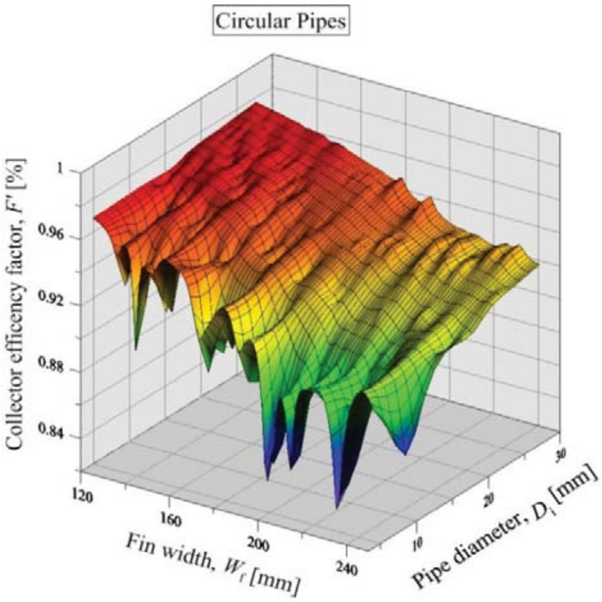

Figure 4 – Collector efficiency surface of the collector with rectangular pipes

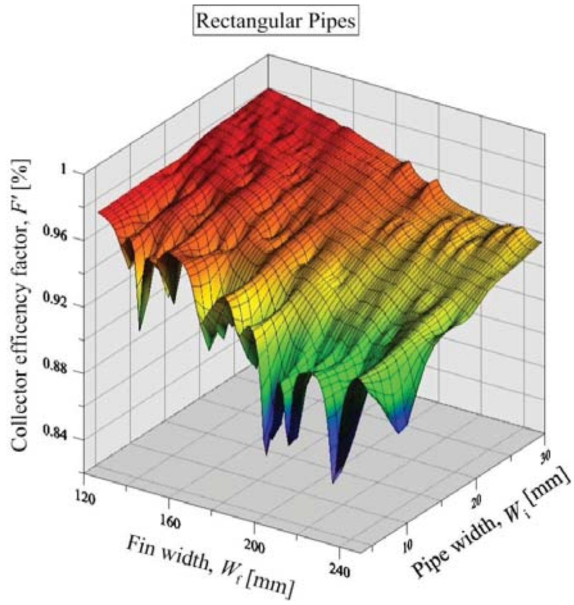

Figure 3 – Collector efficiency surface of collector with circular pipes

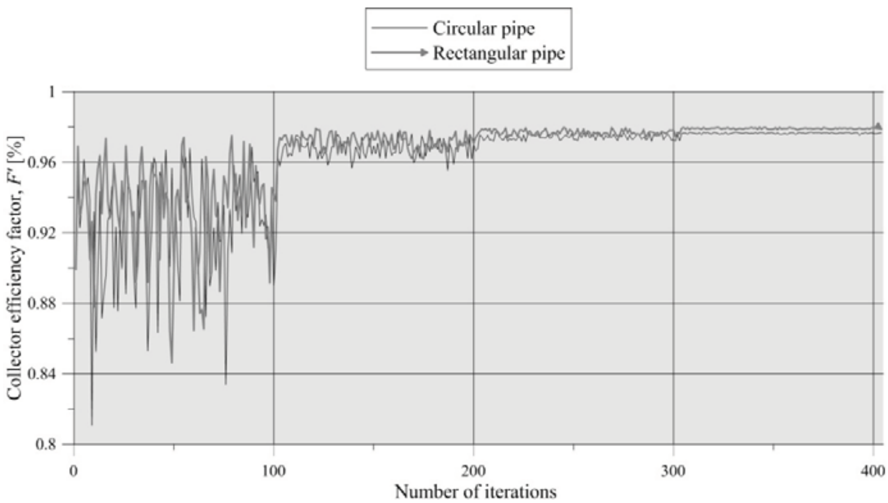

Figure 5 – Comparative diagram of circular and rectangular pipes objective function F' trough all iterations

IV. Collector designing based on optimization results

A. Optimal dimensions

The optimal dimensions for both collectors were found. In every iteration, the collector efficiency factor *F*' was slightly higher for the pipes with rectangular cross-section than that for the pipes with circular cross-section. There is slight advantage of the collector with rectangular pipes to that with circular pipes regarding the collector efficiency factor.

After calculation the optimal dimensions for each case, its design was performed. The design of both solutions was done in Autodesk Inventor software. The achieved results of the collector optimization were directly linked to the design of the absorber plate with pipes. The optimal geometrical parameters are given in Table 2.

The optimal solution of this problem was found at the start of the collector fin width interval W_f and at the end collector pipe dimension interval D_i and W_i a for both collectors. The optimal geometric parameters are given in Table 2. In every iteration, the collector efficiency factor *F*' was slightly higher for the pipes with rectangular cross-section than that for the pipes with circular cross-section.

B. Automation of the collector design

Table 2–Optimal geometric parameters

Symbol	Value	Unit
W_f	120	mm
W_i	30	mm
H_i	20.00	mm
D_i	27.64	mm
t	1.5	mm
Δ	1	mm
N_f	8	ul
L	1200	mm
B	960	mm

To automate a design of the solar collector, first, we establish the optimization model for the collector, and second we establish a parametric CAD model based on the optimal dimensions of the collector. In practice, first we input the non-optimized dimensions of the collector to the optimization model, second we get the optimized dimensions of the collector (given in Table 2) from the optimization model, and third we establish a CAD design. With every change of the input dimensions, we get optimal ones, which are directly linked to the CAD model and final design.

After achieving an optimal solution for both cases their design was performed. Design of both solutions was done in Autodesk Inventor software. The achieved results of the collector optimization were directly linked to the model of the absorber plate with pipes. Figures 6.a and 6.b show optimal CAD models for the input dimensions given in Table 2.

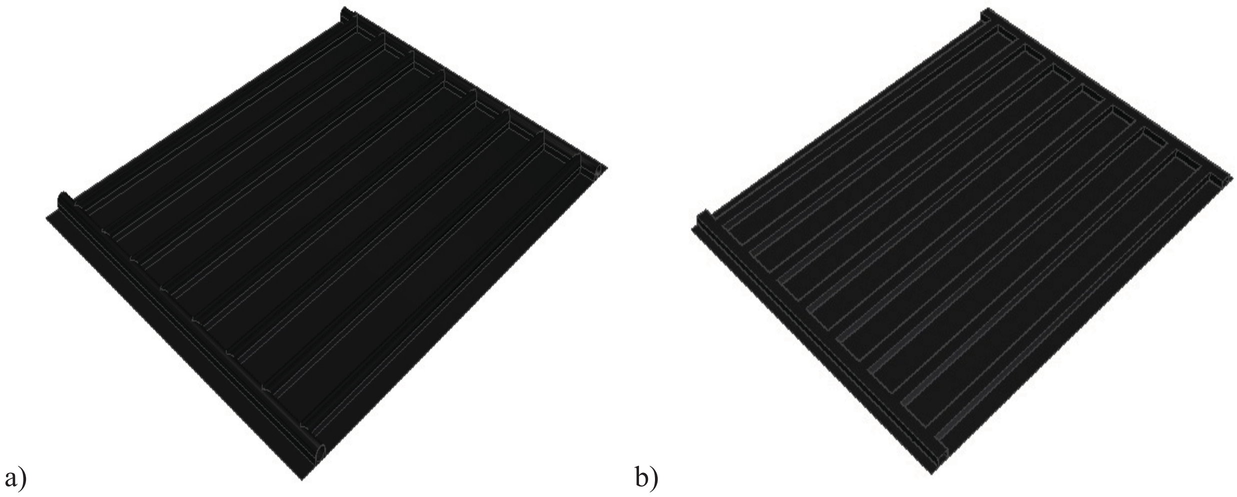

Figure 6– a) Absorber with circular pipes; b) Absorber with rectangular pipes

Figure 6.a shows the CAD model for the case of circular pipes, while figure 6.b shows the rectangular pipe model.

V. Conclusion

In this paper, the change in the collector efficiency as a function of geometry of pipes and the width of a flat solar collector fin was examined and optimized by using random search method. All combinations of variables of pipes for circular and rectangular pipes were considered.

The best solution was achieved when the collector fin width W_f is the smallest, with the largest pipe inner dimensions W_i and D_i. The collector with rectangular pipes had the efficiency 0.3 % higher than that of the collector with circular pipes.

Further research of this problem would require taking into account heat loss as well as a change of the pipe wall thickness and the absorber plate thickness. It is necessary to take into account all types of materials used in solar collector design. To achieve an optimal solution to this problem, a multi criteria optimization should be performed, followed by experimental verification of results.

Nomenclature

C_b, bond conductance (W/m K),
D_i, circular pipe inside diameter (m),
D_o, circular pipe outside diameter (m),
F, standard fin efficiency (-),
F', solar collector efficiency factor (-),

H_{fi}, heat-transfer coefficient in the conduits (W/m^2 K)
H_i, rectangular pipe inside height (m),
k, thermal conductivity of absorber plate (W/m K),
M, quantity defined in equation (3),
t, pipe wall thickness (m),
U_L, overall heat loss coefficient (W/m^2 K),
W_f, fin width (m),
W_i, rectangular pipe inside width (m),
W_o, rectangular pipe outside width (m),
δ, absorber plate thickness (m).

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