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Energy-economic Optimization of Flat-plate Collector

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Abstract

The optimization of solar collector design may be based on energy, economic or energy-economic criteria. Obtaining maximum energy from a given collector area or determining the required minimum area of collector that produces a given amount of energy are examples of energy criteria. Designing a solar collector with a minimum cost is an example of economic criteria. The net present values, internal rate of return and payback period methods are examples of energy-economic criteria. This paper deals with the obtaining collector design parameters that provide the highest net present value. The following design parameters have been accepted as the decision variables: air gap size between the absorber and the cover glazing, emissivity of the absorber, frame insulation thickness, and distance between riser pipes. A detailed analysis is carried out for evaluating the thermal and optical performance, energy flows and losses for typical flat plate solar collector under given operating conditions – producing hot water for household needs. The high-quality flat-plate solar collector was chosen as a reference alternative. The results of modeling indicate that NPV value of solar collector variant with reduced to 50 mm distance between riser pipes is higher than in the reference variant, which indicates that a design change is economically justified.

Keywords: *flat-plate solar collector, optimization, sensitivity analysis, net present value*

1. Introduction

A wide spectrum of flat-plate collectors (FPC) is available on the market today, ranging from low-cost unglazed collectors to sophisticated selective-coated, single-glazed solar collectors. Up to now, a number of studies have been done in order to improve the thermal efficiency of FPC. The ways of increasing the energy performance of solar collector generally can be divided into two categories: effective absorption of solar radiation together with high rate heat transfer from the absorber to a transport media and reduction the heat loss of the collector to the minimum. The increase in optical efficiency can be achieved by application of glazing with antireflective coatings, use of extra clear low-iron glass instead of ordinary float glass together with spectrally selective absorber coatings. The heat transfer from the absorber surface can be maximized by fully wetted absorbers. Heat loss reduction can be achieved especially by using low emissivity absorber coatings, by increasing thickness of back, and by increasing thickness of the air gap between an absorber and collector glazing, alternatively using the low conductive gas instead of the air, or even by evacuating the space between absorber and cover glazing.

However, any improvement in the efficiency of solar collector has its cost. The use of new technologies and new materials always leads to an increase in collector price. Even given thickness of air gap between an absorber and covering glazing has an influence on the cost of the collector because it affects the overall depth of the collector and, thus, the amount of material used in the frame construction. On the other hand, while the solar PV modules price has dropped considerably in the last decades, the price of FPC collectors still remains high and there are no prospects for significant price reduction. Therefore, energy-economic optimization of the FPC has been taken into account in the present paper. Currently, there are not many studies in this area. A critical point, however, is that most of the published studies focused on energy optimization and did not take into account economic effects of the optimization.

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Furbo and Shan (2003) investigated the influence of antireflection treatment on the thermal performance of the solar system. Simulations showed that the thermal performance of SDHW systems with annual solar fractions of 25% and 60%, respectively, is increased by 10% and 4%, respectively, if a collector with a glass with an antireflective coating is used instead of a collector with a standard glass. Later, Kong et al. (2015) carried out the half-year measurement of the SDHW system with and without antireflective coating. The results show that solar gain for the system with solar fraction 75% and an antireflective coating is 2.4% higher in comparison to the solar system without an antireflective coating.

For achieving the maximum conversion efficiency, one important strategy is to use spectrally selective solar absorbers that exhibit a near-blackbody absorptance in the solar radiation region while suppressing emittance at infrared range. In particular, the new low-cost tandem absorber coatings have been extensively investigated by a number of groups. Feng et al. (2015) reported that $TiAlN/TiAlSiN/Si_3N_4$ coatings, deposited on stainless steel substrates can exhibit high absorptance of 0.938 and thermal emittance of 0.09. According to Liu et al. (2012), NbTiON/SiON absorber coating prepared on Cu substrate showed high selectivity with an absorptance value of 0.95 and emittance value of 0.07. Barshilia et al. (2008) studied $NbAlN/NbAlON/Si_3N_4$, and these tandem absorbers showed high absorptance of 0.956 and low emittance of 0.07. In a different work, Wu et al. (2015) reported that high absorptance of 0.948 and low emittance of 0.05 could be achieved by multilayered coating of $Al/NbMoN/NbMoON/SiO_2$ on stainless steel substrate. In another study, Zou et al. (2015) reported a CrAlN–CrAlON based tandem absorber that exhibited a high absorptance of 0.984 and a low emissivity of 0.07.

Brunold (1994) presented a prototype of a new FPC using glass capillary as transparent insulation. The results of the test indicated that an improved transparent insulated FPC could enter into competition with vacuum tube collectors. Further, Duan (2012) demonstrated that application of aerogel can greatly reduce top heat loss of FPC. Beikircher et al. (2015) presented advanced insulation methods for flat plate collectors. The collector front losses have been reduced by transparent insulation materials, the rear losses by an integrated vacuum insulation. The results of the experiment showed that the prototype with double fluorinated ethylene-propylene film and vacuum rear insulation, as well as prototype with transparent honeycomb insulation with ethylene tetrafluoroethylene film, has efficiency comparable to evacuated tube collectors.

Unfortunately, the main disadvantage of investigations presented above is a lack of cost data to show the profitability of the improvements in energy performance. The objective function for the optimization presented in the paper has been formulated according to the energy-economic criteria because it includes the investment costs (the cost of design changes) and also it includes the performance gains after design changes. The following analysis has been performed at first generally, and then in more detail for the most common application: solar domestic hot water system.

2. Variable design

To demonstrate the influence of the design changes on the collector performance, a detailed theoretical model of flat-plate collector Type 205 has been used. The detailed model of flat-plate solar collector allows a detailed calculation of heat transfer in the solar collector. Energy flow from the absorber surface to ambient and from the absorber surface into heat transfer liquid together with temperature distribution in the collector are calculated in the iteration loops. The solar collector can be specified by a number of detailed parameters, optical properties of glazing and absorber, thermophysical properties of main components of solar collector (frame, absorber, and transparent cover) in the model.

The implementation of the model in TRNSYS environment offers the parametric analysis for different construction alternatives for annual solar collector performance in the given solar system application. There is also a possibility to change mathematical models describing the fundamental heat transfer phenomena (closed gap convection, wind convection, forced convection heat transfer in pipes etc.) and perform sensitivity analysis for selection of the models.

A high-quality solar collector with solar glass as a transparent cover and selective absorber coating has been taken into account as an initial case. Specifications of the flat-plate solar collector used in the analysis are provided below.

Tab. 1: Design parameters of the FPC used in the analysis

Collector parameter	Value	Collector parameter	Value
Length	1175 mm	Air gap thickness	30 mm
Width	2017 mm	Absorber material	Aluminium
Height	87 mm	Absorber thickness	0.4 mm
Aperture area	2.25 m^2	Absorber emissivity	0.05
Absorber area	2.185 m^2	Surface treatment	PVD
Header pipe	Cu 22 x 1 mm	Number of riser tubes	11
Cover material	Solar glass	Distance between riser pipes	100 mm
Cover thickness	4 mm	Back insulation thickness	50 mm
Cover transmittance	0.92	Insulation material	Rockwool

Four decision changes in collector design have been investigated. The parameters discussed are back insulation thickness, absorber emissivity, air gap thickness, and distance between riser pipes. These parameters are known to have a significant influence both on the collector performance and on the collector price. Thus, it becomes possible to perform an energy-economic optimization aimed to reduce the payback period of flat-plate collector. For a series of simulations the evaluated parameter varies in the range of set values while the others parameters are kept fixed. The investigation provided below was based on the analysis performed by detailed theoretical model Type 205 available for TRNSYS environment.

2.1. Back insulation thickness

Nowadays, flat-plate collectors at the rear side are insulated by rock/mineral wool or similar insulation materials. Thermal conductivity of dry insulation amounts to 0.03-0.06 W/(m.K) for temperatures between 0 °C and 100 °C (see Fig. 1).

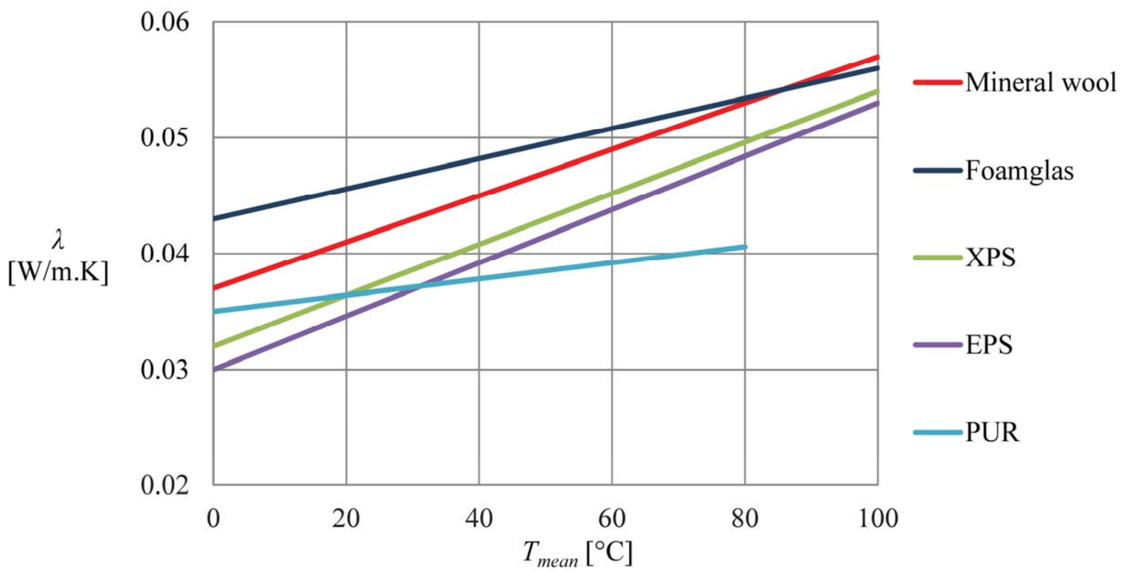

Fig. 1: Thermal conductivity as a function of mean temperature of insulation

For a typical insulation thickness of 40–60 mm, the backside collector heat losses amount to about 0.8 W/(m^2.K) from 3 to 5 W/(m^2.K) total losses. The question for the cost performance optimization is which insulation thickness is significant and which is not? Fig. 2 shows comparison of the efficiency curves for five solar collectors with the same geometrical and physical properties, but with varying thickness of the back insulation. It is apparent from the Fig. 2 that the thickness larger than 30 mm does not make significant improvement in the performance of FPC.

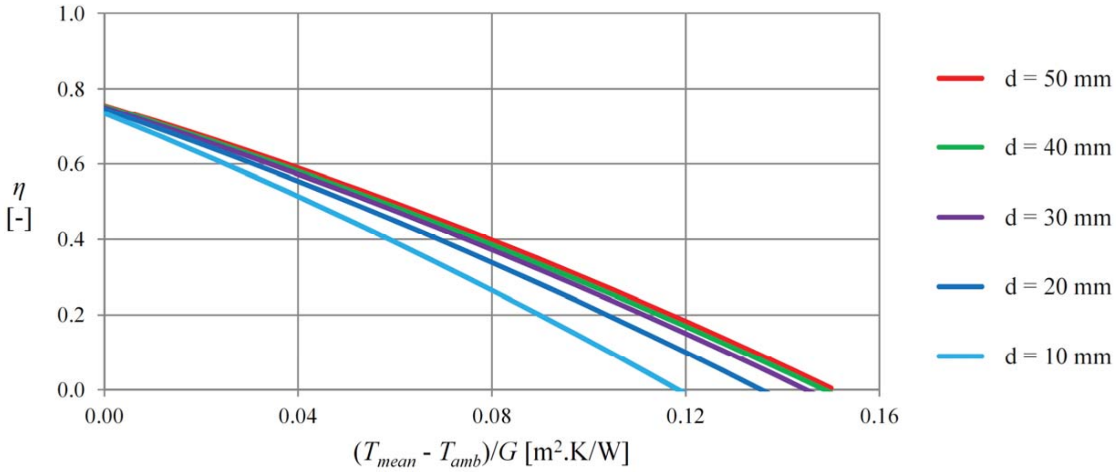

Fig. 2: Collector efficiency for considered design variants

2.2. Absorber emissivity

A solar absorber must have a high absorptivity α for solar (shortwave) radiation and a low emissivity ε for thermal (long-wave) radiation. Selective coatings are used to improve the performance of the solar collector by modifying optical properties both in the shortwave and longwave radiation ranges. For an absorber painted matt black without selective properties, absorptivity is 0.95 and IR emissivity is 0.85. Because of high ε values, such collectors have high heat losses by radiation and thus low efficiency, especially at high operation temperatures. Therefore, practically all single glazed collectors available on the market use selective coatings for the absorber (Tab. 2).

Tab. 2: Optical properties of selective coatings

Absorber coating	Absorptivity α in solar spectrum	Emissivity ε in infrared spectrum
Black chrome	0.95	0.12
Black nickel on polished nickel	0.92	0.11
Black anodized aluminium	0.93	0.07
Ceramic metal (cermet)	0.95	0.05

For the purpose of energy-economic optimization, two versions of absorbing coatings have been considered: a modern PVD coating with an emissivity of 0.05 or older and cheaper electrochemical (galvanic) coating with an emissivity of 0.12 both with the same absorptivity of 0.95. Fig. 3 shows collector efficiency characteristics of considered collector variations as a result of complex modeling. The difference between efficiency characteristics is obvious, especially at high operation temperatures.

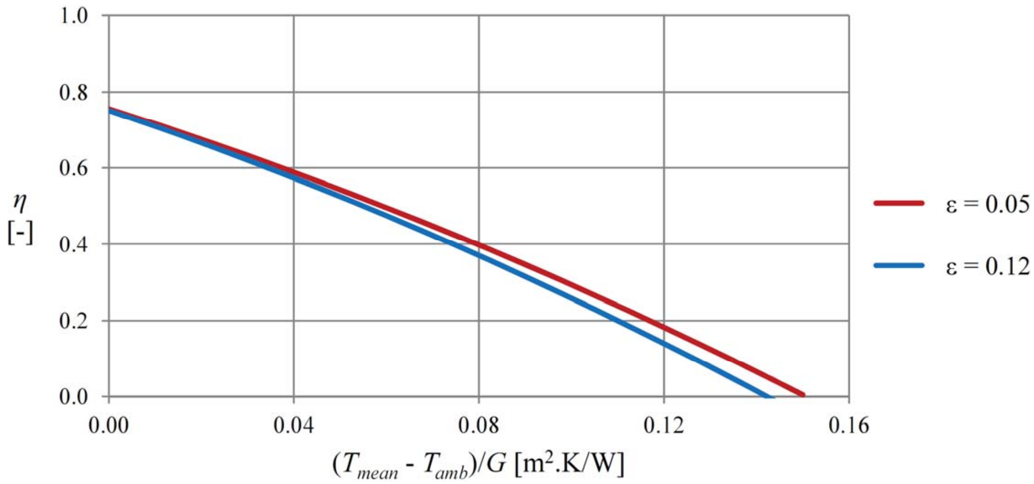

Fig. 3: Collector efficiency for the considered variants with ε = 0.05 and ε = 0.12

2.3. Air gap thickness

To have a good performance of a solar collector it is necessary to limit the thermal losses towards ambient through the front side of collector. Convective heat transfer through the air gap between the absorber surface and glazing has significant influence on these losses. The circulating air between absorber and cover, driven by temperature difference between absorber surface and interior glazing surface, transports the absorbed heat to the glazing. It depends on slope of the collector β and gap thicknesses L. The typical thickness of air gap is 30 mm. The goal is to investigate the influence of the air gap on the effectiveness of solar collector and to determine whether it makes sense to have 30 mm air gap in climatic conditions of Central Europe or the thickness of the air gap could be smaller. The graph in Fig. 4 shows natural convection heat transfer coefficient for closed layer between absorber and cover glazing as a function of the thickness of the air gap. Evidently, convection heat transfer coefficient decreases continuously with an increasing thickness of the air gap. However, Fig. 5 demonstrates a reduced influence of air gap thickness on the collector efficiency characteristics.

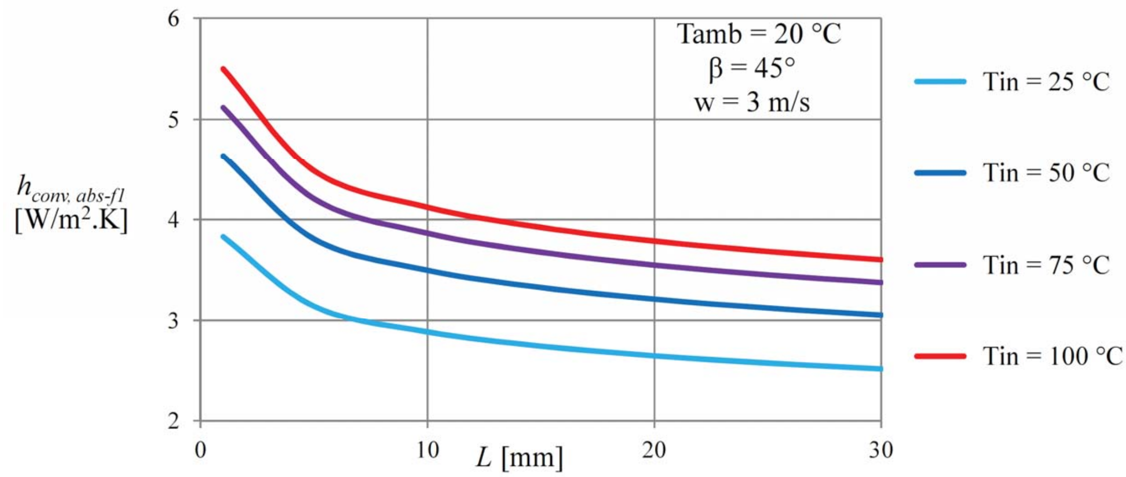

Fig. 4: Natural convection heat transfer coefficient as a function of the thickness of the air gap

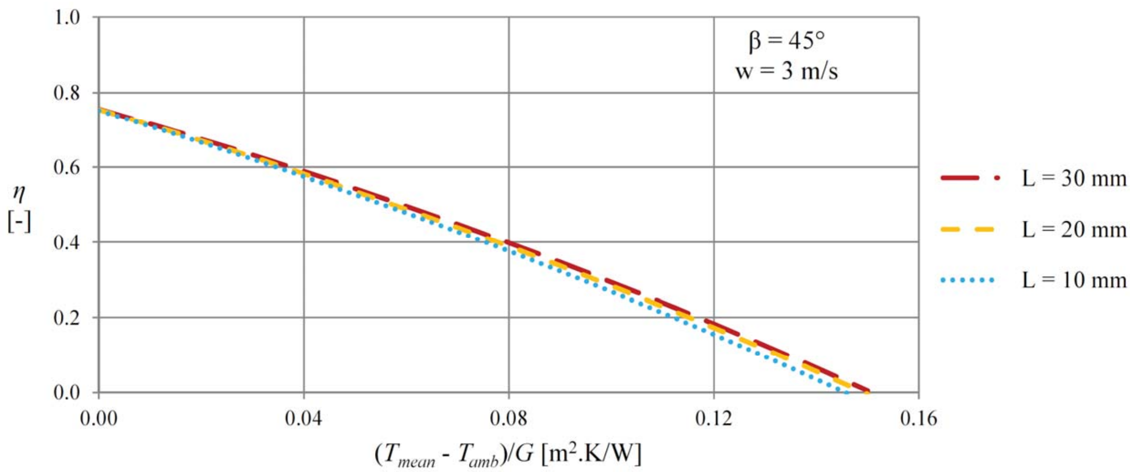

Fig. 5: Collector efficiency for the considered design variants

2.4. Distance between riser pipes

A typical design of the absorbers in solar FPC is represented by a tube and sheet configuration. Different hydraulic collector type (e.g. harp, double harp, or meander) can be used, but conductance of the sheet, conductance of the bond, forced convection heat transfer to the fluid, always have the crucial influence on the thermal performance (heat transfer from absorber surface to the fluid). As for distance between riser pipes, it has a direct impact on the heat conductance of the sheet and, therefore, on thermal performance of FPC. The typical distance between riser pipes is 100 mm. Reducing the distance between riser pipes increases fin efficiency F, collector efficiency factor F' (see Fig. 6) and consequently solar collector efficiency η (see Fig.7). As Fig. 6 shows that thermal conductivity and thickness of absorber also have a significant influence on the heat removal from absorber. For this reason, the reduction of the distance of rising pipes from 100 mm to 50 mmin has been considered in the analysis. Fig. 7 demonstrates a significant increase in the efficiency characteristic of FPC with reduced pipe distance, especially for low operation temperature.

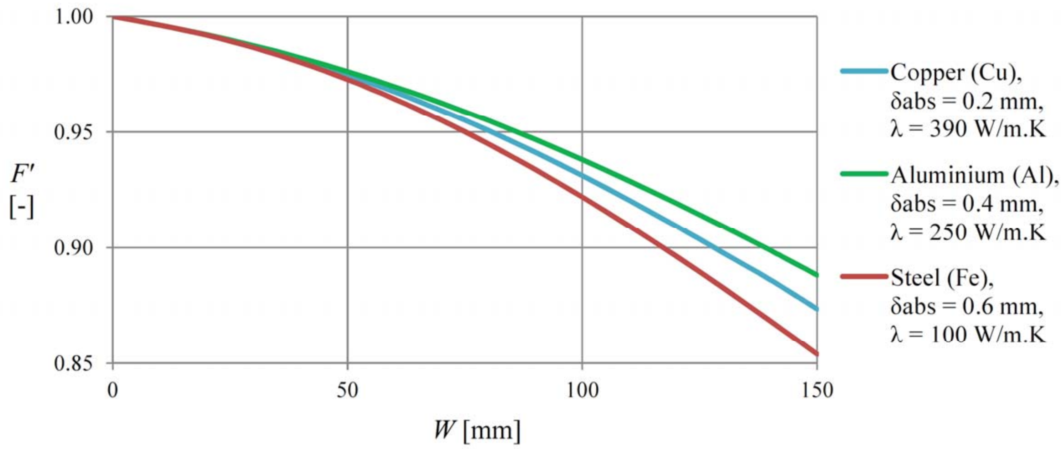

Fig. 6: Collector efficiency factor for different absorber materials as a function of pipe distance

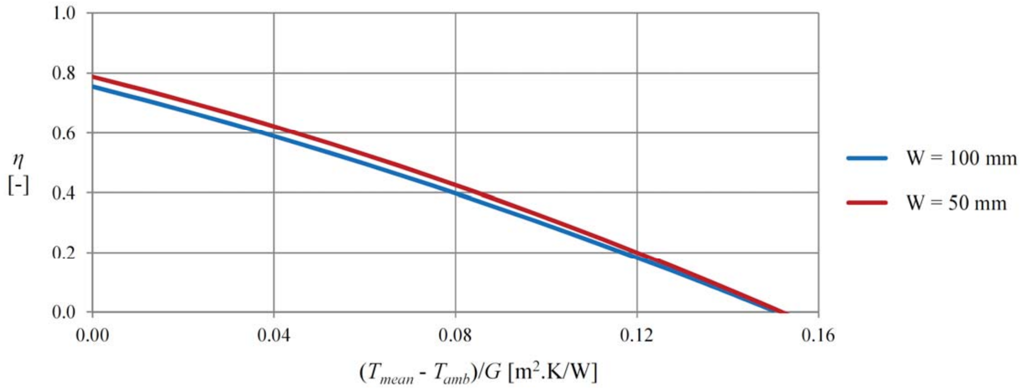

Fig. 7: Collector efficiency for the considered design variants

3. Energy analysis

The annual performance of the different solar collector variants has been evaluated by simulation of solar domestic hot water system with a given solar fraction 50 %. Scheme of the solar system is shown in the Fig. 8.

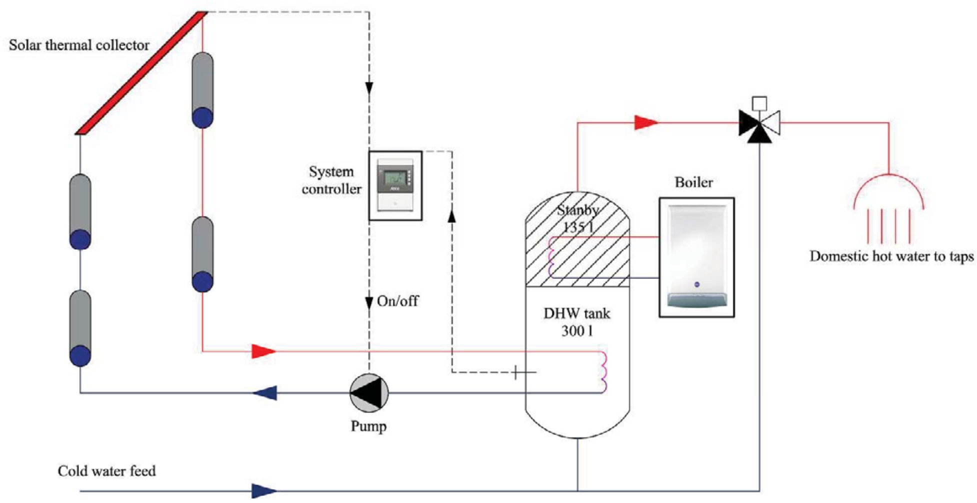

Fig. 8: Schema of simulated solar domestic hot water system

The system specification and the simulation results are shown in Table 4 and Table 5 consequently. The results show that the difference in the annual performance of compared solar collector variants decreases.

Tab. 4: Solar domestic hot water system parameters and operating conditions

Parameter	Description
Location	Athens, Würzburg, and Stockholm
Weather	TMY (Meteonorm)
Collector orientation	South, collector slope: Athens 25°, Würzburg 35° and Stockholm 45°
Collector area	Must cover 50% of domestic hot water heat demand (result between 49.5 and 50.5 %)
Reference area	Gross area
Collector mass flow rate	50 l/h.m^2
Heat transfer medium	Water
Pump control	Pump switching temperature is $\Delta T = 2\ K$ difference between collector output temperature and storage tank temperature in the area of heat transfer surface
Piping	Supply and return pipes are located in the internal and external environments: 7.5 each, DN 16 with 25 mm thermal insulation (λ = 0.04 W/m^2.K). Heat losses are determined towards the inside, respectively outside temperature.
Heat exchanger	Smooth tube heat exchanger with UA = 400 W/K (±15%) for 42 °C / 40 °C (outside temperature/tank storage temperature)
Tank storage	Volume: 300 l, heat loss: 2.2 W/K, height/diameter ratio: 2.5, standby volume 135 l with the temperature 60 °C
Cold water temperature	10 °C
Building interior temperature	15 °C
Hot water consumption	200 l/day (7.00 : 80 l; 12.00 : 40 l; 19.00 : 80 l), hot water temperature 45 °C, annual heat demand 2936 kWh/a

Tab. 5: Comparison of the annual energy gains for different solar collector variants

#	Collector design				Annual energy gain		
	back insulation thickness [mm]	absorber emissivity [-]	width of the air gap [mm]	distance between riser pipes [mm]	Athens [kWh/m^2.a]	Würzburg [kWh/m^2.a]	Stockholm [kWh/m^2.a]
RC	50	0.05	30	100	833	499	450
1	40	0.05	30	100	825	493	435
2	30	0.05	30	100	814	478	425
3	20	0.05	30	100	790	451	406
4	10	0.05	30	100	731	369	311
5	50	0.12	30	100	815	480	437
6	50	0.05	20	100	828	495	447
7	50	0.05	10	100	818	488	430
8	50	0.05	30	50	872	510	464

4. Economic analysis

The investigated design changes in the collector construction cause a change in the price of the collector. Based on the cooperation with the manufacturer of solar collectors, the influence of design changes on the price of the reference solar collector has been evaluated (Tab. 6). A negative value of the price change means the price reduction, while positive value means the price increase. The energy-economic study has also been performed for three cities - Athens, Würzburg, and Stockholm.

Tab. 6: Effect of design changes on the collector price (relative to the gross collector area)

#	Collector design				Price change [€/m^2]
	back insulation thickness [mm]	absorber emissivity [-]	width of the air gap [mm]	distance between riser pipes [mm]	
RC	50	0.05	30	100	0
1	40	0.05	30	100	-1.70
2	30	0.05	30	100	-3.37
3	20	0.05	30	100	-5.07
4	10	0.05	30	100	-6.78
5	50	0.12	30	100	-5.59
6	50	0.05	20	100	-0.50
7	50	0.05	10	100	-1.00
8	50	0.05	30	50	+6.07

Based on the full-year simulation results of SDHW system (Table 5) and on the effect of collector price changing (Table 6), the economic analysis has been carried out by using Net Present Value (NPV) method. NPV is a method used to determine the present value of an investment (collector price changing) by the discounted sum of all cash flows (additional energy gain, i.e. operation cost savings) received from the changed solar collector construction. A positive net present value indicates that the additional energy gain generated by a changing construction exceeds the cost of design changes. Generally, an investment with a positive NPV will be a profitable one and one with a negative NPV will result in a net loss. This concept is the foundation for the Net Present Value Rule, which dictates that the only investments that should be made are those with positive NPV values.

The formula for the discounted sum of all cash flows could be written as

$$NPV = -C_0 + \sum_{i=1}^{T} \frac{C_i}{(1+r)^i} \qquad \text{(eq. 1)}$$

where C_0 is an initial investment costs, C_i is net cash inflow during period T, r is discount rate and T is time.

To calculate NPV profitability indicator, the following parameters have been assumed:

- Calculation of NPV for all collector variants has been carried out in relation to the reference variant.
- Additional energy gain multiplied by heat price has been used as a net cash inflow (Table 5).
- Collector price change has been used as an initial investment cost (Table 6).
- The following heat prices have been used in the analysis: 0.094 €/kWh for Athens, 0.085 €/kWh for Würzburg and 0.146 for Stockholm with annual growth rate 1%. These prices were derived from statistics on average natural gas prices in Greece, Germany, and Sweden (Eurostat) divided by a boiler efficiency of 0.80.
- A discount rate of 0.1% (average interest for private time accounts in Europe) has been used in the analysis.
- The service life of the collectors has been set at 20 years.

The results of calculation are shown in Table 7. The results of the modelling indicate that the only flat-plate solar collector with reduced to 50 mm distance between riser pipes has the positive value of NPV. That means that this design change is economically profitable. New PVD coatings with an emissivity of 0.05 are economically justified compared to old and cheap electrochemical (galvanic) coating with an emissivity of 0.12. Yet reducing the thickness of insulation to a level less than 50 mm or reduction of the air gap width to a level less than 30 mm, as can be seen from the results, does not make an economic sense as of today.

Tab. 7: Net present value for considered collector variants

#	Collector design				Net present value		
	back insulation thickness [mm]	absorber emissivity [-]	width of the air gap [mm]	distance between riser pipes [mm]	Athens [€/m^2]	Würzburg [€/m^2]	Stockholm [€/m^2]
RC	50	0.05	30	100	0		
1	40	0.05	30	100	-13	-8	-42
2	30	0.05	30	100	-32	-32	-69
3	20	0.05	30	100	-75	-76	-122
4	10	0.05	30	100	-183	-212	-395
5	50	0.12	30	100	-28	-30	-36
6	50	0.05	20	100	-9	-6	-8
7	50	0.05	10	100	-27	-18	-57
8	50	0.05	30	50	67	12	34

5. Conclusion

The energy-economic analysis of flat-plate collector in SDHW system with yearly solar fractions of 50% has been carried out. In order to evaluate economically profitable design changes, numerical calculations have been made corresponding to the climatic and economic conditions of Athens, Würzburg, and Stockholm. The following design parameters were used as the decision variables: air gap size between the absorber and the cover glazing from 30 mm to 10 mm with the step 10 mm, emissivity of the absorber 0.12 and 0.05, rear insulation thickness from 50 mm to 10 mm with step 10 mm, and the distance between riser pipes 100 mm and 50 mm. At the end of the analytical study, there following conclusions can be drawn:

- There is a potential for increasing efficiency of the solar flat-plate collector by reducing the distance between rising pipes and, more importantly, this collector optimization is economically reasonable.
- The energy-economic analysis also shows that using new PVD coating with emissivity 0.05 instead of the electrochemical (galvanic) coating with an emissivity of 0.12 was economically justified.
- Back thermal insulation reduction or width of air gap reduction leads to a reduction of the initial price of the collector, but in the long term does not make any economic sense.

6. Acknowledgment

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