A MATHEMATICAL MODELLING OF THE INTERNAL AND EXTERNAL PIPING CONFIGURATIONS EFFECT ON THE SOLAR THERMAL SYSTEM

CSŐVEZETÉKI PARAMÉTEREK ÉS KIALAKÍTÁSOK NAPKOLLEKTOROS RENDSZERRE GYAKOROLT HATÁSÁNAK MATEMATIKAI MODELLEZÉSE

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Abstract

*Countless types of renewable energy can easily be exploited like wind, biomass, and solar. The most common power is solar power; it is usually used to get various outputs like electricity generation by photovoltaic/thermal power plants and local water heating. The task is to introduce environmentally friendly technologies, so the government authorities worldwide motivate the use of solar domestic water heating for its primary usage, low upkeep requirements, and the efficiency of the solar heating systems. Domestic solar hot water units, if effectively designed, are competent in providing most hot water demands in an appropriate environment and cost-effective approach. Despite 50 years of development, business technology has certainly not yet achieved substantive market penetration instead of mainstream electric power and gas alternatives. Various stakeholders will consider solar power heating systems utilised in buildings as an attractive alternative to traditional space and water heating methods. However, their functionality depends on climatic conditions, typical water heating requirements, and even operational parameters that could provide chances for performance optimisation. This study aims to analyse the effect of piping parameters on the solar system in the city of Budapest, Hungary using two programs, T*SOL as a solar system simulator and R-Studio as coding software. The analysis uses the simple model of the solar water heating system considering the following factors (pipe diameters, internal length, external length, Glycol, Thickness, volume flow rate, insulation), aiming to study the effect of the internal and external piping system. The study is carried out by simultaneously changing the values of the variables mentioned above by applying linear modelling and changing the collector type to choose the most appropriate system from the solar fraction aspect.*
Keywords: *Solar thermal system; pipe diameter; insulation; glycol ratio; pipe length*
JEL code: *C63, C93, Q49*

Összefoglalás

A megújuló energiaforrások számtalan fajtája, például a szél, a biomassza és a napenergia könnyen hasznosítható. A legelterjedtebb energia a napenergia; általában különböző célok elérésére használják, mint például a fotovoltaikus/termikus erőművekben történő villamosenergia-termelés és a helyi vízmelegítés. Feladatunk a környezettudatos technológiák bevezetése, ezért a kormányok világszerte ösztönzik az elsődleges felhasználású napenergiával

történő vízmelegítést, az alacsony fenntartási költségek és a napenergiával működő fűtési rendszerek hatékonysága miatt. A háztartási napkollektoros melegvíz-egységek – amennyiben hatékonyan vannak megtervezve – költséghatékony módon képesek a legtöbb melegvíz-igényt kielégíteni. Az 50 éves fejlesztés ellenére az üzleti technológia még biztosan nem ért el érdemi piaci előnyt a villamos energia és a gáz alternatívái helyett. A különböző érdekelt felek az épületekben alkalmazott napenergia-fűtési rendszereket a hagyományos helyiség- és vízmelegítési módszerek vonzó alternatívájaként kezelik. Működésük azonban függ az éghajlati viszonyoktól, a tipikus vízmelegítési igényektől, sőt, még a teljesítmény optimalizálására lehetőséget adó működési paraméterektől is.
*A tanulmány célja, hogy elemezze a csővezetékek paramétereinek hatását a napelemes rendszerre Budapesten, Magyarországon, két program, a T*SOL mint napelemes rendszer szimulátor és az R-Studio mint kódoló szoftver segítségével. Az elemzés a napkollektoros vízmelegítő rendszer egyszerű modelljét használja, figyelembe véve a következő tényezőket (csőátmérő, belső hossz, külső hossz, glikol arány, térfogatáram, szigetelés), azzal a céllal, hogy a belső és külső csőrendszer hatását vizsgálja. A tanulmányt a fent említett változók értékeinek egyidejű változtatásával végzünk lineáris modellezést a kollektor típusának megváltoztatásával, hogy a napenergia-arány szempontjából a legmegfelelőbb rendszert válasszuk ki.*
Kulcsszavak: *Napkollektoros rendszer, csőátmérő, szigetelés, glikol arány, csőhosszúság*

Introduction

Recently has been proven that the large pollutions result from burning oil derivatives, as nowadays we must search for alternative sources of energy that contribute to reducing pollution and harmful products to the environment. Since the industrial revolution hundreds years ago, many human activities have added large amounts of gases to the atmosphere (GHABOUR et al., 2021; RABL - SPADARO, 2016), which play a crucial role in global warming and changing the environment of the atmosphere and its impact on the climate of our planet. On the first hand, industrial development, and the increase in demand for fossil energy will lead to the depletion of fossil fuel sources (GHABOUR - KORZENSZKY, 2021). While on the other hand, an increase in pollution of all kinds in terms of direct impact on the environment and humans alike (GOJAK et al., 2019; MACHOL - RIZK, 2013).

Hot water can also be produced using heat pumps and heat exchangers. Heat exchanger modelling to reduce losses is also reported in the literature (GÉCZI et al., 2019).

Several researchers have also addressed the use of air-to-water heat pumps. They have many applications in swimming pool technology, the food industry, and fish farming technology. (GÉCZI et al., 2013 a,b; GÉCZI et al., 2014; KORZENSZKY – GÉCZI, 2012; TÓTH et al., 2011)

One of the alternative sources of energy is the process of solar domestic hot water (DHW), and there are two generic classes of active solar DHW systems. These include concentrating and non-concentrating collection systems (LUFT, 1985). Evacuated tube-type collectors are categorised as concentrating collectors and offer a high yield under hazy, diffused sunlight conditions; however, they can be costlier than non-concentrating collectors, otherwise known as (FPC) flat-plate collectors (SUMAN et al., 2015; LI et al., 2017).

A great way to cut down the massive power charges due to regular water heating is to invest in solar energy water heaters (SANDEY et al., 2015). Solar energy hot water emitters will not simply reduce the electric power bills but are going to also offer a lot of other advantages in a very cost-effective manner such as: Fighting climate change, protecting air quality, protecting water quality, Monthly savings, Increased home value (GHABOUR – KORZENSZKY, 2022).

In a solar energy system, the energy lost through pipes heading to and returning from the collector can be significant. DUFFIE and BECKMAN (2013) demonstrated that a solar collector with variable UL and $\tau\alpha$ (values are comparable in thermal performance to a combination of pipes plus the solar collector).

Some studies model internal temperature conditions based on measured meteorological data. This model can be used to predict the internal temperature of a room, thereby reducing unnecessary environmental stress (PATONAI et al., 2022; PÁGER et al., 2022). Other authors have validated a novel mathematical model based on measured data in a real solar heating system. Setting up a new model can always be of great help in improving energy efficiency (SZÉKELY et al., 2021).

By looking at the fluid temperature distribution in Figure 1, fluid enters the part of the pipes where losses occur at temperature T_i. An amount of T_i decreases the fluid's temperature before it enters the solar collector due to heat losses to the environment at temperature T_a. The fluid is heated to the collector outlet temperature as it flows through the collector. As the fluid loses heat to the environment while transported through the outlet pipes, the temperature drops to T_0. The usable energy gain of this collector-duct combination, based on energy balance calculations, is equal to:

$$Q_u = \left(\dot{m} \cdot c_p\right)_c (T_0 - T\mathrm{i})$$

The following rate equation can be used to relate this energy gain to the collector's energy gain minus pipe losses:

$$Q_u = A_C F_R[G_T(\tau\alpha) - U_L(T_i - \Delta T_i - T_a)] - losses$$

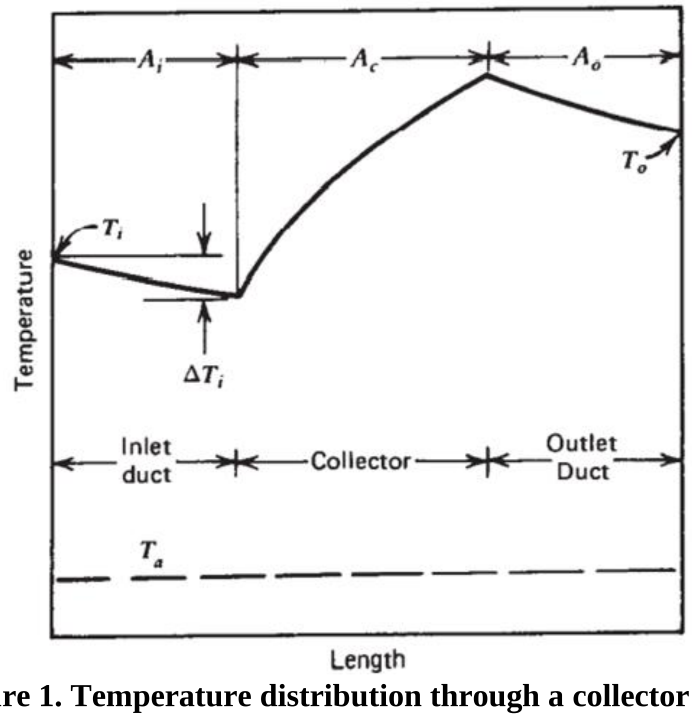

Figure 1. Temperature distribution through a collector system
(DUFFIE – BECKMAN, 2013)

The following formula is used to determine the energy absorbed by the collector and output 37ot he collector loop, minus heating losses (P [W])

$$\mathrm{P} = G_{dir}\,\eta_0\, f_{IAM} + f_{IAM}\, G_{diff}\,\eta_0 - K_0(T_{cm} - T_A) - K_q(T_{cm} - T_A)^2$$

where:

G_{dir} - Part of solar irradiation strikes a tilted surface [W/m²].
G_{diff} - Diffuse solar irradiation striking a tilted surface. [W/m²].
η_0 - Zero-loss collector efficiency.
K_0 – the simple part [W/m²/K].
K_q – the quadratic part [W/m²/K²].
T_{cm} – average temperature in the collector [K].
T_A – air temperature. [K].
f_{IAM} – incident angle modifier. [K].

The efficiency of the collector loop is defined as follows:

$$\text{Collector loop efficiency} = \frac{\text{energy output from the collector loop via the heat exchanger}}{\text{energy irradiated onto the collector area (active solar surface)}}$$

The following is a definition of system efficiency:

$$\text{System efficiency} = \frac{\text{energy output from the solar system}}{\text{energy irradiated onto the collector area (active solar surface)}}$$

This is how the solar fraction is defined:

$$\text{Solar fraction} = \frac{\text{the energy supplied to the stand by tank from the solar system}}{\text{total energy supplied to the stand by a tank (solar system+auxiliary heating)}}$$

According to previous studies and articles, all of them emphasised the solar water heating system in general, but none of it has analysed the effect of the piping configurations that transport water within this system on the overall efficiency or solar fraction. In this research, we aim to cover this gap.

Material and methods

In this study, the simple system is chosen because of its popularity. This system is called solar domestic hot water (DHW), Which consists of a solar collector, tubes, pump, tank, and boiler; the following Figure 2 presents the DHW system.

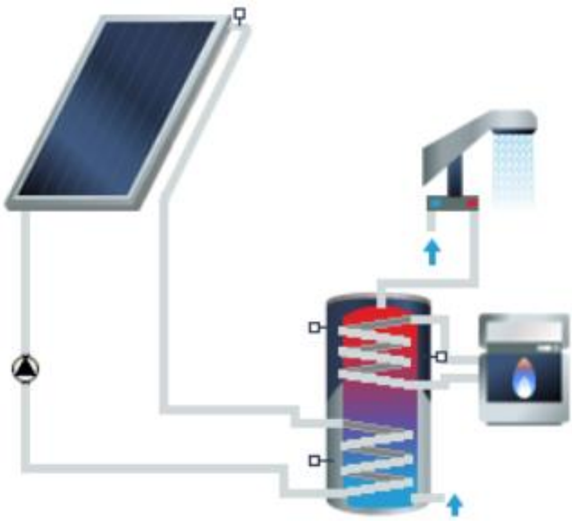

Figure 2. The DHW system

This system contains many variables (factors) that we can vary, which is of the following importance:

- Pipe diameters,
- Internal length,
- External length,
- Glycol,
- Thickness,
- Volume flow rate,
- Insulation

Firstly, using T*SOL software, we must change the value of the previous factors along with changing the other factors, and we also must change the type of collector used to perform a comparison process between the different types of collectors. Secondly, each case study will produce a certain solar fraction according to the chosen parameters.

In this linear experiment with two levels of each factor, 2^k represents the number of experiments that should be used. Then, the number of factors should be specified. In this study, seven factors are preserved as variables. Then the number of elements is reduced from 7 factors to 5 factors because of the complexity of having seven factors ($2^7 = 128$ experiments), So the system has been reduced to two levels ($2^5 = 32$ experiments only) to achieve the best system. After all, values were determined, we performed a comparative analysis between the three types of collectors. To evaluate the effect of every single factor and each two-factor interaction, R-studio has been used to illustrate these effects of single factors and two-factor interactions on the overall system performance.

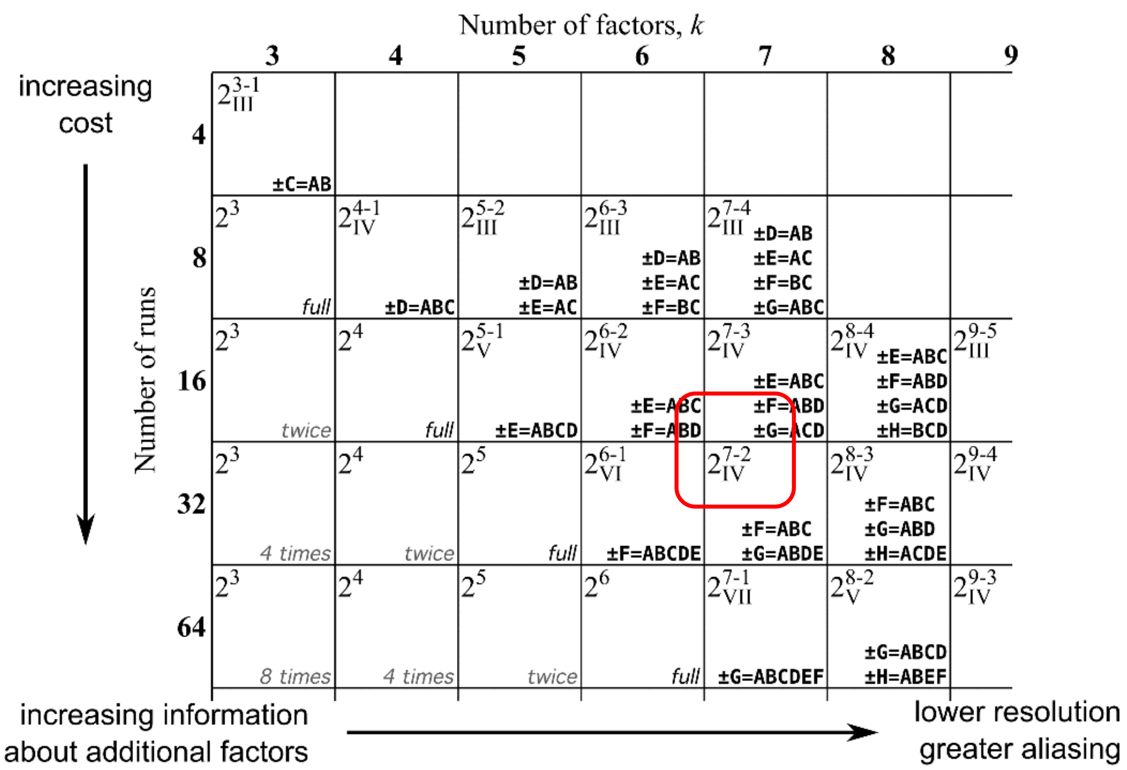

Figure 3. Correlation between cost, resolution, and number of factors

After conducting the experiments using T*SOL software and regulating them in tabular mode, then it was inserted into R-studio software. The actual values have been converted into coded values to obtain the results. Then the coded values generate contour plots for two interacting analyses and Pareto plots for the overall system overview. All variables are considered to have a coded value of +1 or-1 depending on their value for simplicity.

For example, in the city of Budapest, with a change in the value of factor A (pipe diameter) with the use of the type of solar collector Evacuated Tube Collector, we can produce the following equation: in this way, we enter all the results.

A<-c(-1,+1,-1,+1,-1,+1,-1,+1,-1,+1,-1,+1,-1,+1,-1,+1,-1,+1,-1,+1,-1,+1,-1,+1,-1,+1,-1,+1,-1,+1,-1,+1)

Through R-studio software, we can know the extent to which each element affects the system and what are the most critical elements that affect the system.

A linear model predicts a continuous result. Y as follows:

$$Y=\beta_0+\beta_1X_1+\beta_2X_2+\ldots\ldots+\beta_pX_p+\epsilon$$

where

- X is a continuous variable or a discrete variable (age, weight, temperature, etc.)
- β is an unknown parameter that must be calculated.
- ϵ are unknown parameters that must be calculated is regularly distributed, with a constant variance over the data range.

To explain and simplify the previous concept, Table 1 is done:

Table 1. Factors and input values

Factors	Input Values
A (Pipe diameter [m])	A<-c(-1,+1,-1,+1,-1,+1,-1,+1,-1,+1,-1,+1,-1,+1,-1,+1,-1,+1,-1,+1,-1,+1,-1,+1,-1,+1,-1,+1,-1,+1,-1,+1)
B (Lin [m])	B<-c(-1,-1,+1,+1,-1,-1,+1,+1,-1,-1,+1,+1,-1,-1,+1,+1,-1,-1,+1,+1,-1,-1,+1,+1,-1,-1,+1,+1,-1,-1,+1,+1)
C (Lout [m])	C<-c(-1,-1,-1,-1,+1,+1,+1,+1,-1,-1,-1,-1,+1,+1,+1,+1,-1,-1,-1,-1,+1,+1,+1,+1,-1,-1,-1,-1,+1,+1,+1,+1)
D (Glycol [%])	D<-c(-1,-1,-1,-1,-1,-1,-1,-1,+1,+1,+1,+1,+1,+1,+1,+1,-1,-1,-1,-1,-1,-1,-1,-1,+1,+1,+1,+1,+1,+1,+1,+1)
E (Thickness [m])	E<-c(-1,-1,-1,-1,-1,-1,-1,-1,-1,-1,-1,-1,-1,-1,-1,-1,+1,+1,+1,+1,+1,+1,+1,+1,+1,+1,+1,+1,+1,+1,+1,+1)
F (VFR [(L/h)/m^2])	F<-c(-1,+1,+1,-1,+1,-1,-1,+1,-1,+1,+1,-1,+1,-1,-1,+1,-1,+1,+1,-1,+1,-1,-1,+1,-1,+1,+1,-1,+1,-1,-1,+1)
G (Insulation [W/(m·K)])	G<-c(+1,-1,-1,+1,+1,-1,-1,+1,+1,-1,-1,+1,+1,-1,-1,+1,+1,-1,-1,+1,+1,-1,-1,+1,+1,-1,-1,+1,+1,-1,-1,+1)
Solar Fraction	Y_1=c(32.2,41.1,40.2,26.6,38.7,29.9,29.7,32.7,33.6,39.1,38.0,29.3,40.4,27.4,27.0,35.4,34.0,41.0,39.8, 31.7,41.9,29.9,29.1,38.6,33.3,42.1,41.4,29.2,39.9,32.2,31.7,35.4)

Results

Evacuated tube collector (ETC)

Solar fraction when we used ETC (evacuated tube collector) in Budapest.

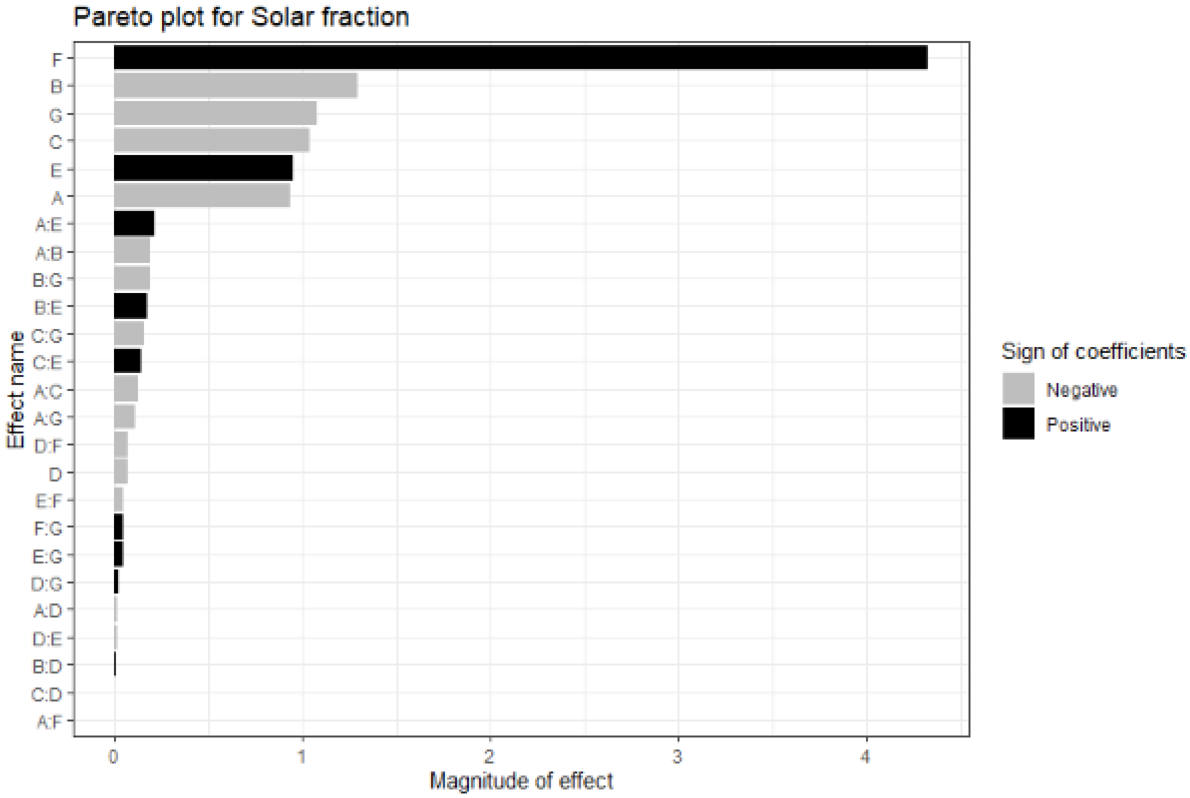

Figure 4. Pareto plot analysis in Budapest in case of ETC
A: Diameter [m], B: internal length [m], C: external length [m], D: Glycol [%], E: Thickness [mm], F: volume flow rate [(l/h)/m^2], G: conductivity [W/(m·k)]

From Figure 4, the Pareto plot chart, the factor F (volume flow rate) has the most significant positive magnitude with around 4.32%, followed by the following factor E (Thickness) with around 0.95%. Contrariwise the factor B (internal length) has a significant negative magnitude with around -1.29 % followed by the following fourth factors G (conductivity) with around -1.07 %, C (external length) With around -1.03%, A(Diameter) with around -0.93 % and D(Glycol) has the lowest magnitude with almost non-existent. Apart from single factors, two interacting factors are AB and BG, with a negative magnitude of -0.19% and -0.18% annually. To get a negative influence from this interaction, we must have two negatives so the sign of the two factors' interaction will stay negative. The third double factor is AE, with a positive magnitude of 0.21 %. To get a positive influence from this interaction, we must have two positive or one positive and one negative sign so the signs of the two factors' interaction will stay positive. The Figure 5. presents two-factor interactions.

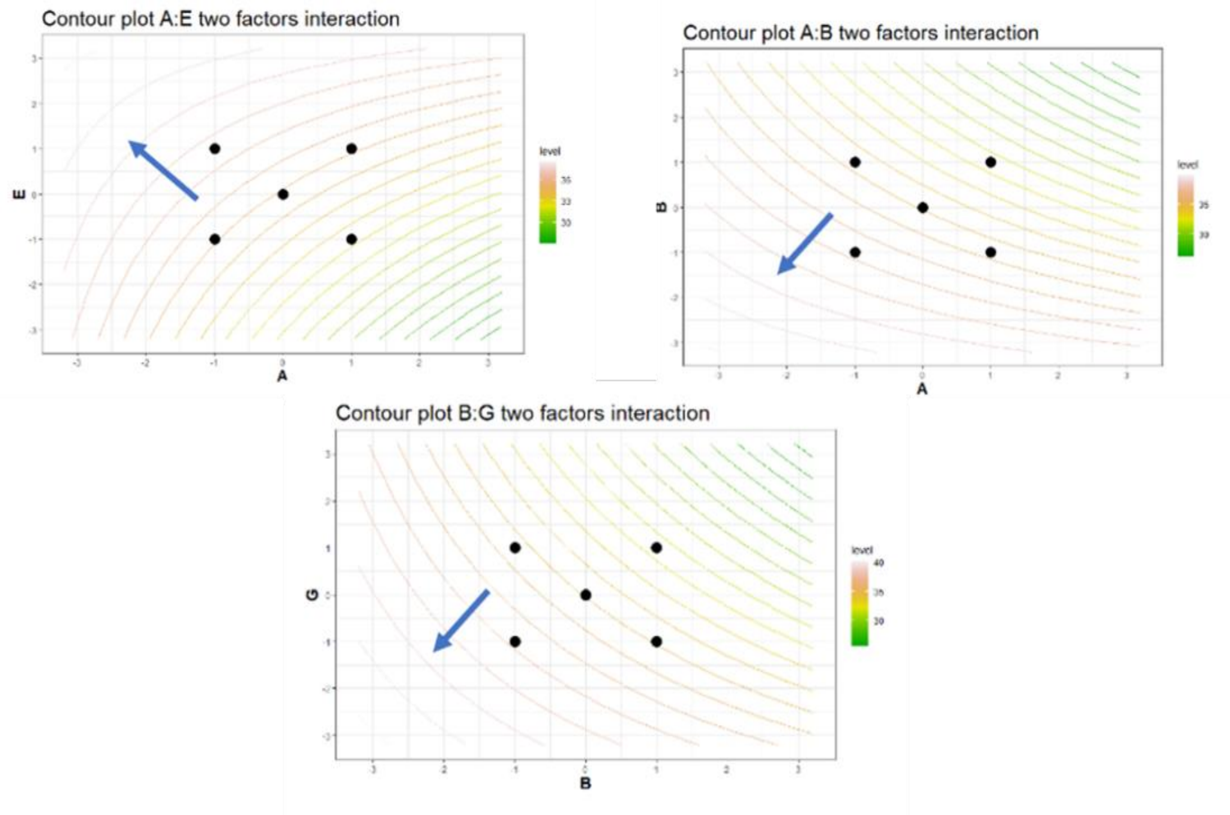

Figure 5. Two-factor interactions in case of ETC

AE: From the contour plot, we see E (thickness) positive and A (diameter)negative for the best performance. When the thickness increases, the losses will be lesser. Moreover, when the diameter decreases, the losses will decrease because we will have less surface area.

AB: From the double factor contour plot, we see that the system performance increases if both the factors are negative individually. Both the A (Diameter) and the B (internal length) should be decreased for the highest solar fraction.

BG: From the double factor contour plot, we see that the system performance increases if both the factors are negative individually. Both the B (internal length) and the G (conductivity) should be decreased for the highest solar fraction.

Flat-plate collector (FPC)

Solar fraction when we used FPC (flat-plate collector) in Budapest:

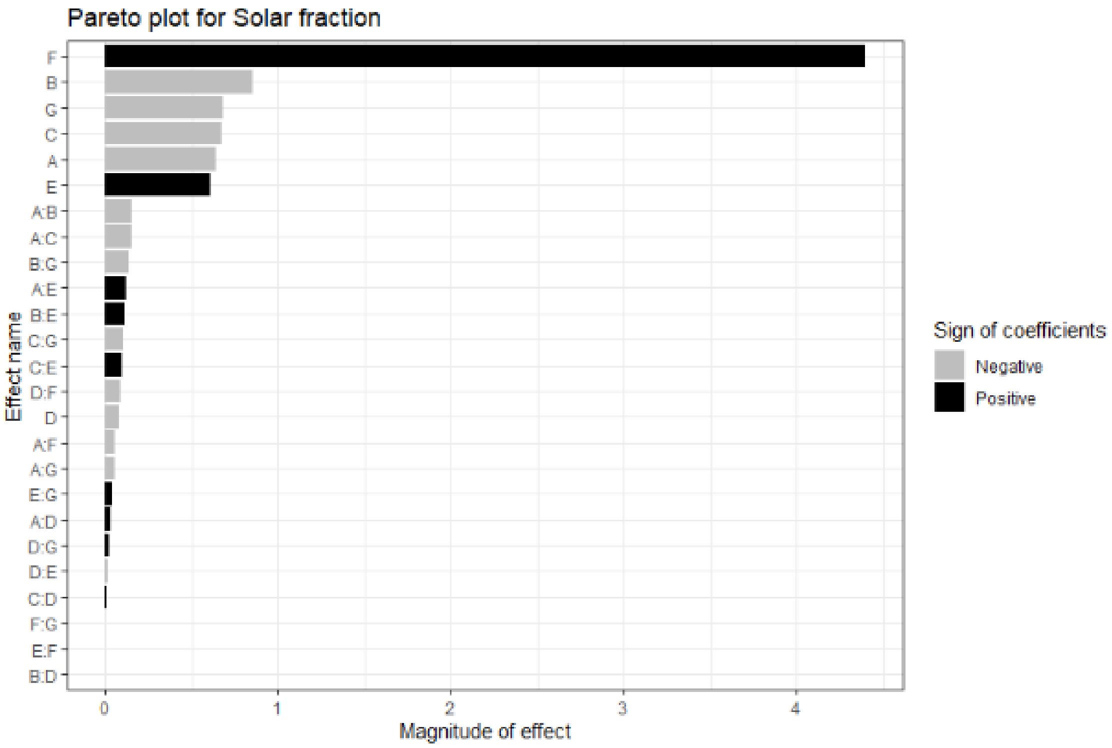

Figure 6. Pareto plot analysis in Budapest in case of FPC
A: Diameter [m], B: internal length [m], C: external length [m], D: Glycol [%], E: Thickness [mm], F: volume flow rate [(l/h)/m^2], G: conductivity [W/(m·k)]

Apart from single factors, three interacting factors are AB, AC, and BG with a negative magnitude of -0.15%, -0.15%, and -0.13 % annually. To get a negative influence from this interaction, we must have two negatives signs so the sign of the two factors' interaction will stay negative. The Figure 7. presents two-factor interaction.

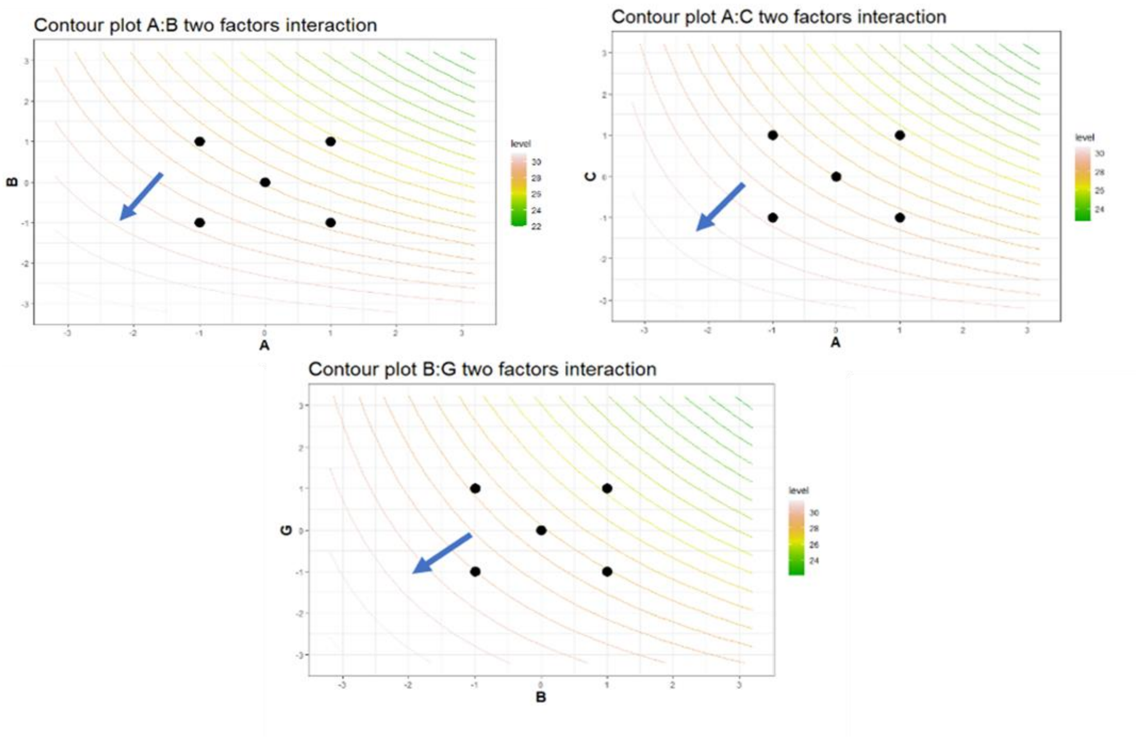

Figure 7. Two-factor interactions in case of FPC

AB: From the double factor contour plot, we see that the system performance increases if both the factors are negative individually. Both the A (Diameter) and the B (internal length) should be decreased for the highest solar fraction.

AC: From the double factor contour plot, we see that the system performance increases if both the factors are negative individually. Both the A (Diameter) and the C (external length) should be decreased for the highest solar fraction.

BG: From the double factor contour plot, we see that the system performance increases if both the factors are negative individually. Both the B (internal length) and the G (conductivity) should be decreased for the highest solar fraction.

Compound parabolic collector (CPC)

Solar contribution when we used CPC (compound parabolic collector) in Budapest:

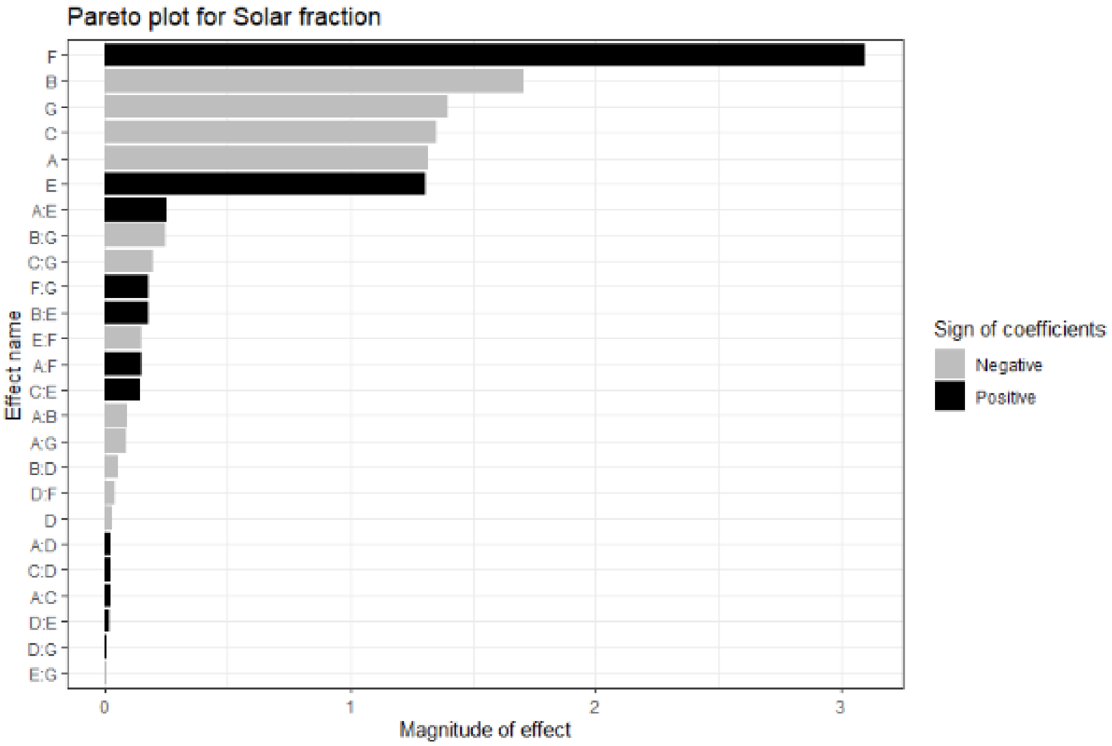

Figure 8. Pareto plot analysis in Budapest in case of CPC
A: Diameter [m], B: internal length [m], C: external length [m], D: Glycol [%], E: Thickness [mm], F: volume flow rate [(l/h)/m^2], G: conductivity [W/(m·k)]

From the figure 8 Pareto plot chart, the factor F (volume flow rate) has the most considerable positive magnitude with around 3.09%, followed by the following factor E (Thickness) with around 1.3%. Contrariwise the factor B (internal length) has a significant negative magnitude with around -1.7%, followed by the following fourth factors G (conductivity) with around -1.39 %, C (external length) With around -1.35%, A (Diameter) with around -1.31% and D (Glycol) has the lowest magnitude with almost non-existent.

Apart from single factors, two interacting factors are BG and CG with a negative magnitude of-0.24% and -0.19 % annually. To get a negative influence from this interaction, we must have two negative signs so the sign of the two factors' interaction will stay negative. The third double factor is AE, with a positive magnitude of 0.25 %. To get a positive influence from this interaction, we must have two positive or one positive and one negative sign so the signs of the two factors' interaction will stay positive. The Figure 9. presents two-factor interactions.

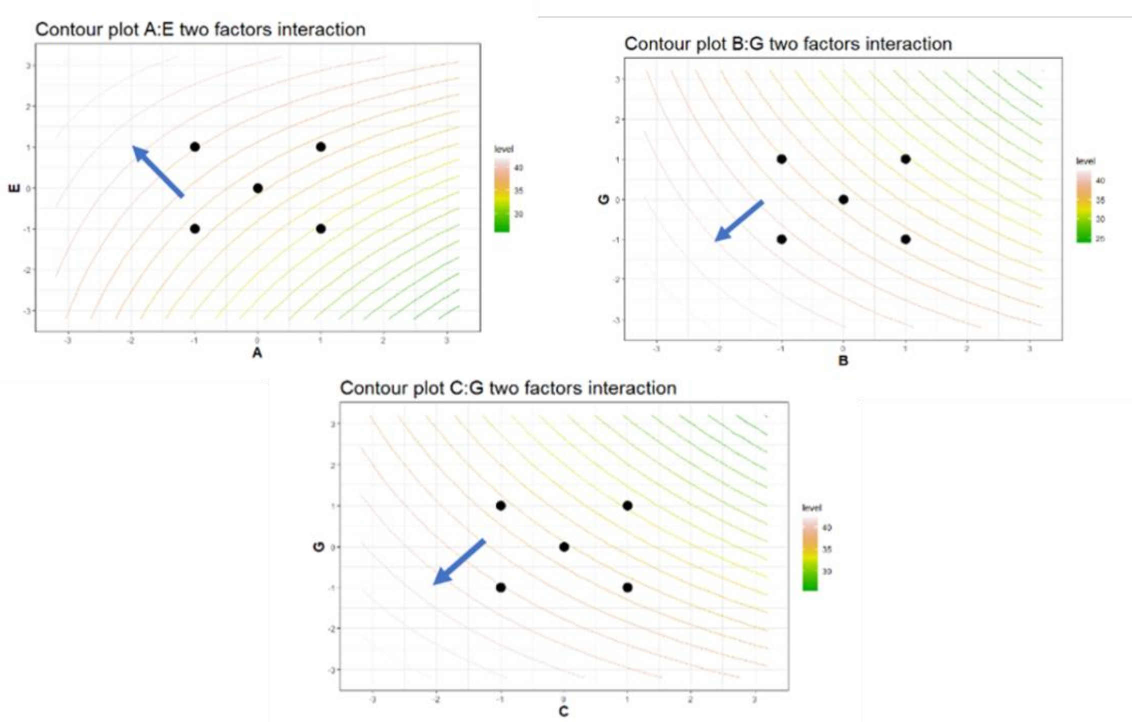

Figure 9. Two-factor interactions in case of CPC

AE: From the contour plot, we see E (thickness) positive and A (diameter)negative for the best performance. That means when the thickness increases, the losses will be lesser, and when the diameter decreases, the losses will be lesser because we will have less surface area.

BG: From the double factor contour plot, we see that the system performance increases if both the factors are negative individually. Both the B (internal length) and the G (conductivity) should be decreased for the highest solar fraction.

CG: From the double factor contour plot, we see that the system performance increases if both the factors are negative individually. Both the C (external length) and the G (conductivity) should be decreased for the highest solar fraction.

Table 2. Single factors magnitudes

FPC		**ETC**		**CPC**	
Factor	**Magnitude**	**Factor**	**Magnitude**	**Factor**	**Magnitude**
Intercept	28.1	Intercept	34.8	Intercept	36.2
A	-0.63	A	-0.93	A	-1.31
B	-0.85	B	-1.29	B	-1.7
C	-0.67	C	-1.03	C	-1.35
D	-0.08	D	-0.06	D	-0.02
E	0.6	E	0.95	E	1.3
F	4.39	F	4.32	F	3.09
G	-0.68	G	-1.07	G	-1.39

Table 3. Two-factors magnitudes

FPC		ETC		CPC	
Factors	**Magnitude**	**Factors**	**Magnitude**	**Factors**	**Magnitude**
A: B	-0.15	A: E	0.21	A: E	0.25
A: C	-0.15	A: B	-0.19	B: G	-0.24
B: G	-0.13	B: G	-0.18	C: G	-0.19

Conclusions

We note at present that in Europe, there is an energy crisis due to the war on Ukraine. For many other reasons, it forces us to search for other energy alternatives. As a solution, solar water heating system can be a good substitution of boiler heaters, because it is cheap and saves electricity and thus saves money. Because solar water heaters are not polluted and are considered safer than electric heaters, therefore, in this research, the solar water heating system was analysed. The effect of pipes that transport water within this system was emphasised because, according to previous studies, they were all talking in general about the solar water heating system, but none has analysed the issue of pipes configurations. A simple solar water heating system was used. First, three different collector types were compared in Budapest, Hungary, considering the following seven factors (pipe diameters, internal length, external length, Glycol, Thickness, volume flow rate, insulation). The complexity of the studied variants was reduced from level seven to five because using seven factors generates 128 experiments. While using five factors only requires 32 experiments. We note from Table 2, that using all types of collectors (FPC, ETC, CPC) in Budapest will generate the same output in different magnitudes as follows; factor F (volume flow rate), factor B (internal length), G (conductivity), C (external length), A (pipe diameter), and E (insulation thickness). On the contrary, two-factor interactions have different orders when using FPC, where the factor E (insulation thickness) has not got a substantial magnitude on the overall solar fraction. Similarly, factor C (external pipes length) has only a substantial effect on the FPC system since this type of collector has the highest energy losses compared to ETC and CPC. Factors A (pipe diameter) and B (internal pipe length) have a more substantial effect in the case of FPC, ETC compared to the CPC system. This is evident since the CPC is considered a concentrating system and can produce temperatures up to 200℃. Also, factor G (material conductivity) has a higher impact in CPC's case than ETC and FPC systems. It was noted that factors D (Glycol ratio) and F (volume flow rate) have a meagre impact on the interaction aspects of the two factors. It was concluded that when using the FPC, the effect of the length of the pipes is evident because their effect appeared in low magnitude values as individual factors and as the interaction of two factors compared to ETC and CPC. This highlights that using FPC is not suggested in central European climates like Budapest, Hungary. Instead, ETC has better outputs for a solar fraction if the system is well-engineered and installed at a slightly higher price.

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