MATHEMATICAL MODELING AND SIMULATION OF A THERMAL SYSTEM CONSISTING OF SOLAR COLLECTORS AND STORAGE TANK WITH AN INBUILT HEAT EXCHANGER

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In this paper is presented the mathematical model of a hot water production system consisting of solar collectors and storage tank with inbuilt heat exchanger. The hot water heating system uses solar radiation as the source of energy, and its mathematical simulation model is developed in Scilab-Xcos. An example of simulation of the thermal system mentioned above is also included in this paper.

Keywords: thermal system, solar collectors, modelling, simulation, Xcos

Nomenclature

t_R – water temperature on the return of the heat exchanger primary flow [^{0}C];
t_T – water temperature on the tour of the heat exchanger primary flow [^{0}C];
θ – water temperature in the storage tank [^{0}C];
t_e – outside temperature;
t_E – equivalent temperature is a synthetic parameter that contains information about the climate represented by the outdoor temperature and the intensity of the solar radiation and it is the same across the surface of the solar collector [^{0}C];
τ –time;
t – temperature;
E_c – synthetic parameter of the solar collector;
E_s – synthetic parameter of the heat exchanger;
G – primary thermal agent flow [m^3/s];
V – storage tank volume [m^3];
A – coil area of the inbuilt heat exchanger [m^2];
A_c – area of the solar collector [m^2];
ρ – water density [kg/m^3];
c – specific heat of the water [j/kg·K];
$\alpha\cdot\tau$ – absorption-transparency coefficient;
U – global heat transfer coefficient of the heat exchanger [W/m^2·K];
U_c – global heat transfer coefficient of the solar collector [W/m^2·K];
I – intensity of the solar radiation [W/m^2];
Q – power delivered by the heat exchanger [W];
F – heat flux correction factor for the solar collector;

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C_{min} – minimum transfer capacity of the thermal agents (respectively primary thermal agent) [W/K];

NTU_s – the number of the heat exchanger heat transfer units - represents the ratio of the transfer capacity of the heat exchanger surface and the transfer capacity of the primary termic agent.

1. Introduction

Research on thermal systems that use energy as the source of energy, the energy generated by solar radiation has great relevance when conventional sources of energy (those that use hydrocarbons as the source) are limited and pollute the environment [1].

Solar energy is the most impressive and possible source of energy for a certain category of consumers. We make reference here especially to the preparation of domestic hot water.

The solar collector is the corresponding equipment for converting solar energy into thermal energy and transferring it to the fluid that heats up [2, 3].

Within 20 minutes, the sun provides the equivalent of the annual energy consumption of mankind. The capture power of a solar collector, oriented to the south and tilted to 45 degrees is 95 ÷ 96% of the solar radiation.

On the territory of Romania, the solar radiation has an annual average between 1000 and 1300 $kW/m^2/year$, depending on the geographic area. On a horizontal surface – 1 m^2 heat-pipe solar collector, we can capture an annual amount of energy between 900 and 1450 kWh, depending the season of course. Daily average radiation may be 5 times more intense in summer than in the winter. But during winter, during a clear day, we can capture 4 ÷ 5 $kWh/m^2/day$, the solar radiation captured being independent of the ambient temperature [2].

Using a hot water system that use as a source of energy solar radiation is economically beneficial and does not pollute the environment.

The disadvantage of this system is that solar energy can only be used during the daytime as long as the intensity of the solar radiation is at a rate that allows it to be valorized.

A good thing is that energy can be accumulated when the intensity of solar radiation permits and can be used when the intensity of the solar radiation is at lower levels or zero (during the night). Accumulation of energy can be done in storage tanks.

This type of installations can also be used as heat input to the heating system, reducing the costs of building heat.

Solar water heating installations are usually made up of three basic components: solar collectors, the heat exchanger and the storage tank. The role of the heat exchanger is to separate the hot water circuit of the thermal agent circuit recirculated through the collectors, in this way it could be treated against limescale. Heat exchanger systems inbuilt in the storage tank are the most common [3]. Fig. 1 shows a schematic diagram of a thermal system consisting of solar collectors and the storage hot water tank with inbuilt heat exchanger, the themal agent (water) being circulated by a pump.

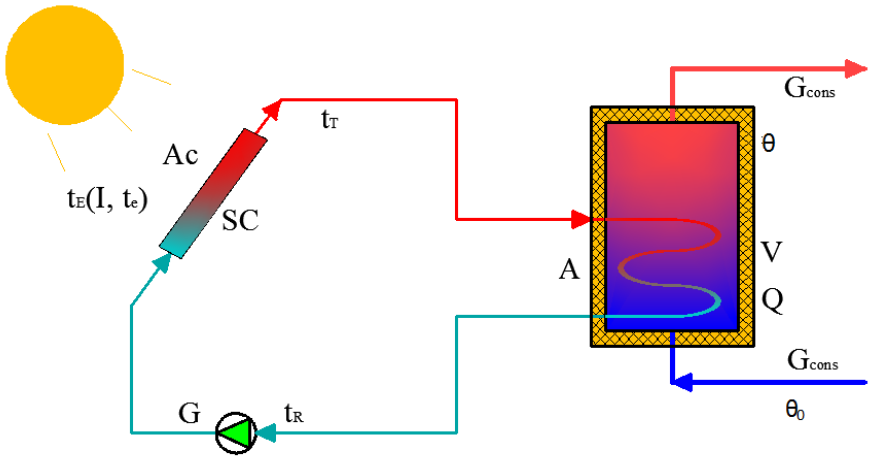


Fig. 1. Scheme of a thermal system consisting of solar collectors and storage tank with an inbuilt heat exchanger.

This article presents a mathematical model of a solar thermal system consisting of solar collectors with an inbuilt heat exchanger in a storage tank.

2. Mathematical model of a thermal system consisting of solar collectors and storage tank with an inbuilt heat exchanger

The equations describing the mathematical model are the following [3, 4]:

$$\frac{d\theta}{d\tau} = -\frac{G}{V} \cdot \frac{(1-E_s)\cdot(1-E_c)}{1-E_c \cdot E_s} \cdot (\theta - t_E) \tag{1}$$

$$t_E = \frac{\alpha \cdot \tau}{U_c} \cdot I + t_e \tag{2}$$

$$E_c = e^{-\left(\frac{F \cdot U_c \cdot A_c}{G \cdot \rho \cdot c}\right)} \tag{3}$$

$$E_s = e^{-NTU_S} \tag{4}$$

$$NTU_s = \frac{U \cdot A}{C_{\min}} = \frac{U \cdot A}{G \cdot \rho \cdot c} \tag{5}$$

$$t_T = \frac{(1-E_s)\cdot E_c}{1-E_s \cdot E_c} \cdot \theta + \frac{(1-E_c)}{1-E_s \cdot E_c} \cdot t_E \tag{6}$$

$$t_R = E_s \cdot t_T + (1-E_s)\cdot \theta \tag{7}$$

$$Q = G \cdot \rho \cdot c \cdot (t_T - t_R) \tag{8}$$

It was assumed that the storage tank has no heat loss to the outside environment and does not consume hot water from the tank [3, 4].

Starting from the above equations [3, 4], we developed the schemes of the Figs. 2, 3 and 4 in Scilab-Xcos [5] with which simulations can be made for various scenarios. Thus, for the various physical characteristics of the inbuilt heat exchanger, storage tank and solar collectors and various solar radiation intensities, external temperatures and heat flow rates, it is possible to see the evolution in time of the water temperatures on the flow and return of the primary heat exchanger, the equivalent temperature, the water temperature in the storage tank and the power delivered by the heat exchanger.

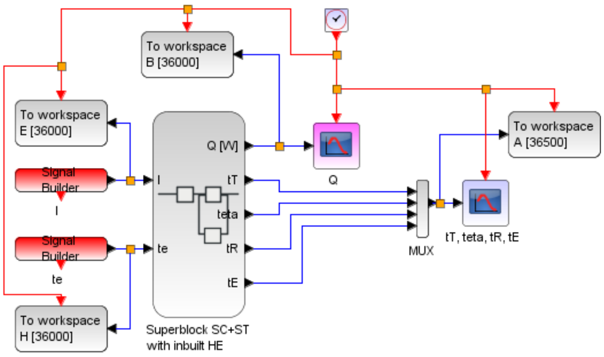


Fig. 2. Scilab-Xcos scheme for simulating a thermal system using solar collectors.

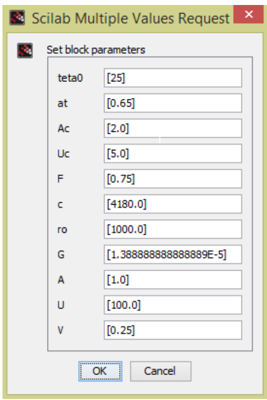


Fig. 3. Superblock SC + ST parameters box with inbuilt HE in Fig. 2.

The Scilab-Xcos environment has a free license. The program being realized in this environment, allows the immediate implementation without cost in the thermal systems. By simulating it, the thermal systems can be made more efficient. This program is also useful for specialists who work in the design of thermal systems and those who perform mathematical modeling and simulation programs.

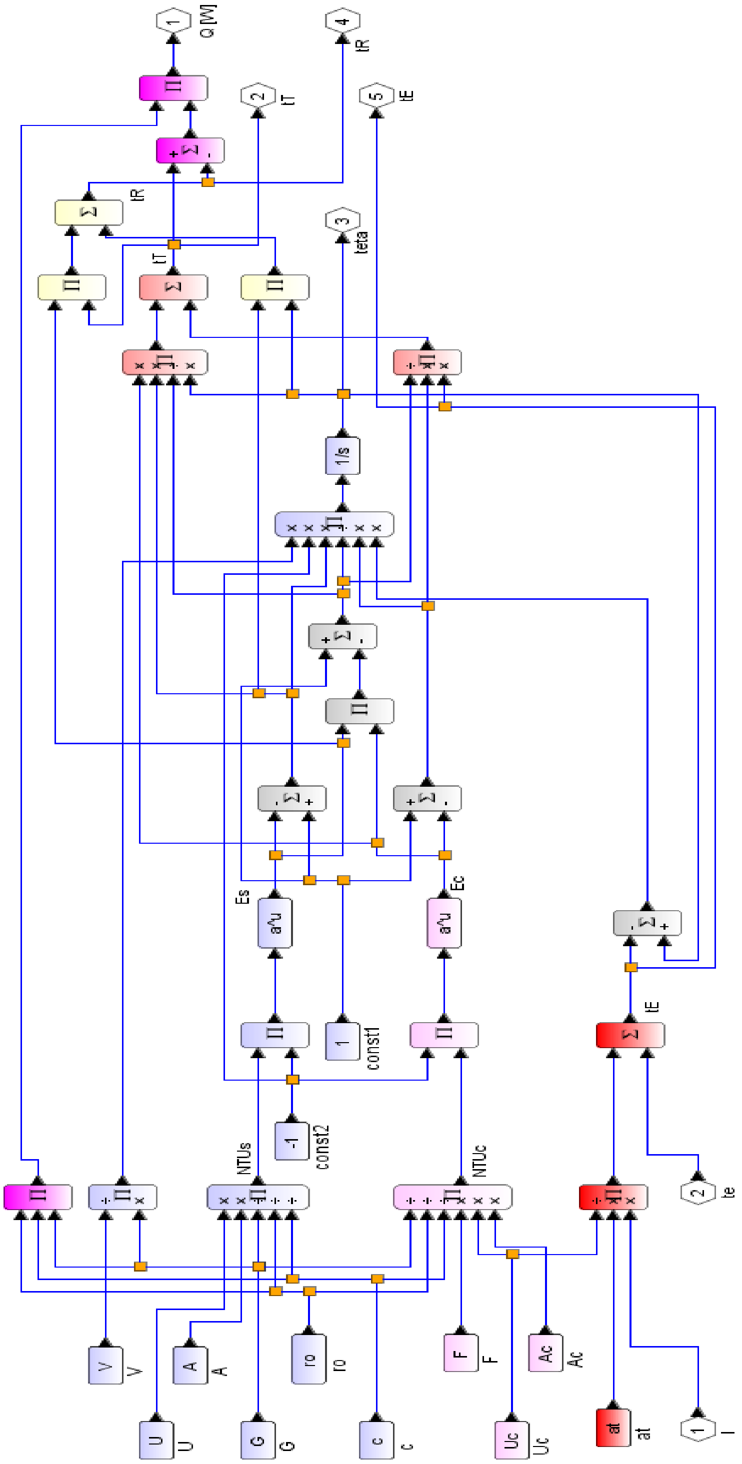
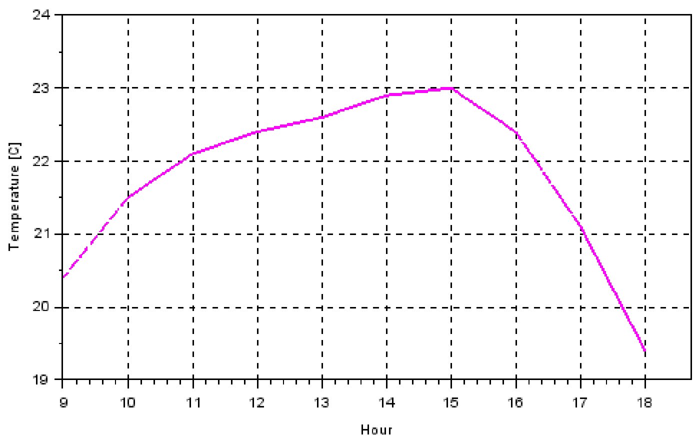


Fig. 4. Scilab-Xcos diagram of the superblock SC + ST with inbuilt HE in Fig. 2 was developed starting from equations 1 ÷ 8.

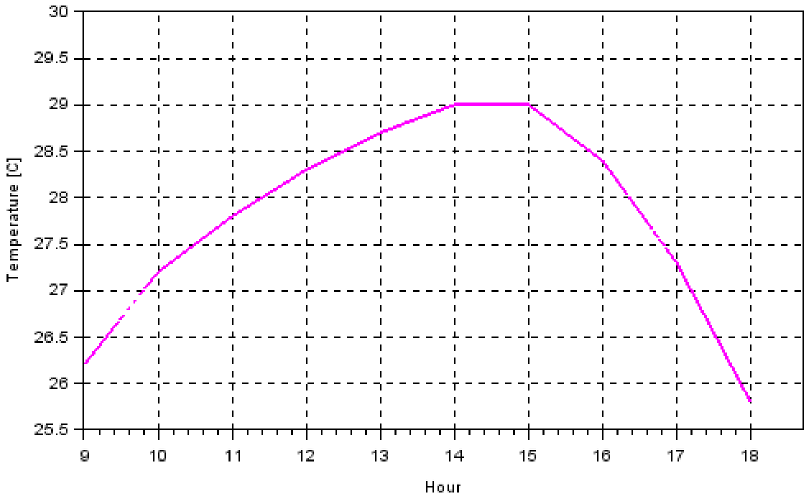
3. Example of simulation

Initial data [3]:

- Volume of the storage tank $V=0.25\ m^3$;
- Initial water temperature in the storage tank $\theta_0=25\ ^0C$;
- Coil area of the inbuilt heat exchanger $A=1\ m^2$;
- Global heat transfer coefficient of the coil inbuilt heat exchanger $U=100\ W/m^2\cdot K$;
- Flow rate of the thermic agent delivered through the system $G=0.05\cdot 3600\ m^3/s$;
- Area of solar collectors $A_c=1\cdot 2\ m^2$ and $A_c=2\cdot 2\ m^2$;
- Transparency-absorption coefficient of the solar collector $\alpha\cdot\tau=0.65$;
- Geometric correction factor $F=0.75$;
- Global heat transfer coefficient of the solar collector $U_c=5\ W/m^2\cdot K$;
- Outside air temperature t_e [^{0}C] during the simulated time period (one day from May and July from 09 to 18 hours) in Bucharest city has the evolution according to the graph below (Fig. 5) [6];



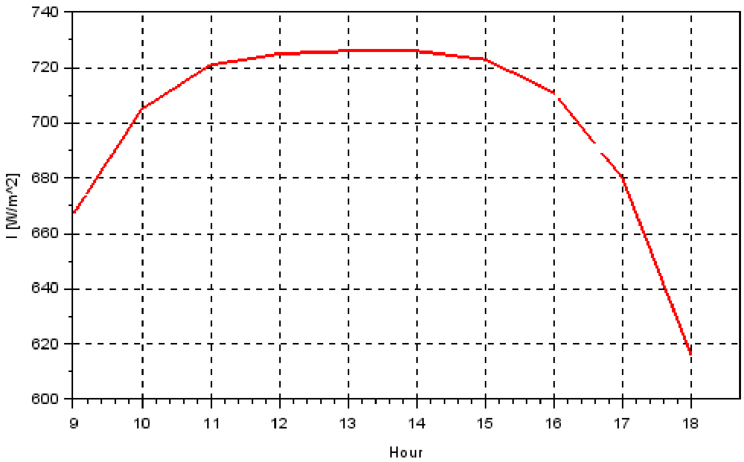
a) day of May



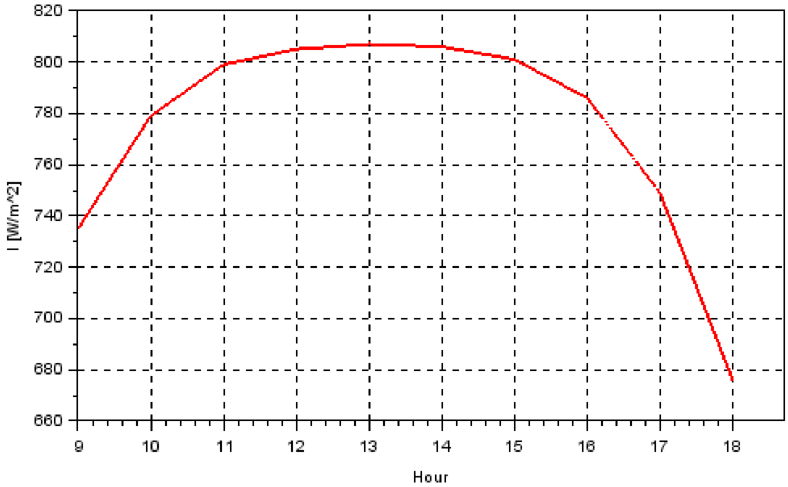
b) day of July

Fig. 5. Evolution of the outside air temperature over simulated time period.

- Intensity of the solar radiation *I [W/m²]* during the simulated time period (one day from May and July from 09 to 18 hours) in Bucharest city has the evolution according to the graph below (Fig. 6) [6];



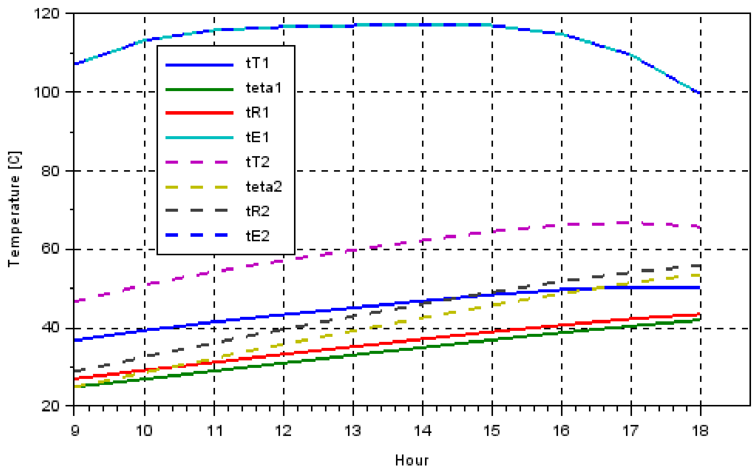
a) day of May



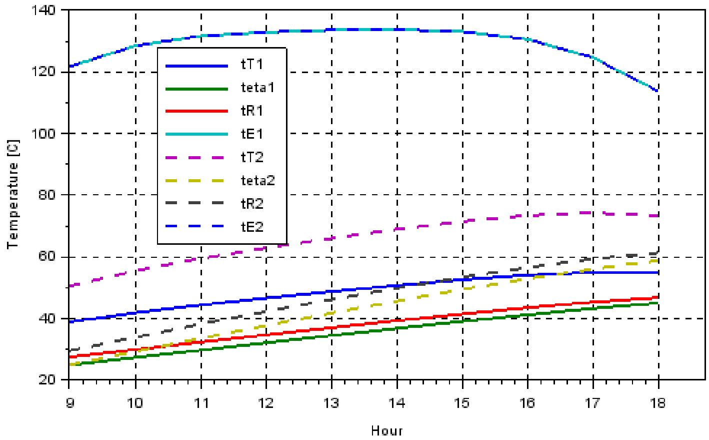
b) day of July

Fig. 6. Evolution of solar radiation intensity over simulated time.

Following the simulation, it can be seen graphically how the water temperatures and power delivered to the system evolved during the simulated time period and for the simulation conditions (Figs. 7 to 8).

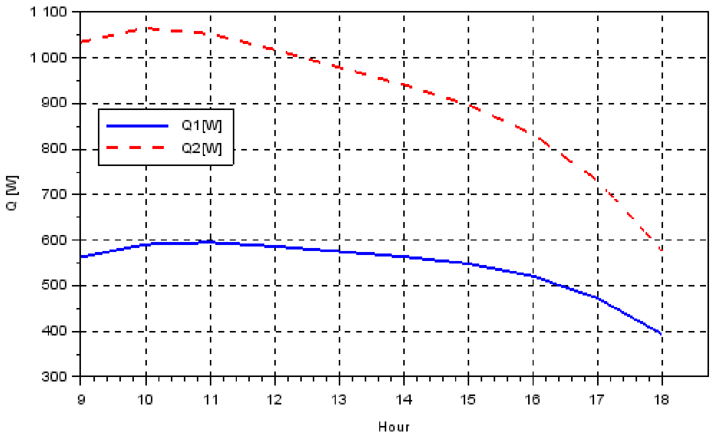


a) day of May

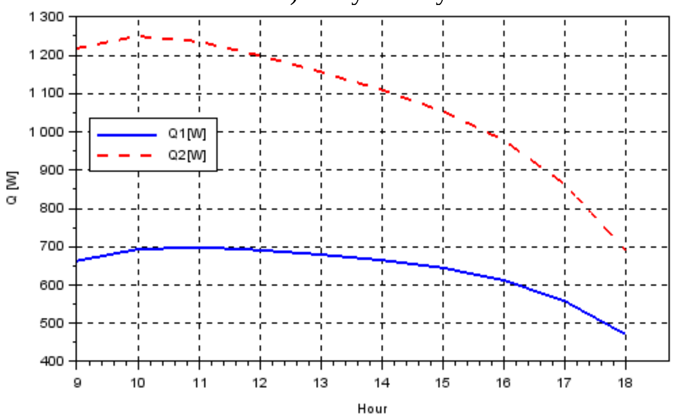


b) day of July

Fig. 7. Time evolution of water temperatures on trickle and return of primary heat exchanger, water temperature in storage tank and equivalent temperature over simulated time period for 1 or 2 solar collectors.



a) day of May



b) day of July

Fig. 8. Time evolution of power delivered by the heat exchanger during the simulated time period for 1 or 2 solar collectors.

4. Conclusions

The calculation program (Figs. 2, 3 and 4) elaborated by the author of this article in Scilab-Xcos solves the mathematical equations (1 ÷ 8) describing the evolution in time of the water temperatures on the flow and return of the heat exchanger primary flow, the water temperature in the storage tank and the heat power output delivered by the hot water heat exchanger using the solar energy source. This program is immediately applicable and is useful in designing, building and operating the solar collector systems linked with a heat exchanger buit in into an accumulation tank, making simulations and seeing how the parameters mentioned above evolved over the simulated time period and for the specific conditions in each case.

R E F E R E N C E S

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