Proc. Estonian Acad. Sci. Phys. Math., 1993, 42, 2, 195—202
https://doi.org/10.3176/phys.math.1993.2.07

UDC 697.329

Teolan TOMSON *

A METHOD FOR EFFICIENCY IMPROVEMENT IN SOLAR HEATING SYSTEMS WITH SEASONAL STORAGE

(Presented by G. Liidja)

Abstract. Due to the descending conversion curve of a flat solar collector and the comparatively high temperature of water in a seasonal storage tank the average value of solar conversion efficiency in a traditional Central Solar Heating Plant with Seasonal Storage (CSHPSS) stays low. Remarkably better technological results can be achieved in a modified CSHPSS which has additional storage for the daytime heat production and a heat pump (HP) between the storage tanks, which stabilizes the inlet temperature of the solar collector at a low value.

Introduction

In Nordic countries like Estonia, solar energy can be used for heating purposes only by using the seasonal storage method. The circuit diagram of a typical Central Solar Heating Plant with Seasonal Storage (CSHPSS, [1]) is represented in Fig. 1, including: *1* — a solar collector (farm); *2* — a storage tank; *3* — an auxiliary heat generator like gas, oil or electrical boiler, *4* — load. In some cases a heat pump (HP) is used as an auxiliary heat generator for stabilizing the abating temperature of the storage during the discharge period (winter). The stored water reaches its maximum temperature $\Theta_{w\max} \approx 70\ldots80\,^{\circ}\mathrm{C}$ in autumn and its minimum, $\Theta_{w\min} \sim 40\,^{\circ}\mathrm{C}$, in spring. In summer the solar irradiation is accumulated into the water mainly by a flat solar collector, using summary irradiation $Q(t)$ (W/m^2). The conversion curve of a collector with typical data is represented in Fig. 2. Any flat solar collector has a descending curve with falling conversion efficiency $\eta(p)$ as a function of the characteristic parameter

$$p = (\Theta_w(t) - \Theta_a(t))/Q(t),$$

where Θ_w is the inlet temperature of heated water (in the collector), Θ_a is the temperature of the ambient air. Due to the falling conversion curve, the long-term average efficiency remains low $\bar{\eta} = 0.2\ldots0.35$ and the small Nordic solar resource is poorly used.

---

* Eesti Teaduste Akadeemia Termofüüsika ja Elektrofüüsika Instituut (Institute of Thermophysics and Electrophysics, Estonian Academy of Sciences). Paldiski mnt. 1, EE-0001 Tallinn. Estonia.

There still exists a possibility of increasing the (long-term) efficiency of solar energy conversion in CSHPSS by a HP at the output port of the solar collector [2, 3], using an intermediate storage between the solar collector and the HP to stabilize the inlet temperature of the solar collector at a low value. The modified structure of the improved CSHPSS is given in Fig. 3, where *5* is the intermediate storage tank and *6* is the HP. The obtained technological gain is analysed by the calculated charging process in both versions of CSHPSS with the impulse model of solar energy input.

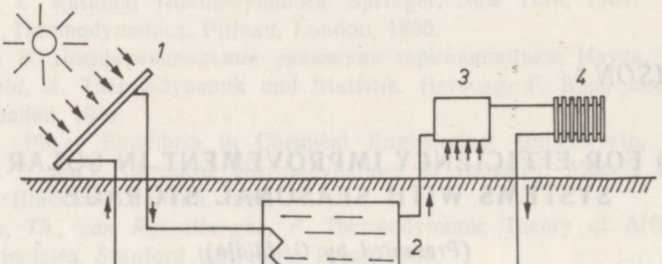

Fig. 1. The traditional structure of a CSHPSS: *1* — solar collector, *2* — storage tank, *3* — auxiliary heat generator, *4* — load.

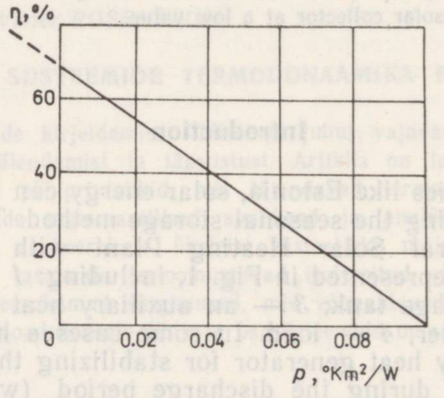

Fig. 2. The typical conversion curve of a flat solar collector.

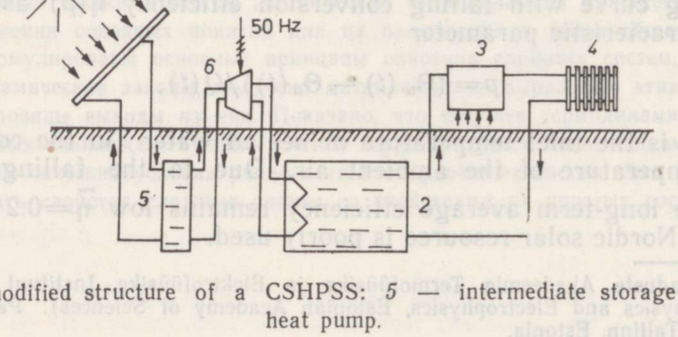

Fig. 3. The modified structure of a CSHPSS: *5* — intermediate storage tank, *6* — heat pump.

Solar irradiation model

In Fig. 4 "real" (i. e. statistical) solar irradiation curves, based on [4], but recalculated (by algorithm 3.6.2. [5]) for a South-faced collector with a tilt angle of 45° in the time interval from 9 a. m. to 3 p. m. (solar time), are represented. For these six hours $h=6$ $Q(t)$ is approximated by the average value of $Q(i)$ as a function of the charging time

$$Q(i)=Q_0 \cos i/4. \tag{1}$$

In this empirical formula $Q_0=650$ W/m^2=0.65 kW/m^2 is the maximum value of $Q(i)$ around March 21 and $i \in \{1 \dots 180\}$ the day number of charging (meaning degrees in (1)).

In Fig. 4 the dashed horizontal line $Q(i)$ corresponds to approximation (1) and the continuous horizontal line shows the "real" short-term average value of $Q(t)$. The irradiation before 9 a. m. and after 3 p. m. is considered zero due to its low value assumed to remain under the threshold value of collector operation.

Ambient temperature model

The real ambient temperature $\Theta_a(t)$ is approximated with the constant short-term average value of $\Theta_a(i)$ (per day) in the said time interval, 9 a. m. — 3 p. m., as a function of the day number. The "real" $\Theta_a(i)$ (continuous) and its empirical approximation (dashed line)

$$\Theta_a(i)=\Theta_{a\,\max} \cos 0.857(105-i)=18.4 \cos 0.857(105-i) \tag{2}$$

are based on [6] and represented in Fig. 5.

The maximum of the ambient temperature $\Theta_{a\,\max}=18.4$ °C does not coincide with the maximum of solar irradiation (at the horizontal surface) in June.

Other simplifications and calculation conditions

Thermal losses in the seasonal storage tank (pipelines, etc.) are eliminated during the charging process. In addition, thermal losses of the solar collector outside the six-hour charging period are eliminated, too. If the fluid (water) mass in the collector is much smaller than that in the intermediate storage and its circulation stops automatically while the irradiation drops below the threshold value, such a simplification does not cause any remarkable error. The relation between the water mass in the intermediate storage W_m and that in the seasonal storage W_s is assumed to be $W_m=0.1W_s$ for the first calculation though probably still not the optimum yet. Thermal energy losses in the HP will be eliminated. With a nonconstant temperature difference between both storages the coefficient of the performance of the HP will be varying. That will cause an increasing electric power input up to autumn.

Here power "losses" in the HP have been ignored at this stage of investigation and will be taken into account in the final discussion. Calculations have been made for a specific system (per unit of solar collector surface $S_c=1$ m^2) with the recommended relation [1] between the collector area S_c and the stored water capacity $S_c/W_s=0.3$.

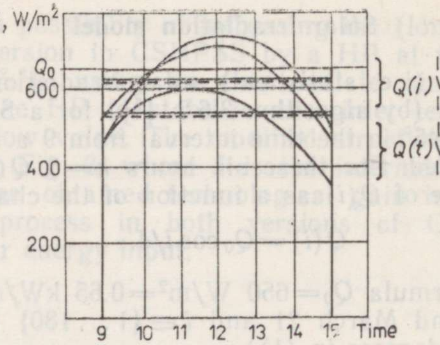

Fig. 4. The impulse model $Q(i)$ of the solar irradiation specific density $Q(t)$ in March (III), June (VI), and September (IX).

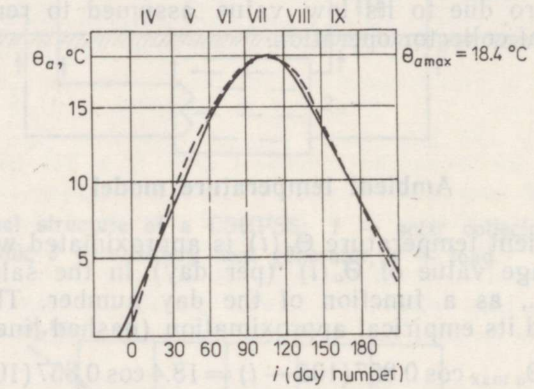

Fig. 5. The average temperature of the ambient air $\Theta_a(t)$ between 9 a. m. and 3 p. m. in Tallinn and its empirically approximated value (dashed line).

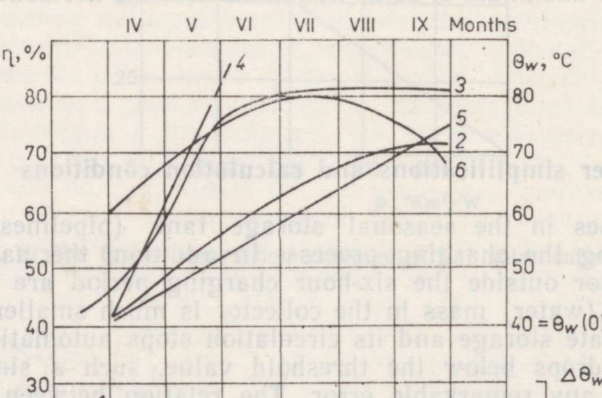

Fig. 6. Results of the analyses: *1* — efficiency η_i and *2* — temperature $\Theta_w(i)$ for the traditional CSHPSS, *3* — real temperature in Ingelstad I_c, *4* — calculated temperature $\Theta_w(i)$ at the modification ($S_c=1$), *5* — the same (with $S'_c=0.25$), *6* — efficiency η_i for the modified CSHPSS with $S'_c=0.25$, *7* — the amplitude of temperature oscillation $\Delta\Theta_{wm}$ in the intermediate storage.

The charging period is expected to be ~ 180 days from April 1 to October 1 when the day-time average value of ambient temperature (in Estonia) is above the freezing point and the system can operate with (cheap) water in the first contour.

We also ignore the water stratification effect in the storage tank (which makes the real long-term efficiency higher than that in the calculated model).

The charging of the seasonal store in a traditional CSHPSS

The yield of energy accumulated in the seasonal storage tank can be described as follows:

$$E(i)=\sum_{j=1}^{i} E_j\eta_j, \qquad j\in\{i\} \tag{3}$$

where the amount of energy per day is

$$E_i=hS_cQ(i).$$

With $S_c=1$

$$E_i=hQ_0\cos i/4.$$

The short-term average (per day) efficiency η_i can be calcylated by simulating the conversion curve (Fig. 2).

$$\eta_i=\eta_{\max}-U_L(\Theta_w(i)-\Theta_a(i))/Q(i), \tag{4}$$

where $U_L=7^W/m^2\,{}^\circ K$ is the (typical) value of thermal losses in the solar collector, $\Theta_a(i)$ is the temperature from equation (2), $\eta_{\max}=0.7$ is the typical value of efficiency at $p=0$, and $\Theta_w(i)=\Theta_{w\,\min}+E(i)/c_wW_c$ is water temperature in the storage tank. The heat capacity of water $c_w=1$. Fixing the above typical values (for specific storage capacity $W_s=3000\,l$), we get the final calculation model for the investigated charging process

$$\Theta_w(i)=40+\frac{860\cdot 0.65\cdot 6}{3000}\sum_{j=0}^{i-1}\eta_j\cos j/4;$$

$$\eta_i=0.7-\frac{7}{650\cos i/4}\left[40+\frac{860\cdot 0.65\cdot 6}{3000}\sum_{j=0}^{i-1}\eta_j\cos j/4-\right.$$
$$\left.-18.4\cos 0.857(105-i)\right], \tag{5}$$

where $j=0:\eta_0=\eta_{\max}$.

The number 860 is the transformation coefficient 1 kWh=860 kcal. The results of the calculation are represented by curves *1* and *2* in Fig. 6. We can see that the efficiency of the collector (farm) (curve *1*) drops to zero in August and the rise of water temperature (curve *2*) stops. It is not possible to make use of almost half of the solar energy amount (during the second half of summer). This is the physical basis for the remarkable reserve in solar heating technology in Nordic countries.

If we compare the temperature calculated by the given model (curve *2*) with that really measured at Ingelstad I_c [1] (curve *3*), we can see quite a good coincidence of curves *2* and *3*. The differences are accounted for by the nonequality of conditions in the south of Sweden and Estonia, different technical parameters of solar collectors and the simplifications made by us. In any case the form of both curves is the same, which gives evidence of sufficient correctness of the applied model.

The charging of the seasonal store in the modified CSHPSS

In this case we make an additional simplification and assume the water temperature in the solar collector to be constant $\Theta_{wm}(0)$ by the calculation of η_i in (4). In fact it still oscillates in a narrow range $\Delta\Theta_{wm}$ near $\Theta_{wm}(0)$, as we can see below. The energy accumulated in the intermediate storage tank per day is described in (3) and results the temperature step in it

$$\Delta\Theta_{wm}(i) = E_i / W_m.$$

As we assume there are no losses in the HP, the corresponding temperature step in the seasonal store will be

$$\Delta\Theta_w = \Delta\Theta_{wm} \cdot W_m / W_s = E_i / W_s,$$

and we can make some corrections in the system of equations (5). The power in the HP should be sufficient to transport (the maximum of) the accumulated energy to the seasonal store within 24 hours, and restore the initial temperature $\Theta_{wm}(0)$ for the next day.

The operation mode of the HP (continuous or the pulse-width one) has to be discussed separately. With these estimations we can find for the modified CSHPSS

$$\Theta_w(i) = 40 + \frac{860 \cdot 0.65 \cdot 6}{3000} \sum_{j=0}^{i-1} \eta_j \cos j/4,$$
$$\eta_i = 0.7 - \frac{7}{650 \cos i/4} [10 - 18.4 \cos 0.857 (105 - i)], \tag{6}$$

where $j=0 : \eta_0 = \eta_{max}$.

In the equations we have assumed $\Theta_{wm}(0) = 10\,°C$ which value has to be specified by optimizing the complete CSHPSS.

The everyday temperature step in the intermediate storage tank has the calculated (at estimated conditions) value

$$\Delta\Theta_{wm}(i) = \frac{\eta_i \cdot h \cdot Q_0 \cos i/4}{W_m} = \frac{860 \cdot 0.65 \cdot 6}{300} \eta_i \cos i/4.$$

The results of the calculation are given also in Fig. 6. Curve *4* shows $\Theta_w(i)$ with the same collector area $S_c = 1$. Due to the high efficiency of conversion, the rise of temperature $d\Theta_w(i)/di$ is too high for the storage capacity and will result in thermal overloading of the storage tank at $\Theta_w(i) > 80\,°C$. In order to preserve the same storage capacity, curve *5* is calculated for the reduced area $S'_c = S_c/4$ of the collector, where

$$\Theta_w(i) = 40 + \frac{860 \cdot 0.65 \cdot 6}{4 \cdot 3000} \sum_{j=0}^{i-1} \eta_j \cos j/4. \tag{7}$$

Curve *6* in Fig. 6 represents η_i of the collector with the reduced area, and curve *7*, the amplitude of temperature oscillation in the intermediate storage tank. Due to $\Theta_{wm}(0) < \Theta_a(i)$, the solar collector is mostly operating in the regime of a convective thermal converter (from the ambient air) and the system realizes $\eta_i > \eta_{max}$.

Summary

To assess the possible technological gain from the modification of CSHPSS, we have to compare the calculated solar energy yield per m^2 for both modifications of the collector.

(a) In the analysed example we get $E(1) = \Delta\Theta_w \cdot W_s/860 = 31 \cdot 3000/860 = 108$ kWh for the traditional CSHPSS during the charging period.

(b) In the analysed example we get $E(2) = 4 \cdot \Delta\Theta_w \cdot W_s/860 = 4 \cdot 34 \cdot 3000/860 = 474$ kWh for the modified CSHPSS during the charging period. With the estimated value of COP = 2.5, the effective energy yield is $E_{ef} = E(2)(1 - 1/\mathrm{COP}) = 284$ kWh. The effective gain of the modification is $E_{ef}/E(1) = 284/108 = 2.63$. Thus, even if the gain is calculated with some error, we can still conclude that:

(1) the modification of CSHPSS discussed in this paper provides essential technological advantage;

(2) by this method solar energy can be accumulated without any technological limits all summer round;

(3) the area of the solar collector (farm) can be reduced crucially. It allows the use of solar technology in districts with a high density of population;

(4) the solar collector design policy has to be revised — probably a greater energy yield could be achieved by using less expensive collectors with cheaper thermal insulation.

In addition, if the economic analysis will confirm the benefit of the modification, an optimization of the components of the system has to be carried out.

REFERENCES

1. *Dalenbäck, I.-O.* Central Solar Heating Plants with Seasonal Storage. Status Report. Dep. of Building Services Engineering, Chalmers University of Technology, Göteborg, Sweden, 1990.
2. *Рей Д., Макмайкл Д.* Тепловые насосы. Энергоиздат, Москва, 1982.
3. *Grathwohl, M.* World Energy Supply. W. de Gruyter, 1982.
4. *Руссак В.* Радиационный режим в Тыравере. Препр. А-7, АН ЭССР, Таллинн, 1987.
5. *Даффи Дж. А., Бекман У. А.* Тепловые процессы с использованием солнечной энергии. Мир, Москва, 1977.
6. *Прилипко Г. П.* (ed.). Климат Таллина. Гидрометеоиздат, Ленинград, 1982.

Received
September 30, 1992
Revised
December 4, 1992

Teolan TOMSON

SESOONSE SALVESTIGA HELIOKÜTTESÜSTEEMI MUUNDUSTEGURI TÕSTMISE MEETOD

Suvalise tasapinnalise heliomuundi muunduskarakteristiku langeva iseloomu ja sesoonses salvestis talletatava vee piisavalt kõrge temperatuuri tõttu jääb süsteemi keskmine muundustegur madalaks. Tunduvalt paremaid tehnilisi tulemusi tagab lisasalvesti kasutamine koos soojuspumbaga mõlema salvesti vahel. See võte lubab hoida heliomuundisse siseneva vee temperatuuri stabiilsel madalal tasemel.

Теолан ТОМСОН

МЕТОД ПОВЫШЕНИЯ КОЭФФИЦИЕНТА ПРЕОБРАЗОВАНИЯ СОЛНЕЧНОЙ ЭНЕРГИИ В ГЕЛИОСИСТЕМЕ С СЕЗОННЫМ АККУМУЛЯТОРОМ

Из-за мягкой характеристики преобразования любого солнечного преобразователя и относительно высокой температуры воды в сезонном аккумуляторе среднее значение коэффициента преобразования солнечной энергии остается низким в традиционной гелиосистеме. Значительно высокие технические характеристики могут быть получены в гелиосистеме, дополненной промежуточным аккумулятором для суточной продукции теплоты и тепловым насосом между указанными аккумуляторами, который стабилизирует температуру воды на входе солнечного коллектора при низком значении.