Proc. Estonian Acad. Sci. Engng., 1997, 3, 4, 302–309

https://doi.org/10.3176/eng.1997.4.07

PRELIMINARY ANALYSIS OF THE ENERGY BALANCE OF A SOLAR-HEATED HOT-BED

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Received 18 December 1996, in revised form 18 September 1997

Abstract. Daily temperature curves for soil and room temperatures are calculated according to a simplified simulation model, based on the balance of energy fluxes. An open field, an unheated hot-bed and a hot-bed with combined additional solar heating are analysed for the first day of the spring season. The calculated results are compared with real soil temperatures in four depths. Approximate capital costs of a solar-heated hot-bed are estimated.

Key words: solar-heated hot-bed, simplified simulation model, soil and room temperatures.

1. INTRODUCTION

In addition to domestic hot water production, solar energy can be utilized in other technological fields. A theoretical preliminary study, based on computer simulation for a hot-bed, was conducted at the Estonian Energy Research Institute. The problems of seasonally solar-heated greenhouses were studied. However, because of large volume (20 m^3 water per one m^2 of greenhouse floor [[1]]), hot water-energy seasonal storage tanks have proved technically and economically unacceptable.

Hot-beds are low (practically without walls) transferable constructions with no ventilation problems in summer, mainly used in spring (occasionally also in autumn). Therefore they have an advantage of being solar-heated. However, the problem is how to maintain the room temperature T_r and the soil temperature T_s equal, at the level recommended by plant physiologists

$$T_r = T_s \approx 20\,°\mathrm{C}. \tag{1}$$

In greenhouses, this condition is ensured automatically, because plants are located centrally on the boards, in the centre of the space.

The objective of the analysis is to determine daily soil and hot-bed air temperatures according to Eq. (1), depending on natural (solar radiation and ambient temperature) and artificial parameters (data of the solar collector, size of the storage tank, temperature of heating water, battery size and location).

2. SIMPLIFYING PRESUMPTIONS

Our analysis contained a numerical example for the first day of the plant-growing season in spring, based on average (statistical) data for the ambient temperature $T_a(h)$ and the solar irradiation $I(h)$. Solar energy is described by the irradiation $I(h)$ cosine-pulse model, and the daily ambient temperature $T_a(h)$ is determined by a sine model similar to [2]. Provisionally, 6 April was chosen, because on an earlier date, a hot-bed (soil) is still frozen, whereas on a later date, solar heating is meaningless.

The problem was reduced to an one-dimensional model, i.e., the heat balance of the unit surface in the centre of the hot-bed was calculated, neglecting the edge effects. Other significant simplifying conditions and hypotheses were:

1) the soil was considered melted;

2) a 30 cm soil layer was considered to be a homogeneous isothermal medium;

3) the ground (subsoil) was considered to be an "insulation" with the zero value of heat capacity;

4) the heat capacity of the surface water (probable flowing) at 120 cm under the soil was considered of indefinite magnitude, i.e., its temperature $T_g(h) = 7$ °C was considered constant.

3. SUBJECT OF ANALYSIS

The subject of the analysis was an open field, a non-heated ("cold" hot-bed without additional solar heating) and a combined (simultaneous heating from below and from the top) hot-bed. In fact, both the hot-bed with the selective heating from the top and that from below were analysed. However, these data will not be discussed in this article since they do not provide a result close to the preferred regime (1). An open field gives the required background, since a non-heated hot-bed is the first inexpensive option towards solar energy use.

4. METHOD OF ANALYSIS

The analysis, based on the balance of the heat fluxes described by the system of algebraic expressions for each time interval (hour h), used the standard

EXCEL5 program. For instance, on the open soil surface (without plants in spring), energy balance is described by

$$Q_r(h) = Q_{ks}(h) + Q_e(h) + Q_\lambda(h) + Q_R(h) \pm Q_s(h), \qquad (2)$$

where $Q_r(h)$ is the heat generated by solar irradiation $I(h)$; $Q_{ks}(h)$ is the convective heat flux, which may be calculated from data [3]; $Q_e(h) \approx Q_{ks}(h)$ is the heat flux via evaporation; $Q_\lambda(h)$ is the heat flux via calculated ground transconductivity; $Q_R(h)$ is the heat flux via infrared radiation, which may be calculated through an imaginary surface with the temperature $T_a(h)$; $Q_s(h)$ is the heat flux stored in the soil mass. It is negative at the low value of $I(h)$ when soil is heating the air above ($T_a < T_s$). This balance is illustrated for an open field in Fig. 1.

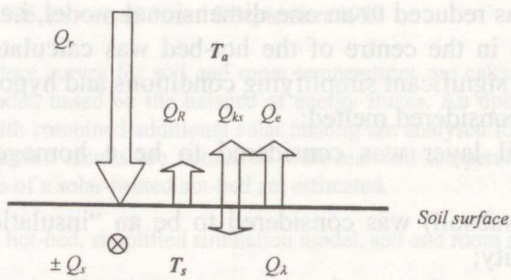

Fig. 1. Heat fluxes in the energy balance of the open soil.

5. CALCULATION RESULTS

All the modifications of hot-beds have sophisticated balance (as compared to the example), with additional heat fluxes from the heating system and from the corrected heat balance Eq. (2). For instance, $Q_{ks}(h) = 0$, when $T_r > T_s$ and $Q_\lambda(h) = 0$, if a radiator warms the soil from below. To concentrate on the key issues, we present here the results of the analysis only. Figure 2 shows the calculated daily temperature curves for the open field soil T_{so}, the cold hot-bed air T_{rc} and the soil T_{sc} as well as for the solar-heated hot-bed air T_{rs}, and the soil T_{ss}. Thus the calculations were made for constant heating on the power level, which is half (of the average value) of natural solar irradiation.

Authors consider the calculated $T_{rs} \approx T_{ss} \approx 19\,°C \pm 2\,K$ regime acceptable, and based on these data, a heating system can be designed. Figure 3 shows the hydraulic circuit diagram of the designed (not realized!) solar hot-bed with combined heating.

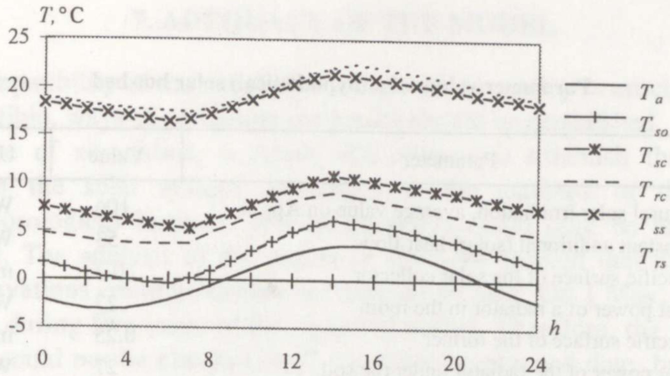

Fig. 2. Daily temperature curves of the ambient temperature T_a and the results of simulation on 6 April.

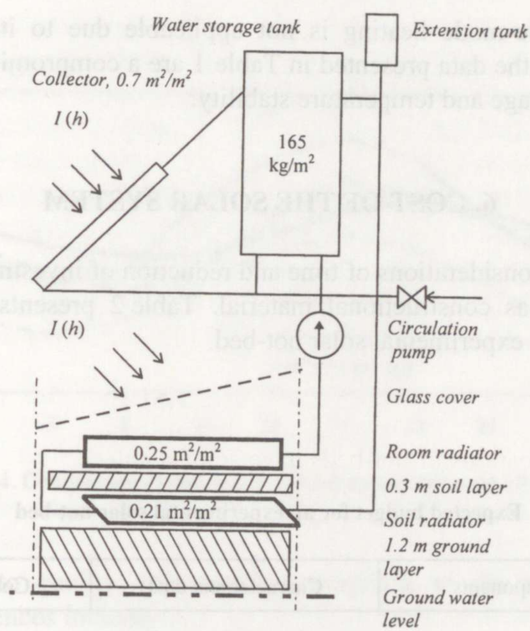

Fig. 3. Circuit diagram of an experimental solar hot-bed with combined heating.

To provide the high efficiency of the solar collector and to avoid an intensive evaporation from the soil, the heating system is recommended to be designed for a modest value of water temperature. Table 1 shows some characteristic technical data of the system.

Table 1

Parameter values of a (hypothetical) solar hot-bed

Parameter	Value	Unit
Natural solar irradiation, average value on Apr. 6	106	W/m^2
Constant additional (solar) heat flow	53	W/m^2
Specific surface of the solar collector	0.7	m^2/m^2
Heat power of a radiator in the room	27	W/m^2
Specific surface of the former	0.25	m^2/m^2
Heat power of the radiator under the soil	27	W/m^2
Specific surface of the former	0.21	m^2/m^2
Average temperature of heating water	36.4	°C
Temperature drop of heating water	16.4	K
Specific volume of heated water storage	165	kg/m^2

Selective, pulse-mode heating is not applicable due to its higher cost of realization. Thus, the data presented in Table 1 are a compromise between water volume in the storage and temperature stability.

6. COST OF THE SOLAR SYSTEM

Based on the considerations of time and reduction of investment costs, plastic is recommended as constructional material. Table 2 presents an approximate budget of a 12 m^2 experimental solar hot-bed.

Table 2

Expected budget for an experimental solar hot-bed

Components	Characteristic data	Cost, EEK
Collector	8.4 m^2, 2 000 EEK/m^2	16 800
Water storage	2 000 kg, glass-plastic	3 000
Circulation pump	0.5 m^3/h	1 000
Valves	4 units	400
Pipes	Ø12/18	250
Radiators (self-made)	≠ 4 mm PV plastic sheets	500
Insulation	pipes and storage	1 000
Reserve	~ 6 % from above	1 465
Total		~24 000

7. ADEQUACY OF THE MODEL

The compatibility of the simulated model with the reality is crucial. In case it is incompatible, ways of correcting the model should be established.

The date of simulation, 6 April, was chosen to establish the maximum capacity of the solar system. According to the database of the Estonian Hydrometeorological Institute, soil temperatures could only be taken for the melted soil. The analysis of the period of 1985–94 showed that the first "full time" observations could be carried out only on 10 May. On 1 May, the soil was still frozen during five years of the observed period. Therefore, the adequacy of the model could not be checked on 6 April, on the planned date, but the (open field) model could be used for 10 May. Figure 4 shows the comparison of real and simulated temperatures. Attention should be paid to the real temperature distribution in the soil at the depths of 0.05, 0.1, 0.15, and 0.2 m (Fig. 5). Bold curve shows the average temperature of the soil layer of 0.3 m used in our model.

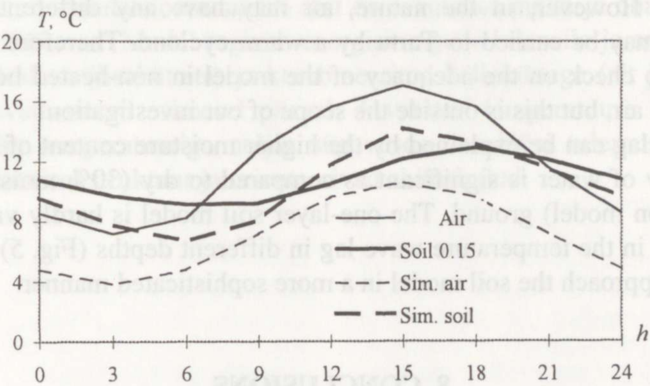

Fig. 4. Comparison of real and simulated temperatures on 10 May.

With regard to quality, the model corresponds to the reality. The most significant differences include:

- Natural soil is more inertial than that given by the model. The range of temperature fluctuations at the depth of 0.15 m was almost twice lower than that of the simulated temperatures.
- The boundary values of (daily) temperatures in the soil showed a three-hour delay relative to the corresponding ambient temperatures.
- The daily ambient temperature exceeded the soil temperature (equaled to it at the surface, at the depth of 0.05 m), but the value of the simulated air temperature remained always below the soil temperature.

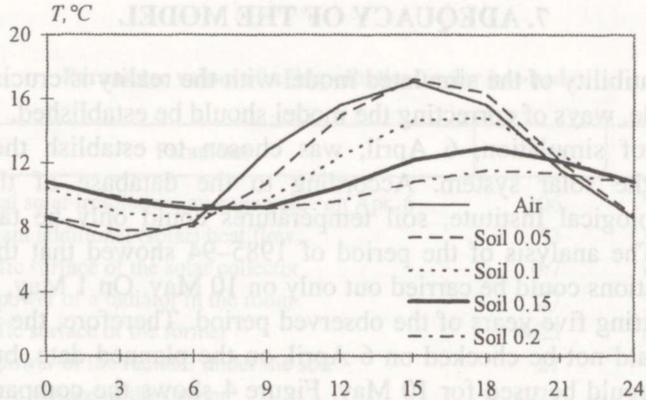

Fig. 5. Real temperature of the open field soil in different depths (m) in Tartu on 10 May: average over the period of 1985–94.

The latter can be explained by the fact that in the model the air is warmed up by the soil. However, in the nature, air may have any different origin, for example, it may be carried to Tartu by a warm cyclone. Therefore it would be interesting to check on the adequacy of the model in non-heated hot-bed space with isolated air, but this is outside the scope of our investigation.

The time lag can be explained by the higher moisture content of the soil: the heat capacity of water is significant as compared to dry (30% moisture used in the simulation model) ground. The one-layer soil model is hardly valid because of variations in the temperature wave lag in different depths (Fig. 5). It refers to the need to approach the soil model in a more sophisticated manner.

8. CONCLUSIONS

In general, the simplified simulation model proposed describes thermal processes in a solar-heated hot-bed, showing technological constraints and requirements to the heating system.

To follow the requirement of equal soil and hot-bed temperature levels (1), both heating from below and from the top must be considered. The cost of solar equipment is high – approximately 2 000 EEK per m^2.

It is not clear whether the recommended condition (1) is obligatory. Ambiguity remains, even after consultations with the researchers of the Estonian Agricultural University. If the temperature levels were lower, the additional cost of one m^2 may be reduced.

Possible future studies should focus on improving the soil model allowing for the description of the time lag of the temperature wave.

ACKNOWLEDGEMENT

We thank the Estonian Science Foundation for financing most of these investigations under grant No 77 during 1994–95.

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PÄIKESEKÜTTEGA LAVA ENERGIABILANSI EELANALÜÜS

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Lihtsustatud simulatsioonimudeli abil on arvutatud mulla ja õhu ööpäevased temperatuurikõverad. Mudel tugineb energiavoogude bilansile ja analüüsitud on avamaa, külmlava (lisakütteta) ja kombineeritud helioküttega (alt ja pealt) lava näitajaid kevadsesooni esimesel päeval. Arvutatud temperatuure on võrreldud mulla reaalse temperatuuriga neljas sügavuses. Analüüsi tulemusel on leitud heliokĂĽttesüsteemi struktuur ja orienteerivad ehituskulud.