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INVESTIGATION OF SENSIBLE HEAT STORAGE AND HEAT INSULATION IN THE EXPLOITATION OF CONCENTRATED SOLAR ENERGY

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This paper analyses the exploitation of solar energy by wholly relying on it to heat homes by 100% solar heating in Hungary. It determines the necessary amount of heat and the heat storage capacity and considers the time sequence between charge and discharge. Further, it provides a feasible technology for sensible heat storage and it determines the sizes of heat store-building, the thickness of heat insulation and it calculates the heat losses of heat storage. On the basis of the results, the paper provides proposals for the method of heat storage and for the technical parameters to be considered for the heat insulation. It describes the application of the heat storage method for district heating and electricity generation.

Keywords: solar energy, sensible heat storage, heat insulation, 100% solar heating of home, electrical energy generation

Introduction

We have been striving for a long time to be capable of collecting the energy of solar radiation and of storing it. Certainly, we would like to store and use solar energy for a long time without suffering any great losses. The question is, whether the collected and stored energy could provide 100% of the homes' heatingthe whole year round or whether it could generate electricity over several months? To achieve that several problems need to be solved:

- The flux of solar energy is low.
- There is no harmony between energy generation and consumption and it is incalculable as a function of time. Because of that big energy storage is needed.
- Efficient and economic energy storage for a long time is an unsolved problem.

This paper analyses this issue and presents a feasible technological solution of how the buildings could continuously be supplied with heat energy from the direct solar radiation and how the energy must be stored as sensible heat storage and how the heat insulation of the heat storage facilities must be planned [1].

Calculations for the size of solar radiation field and for the heat storage capacity

The solar radiation, that passes directly through the atmosphere to the Earth's surface, is called direct solar radiation. The period, when the direct radiation is more than 210 W/m^2, is called sunny hours. In Hungary, the number of sunny hours varies between 1900–2200 hours per year, which is quite long compared to that in the world. The indicated data are based on statistics of several years [2, 3, 4]. The direct radiation is approx. 1000 W/m^2 on the surface of the Earth in fine weather. This value is lower under cloudy weather conditions and during air pollution. We use in the following calculations the average sunny hours of 400 W/m^2 *(Fig. 1).*

In a year's time period, perpendicularly to the direction of solar radiation, we can estimate the amount of the collectable direct solar energy as below:

$$\begin{aligned} &2000\,\frac{h}{year}\cdot 3600\,\frac{s}{h}\cdot 400\,\frac{W}{m^2} = \\ &= 2880\,\frac{MJ}{(m^2\cdot year)}. \end{aligned} \tag{1}$$

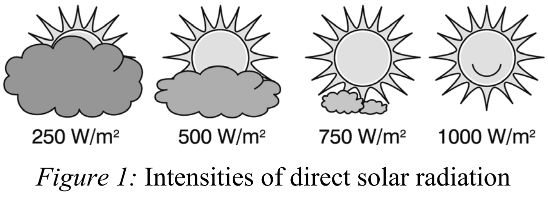

Figure 1: Intensities of direct solar radiation

Heat energy consumption of a family house

In a dwelling-house. heat energy is used for heating and hot water production. Without detailed explanation of the calculations, we have estimated alltogether 80000 MJ heat energy consumption per year for five persons and an average house of cc. 100 m^2. That number is equivalent to approx. 2350 m^3 natural gas (34 MJ/m^3). *Table 1* shows the energy consumption (heating and hot water generation) in each month of a year.

As a matter of fact, new houses and block houses have lower energy requirements.

The task is to collect the above indicated 80000 MJ heat energy and the heat losses of the heat storage “tank”.

Sizes of the solar field

We can collect energy of approx. 400 W on a surface area of 1 m^2. This energy can be collected by a surface right-angle to solar radiation in sunny hours and if there are approx. 2000 sunny hours/year in Hungary. We can calculate this surface area of solar radiation by using the following formula (the calculation relates to the demand of 80000 MJ energy):

$$A = \frac{80000 \frac{MJ}{year}}{400 \frac{J}{(s \cdot m^2)} \cdot 2000\, h \cdot 3600 \frac{s}{h}} = \qquad (2)$$

$$= 27.75\, m^2 \approx 28\, m^2$$

This 28 m^2 does not include the heat losses.

Table 1: Energy consumption of a dwelling-house per year

period (days)	sunny hours	collectable direct solar energy per m^2 [MJ/m^2]	**Charge** [MJ] collected solar energy on 27.75 m^2	heating [MJ]	hot water production [MJ]	**Discharge** [MJ] total heat energy requirement	**Amount of energy to be stored** [MJ]
Apr (30)	187	269	7470	1840	1200	3040	4430
May (31)	253	364	10110	900	1240	2140	12400
June (30)	267	384	10670	0	1200	1200	21870
July (31)	297	428	11870	0	1240	1240	32500
Aug (31)	278	400	11110	0	1240	1240	42370
Sept (30)	202	291	8070	260	1200	1460	48980
Oct (31)	139	200	5550	1900	1240	3140	51390 **≈52000 MJ**
Nov (30)	63	91	2520	9470	1200	10670	43240
Dec (31)	40	58	1600	14730	1240	15970	28870
Jan (31)	57	82	2280	16830	1240	18070	13080
Feb (28)	83	120	3320	12100	1120	13220	3180
Mar (31)	136	196	5430	7360	1240	8600	10
year (365)	2002	2883	80000	65390	14600	79990	

Capacity of heat storage

A heat storage “tank” shall be used due to the sequence of time between charge and discharge. Table 1 shows the calculating of the capacity of heat storage “tank”. The heat capacity depends on the charge and the discharge. The total capacity of the heat storage “tank” amounts to 52000 MJ. This size of heat storage “tank” can ensure heat energy supply for a house all the year round.

Method of heat storage and sizes of the heat storage “tank”

The method of sensible heat storage is the simplest one. We have surveyed many heat storage materials and have chosen magnesite brick. Calculations with magnesite brick showed the best results. *Table 2* shows the properties of the magnesite brick.

Corundum (95% Al_2O_3) brick is also a very good heat storage material: its density of energy amounts to 3.3 MJ/(m^{3}K) and its melting point is 2020 °C.

Table 2: Properties of magnesite brick [5, 6]

Content	Application range of temperature ΔT	Specific heat J/(kgK)	Density kg/m^3	Density of energy MJ/(m^{3}K)	Heat conductivity W/(mK)	Price $/ton
37–98 % MgO 1–60 % CaO and/or Cr_2O_3	65–500 °C (melting point: 2852 °C)	1172	3020	3.54	8.4 (on 500 °C)	100–500

We can calculate the mass and volume of magnesite brick from the energy capacity of heat storage "tank" (≈52000 MJ), from the planned range of temperature ($\Delta T = 500 - 65\ °C = 435\ °C$) and from its specific heat and density. The following calculation is applicable:

$$Q = c \cdot m \cdot \Delta T \rightarrow m = \frac{Q}{c \cdot \Delta T} \tag{3.a}$$

$$\begin{gathered} m = \frac{52 \cdot 10^9 J}{1172 \dfrac{J}{kg \cdot K} \cdot 435\ K} = 101997\ kg \\ m \approx 102\ tons \end{gathered} \tag{3.b}$$

$$\begin{gathered} V = \frac{m}{\rho} = \frac{102\ tons}{3,02\ tons/m^3} = 33,7\ m^3 \\ V \approx 34\ m^3 \end{gathered} \tag{4}$$

This size seems to be a normal value and normal scale. If the end point of maximum temperature were just 430 °C, the size of heat receiver would be 40 m^3. However, the 500 °C of maximum temperature is real too, scilicet the thermooils (heat transfer fluids) work on 580 °C (1060 °F) in the existing concentrated solar power plants. The temperature difference, needed to the heat exchange, is ensured.

Heat insulation and heat losses

Heat store-building made of bricks

Hereinafter, the heat storage "tank" will be named as heat store-building because there is no tank in the construction. We analyise here only a cubic shaped heat store-building. The construction is shown in *Fig. 2*.

We make a difference between the bottom and the upper parts of the store-building as follows [7]:

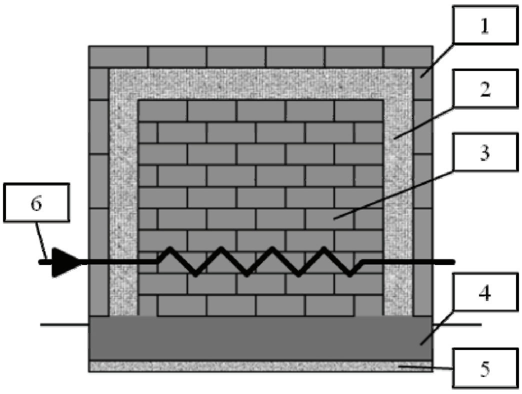

Figure 2
1 – external wall, 2 – coat of heat insulation from rock wool, 3 – magnesite bricks, 4 – concrete pad, 5 – gravel bed, 6 – pipe of heat transfer fluid

The bottom part is in contact with the soil and the upper parts of the store-building are in contactwith the the ambient air. The upper parts are built up from lateral-walls and from the roof. We calculated these parts (wall and roof) in the same way. The thermal resistance of the upper part and of the bottom part ($R_{cond} = \delta/\lambda$, respectively $R_{conv} = 1/\alpha$) are indicated below:

$$R_{\text{joint}} = \frac{1}{\alpha_{conv} + \alpha_{rad}} = \frac{1}{\alpha} \tag{5}$$

$$R_{uppers} = R_{cond} + R_{joint} \tag{6}$$

$$R_{uppers} = R_{ins} + R_{brick} + R_{\text{joint}} \tag{7}$$

$$R_{bottom} = R_{concret} + R_{gravel} + R_{soil} \tag{8}$$

The value of the heat transfer coefficient between the external side of the wall and the ambient air is $\alpha = 24\ W/(m^2K)$. This value has been derived from a Hungarian architectural standard (MSZ 04-140-02). The foundation of the store-building would be constructed from cellular concrete: its density is 700 kg/m^3 and its bearing strength is more than 150 N/m^2.

Table 3 shows the material properties of the store-building, which we have used in the calculation process [6, 7, 8,].

Table 3: Applied value of λ thermal conductivities and δ coating thickness

rock woll		brick/barge stone	cellular concrete	gravel	soil
°C	W/(mK)	0.64 W/(mK)	< 0.17 W/(mK)	0.35 W/(mK)	1.3 W/(mK)
500–400	0.180				
400–300	0.100				
300–200	0.070				
200–100	0.049				
<100	0.038				
δ_{ins}= to be determined		$\delta_{brick} = 0.12$ m	$\delta_{concrete} = 0.6$ m	$\delta_{gravel} = 0.3$ m	$\delta_{soil} = 0.4$ m

The thermal conductivity of the heat insulation (rock wool) increases significantly with the rise of temperature λ(T). The curve can be seen in *Fig. 3*.

The above mentioned function λ(T) has been considered in the calculation process. Actually, in every month we experienced various heat resistances. *Table 4* shows the values of the ambient temperature and the soil temperature at a dept of 1 m.

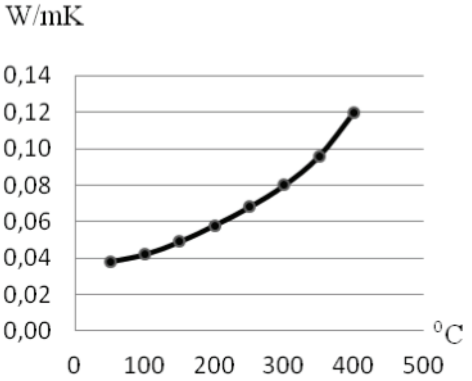

Figure 3: Thermal conductivity of rock wool versus temperature

Heat losses of the heat store-building

We calculated the heat current as heat conduction through the flat wall. The heat transfer between the external surface of the wall and the ambient air (at the joint) equals to the conductive heat current in the wall. If we know the temperature of the external surface of the wall, the internal temperature

$$\Delta T_{conductiv} = T_{magnesite\ brick} - T_{outside\ wall} \qquad (9)$$

$$\Delta T_{conductiv} = T_{\text{int}} - T_{\text{ext}} \qquad (10)$$

and the thickness of heat insulating material δ_{ins}, we are able to calculate the heat current $\dot{q}$ [W/m^2]:

$$\dot{q} = \frac{\Delta T_{transfer}}{R_{transfer}} \quad és \quad \dot{q} = \frac{\Delta T_{cond}}{R_{cond}} \qquad (11,12)$$

$$R_{cond} = \frac{\Delta T_{cond} \cdot R_{transfer}}{\Delta T_{transfer}} \quad \rightarrow \quad \dot{q}\ ;\ \delta_{ins} \qquad (13)$$

$$Q = \dot{q} \cdot A \qquad (14)$$

We designed the maximum internal temperature (T_{int}) and the maximum external temperature of the wall's surface area (T_{ext}) to be 16 °C under conditions in October. Further, we calculated 40 cm thick insulating material (rock wool), which represents a realistic value. Table 4 shows the heat losses suffered in each month and all the year round. The calculations were performed on one house (with a store building volume of 34 m^3), on 50 houses (with a store building volume of 1700 m^3) and on 100 houses (with a store building volume of 3400 m^3).

It is a remarkable result that the specific heat losses fall with increasing store-building size (m³). The amount of decrease is remarkable. The cause of that is that the specific surface "A/V – surface/volume" decreased. Further, we calculated the following values: the specific heat loss is as high as 14% in the case of store-building of 500 dwelling-houses (with size of 17000 m^3) and it is as high as 11% in the case of 1000 dwelling-houses (34000 m^3)!

We analysed the dependence of specific surface area "A/V" on the volume "V". We performed the analysis by using a cube. *Table 5* shows the results of the volume (V [m^3]) and the specific surface (A/V [m^2/m^3]) with different lengths of the edge of the cube. Then we graphed them in *Fig. 4*.

Table 4: The heat losses of different sized heat store-buildings with 40 cm thickness of the rock wool

							34 m^3	1700 m^3	3400 m^3
	T_{int} [°C]	T_{ext} [°C]	T_{amb} [°C]	q_{upper} [W/m²]	T_{soil} [°C]	q_{bottom} [W/m²]	Q_{total} [GJ]	Q_{total} [GJ]	Q_{total} [GJ]
Apr (30)	102	12	12	8	10	20	1.6	22	35
May (31)	168	18	17	16	14	33	3.2	43	68
June (30)	247	21	20	28	18	49	5.1	70	111
July (31)	335	24	22	45	20	67	8.2	111	177
Aug (31)	417	24	21	69	21	84	12.1	164	260
Sept (30)	472	21	17	94	19	97	15.4	209	332
Oct (31)	492	15	11	104	14	102	17.5	237	377
Nov (30)	424	9	6	74	10	88	12.5	169	268
Dec (31)	305	4	2	40	7	63	7.4	100	159
Jan (31)	174	1	0	18	5	36	3.5	48	76
Feb (28)	91	2	2	8	4	19	1.5	20	32
Marc (31)	65	6	6	5	5	13	1.1	14	23
total heat losses of a year [GJ]							89.1	1209	1919
total heat consumption of a year [GJ]							80.0	4000	8000
heat losses versus heat consumption per cent [%]							111%	30%	24%

Table 5: The specific surface area of a cube versus its size

a [m]	1	2	3	4	5	6	7	8	9	10	20	30	40	50
A [m²]	6	24	54	96	150	216	294	384	486	600	2400	5400	9600	15000
V [m³]	1	8	27	64	125	216	343	512	729	1000	8000	27000	64000	125000
A/V [m²/m³]	6.00	3.00	2.00	1.50	1.20	1.00	0.86	0.75	0.67	0.60	0.30	0.20	0.15	0.12

The next algebraic formula describes the function of Fig. 4:

$$y = \frac{6}{\sqrt[3]{x}} \qquad (15)$$

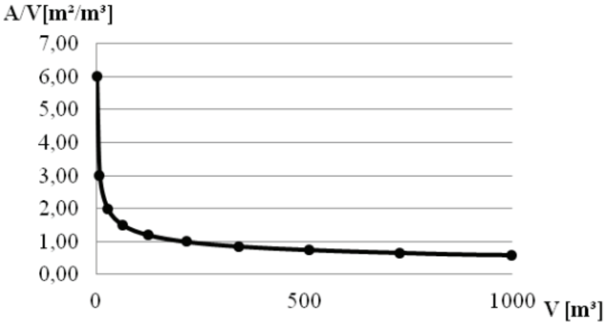

Figure 4: Specific surface versus volume of cube

Conclusions

The paper sets out that it is possible to store solar energy all the year round or for a long period. The stored heat energy stored can meet the total heating demand of the houses or can also generate electricity in Hungary. We can keep the heat losses at low level (<20%). Certainly we must consider some technical facts.

Heat energy shall be stored as below:

- at high temperature: the higher the better,
- using materials with high energy density [MJ/(m^{3}K)] (using one of solid materials, for example magnesite brick) and
- in store-building whose size is big enough, because the heat losses shall be low.

We would emphasize here that the increase of size, up to a certain size, is one of the best heat insulation technique.

The heat storage in solid material is easy and safe. No steel tank is used and the brick isn't flammable and explosive. In my opinion this method should be used for district heating and for electricity generation.

Our next goals are:

- to determine the optimum size of the heat store-building and the thickness of heat insulation coat [9, 10] and
- to investigate different heat transfer materials. We would like to achieve higher temperature in the store-building. Perhaps gaseous materials would be good heat transfer materials from the solar trough to the store building.

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