Utilizing of Water Phase Transitions in Seasonal Heat Storage Systems

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Abstract

Utilizing of the solar energy for heating existing family houses requires seasonal heat magazines with a capacity at least 50 kWh/m² of a dwelling area. Depending on the house size, 3000 - 8000 kWh heat has to be available in the magazine at the end of autumn. Closed heat magazines with desired energy content are neither technically, nor financially justifiable. Open soil heat magazines, utilizing sensible heat, are known [1, 2], but they are justified only for large capacity systems (GWh size). Only then, the ratio of volume to surface area is large enough to keep thermal losses of a magazine at an acceptable level. Another solution, combination of deep borehole with a heat pump is frequently used. However, the return on investment of such system frequently exceeds 10 years. Increasing the capacity of seasonal heat depositories is therefore highly desired.
In the present article a seasonal heat storage system, making use of the water latent heat is described.
As a result, the heat capacity of wet soil heat magazine can exceed 70 kWh/m³ without any heat losses and the surface area of the magazine for a house with the dwelling area of ca 100 m² can be kept below 100 m².

Keywords: water latent heat; PCM, seasonal heat storage; Sun heat collector; heat pump.

1. Introduction

1.1. Heat collection

Energy consumed by single family houses (SFH) in Sweden represents more than 50% of the total useful energy production [3]. Similar situation is valid for the rest of the Europe, even if the absolute energy amount differs, depending on the geographical position of a house [4]. Solar heat, collected during the year, can easily cover necessary energy demand, provided the summer heat excess could be stored until the beginning of a heating season. The annual distribution of the energy consumption and solar energy resources for a family house is demonstrated in fig.1.

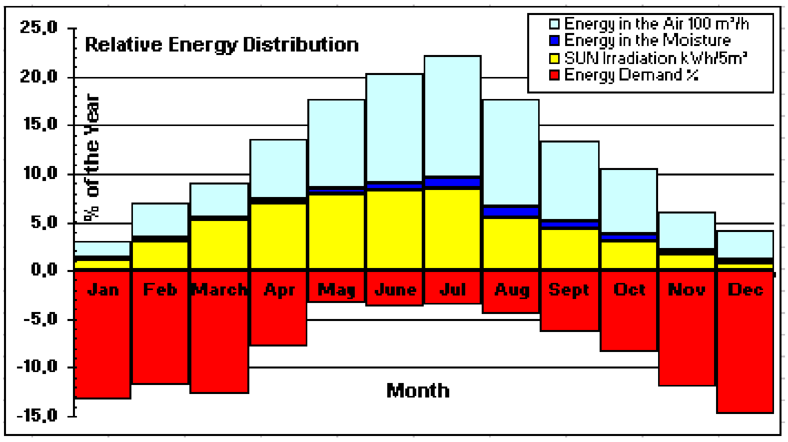

Fig.1. Relative annual distribution of energy demand and resources.

The data for the Fig. 1 were measured at the house at 59° 25´N, 17° 50´E (Sweden, Stockholm area) during the year 2009. The absolute annual energy consumption was 11 MWh. The instantaneous solar energy intake (both collected solar heat and heat obtainable from the moist air) could supply the house with the heat from the middle of March to the end of October. The amount of a collected heat can be increased by increasing the area of solar heat collectors (SHC), but as long as the function of SHC is limited to direct solar heat collection, its heat collection efficiency cannot exceed 50%. It can be increased only if the SHC is adapted for collection of the heat accumulated in the humid air as well. But even if the heat is collected both from the Sun radiation and the atmospheric air, it cannot deliver more than about 40 % of the annual energy demands. About 60% of the heat requirements have to be delivered either by oil, gas, electricity or hopefully by the solar energy stored during summer in a seasonal heat magazine.

1.2. Heat storage

Apart from the conversion of the solar radiation and CO_2 to the methanol [5], there exist two methods for the storage of the solar heat, utilizing physical properties of the storage material. One is based on a specific heat (c_p) of the storage material and the other takes the advantage of latent heat of storage material phase transitions. The latter property is applicable for the seasonal heat storage only with water, even if there exists an extensive literature on other phase change materials (PCM) for the heat storage in buildings [6]. The heat amount, obtainable from a magazine making use of a specific heat, can be calculated by means of a following equation:

$$\Delta H_{Us} = M.c_p(t_h - t_l) - \Delta H_L \quad (1)$$

where M = Mass. of the storage material, c_p = heat capacity (kWh/m³°C), t_h = highest temperature in the tank in °C, t_l = lowest applicable temperature and ΔH_L are heat losses during the storage time. So a tank with 100 l 80°C hot water cannot deliver more than ca 120 l water 40° C warm. Latent heat of freezing water (WLH) is 334 kJ/kg or 92,8 Wh/kg, which corresponds to the energy needed for heating of 1,14 l of water from 10°C to 80°C. Because the temperature of the energy released during the phase change is 0°C, the utilizing of WLH is possible only when a heat pump increases the temperature of a heat delivery medium to utilizable value. The energy amount, ΔH_T, can be calculated by means of the following equation:

$$\Delta H_T = M_w \text{ x } (c_p.t_h + \Delta H_{ls} \text{ x } (1- 1/COP)) \quad (2)$$

where M_w = mass of water, ΔH_{ls} = water phase transition heat, COP = coefficient of the heat pump performance. The amount of 40°C warm water, available from a tank with 100 l of 80 °C hot water increases to 444 l, when both sensible heat and the WLH is included. This means 3.7 times increase of the utilizable heat in the container. The disadvantage of the WLH use in closed water tanks is the expansion of freezing water. It will destroy any vessel with rigid walls. The problem can be solved by using a flexible wall material or by a tank filled with spheres containing water [7]. However the problem does not exists in opened soil heat magazines soaked with water.

2. Experimental

There has been built a heating system for a small family house with the 50 m² dwelling area and equipped attic. It is already three years in the operation. The system consists of an opened SHC with collection area 4,5 m², adapted for the collection of both solar radiation and the atmospheric air heat, a 2,5 kW heat pump and a heat magazine 4x8x1 m filled with water saturated soil. The scheme of the system is in fig. 2. It contains two circuits with circulating fluids. The heat pump fluid, driven by the compressor 6, delivers heat in loop 7. After decompression in the throttle valve 8, the cold fluid passes the warm flat heat exchanger 3 and continues to the earth loop 5, which is 60 m long, 12 mm o.d. Cu tube, situated 1m below the magazine surface. In this tube the fluid temperature is equalized with the wet soil temperature surrounding the tube. The second circuit, containing brine, transfers the heat collected in the SHC 1 either to the heat pump fluid (path 1, 2P, 2A, 3, 10, 4) or, when the heat pump compressor is not in the operation, to the tube heat exchanger 9 situated ca 50 cm below the surface of the heat magazine (liquid path 1, 2P, 2B, 9, 11, 10, 4). This heat exchanger consists of twenty 4m long PE tubes 20 mm o.d. connected in parallel with the in - and outgoing 32mm wide PE tubes. The three way valve 2 is operated by the voltage for the heat pump compressor. The circulation pump 4 starts to run when the temperature

of the brine is 3° C above the temperature of the wet soil in the middle of the magazine or when the heat pump is in the operation.
The soil heat magazine contains drainage tubes too, distributing the rain water from the roof of the house (not drawn in the figure 2). The irrigation system is placed 10 cm above the heat exchanger 9.

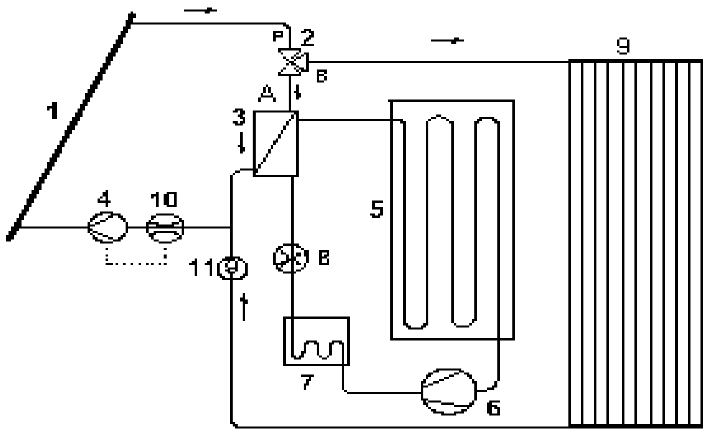

Fig. 2. Scheme of the SFH heating system.

2. Results

Temperatures in the magazine during last three winter seasons are in the table 1 and in figures 3-5. The sensor measuring the soil reference temperature (red line in Figs 3-5) is placed ca. 3 m from the northern side of the magazine, close to the water supply tube for the house.

Table 1. Temperatures at different depths of the magazine in winter.

Description	Season	Min	Max	Average	Std. Dev.
Reference Temp. °C	07-08	6,1	10,9	7,54	1,36
	08-09	5,1	10,9	7,16	1,64
	09-10	4,9	10,7	6,83	1,79
1,1 m below surface °C	07-08	-2,4	5,9	0,09	1,32
	08-09	-4,3	10,1	1,03	3,10
	09-10	-5,9	9,5	0,34	3,44
40 cm below surface °C	07-08	-3,9	16,0	1,78	2,95
	08-09	-3,5	18,8	2,72	4,87
	09-10	-3,3	18,1	2,78	4,67
Outside Temperature °C	07-08	-7,8	37,5	4,16	5,72
	08-09	-12,3	28,3	2,57	6,14
	09-10	-18,4	27,3	1,70	7,11

The thermal properties of the house were calculated by means of following equation:

$$\Delta H / t_{int} = 21{,}463 - 0{,}7817 \times t_{out} \quad (3)$$

where t_{int} = temperature in the house in °C and t_{out} = outside temperature. Data for the calculation of the intercept and the slope (r = 0,8811) were collected during one year and reduced to month averages. The calculated energy consumption for the winter season 2007 - 2008 was 2550 kWh,

for season 2008 – 2009 was 2720 kWh and for the winter 2009 – 2010 the house required 2820 kWh to keep inside temperature 20°C.
The water content in the magazine at the beginning of November 2009 was 74% and the soil temperature in the magazine was 5,6°C. The nominal heat content in the 32 m³ water saturated soil was calculated as follows: sensible heat of water: 154 kWh; latent heat of water: 2198 kWh and the sensible heat of the soil: 26 kWh. Totally 2378 kWh. The heat content of the magazine covers, depending on the winter weather, 80 – 90% of the heat requirement. Actually, the magazine delivered all heat required even in the winter 2009 – 2010 in spite of the unusually low air temperatures. The explanation can be found in the open structure of the heat magazine. Both water and heat can freely penetrate beyond the nominal magazine boundaries, so that increasing the frozen zone 50 cm over the nominal magazine size doubles the heat capacity. The increased frozen volume delays the melting of the ice in the magazine to the middle of May (compare Figs 4 and 5), but that does not influence the system function.

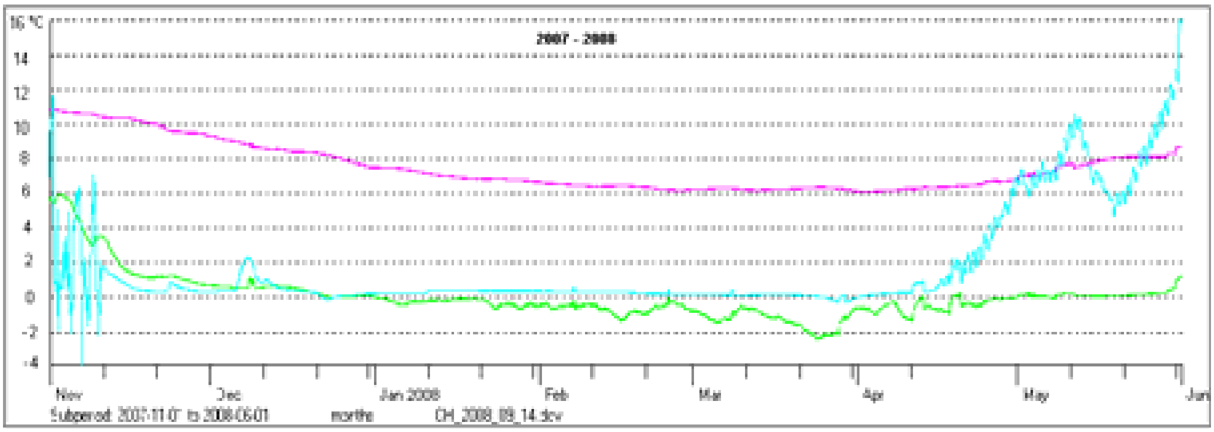

Fig. 3. Temperatures in the magazine during the winter season 2007-2008

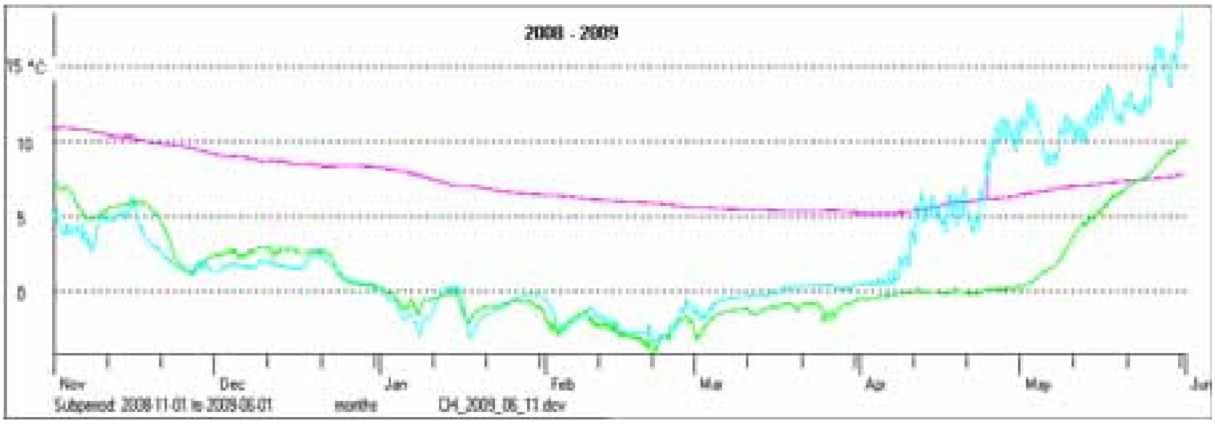

Fig. 4. Temperatures in the magazine during the winter season 2008 - 2009

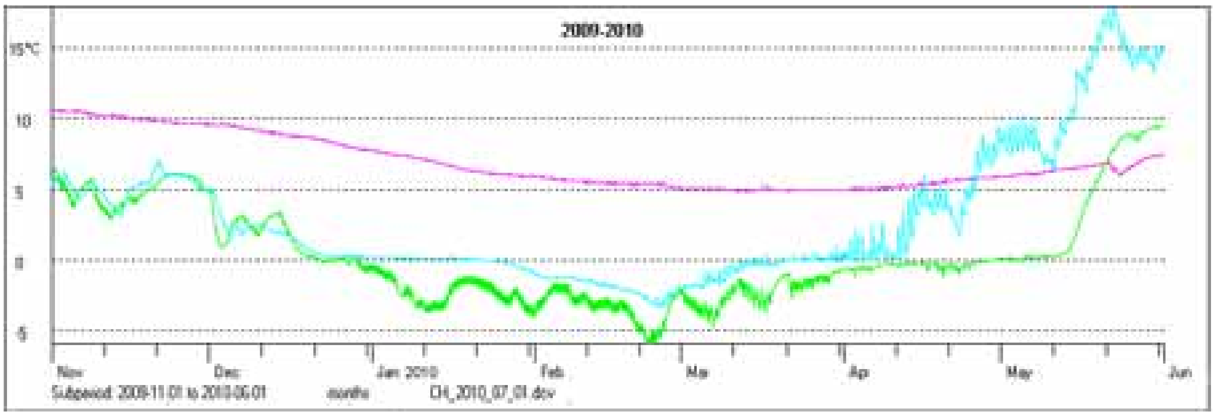

Fig. 5. Temperatures in the magazine during the winter season 2009 – 2010.

Colours in figures 3-5: reference temperature, 3 m from the magazine side.
Temperature ca. 40 cm below the magazine surface.
Temperature 10 cm below the heat collection tube.

3. Summary

- Utilizing of water latent heat in seasonal heat storage earth magazines increases the storage capacity per volume at least ten times in comparison with existing sensible heat based soil or rock magazines.
- No measurable or visible changes in the seasonal heat storage magazine utilizing latent heat of water freezing were observed during three years in operation.
- The spring and summer excess of solar heat, transferred to the magazine, not only melts the ice, but increases the magazine temperature close to surface above the outside temperature too. This prolongs the vegetation period of vegetables grown in the magazine soil.
- The SHC surface cooling during the heat pump operation substantially increases the heat collection efficiency and opens the possibility of heat collection with the same SHC also from the air during cloudy days and nights.
- The SHC with double function increases the instant heat delivery about one month in the autumn.
- The 5 m^2 opened SHC surface delivers sufficient heat for melting 30 – 50 m^3 ice in the magazine during the summer.
- Current design of heating system uses three possible heat sources: solar heat, heat in the atmospheric air and in the absence of heat in the SHC, the accumulated heat in the water soaked soil. This feature is unique among heat pump combined systems.
- The choice of the heat source is controlled entirely by the availability of the heat in the source.
- Even if he heat delivered by SHC is not sufficient for current needs, it is not switched off. Instead, it is completed by the heat from the heat magazine. This is possible, because the soil heat exchanger 9 is in series connection with the flat heat exchanger 3. The heat pump receives therefore always necessary heat amount independently on the weather, air temperature or an annual season.

4. References

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