MODELLING OF THERMAL PROCESSES IN THE SOLAR AIR HEATING SYSTEM WITH HEAT ACCUMULATOR

Vasyl Zhelykh, Khrystyna Kozak, Olena Savchenko
National University Lviv Polytechnic, Ukraine

Abstract. In order to identify the thermal processes that occur between the basic elements of the solar air heating system (SAHS), the graphs of the theory have been proposed to increase thermal capacities. Based on the obtained graphs, the general balance equations have been formulated, which formed the basis of the balance equations systems taking into account the features of the SAHS operation. In regard with the physical and chemical properties of heat-accumulating materials, commonly used in SAHS, the capacity of heat accumulator is used to cover the thermal loss of a building at night. On the basis of the data obtained, the solar air heating system (SAHS) with an air solar collector and a thermal battery has been developed.

Keywords: solar air heating system, graph theory, heat accumulative material, solar air collector.

Introduction

It is known that the thermal condition of the premises is determined by the effective operation of heating systems. As a result, the cost of heating the buildings comprises a large part of the budget allocated for the maintenance of buildings and structures. Thus, microclimate maintenance systems consume approximately 30-40% of the energy resources of Ukraine in comparison to total quantity. This necessitates the development of special systems designed for maintenance of the thermal regime in the premises, which allows to reduce the share of the use of traditional energy resources. The promising direction of developing such energy-saving systems is the introduction of air heating, which is based on devices that use renewable energy sources, in particular solar energy. Solar collector is particularly important in solar heating system, being the main element of the whole system, and which accounts for most of its cost. In order to ensure efficient operation of the system throughout the year, it is necessary to use coolant substances that are resistant to negative temperatures and corrosion. Air can serve as a coolant. Air systems have advantages over liquids: no risk of freezing or boiling of the coolant; higher solar energy use; easier management, higher durability and lower cost of equipment.

However, for the efficient operation of solar air heating systems, a thermal battery should be provided, which would increase their reliability and provide coverage at night and in high clouds.

In this article, the thermal processes that occur in the solar air heating system with a thermal battery in different modes of its operation are analysed as well as properties of heat-accumulating materials, commonly used in air heating.

The purpose and objectives of the study

Analysis of the thermal processes that occur between elements of the solar air heating system.

Determination of heat-accumulative material for efficient operation in air heating.

Analysis of existing data

As an accumulative material in air heat supply systems stone flaps (better pebbles) are commonly used. It is also advisable to use hollow constructions of buildings in particular panels of walls and ceilings, passing through them heated air.

The gravel accumulator of the heat is large, and with 1000 MJ energy, which volume is approximately 4 times bigger in comparison with the volume of the water battery and 17.5 times larger than the battery with paraffin. As a consequence, there is the need for large areas and building volumes (Hee W. Ryu et al., 1992)

The disadvantages of using capacitive heat accumulators (HA) are as follows: large volume of compartments for their construction, which results in considerable construction costs; in addition to a significant heat loss due to the external walls of these compartments.

It is necessary to pay attention to the heat capacity of the material. The higher the value of the coefficient of heat, the faster the heat is lost. This factor is one of the most important disadvantages of water accumulators in comparison with gravel ones. When choosing HA, attention is paid to the thermal conductivity and material density, chemical stability, non-toxicity, availability and low cost.

Phase-transition heat-accumulating materials. The main advantage of this type is the high specific density of energy, which significantly reduces the mass and volume of the battery if compared with the capacitive batteries.

According to the physical properties of paraffin and Glauber's salt (Alexandrov et al., 2009) to produce 1 GJ of heat, the volume of the battery with a phase transition substance should be 2.5 – 5 times less than filled with water. This greatly simplifies the problem of the need for large areas for the installation of a thermal battery, as well as it strengthens the construction of the building with additional support.

Matrices or small capacities with phase transition materials (FHM) are placed in the construction of the building e.g. walls, suspended ceiling, under the floor, etc. The accumulation material will accumulate heat energy not only from the solar collector (SC), but also excess of heat generated by people, equipment, solar radiation, etc.

Fig. 1 shows the solar air heating system with a thermal accumulator filled with FHM which was presented by Sharma (2009, pp. 333-334).

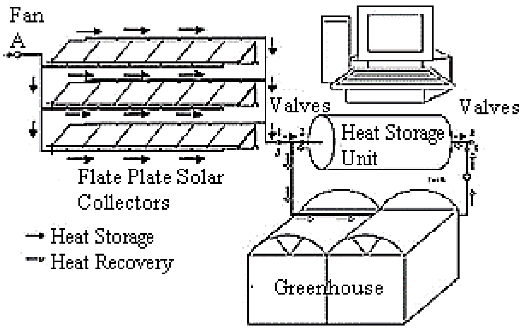

Figure 1. Scheme of SAHS of greenhouses with phase-transition thermal accumulator

The system consists of several main units: 1 – 27 m^2 oriented to the south side of flat-plate SC block type; 2 – phase-transfer thermal battery, filled with 6 tons of paraffin; 3 – experimental greenhouse (180 m^2); 4 –heat transfer unit; 5 – system for collecting information. Energy and exergy analyses were applied in order to evaluate the system efficiency. During the experimental period, it was established that the average net energy and exergy efficiencies were 40.4% and 4.2%, respectively. The figures obtained are average for systems of this type. However, with the use of more advanced airborne solar collectors with a developed form of heat absorbing plate and more efficient heat-accumulating, these indicators would be higher.

Paraffin has the least heat of phase transition among applied heat-accumulating materials with phase transition: 144 – 189 MJ / m^3, in addition it has low heat capacity and high melting temperature as for use with air solar collectors (approximately 44 °C).

A considerably better option for such systems is a thermal accumulator based on Glauber's salt.

There has been a considerable number of different designs available of air solar collectors with a built-in layer of heat accumulation material.

Fig. 2 shows the growth of flat solar collector designs with plastic case and integrated thermal accumulator with Glauber's salt. This construction was showed by Seddegha (2015, p. 528).

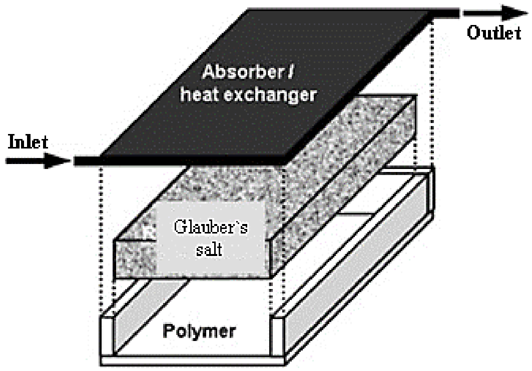

Figure 2. Scheme of SAC with heat accumulator

The advantages are a relatively low melting point and a high amount of heat released during the phase transition, as for Glauber's salt it is 251 MJ/m^3.A thermal battery based on a saturated solution of Glauber's salt at a temperature above 32 ° C can effectively maintain a temperature of 32 ° C with a large accumulation or energy recovery resource. Of course, for hot water this temperature is too low, whereas for air heating is sufficient.

The disadvantage of such instructions is a small capacity of thermal accumulators and a too big size and weight.

In addition, there is a need for the installation of additional air channels for the transfer of coolant from the collector to the consumer heat, which significantly increases the heat loss in the environment.

The experiments and their analysis

Passive solar heating systems are structural elements of the building that provide internal air heating through solar radiation.

In order to increase the reliability of the heating system of the premises, the coverage of loss at night and in cloudy weather, it is necessary to install thermal heat accumulators. In air heat supply systems, as accumulative material, stone stumps, especially pebbles, water and phase-shift thermal accumulators are commonly used.

Fig. 3 presents the principle of work of the SAHS with a thermal accumulator (Zhelykh et al.,2017).

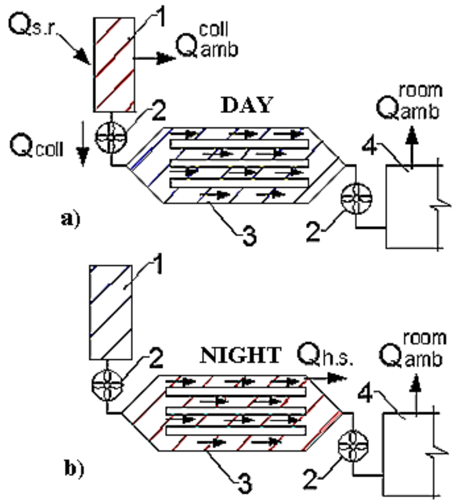

Figure.3. Principle of work of the SAHS with a thermal accumulator
day cycle of the SAHS work; b) night cycle of the SAHS work;
1 –air solar collector; 2 – fan; 3 – heat accumulator; 4 – heated room

During a sunny day, SAC converts solar energy into heat energy, the cooled air enters the reservoir from the room, warms up, flushes the heat accumulator that accumulates heat, and enters the heated room. At night or in cloudy weather, the solar collector does not work, the thermal accumulator is discharged, releasing energy to heat the room.

To study the thermal processes that occur between the main elements of the system, the graphs theory suggested graphs of heat capacities.

Fig. 4 shows the operation of the SSPO during the sunny day, which is depicted as a system of thermal capacities between the elements of which is heat transfer and which interacts with heat sources.

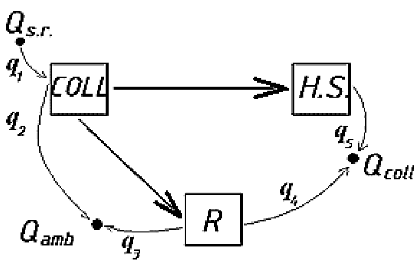

Figure 4. The graph of thermal capacities of the SAHS with a charged rechargeable accumulator

In the zone the thermal capacities are isolated, that is, the nodes of the graph: (*COLL*) – a solar collector; (*H.S*) – heat accumulator; (*R*) – a heated room. Sources of heat for SAHS: solar radiation (*Qs.r.*); environment (*Qamb*); heat transfer from the solar collector (*Qcoll*).

The overall balance of heat flows is as follows:

$$\pm Q_{coll} \pm Q_{amb} \pm Q_{s.r} = 0 \quad .(1)$$

For the mode 1 (Fig. 3, a), when the solar collector is operating, the system of equations will look like this:

$$\begin{cases} Q_{coll} = F_{abs} \cdot F_R \left[S - U_L (T_f - T_{amb}) \right]; \\ Q_{ambl} = h_{ambl} \cdot F_{coll} \cdot T_{amb} + k \cdot F_i \cdot (T_{room} - T_{amb}), \end{cases} \quad (2)$$

where F_{abs} – area of the heat absorber, m[2]; T_f – air flow temperature, °C; T_{amb} – external air temperature, °C; F_{coll} – area of the glass plate of the solar collector, m[2]; T_{room} – the room temperature, °C; F_i – area of the house facade components, through which there is a loss of heat into the environment, m[2]; k –correction factor for additional heat loss, U_L –total heat loss coefficient from the solar collector, W/(m[2]·K); h_{ambl} – the coefficient of convective heat exchange between the collector housing and the environment.

The energy of solar radiation absorbed by the SC, *S*, W/m[2], is calculated by the formula:

$$S = \left[I_b \cdot P_b (\tau\alpha) + I_d \cdot P_d (\tau\alpha) \right], \quad (3)$$

where I_b – the intensity of direct solar radiation falling on a horizontal surface, m[2]; I_d – the intensity of scattered solar radiation falling on a horizontal surface, m[2]; P_b, P_d – the coefficients of the SC position for direct (table value) and diffused radiation, respectively; $\tau\alpha$ – absorption capacity.

$$P_d = \cos^2 \frac{\beta}{2} \quad (4)$$

in which β – angle of the solar collector, degree.

The coefficient of heat recovery from the collector, F_R, is determined by the formula:

$$F_R = \frac{L \cdot C_{air}}{U_L} \left(1 - e^{(-U_L \cdot F')/(L \cdot c_p)} \right) \quad (5)$$

where *L* – air flow per unit area of the SC, m[3]/(c/m[2]), C_{air} – heat capacity of the air, J/(kg·°C),

F' – the efficiency of the absorber of solar energy [4].

Fig. 5 shows a graph of thermal capacities, which corresponds to the second mode of the SAHS.

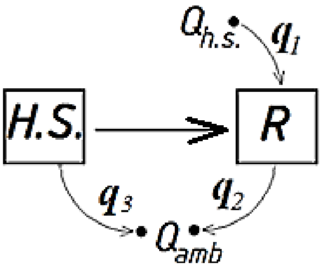

Figure 5. The graph of thermal capacities of the SAHS with a discharged heat source

The following thermal capacities are identified in the zone: (*H.S.*) – heat accumulator; (*R*) – heated room. Sources of heat for SAHS are environment (Q_{amb}); heat transferred from heat accumulator ($Q_{h.s.}$).

For this mode, the overall balance of heat flows has the following formula:

$$\pm\ Q_{amb} \pm Q_{h.s.} = 0 \quad (6)$$

For the option of SAHS when the phase-change heat accumulator gives the accumulated heat of, equations reads:

$$\begin{cases} Q_{ambl} = k \cdot F_i \cdot (T_{room} - T_{amb}); \\ Q_{h.s.l} = m \cdot H_{fl} / \rho, \end{cases} \quad (7)$$

where m – weight of heat-accumulating material, kg; H_{fl} – heat of melting of phase transition material (for Glauber's salt $H_f^{г.с} = 251 \frac{MJ}{m^3} = 173 \frac{kJ}{kg}$); ρ – density of Glauber's salt, ρ=1330 kg/m³.

Thermal power of a capacitive HA, *Qh.s*, W (stone, water) is determined by the following formula:

$$Q_{h.s.} = V \cdot C \cdot \rho \cdot \Delta t, \quad (8)$$

where V – the volume of HA material, m³.

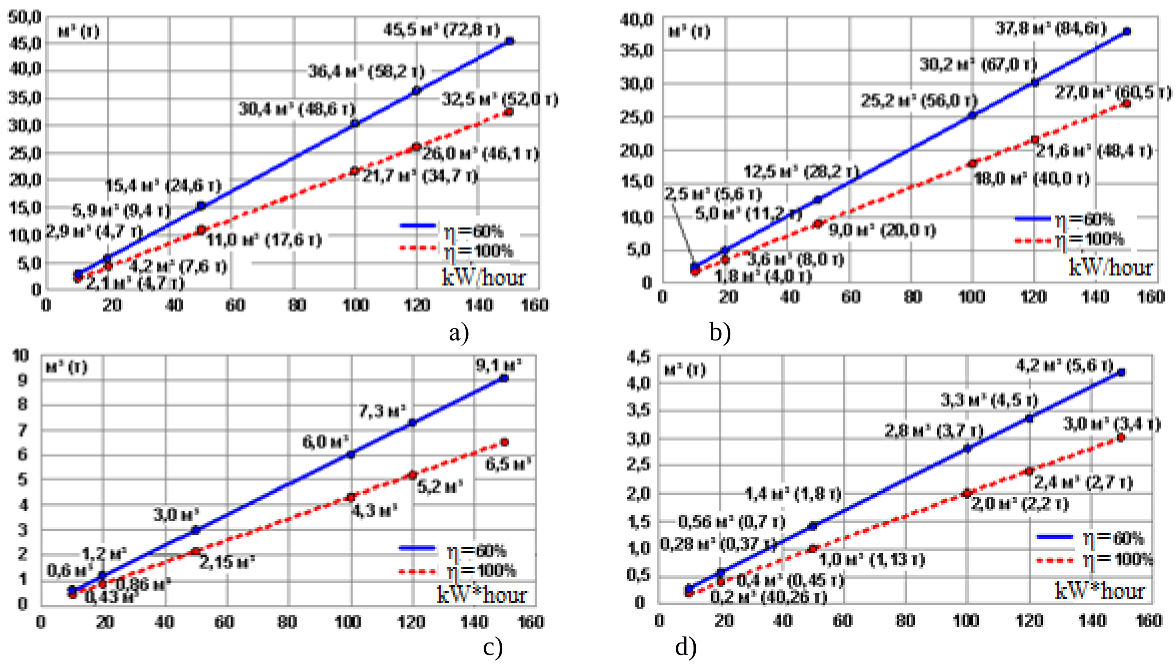

Figure 6. The required volume of HA to cover the heat loss of the house at night;
a) pebble (sand); b) natural stones; c) water; d) Glauber's salt

Assume that the thermal battery is designed to cover the load at night, from 9:00 pm to 7:00 am, that is, 10 hours. Fig. 6 shows the required volume (mass) of HTA to compensate the heat loss of the building at night.

Fig.7 shows a comparison of the sizes of heat accumulators with different TAMs of the same power.

Consequently, in order to accumulate heat in a residential house, it is advisable to use a thermal accumulator based on water or a saturated solution of Glauber's salt.

However, water has a drawback – low heat capacity, while Glauber's salt can provide warmth for a long time, approximately for 10 – 14 hours.

Having analysed the data obtained, a system of solar air heating with a thermal battery has been developed on the basis of a saturated solution of Glauber's salt.

Fig. 7 shows the possible options for the location of the solar air collector in the SAHS:

- an air solar collector is located in (Fig. 7, a) or on (Fig. 7, b) the outer wall;
- an air solar collector is installed directly on the roof of the house (Fig. 7, c).

The heat-accumulating coating 3 with a saturated solution of Glauber's salt in the form of a matrix is located in the air line 2, which is located in the suspended ceiling 6. On the sunny day, if necessary, the heating of the room is heated in the air solar collector 1. Due to convection, the coolant rises to the air line 2, and through the distributor grille 7 enters the room. In cloudy weather or at night, when the temperature in the room is lowered to 20 ° C, the temperature sensor 8 reacts, the fan 4 connected to it is switched on, the thermal battery frees up the accumulated heat. Fresh air enters through window ventilation valves 9, is removed through the ventilation duct 10.

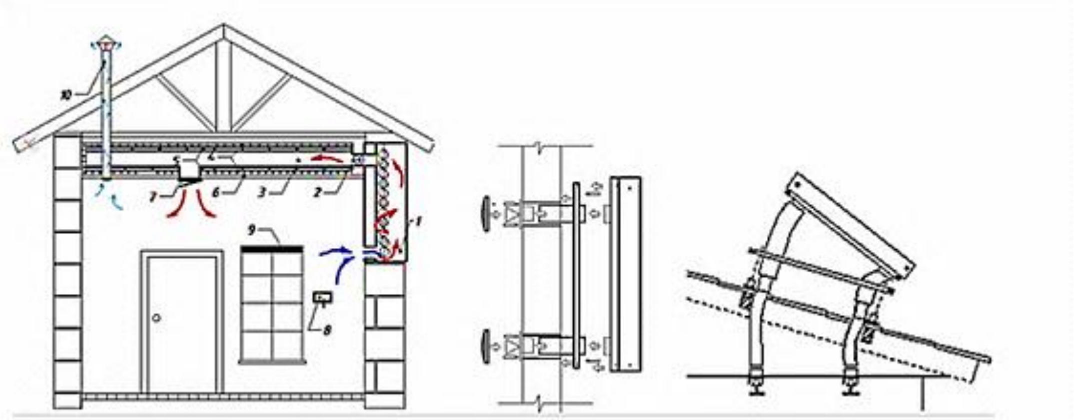

Figure 7. The schemes of SAHS on the basis of air solar collectors with the thermal accumulator installed:

a) in the construction of the outer wall; b) on the outer wall of the building; c) on the roof of the house

1 – solar air collector; 2 – air dukt; 3 – fan; 4 – eat-absorbing coating with saturated solution of Glauber salt; 5 – thermal isolation of the duct; 6 – underlay ceiling; 7 - discharge grill; 8 – temperature sensor; 9 - window air vent valve; 10 - ventilation duct

Conclusions

The basic modes of operation of the solar air heating system with a thermal accumulator analysed in this article. Using the theory of graphs, thermal processes that occur between elements of the system are investigated.

Taking into account the results obtained, the systems of balance equations have been developed. The analysis of heat accumulative materials in commonly used in these systems has been carried out. In regard with their physical and chemical properties, the capacity of heat accumulator (on the basis of pebbles, natural stone, water and Glauber salt) is determined, which is required to remove thermal load in the house for 10 hours.

According to the data obtained, to heat a house with a heat loss of 6 kW, Δt = 20 °C and thermal energy efficiency of 60%, 18.2 m^3 (29 tons) of pebbles; 15.1 m^3 (33.7 tons) of natural stone; 3.6 m^3 of water and 1.68 m^3 (763 kg of Glauber salt) of Glauber's salt solution are necessary. Thus, for the accumulation of heat in a residential building, it is expedient to use a phase transition TA.

On the basis of the research, the heating system, the main elements such as air solar collector and a thermal accumulator of Glauber's salt, have been developed.

References

1. Hee W. Ryu, Sung W. Woo, Byung C. Shin, Sang D. Kim. (1992). Prevention of super cooling and stabilization of inorganic salt hydrates as latent heat storage materials. Solar energy materials and solar cells, 27, 161-172. https://doi.org/10.1016/0927-0248(92)90117-8
2. V.D. Alexandrov, O.V. Sobol, S.A. Frolova, I.V Rural, A.Yu. Sobolev, S.G Bugasova, N.V. Shchebetovskaia, D.P. Loiko, V.N Ardaev, O.E. Silchenko, M.V Stasevich (2009). Heat-storage materials based on crystalline hydrates. Modern building materials, 1 (75), 100-103. http://journal.diat.edu.ua/stat/8_69_full_ru.pdf
3. A. Sharma, V. Tyagi , C. Chen, D. Buddhi (2009). Review on thermal energy storage with phase change materials and applications. Renewable and Sustainable Energy Reviews, 13, 318-345. https://pdfs.semanticscholar.org/e07c/4a2bb3255b0bd0eb123f97d460758441300e.pdf
4. S. Seddegha, X. Wanga, A. D. Hendersona, Z. Xingb. (2015). Solar domestic hot water systems using latent heat energy storage medium. Renewable and Sustainable Energy Reviews, 517-533. https://doi.org/10.1016/j.rser.2015.04.147
5. V. Zhelykh, K. Kozak, O. Savchenko. (2017). Providing the thermal condition in the room by the solar air heating system and determining its basic characteristics of the work. Materials and energy-saving technologies in the construction industry, 9-28.

About the authors

Vasyl Zhelykh. Professor at Department of Heat and Gas Supply and Ventilation, DSc
National University of Lviv Polytechnic, Lviv, Ukraine.
E-mail: Vasyl.M.Zhelykh@lpnu.ua

Khrystyna Kozak. Assistant at Department of Heat and Gas Supply and Ventilation
National University of Lviv Polytechnic, Lviv, Ukraine.
E-mail: Khrystyna.R.Kozak@lpnu.ua

Olena Savchenko. Associate Professor at Department of Heat and Gas Supply and Ventilation
National University of Lviv Polytechnic, Lviv, Ukraine.
E-mail: Olena.O.Savchenko@lpnu.ua