Design of a Solar Hybrid System

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***Abstract*—This article deals with the fundamentals of solar hybrid systems design. In the first part it deals with the theory of such systems both the thermodynamics and the control logic of the system are discussed. In the second part an actual design of a solar hybrid system is presented.**

I. THEORY

A. *Main elements of a solar hybrid system*

Solar hybrid systems are heating installations with multiple heat sources and with multiple heat sinks. Common heat sources of a solar hybrid system are:

- Solar collectors
- Gas or coal fired boiler
- Electric boiler
- Heat pump

Common heat sinks of a solar hybrid system are:

- Domestic hot water
- Space heating
- Space cooling with absorption chiller
- Swimming pool heating

The main parts of a solar hybrid system are:

- Solar collector array
- Auxiliary heater
- Heat accumulator
- Automatic energy management system

In solar hybrid systems both flat plate and vacuum tube solar collectors can be used. Both types of collectors have advantages and disadvantages.

Flat plate collectors come with a lower price therefore a larger collector area can be installed. Also flat plate collectors have an advantage over vacuum tube collectors in areas where frequent snowfall occurs, due to relatively larger heat losses through the glassing.

Namely, on flat plate collectors a small amount of sunlight passing through the layer of snow covering the collector heats up the absorber which then heats up the glassing. That way a thin liquid water film forms between the glass and the covering snow which allows the snow to slide down.

The advantage of the vacuum tube collector over the flat plate ones is in the higher output temperature. Higher temperatures allow space cooling to be achieved with supplying the heat to the absorption chiller by the vacuum tube collectors.

Size of the solar collector area in hybrid systems depends on the heat demand of the heated space during the periods of Feb.-March-Apr. and Sept.-Okt.-Nov.

Namely, in solar hybrid systems solar energy provides a part of the total energy needed for heating. Depending on the type of the heating installation and weather conditions this part goes from 10% to 60%.

Picture 1. Solar collector array

The auxiliary heating unit in the solar hybrid systems provides heat for the space heating. The heating capacity of the auxiliary unit matches the peak demand of space heating and domestic hot water preparation combined.

The central unit is the heat accumulator. Its purpose is to store and distribute the heat produced by the solar collector array and the auxiliary heating source.

The energy management unit is an automatic control system for controlling the heat sources and the temperatures of the heat sinks. The control system consists of software embedded in the microprocessor unit with digital and analog inputs and outputs, temperature sensors and actuators.

B. *Principles of heat transfer inside the storage tank*

The heat accumulator is a vertical cylindrical water tank in which a process of combining the energy from two heat sources with different output temperatures occurs.

The change of density of water due to change of temperature allows stratification of the water stored in the storage tank. Inside the storage, a temperature gradient from bottom to top of the tank is formed, where the lowest temperature is at the bottom of the tank and the hottest water is at the top.

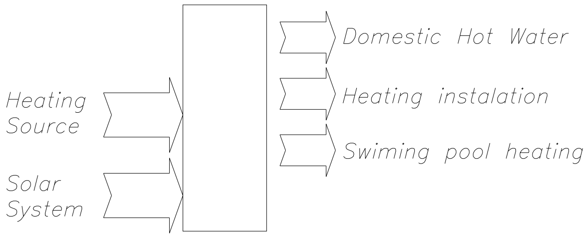


Figure 1. Energy balance of a solar hybrid system

Stratification of the storage tank allows the heat gain from the solar array to be added to the heat produced by the auxiliary heat source. Besides that, stratification allows heat to be drawn at different temperatures from the tank to meet the needs of different heating systems.

During the periods of moderate solar gains, the energy from the solar array is added into the storage tank at the lowest temperature point. The heat from the auxiliary heater is added to the water inside the tank at the medium temperature level. Energy needed for space heating is drawn from the tank at the medium temperature level.

In order to combine the energy from the solar and the auxiliary heat sources to meet the space heating demand the following condition must be met: The difference between the mean temperature of the solar array and the temperature of the return line of the space heating installation must be positive.

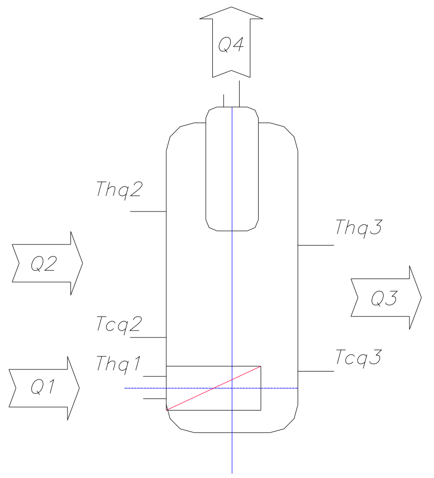


Figure 2. Temperature layout of the storage tank

Fig 2: Q1- energy input from the solar array, Q2-energy input from the auxiliary heat source, Q3- energy output to the space heating installation, Q4 – energy output to the domestic hot water, Thq1-forward line temperature of the solar collector array, Tcq1-return line temperature of the solar collector array, Thq2- forward line temperature of the auxiliary heat source, Tcq2-return line temperature of the auxiliary heat source, Thq3-forward line temperature of the space heating installation, Tcq3-return line temperature of the space heating installation, Tq4- forward line temperature of the domestic hot water installation.

Heat balance of the storage tank:

$$Q_1 + Q_2 = Q_3 + Q_4 \text{............ (1)}$$

Let's assume that: $Q_4 = 0$ then:

$$Q_1 + Q_2 > Q_3$$

$$k_1 m_1' \Delta T_1 + k_2 m_2' \Delta T_2 > k_2 m_3' \Delta T_3$$

$$k_2 m_2' = k_2 m_3' > km'$$

$$k_1 m_1' \Delta T_1 + km' \Delta T_2 > km' \Delta T_3$$

$$k_1 m_1' \Delta T_1 + km'(T_{hq2} - T_{cq2}) > km'(T_{hq3} - T_{cq3})$$

$$k_1 m_1' \Delta T_1 + km'(T_{hq2} - T_{cq2}) - km'(T_{hq3} + T_{cq3}) > 0$$

$$T_{hq2} = T_{hq3} = T$$

$$k_1 m_1' \Delta T_1 > km'(T_{cq2} - T_{cq3}) \ldots\ldots\ldots\ldots \text{(2)}$$

Where:
k_1- heat capacity of solar working fluid
m_1'-mass flow rate of solar working fluid
k_2-heat capacity of water
m_2'-mass flow rate of water in the auxiliary heating loop
m_3'-mass flow rate of water inside the space heating loop
ΔT_1- temperature difference between the forward line and the return line of the solar array
ΔT_2-temperature difference between the forward line and the return line of the auxiliary heater
ΔT_3-temperature difference between the forward line and the return line of the space heating installation.

The equation (2) shows the amount of energy supplied by the solar array.
$km'(T_{cq2} - T_{cq3})$ Is the heat energy needed to heat up the water from the space heating return line up to the temperature level of the intake of the auxiliary heat source.

This amount of energy is supplied by the solar array. In other words, the energy from the solar array allows the intake temperature of the auxiliary heater to be higher.
This way the auxiliary heater operates with less temperature difference, therefore using less energy.

When the auxiliary heating device is operating part of the energy is used to heat up the domestic hot water. Temperature of the water in DHW systems has to reach 60^{o}C. If this temperature is not reachable by the heating system (in case of panel heating installation) an electric heater is used to match the remaining temperature difference.

In order to prevent mixing and to retain the stratification inside the heat storage tank, a built-in tank is used for storing the DHW. This tank is placed inside at the top of the main tank at the highest temperature level. This prevents heat dissipation from the DHW to the heating water when only the electric heater is switched on.

During summer when there is no demand for space heating, energy output from the solar collector array is greater than the energy needs of the DHW subsystem. Therefore, a heat sink has to be considered to prevent overheating of the system.

An elegant way to cool down the system is to use a swimming pool as a heat sink.

C. Controll Strategy of a Solar Hybrid System

Tasks for the control unit of the solar hybrid system are:

- Maintaining the set point temperature of the heated area.
- Maintaining the set point temperature for the DHW subsystem.
- Maintaining the set point temperature for the swimming pool.
- Maintaining the set point temperature for the auxiliary heat source
- Maintaining the minimal and maximal set temperatures of the storage tank.
- Limiting the maximal temperature of the solar array.
- Managing the energy flow to maximize the usage of solar heat gain.

The control strategy consists of sets of conditions which are implemented into the control algorithm. Some of these conditions are determined by the user, for example the heated space temperature and the DHW temperature.

On the other hand some of these conditions are limited by the equipment and safety, for example the maximal temperatures of the: solar collector array, storage tank and the auxiliary boiler. And third, some temperatures are determined by the control software: for example the set point temperature for the solar array.

Picture 2. Control unit

Inputs of the control unit are:

1. Room thermostat of the heated space.
2. Temperature of the DHW forward line temperature.
3. Swimming pool water temperature
4. Temperature of the forward line of the auxiliary heat source.
5. Solar array forward line temperature
6. Temperature of the lowest temperature layer of the storage tank.

Outputs of the control unit are:

1. Solar array on/off –by means of controlling the circulator pump.
2. Auxiliary boiler on/off
3. Space heating circulator pump
4. DHW circulator pump
5. DHW electric heater
6. Swimming pool heating circulator pump

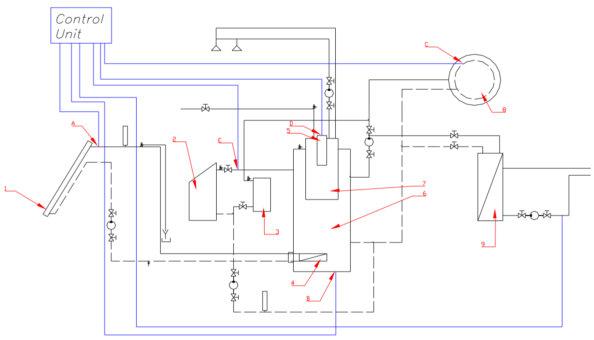
The heat demand of the heated area is dependent on the outside temperature. Also more solar radiation is available during the months with relatively low heat demand.
In order to collect as much as possible solar energy, the energy management system has to decide where to distribute the collected energy. During low heat demands energy can be stored in the heated area itself.
Meaning, when the output temperature of the solar collector array is high enough, the energy from the solar array can be distributed directly into the heated area.
Energy flow management is also important because the solar flat plate collector can also act as a heat sink. This characteristic of the collectors can be used to cool down the system during nights in summer months to prevent overheating.
However this circumstance is not desirable during winter months. When the outside temperature is low, heat produced by the auxiliary source can be dissipated through the solar collector array to the atmosphere. To prevent this, the control unit must be able to recognize the conditions in which energy dissipation can occur.
Recognizing is done by software subroutines. These are various pre-programmed functions which are automatically activated when certain conditions are met. For example: mean temperature of the solar array drops below preset value – this means that there is no energy gain from the solar array. There are two ways to cope with energy dissipation:

1. The setting up of the kick-in temperature of the solar array higher than the temperature of the medium layer of the storage tank.
2. The ΔT method, solar array starts and remains in operation only when there is a positive temperature difference between the forward flow and the return flow lines. In this case there is a minimal allowed value for ΔT.

The first solution is usable in systems with fixed set point temperatures. An example for this is a solar DHW-only system. However when heating is present the temperature of the auxiliary heat source varies. Therefore it is better to use the second method because that way more solar energy can be collected.

II. DESIGN OF A SOLAR HYBRID SYSTEM

Our company received an order to build a solar system for



Picture 3. Design layout of a solar hybrid system

heating assistance during winter, and for heating of the swimming pool during summer. The system was to be built in a four person lived house in Subotica. The property has the following characteristics:

Total living area is 240 (m^2) which is pre equipped with a central heating installation with radiators. This installation uses a coal fired 35 (kW) boiler as a primary heat source. Secondary heat source of the heating installation is a 18 (kW) electric boiler. For DHW preparation an 80 (l) electric boiler is used. The house has a good thermal insulation, and a relatively good orientation towards the South. Also the property includes a 40 (m^3) swimming pool located outdoors. For the purposes of the task we have proposed a solar hybrid system with the following characteristics:

- The solar hybrid system will provide heating assistance and DHW to reduce the usage of electrical energy.
- The solar array consists of 5 solar collectors mounted on the roof facing South-West.
- Type of solar collectors is flat plate ES1, produced by our company
- Total net area of installed solar collectors is 9,7 (m^2)
- Combined storage tank with accumulation of heating water and with a built in storage tank for the DHW subsystem. Total volume of the tank is 1000 (l), volume of the DHW sub tank is 90 (l). The storage vessel is produced by our company.
- Automatic control unit is a standard PLC with control software made by our company.
- All the necessary equipment is to be mounted into the existing boiler room

Primary purpose of this system is to reduce the usage of electrical energy for space heating and to provide heating for the swimming pool.

Picture 3. Storage tank during installation

III. CONCLUSION

In this article one possible solution for a design of a solar hybrid system is presented. This system combines two or more energy sources to provide energy for space heating, DHW preparation and for heating of the swimming pool in a family house. This system has the following advantages:

- Adding solar energy into the energy balance of the house results in using less energy that comes from fossil fuels.
- In a solar hybrid system the amount of solar energy that goes into the house is easily controlled – the solar collector array can be switched off when not needed.
- For this particular heating installation it also increases comfort since it reduces temperature oscillations inside the heated space.

Solar hybrid systems can be implemented on any heating system that is using water as a working fluid.

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