HEAT PUMP INSTALLATION "WATER TO WATER" WITH SOLAR ASSISTANCE IN HEAT SUPPLY WORKING CONDITIONS

Pencho ZLATEV[+], Zhivko KOLEV [+], Valentin BOBILOV[+], Plamen MUSHAKOV[+], Georgi GENCHEV[+]

[+]UNIVERSITY OF RUSE "ANGEL KANCHEV", Bulgaria.

Abstract. In this work results from modelling investigation of the cooperative work of heat pump "water to water" and solar thermal collectors in heating work conditions have been presented. An evaluation of the increased heat pump efficiency in cooperative work with solar collectors has been made. A variant of an installation scheme for practical implementation enables collaboration of the collectors and the heat pump has been proposed. The solar collectors can be used for producing of domestic hot water (DHW) as priority or to help the heat pump in heating work conditions.
Keywords: modelling investigation, heat pump "water to water", solar thermal collectors.

1. INTRODUCTION

1.1. Cooperative use of solar thermal collectors and heat pumps

The technical realization of the heat pump installation with assistance from flat solar collectors requires a combination of two different installations in nature. In the installations with flat plate collectors it is needed the use of heat accumulators and an additional energy source, while in ground source heat pump installations for heating, heat accumulator is not needed because the heat source is also an accumulator.

The combining of this type of installations requires to be considered for what technology needs the received heat energy will be used, which allows possibility for implementation of multiple scheme solutions.

Generally the assistance of heat pumps by solar thermal collectors may be implemented in consistent or in parallel scheme of connecting of the collectors to the heat pump.

In this case an interest is the consistent scheme of connecting of solar collectors and heat pump, which allows the received heat energy from the collectors to be used to increase the heat pump efficiency or to be used directly by consumers, depending from the received temperature in the solar collectors' heat accumulator. Another advantage of the parallel connection scheme is the ability to optimize the performance of the installation in terms of maximum efficiency of the collectors or maximum coefficient of performance (COP) of heat pump.

Disadvantage of the consistent scheme of connecting of collectors and heat pump is the fact that in the cooling work conditions the received heat energy from the solar collectors can be used only in installations with sorption heat pumps.

Practical interest is the investigation of compressor heat pumps "water to water" connected successively with an installation of solar thermal collectors, assisting the heat pump in heating work conditions and used for warming water for domestic needs.

2. LABORATORY SOLAR THERMAL INSTALLATION WITH AN ADDITIONAL HEAT SOURCE - HEAT PUMP "WATER TO WATER"

Figure 1 shows a principal scheme of a laboratory heat pump installation "water to water" consistently connected to three solar thermal collectors [1].

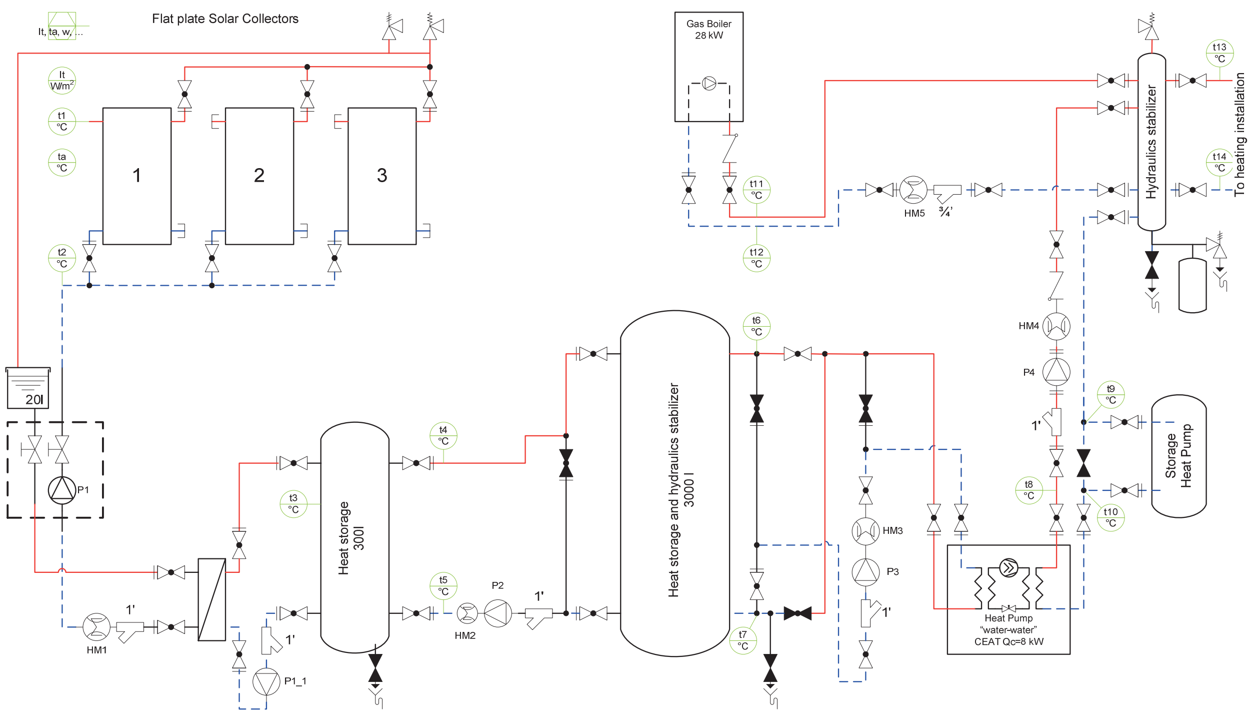

Fig.1. *Laboratory solar thermal installation with an additional heat source – heat pump "water to water"*

2.1. Description of the installation

The installation is a system consists of three solar thermal collectors, which via separating laminar heat exchanger are connected to the heat accumulators in the system with volumes of 300 and 3000 liters. The thermal accumulators are connected to the evaporator of the heat pump "water to water" with a maximum heat power of 8 kW. Both the heat accumulators in the system are used as a heat source of the heat pump. The solar collectors and the heat pump are connected in a consistent scheme.

For its part, the heat pump is connected to the heating installation and it is provided the use of an additional heat source - gas boiler, for the heating work conditions. It has been provided that the heat accumulator of the heat pump will be used only in cooling work conditions, which is not a subject of this work.

2.2. Modelling investigation of the solar collectors in the installation

The modelling investigation the work of the solar thermal collectors in the installation has been carried out in order to evaluate their effectiveness and the amount of received heat energy for the meteorological conditions in town of Ruse. For this purpose collected weather data using weather station DAVIS model "Vantage Pro 2" for the entire previous year have been used.

The coordinates of the place where the solar collectors have been situated are:

- latitude 43°51'12" north;
- longitude 25°58'20" east.

The orientation of the solar collectors is:

- azimuth 0° (pure south);
- inclination to the horizon β=45°.

The accuracy with which the main parameters have been measured from the weather station are:

- intensity of the solar radiation on a flat surface (at intervals of 50 to 60 seconds, in the range from 0 to 1800 W/m^2) – an accuracy of ± 5%;
- external temperature (at intervals of 10 to 12 seconds) – an accuracy of ± 0.5 °C for temperatures higher than -7 °C and an accuracy of ± 1 °C for temperatures below -7 °C;
- wind velocity (at intervals of 2.5 to 3 seconds) - an accuracy of ± 5%;
- wind direction (at intervals of 2.5 to 3 seconds) - an accuracy of ± 3 %.

For an evaluation of the solar radiation intensity in the plane of the collectors the method of Loui and Jordan (1963) has been used [2]:

$$I_T = I_b R_b + I_d\left(\frac{1+\cos\beta}{2}\right) + I\rho_g\left(\frac{1-\cos\beta}{2}\right), \quad (1)$$

where: I_b is the beam solar radiation, MJ/m^2;

R_b – correction factor for the direct component of solar radiation takes into account the orientation of the collectors;

I_d – diffuse component of solar radiation from the sky, MJ/m^2;

β - angle of inclination of the collectors to the horizon, °;

I = I_b + I_d – the sum of direct and diffuse components of solar radiation from the sky on a horizontal surface, MJ/m^2;

ρ_g – coefficient of reflectivity of the earth's surface for sun radiation depends on the season (in the case the average value is 0.6).

The measured and calculated data for solar radiation on horizontal and inclined surfaces have been further processed as they have been averaged by months. The received results are presented in Figure 2.

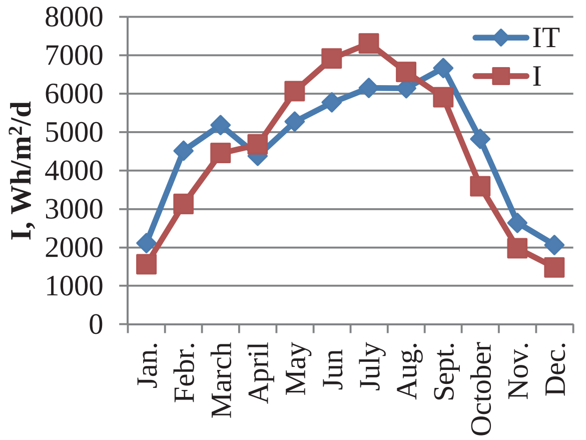

Fig.2. *Measured solar radiation (I) and solar radiation in the plane of solar collectors (IT)*

The results for the individual components of solar radiation reaching the collectors' plane, which have been determined by the method of Loui and Jordan, have been presented in Figure 3.

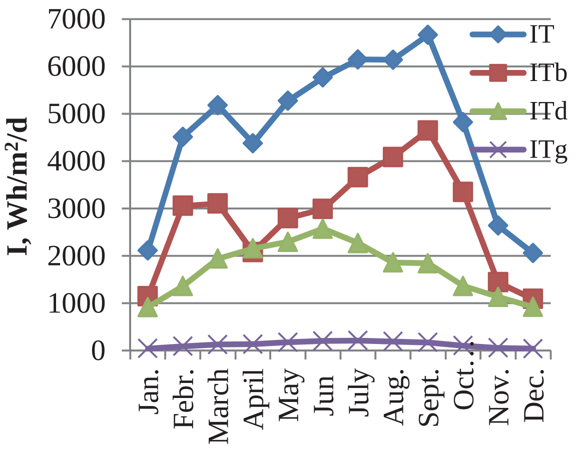

Fig.3. *Calculated solar radiations in the plane of solar collectors (IT), beam (ITb), diffuse (ITd) and ground reflected (ITg)*

Adding in equation (1) the coefficients taking into account the transmission and absorption of the various components of solar radiation it has been received an equation (2) which gives the amount of solar radiation reaching the absorber of solar collectors [2]:

$$S_T = I_b R_b (\tau\alpha)_b + I_d (\tau\alpha)_d \left(\frac{1+\cos\beta}{2}\right) + I\rho_g (\tau\alpha)_g \left(\frac{1-\cos\beta}{2}\right), \quad (2)$$

where: S_T is the absorbed solar radiation per unit active area of solar collectors, MJ/m^2;

$(\tau\alpha)_b$, $(\tau\alpha)_d$, $(\tau\alpha)_g$ are respectively the products of the transmittance and absorption coefficients, for direct, diffuse and reflected from the ground components of solar radiation

Using equation (2) the effective incident angles of the individual components of solar radiation and the influence of the angle of incidence of solar radiation on the absorbability of the absorber have been calculated for each measured value of solar radiation. The entire amount of data has been further processed and has been averaged by months. The results are presented in Figure 4.

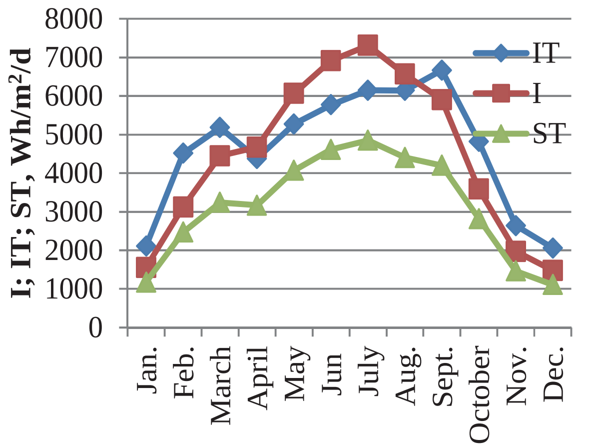

Fig.4. *Measured solar radiation (I), solar radiation in the plane of solar collectors (IT), absorbed solar radiation from collectors (ST)*

The presented in Figure 4 data for the absorbed solar radiation per unit active area of solar collectors is the maximum amount of energy that can one square meter of solar collectors to absorb.

The actual amount of energy, which the collectors receive in the buffer vessels is less and depends from a number of factors such as: the efficiency of the absorber rib of solar collector; the coefficient of discharge of the collector; the heat losses from the collectors, pipes and buffers.

The amount of useful taken energy from the collectors has been calculated by equation (3) and for this purpose the catalogue data of solar collectors in the installation have been used [2, 4].

$$Q_U = A_C F_R [S_T - U_L (Ti - Ta)] \quad (3)$$

The coefficient of heat remove is Fr = 0.7 and the heat transfer coefficient between the absorber and environment is U_L = 6.18 W/m^{2}K.

The solar collectors are selective with effective absorbability α = 93 %. The surface area of the absorber for every one of the three collectors is Ac = 2.2 m^2.

The results from the applying of equation (3) are shown in Figure 5. The blue colour shows the months in which the received heat energy from the collectors will not be used by the heat pump, which means that the collectors will assist the heat pump only during the heating season.

The main difficulty in the calculation of the useful taken heat energy from the collectors is the determination of the temperature T_i of the incoming in solar collectors' heat medium.

For this purpose, some assumptions concerning the heat pump work have been made.

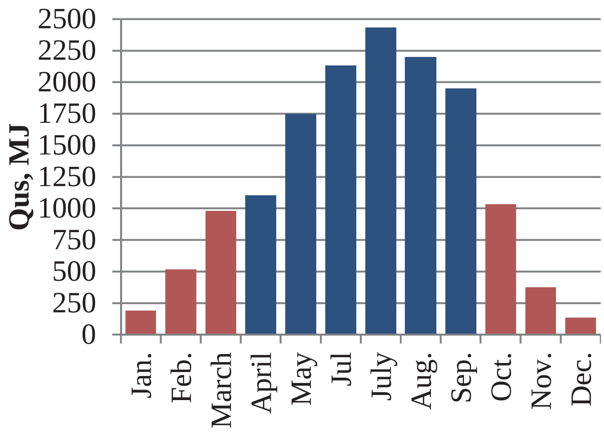

Fig.5. *Useful thermal energy from solar collectors in the installation*

It has been assumed that the evaporating temperature of the refrigerant in heat pump will be a constant of 5 °C, independently of the heat pump load. It has been assumed that the temperature of the bottom of the large buffer (with capacity of 3000 l), in which the output water from the evaporator of the heat pump enters, will be 8 °C. So the received minimum temperature difference between the heat medium temperature and the temperature of vaporization will be 3 K.

The buffers in the installation have been designed as hydraulic switches and with the condition that the mass flow of heat medium in the solar collectors' contour is equal to the mass flow of heat medium between the two buffers, it can be assumed that the temperature of heat medium in the bottom of the small buffer (300 l) will be equal to the temperature in the bottom of the large buffer (3000 l) and will be equal to 8 °C.

The effectiveness of the heat exchanger, connecting the solar collectors with the installation has been assumed to be 80 %. In the heat exchanger which separates the solar collectors from the storage volume it has been also assumed that the minimum temperature difference between the heat mediums will be 3 K. Therefore the input temperature in the solar collectors T_i can be assumed to be a constant and equal to 11 °C.

Therefore, the task of determination the efficiency of the heat pump is to find these temperatures:

- output temperature of the solar collectors T_o;
- temperature in the higher part of the two buffers;
- input temperature of the water in the heat pump evaporator.

2.3. Evaluation of the heat pump effectiveness in cooperative work with solar collectors

The determination of the output temperature of solar collectors has been implemented according equation (4) [4].

$$To = Ta + \frac{S_T}{U_L} + \left((Ti - Ta) - \frac{S_T}{U_L} \right) e^{\left(-\frac{U_L F' A_c}{m C_P} \right)} \quad (4)$$

In this case modelling investigation for the collector output temperature has been done at constant specific mass flow m = 50 kg/h/m^2 of the heat medium through the collectors.

Practical interest is the change of output temperature of heat medium from the collectors during the months of heating season (coloured in red in Figure 5). Applying equation (4) for every hour, the change of the output temperature of collectors has been determined for these months by hours from the day. The results are presented in Figure 6.

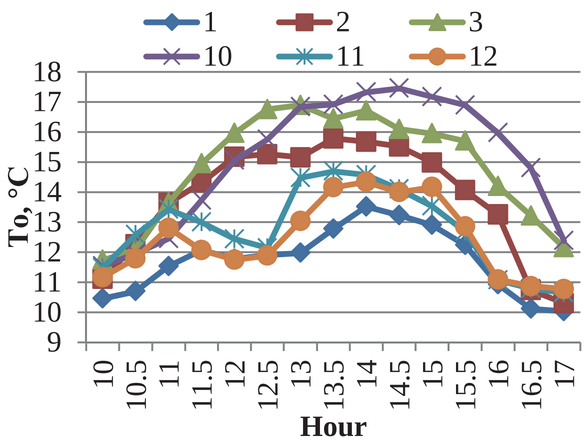

Fig.6. *Output temperature from solar collectors*

The determination of the input temperature of heat medium in heat pump will be made on the basis of energy balance.

Given the previous assumptions (the temperature difference between the heat exchanger, separates the solar collectors from the heat accumulator is constant of 3 K, the mass flows of heat medium on its both sides are equal) and knowing the changes of the output temperature, the temperature in the higher part of the buffers has been determined.

Since the mass flow of the pump is bigger than the mass flow provided by the recirculation pump between the two buffers, to find the input temperature in heat pump we can write the system of equations (5):

$$Qs = m_1 C_P \Delta T_1 = m_1 C_P \left(To_1 - Tв_1 \right)$$
$$Q_{HP} = m_2 C_P \Delta T_2 = m_2 C_P \left(Tв_2 - To_1 \right) \quad (5)$$

where Q_S is the heat energy received from the solar collectors;

m_1 - the mass flow between the two buffer vessels, which is equal to the mass flow through the solar collectors (300 kg/h);

$\Delta T_1 = To_1 - Tв_1$ – the temperature difference between the top and the bottom of buffer vessels;

m_2 - the minimum mass flow, which is required for operation of the evaporator of heat pump (776 kg/h);

$\Delta T_2 = Tв_2 - To_1$ – the temperature difference between the entering heat medium in heat pump evaporator and the bottom of buffer vessels;

Q_{HP} – the absorbed by the heat pump evaporator heat energy, which is equal to the power produced by the solar collectors;

C_P – the specific heat capacity of the heat medium.

With the proviso that the absorbed from the evaporator heat energy is equal to the supplied energy from the solar collectors, for the input temperature in heat pump it can be written equation (6).

$$Tв_2 = \frac{m_1 C_P \Delta T_1}{m_2 C_P} + To_1 \quad (6)$$

The change of the temperature $Tв_2$ of the input in heat pump heat medium, by hours in the different months during the heating season is presented in Figure 7.

With this temperature it will be calculate the actual COP of heat pump and it will be compared with the catalogue value.

The determination of the actual COP of heat pump in the installation will be done in accordance with equation (7) [3]:

$$COP_{actual} = COP_b \left(k_0 + k_1 T_{B2} + k_2 T_{B2}^{\ 2} \right), \quad (7)$$

where: COP_{actual} is the actual efficiency of heat pump as a function of input temperature (method proposed by Tarnawski - 1990) [7];

COP_b – the catalogue efficiency of heat pump determined at standard conditions;

$к_0$, $к_1$, $к_2$ – correlation coefficients for heating work conditions;

$Tв_2$ – the input in heat pump temperature.

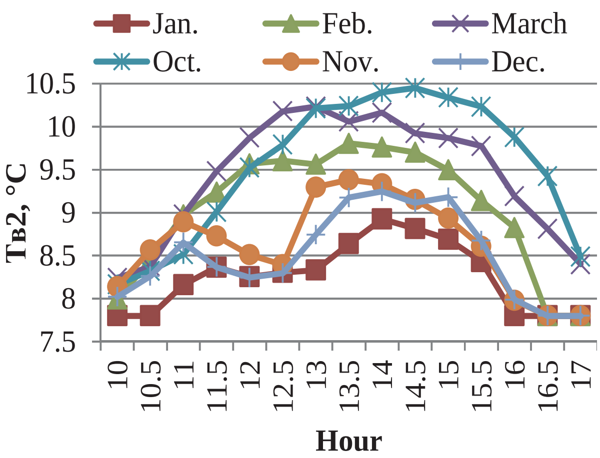

Fig.7. *Input temperature for the heat pump*

The values of the correlation coefficients are as follows:

$k_0 = 1$;

$k_1 = 1.559709 \times 10^{-2}$;

$k_2 = 1.5931 \times 10^{-4}$.

The catalogue COP of heat pump for input heat medium temperature of 8 °C and output temperature to the heating installation of 55 °C is $COP_b = 2.667$.

The heating power of heat pump at output temperature to the heating system of 55 °C amounted to 5.6 kW, and the electric power consumed by the compressor in this mode of operation is 2.1 kW.

Given these data and replacing them in equation (7) it has been calculated the change of COP with change of the input temperature to the heat pump. The results of this calculation are shown in Figure 8.

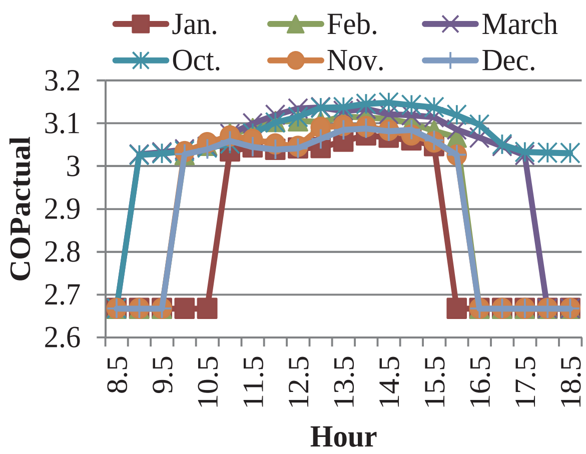

Fig.8. *Solar assisted COP of the heat pump*

3. PROPOSAL SCHEME FOR PRACTICAL IMPLEMENTATION OF SOLAR ASSISTED HEAT PUMP “WATER TO WATER”

The shown in Figure 1 scheme of a laboratory installation operates with significant accumulation volumes, which in practical terms is inappropriate. In practice, the ground-connected heat pumps do not require heat accumulator of its input, which necessitates in the scheme shown in Figure 1 to be made adjustments to allow practical implementation of solar assisted heat pump "water to water" in heating work conditions, with the ability to use the solar collectors for warming of domestic hot water. It should be noted that in practice the domestic hot water supply has priority, which requires the scheme to be configured so as to allow the setting of priority of domestic hot water installation before the heating one. Further, the temperature in the domestic hot water tank is generally equal to or higher than 55 °C, which is too high input temperature for the heat pump.

For these reasons it has been proposed in practice to realize a scheme of solar assisted heat pump such as that shown in Figure 9.

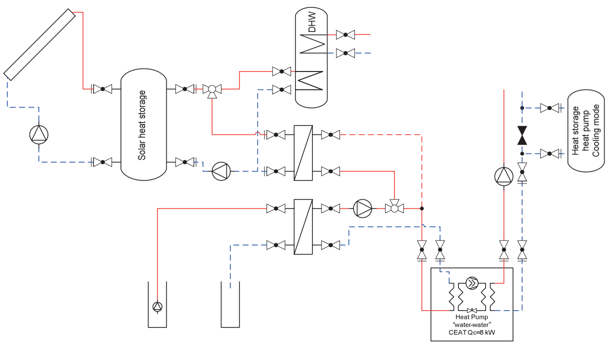

Fig.9. *Proposed scheme for solar assisted heat pump installation for DHW and heating*

4. CONCLUSION

From the made model it can be concluded that in such configured system for the entire heating season the average increase of the actual COP of the heat pump will range in the range of from 12 % to 15 %.

To achieve a greater increase of COP of the heat pump it is necessary to increase the collector area, but this would reduce efficiency of the solar collectors and hence a significant resizing of the domestic hot water installation for the summer season when collectors do not support the heat pump work.

It has been estimated that the use of three solar collectors consistent connected to heat pump "water-water" with a maximum heat power of 8 kW, it can be achieved an average power saving of 13 %, which amounts to 601 kWh for the heating season.

The use of solar collectors to assist the work of heat pump "water to water" is effective for the geographical location of Ruse because there is easy access to groundwater and allows the installation of this type of heat pumps. The use of solar collectors for domestic hot water and to assist the heat pump in heating mode will be more profitable.

REFERENCES

[1] Bobilov, V., P. Zlatev, Zh. Kolev, Pl. Mushakov, G. Genchev. *Investigation of solar thermal installation with optional power source heat pump "water to water"*. Scientific Conference of University of Ruse, volume 50, series 1.2, Ruse, Bulgaria, p.83-89, in Bulgarian (2012).

[2] Duffie J., W. Beckman. *Solar Engineering of Thermal Processes.* 2nd edition, John Wiley & Sons New York (1991).

[3] *RETScreen ENGINEERING &CASES TEXTBOOK*. Ground-Source Heat Pump Project Analysis, Minister of Natural Resources, Canada 2001-2005.

[4] Ursula, E. *Technologies for Buildings*. Wiley (2003).