Solar heating and hot water supply of high-rise buildings

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Abstract. Southern Russia, the Far East and Siberia regions have a lot of solar sources. These climate conditions are appropriate for using such combined power systems. Combined power systems are capable of providing building with heat in winter partially. In summertime the same system satisfies hot water demands.

Numerical modeling is carried out to prove the utility of the combined power systems. One of the calculations is based on the Black Sea coast climate conditions. The input data was seventeen-storeyed public building with 3 columns of 68 solar thermal panels Vitosol 100 SH1 on the southern side of its facades. Each panel is installed with a 90-degree tilt towards the horizon and connected with the next by series connection.

Automatic control system supplies air temperature set at 18 degrees Celsius in the daytime and 12 degrees in the nighttime (standby conditions). In view of the above, the solar thermal system completely covers heating systems energy requirements. In the summertime solar thermal system covers about 60% of hot water demand.

Numerical modeling also showed that in low temperature conditions of Far East climate the described system covers only 30% of heating systems energy requirements. But it covers almost 90% of hot water demand. This difference between working data (60% and 90%) for summertime is related to higher number of sunny days in the Far East than in the Black Sea coast region.

The numerical modeling of solar thermal combined systems with big solar collectors area showed some advantages. It is possible to use the produced energy all year round. Also the system proved its universality: it supports both heat and hot water systems. The system ensures high level of efficiency in many climate zones. Another important advantage is that such system produces non-polluting energy. However, some of the described issues are not shown in climate conditions of other regions, i.e. Central and Northwestern Russia.

1. Introduction

High-rise buildings became an integral part of the present-day urban development. Each of these buildings demands high power inputs from city heating and electricity networks. Using non-polluting energy sources helps us to reduce fuel expenses and carbon emissions, which lead to pollution of the environment. One of such non-polluting means is solar thermal system for high-rise buildings. This system helps to release tension on hot water demand system and heating system.

Fastening solar thermal collectors on a facade of the building has its benefits. One of them is that outer walls area of high-rise buildings is much larger than roof area. The other one is that solar thermal panels provide additional thermal insulation for buildings walls. Also using walls instead of roof
simplify maintenance of house-top engineering equipment. Moreover, such use of empty walls space is quite cost-effective.

Southern Russia, the Far East and Siberia regions have a lot of solar sources. These climate conditions are appropriate for using such combined power systems. Combined power systems are capable of providing building with heat in winter partially. In summertime the same system satisfies hot water demands.

Solar thermal panels should be placed at a 90 degree angle. It leads to increase in solar radiation absorption rate. This is explained by low altitude of sun above the horizon in wintertime. Direct solar radiation hits the surface of solar thermal panel at an angle close to normal.

On the other hand, using such tilt angle reduces risk of overheating of solar thermal panels in the summertime. In such conditions of high altitude of sun above the horizon, direct solar radiation hits the surface of solar thermal panel at an angle diverged from the normal position [1].

2. Numerical modeling of solar thermal systems
Numerical modelling is carried out to prove the utility of the combined power systems. It is customary to evaluate economic efficiency of solar thermal systems based on monthly averages [2] of direct and diffuse solar radiation [3].

Following such approach, the monthly produced by solar thermal system energy \( Q_{\text{sol}}^m \), MJ, is determined by the equation:

\[
Q_{\text{sol}}^m = 3.6 I_{\text{tot}}^v \eta S n
\]  

\( I_{\text{tot}}^v \) – total solar radiation falling to the vertical surface, kW/m\(^2\) [2]
\( \eta \) – optical efficiency of solar thermal collector;
\( S \) – absorber area of solar thermal collector, m\(^2\);
\( n \) – number solar thermal collectors.

The amount of energy needed to supply the consumer with hot water for a month \( Q_{\text{hw}}^m \), MJ, is determined by the equation:

\[
Q_{\text{hw}}^m = 4.19 m_{\text{hw}}^m (t_{\text{rec}} - t_{\text{cw}})
\]  

\( m_{\text{hw}}^m \) – the required amount of hot water per month, kg;
\( t_{\text{rec}} \) – required hot water temperature, °C;
\( t_{\text{cw}} \) – cold water temperature, °C.

Heat load of the building for each month \( Q_{\text{heat}}^m \), MJ, is determined by the equation:

\[
Q_{\text{heat}}^m = 4184 \cdot D Q_{\text{heat}} \left( 10 \frac{t_{\text{in.des}} - t_{\text{out.des}}}{t_{\text{in.rec}} - t_{\text{out.act}}} + 14 \frac{t_{\text{in.des}} - t_{\text{out.des}}}{t_{\text{in.rec}} - t_{\text{out.act}}} \right)
\]  

4184 – conversion ratio of units Gcal/h into MJ;
\( D \) – number of days in a month;
\( Q_{\text{heat}} \) – heat load of the building under design conditions, Gcal/h;
\( t_{\text{in.des}} \) – indoor temperature under design conditions, °C;
\( t_{\text{out.des}} \) – outdoor temperature under design conditions, °C;
\( t_{\text{in.rec}} \) – required indoor temperature of heating system operating in the main mode, °C;
\( t_{\text{in.rec}} \) – required indoor temperature of heating system operating in the standby mode, °C;
\( t_{\text{out.act}} \) – actual outdoor temperature, °C;
10 – duration of heating system operating in the main mode, h; 14 – duration of heating system operating in the standby mode, h.

The monthly hot water supply can be estimated, %, by the following equation:
Similarly monthly heating load supply can be estimated, \( \% \), by analogical equation:

\[
p_{m}^{\text{heating}} = \frac{Q_{m}^{\text{heating}}}{Q_{m}} \cdot 100
\]

(4)

The input data for calculating solar thermal systems was seventeen-storeyed public building with 3 columns of 68 solar thermal panels Vitosol 100 SH1 on the southern side of its facades. Here are some of the primary characteristics of Vitosol 100 SH1 from device specifications:

- Absorber surface area \( S = 2.3 \text{ m}^2 \);
- Optical efficiency \( \eta = 81\% \);
- Heat loss coefficient \( k = 3.48 \text{ W/m}^2\text{°C} \);

Each panel installed with a 90 degree tilt towards the horizon and connected with the next one by series connection.

The most common plumbing fixtures used in public buildings are washbasins with mixers. The standard hourly flow rate of hot water for washbasins with mixers is 8 liters per hour [4]. There are 18 washbasins on each floor. Hot water temperature in the urban hot water system should be not less than 60 and not more than 75 degrees Celsius [5]. Despite the requirements of standards in this study we set temperature of hot water at 35-40 degrees Celsius. It is justified by the absence of necessity such high temperatures in a public office building.

The heating system has two modes. One of them is the main, another is standby mode. Automatic control system supplies air temperature on 18 degrees Celsius at daytime and 12 degrees at nighttime (standby conditions). For example, in the Far East climate conditions heating system load for seventeen-storeyed public building is 0.544 Gcal/h at the nighttime and 0.480 Gcal/h at the daytime (design conditions). In the Southern Russia climate conditions the heating system load is 0.213 Gcal/h at the nighttime and 0.149 Gcal/h at the daytime (also design conditions).

One of the calculations was made for the Black Sea coast climate conditions in Sochi. Taking into account all above the solar thermal system completely covers heating systems energy requirements. In the summertime solar thermal system covers about 60\% of hot water demand.

Numerical modeling also showed that in low temperature conditions of Far East climate in Blagoveshchensk the described system covers heating systems energy requirements only for 30\%. But it covers almost 90\% of hot water demand in summer.

This difference between working data (60\% and 90\%) for summertime is related to higher number of sunny days in the Far East than in the Black Sea coast region. The percentages are determined by (4) and (5).

The performance evaluation method of solar thermal systems application described above showed us the high levels of utility of such systems. This method does not allow a detailed analysis of the time intervals, in which the deficit of the generated energy could be observed.

3. The detailed mathematical model of solar thermal systems

In the proposed mathematical model, the following parameters are taken into account:

- Hourly values of solar radiation (which are contained in Research and applied handbook of USSR climate) [6].
- Change in the heat losses of the solar collector \( Q_{loss} \) as a function of the heat transfer agent and environment temperatures.
- Change in the heat transfer coefficient \( K \) of the storage tank heat exchanger, which depends on the flow regime and the temperature of the heat transfer agent and water.

As proved by preliminary numerical experiments carried out by the authors, the last two parameters exert a significant influence on the accuracy of the simulation results.
The process of supply and accumulation in the storage tank of thermal energy occurs continuously. Therefore, selecting the time interval for monitoring all system parameters brings a significant effect on the accuracy of the simulation results. The performed calculations showed that the time interval providing the required accuracy is 5 minutes.

According to the mentioned mathematical model, the amount of heat, converted by the collectors every hour, is determined by the equation:

\[ Q_{\text{sol}}^h = (I_S P_S + I_D P_D) \eta S n - Q_{\text{loss}}^h \]  \tag{6}

\( I_S \) – direct solar radiation falling to the horizontal surface, MJ/m² [6];
\( I_D \) – diffuse solar radiation falling to the horizontal surface, MJ/m² [6];
\( P_S \) and \( P_D \) – position coefficients of the solar collector for direct and diffuse solar radiation [7];
\( Q_{\text{loss}}^h \) – hourly heat loss of the collector, MJ;
\( \eta, S \) and \( n \) – as in the previous model.

Thermal losses of the solar collector \( Q_{\text{loss}}^h \), MJ, is determined by the equation:

\[ Q_{\text{loss}}^h = 10^{-6} k_n S (t_{\text{col}} - t_{\text{out, act}}) \]  \tag{7}

\( t_{\text{col}} \) – collector heat transfer temperature, °C

The amount of heat required to provide the users with hot water every hour \( Q_{\text{hw}}^h \), MJ, is defined similarly to (2). The required amount of hot water per month \( m_{\text{hw}}^m \) is replaced by the required amount of hot water per hour \( m_{\text{hw}}^h \), kg.

The amount of heat required to provide a load on the building’s heating system every hour \( Q_{\text{heat}}^h \), MJ, is determined by the equation:

\[ Q_{\text{heat}}^h = 4184 \cdot Q_{\text{heat}} \cdot \frac{t_{\text{in, rec}} - t_{\text{out, rec}}}{t_{\text{in, rec}} - t_{\text{out, rec}}} \]  \tag{8}

\( t_{\text{in, rec}} \) – required indoor temperature of heating system at a particular hour, °C.

The share of heat energy \( Q_{\text{sol}}^h \) converted by a heat exchanger \( Q^h \) for heating water purposes which would be available to the users is determined by the equation:

\[ Q^h = K F \Delta t_{\text{in}} \tau \]  \tag{9}

\( K \) – heat transfer coefficient of heat exchanger, W/m²°C;
\( F \) – heat exchanger surface area, m²;
\( \Delta t_{\text{in}} \) – logarithmic temperature difference, °C;
\( \tau \) - period, sec.

\[ \Delta t_{\text{in}} = \frac{(t_{\text{in1}} - t_{\text{in2}}) - (t_{\text{in2}} - t_{\text{in1}})}{\ln\frac{t_{\text{in1}} - t_{\text{in2}}}{t_{\text{in2}} - t_{\text{in1}}}} \]  \tag{10}

\( t_{\text{in1}}, t_{\text{in2}} \) – heat transfer agent temperatures at the beginning and at the end of heat exchanger channel, °C;
\( t_{\text{w1}}, t_{\text{w2}} \) – water temperatures in the lower and upper parts of the storage tank, °C.

Here (10) is nonlinear equation. This equation is solved by iterative methods [8].

The basic equations of the mathematical model for calculating the system’s indicators every hour are described above. For more detailed simulation of the system operation, the input data like solar radiation amount \( I_S, I_D \) and outside temperature \( t_{\text{out, act}} \) are interpolated for shorter time intervals. The general formula for linear interpolation:

\[ y = y_0 + \frac{y_1 - y_0}{x_1 - x_0} (x - x_0) \]  \tag{11}
Here $y$ indicates the value of the unknown quantity (solar radiation amount or outside temperature), $x$ indicates a new time interval.

In this way the system is simulated every 5 minutes. It shows what is the proportion of solar radiation is converted into a heat energy including heat loses. Using this mathematical model it is possible to see the value of temperature of water at the exact moment and also if the temperature suits the user requirements.

4. Results and discussion

Change in water temperature during the cloudy day in Blagoveshchensk is shown on fig.1. The graph shows that in the morning the water temperature may not be sufficiently heated. By 10 am the water temperature in the system reaches the required temperature and continues to grow. The temperature rises until about 15 pm, as during this period the heat input into the system exceeds its consumption. After 15 pm the water temperature in the system begins to decrease, since the intensity of solar radiation at this time of day decreases.

![Figure 1](https://via.placeholder.com/150)

**Figure 1.** Hot water system performance on a cloudy day in June, Blagoveshchensk

Change in water temperature during the sunny day in Sochi is shown on fig.2. The water temperature reaches the required value around 11 am and is provided up to 17 pm. After 17 pm, the water temperature drops below the required 40 °C but the water is still suitable for use in the hot water system, until its value is below 30 °C. This water temperature is provided up to 19 pm. Thus, after 19 pm the hot water system requires the connection of a back-up device for water heating.
Similarly, this method of calculation makes it possible to estimate the provision of thermal energy of the building during the heating season.

On fig. 3 shows the change in the heat load of the building during the day, as well as the amount of thermal energy produced by the installation on a sunny day in December in Blagoveshchensk. The sharp break of the heat load curve in the graph is due to the transition from standby mode to main mode.

Solar heating system performance curve has a wavy appearance. This is due to the inclination angle of the solar collector. In the morning and in the evening, there is low altitude of sun above the horizon. This means that its rays fall on vertically oriented collectors at an angle close to the normal. In the daytime, the sun is higher and the angle of incidence of its rays on the collectors deviates from the normal. This leads to a reduction in the proportion of converted solar radiation.

**Figure 2.** Hot water system performance on a sunny day in June, Sochi

**Figure 3.** Solar heating system performance on a sunny day in December, Sochi

**5. Conclusions**

The numerical modeling of solar thermal combined systems with big solar collectors area showed some advantages. It is possibility to use produced energy all year round. Also the system showed its universality – it supports both heat and hot water systems.
The system has high level of efficiency in many climate zones. But some of described points is not showed in climate conditions of other regions, such as Central and Northwestern Russia because of low level of solar radiation sources.

And one more important advantage is that system produces non-polluting energy, because the problem of environment pollution in big cities is always a subject of current interest.

Mathematical model, described in this paper, allows evaluating efficiency of solar thermal system located in any geographical position.

High degree of attention to detail in the mathematical modeling of solar heating systems, both high-rising buildings and any other, allows us to give a more detailed assessment of the degree of autonomy of the system. With this information at the design stage, it is possible to provide the most suitable backup sources of energy.

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References
[1] 1990 Solar cool and heat supply systems edited by Sarnatsky E V and Chistovich S A (Moscow: Stroyizdat) p 143
[2] 2012 Building climatology SP 131.13330.2012
[3] Butuzov V 2004 Increasing efficiency of heating systems based on renewable energy sources (Krasnodar) p 34
[4] 2012 Domestic water supply and drainage systems in buildings SP 30.13330.2012
[5] 2009 Hygienic requirements for ensuring the safety of hot water systems SanPiN 2.1.4.2496-09
[6] 1988-1993 Research and applied handbook of USSR climate (Leningrad, Moscow: Gidrometeoizdat)
[7] 1986 Departmental building codes Installations of solar hot water supply VSN 52-86
[8] Kitaytseva E, Konstantinova D 2017 Numerical simulation of the operation of heat exchangers in solar heating systems (Moscow: BST publishing) pp 30-32.
[9] Efremova O, Khvorova L 2017 Mathematical Modeling of Solar Heating Systems (Barnaul: Izvestiya AltGU Journal #4) pp 98-103
[10] António J M M 2017 Araújo Solar thermal modeling for rapid estimation of auxiliary energy requirements in domestic hot water production: Proportional flow rate control (Energy, #138) pp 668-681
[11] Haller M Y, Bertram E, Dott R, Afjei T, Carbonell D, Ochs F, Heinz A, Cao S, Siren K 2015 Components and thermodynamic aspects, Solar and Heat Pump Systems for Residential Buildings (DOI: 10.1002/9783433604830.ch03)