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Development of the Computer-Aided Application for the Use of Solar Energy in the Hot Water Supply System of Russian Permafrost Regions

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This paper presents a hardware-software application for the study of built hybrid hot water supply systems functioning year-round and using solar energy and additional heating sources. It compares the achievable efficiency of the constructed systems with design calculations. The application uses a new computer-aided application that allows controlling the operation modes of systems, accumulation and transmission of the obtained data over long distances, its processing and presentation in the required table or graphical format. This application is used to analyze the effectiveness of a solar hybrid hot water system located in the city of Yakutsk. The system includes three groups of evacuated collectors, three header tanks and a gas boiler. For this system, experimental data are given on hourly, daily (on working days, weekends and holidays), monthly and annual operation modes. It was established that the annual solar fraction is 0.29 and it does not correspond to the design estimate of 0.51. The temperature of the water supplied to the consumer in the cold six months at a daily flow rate of 4 m^3/d is 47 ± 3.1 °C, which lower than the design calculation of 57 ± 2.5 °C. Based on the analysis of the obtained experimental data recommendations are proposed to improve the efficiency of the system to the design level while reducing the consumption of natural gas. The paper also outlines the ways of improving the hardware-software application.

1. Introduction

The rapid population growth and urbanization (Avtar et al., 2019) lead to the growth of the global economy (Balatsky et al., 2015) that significantly expands global demand of clean water and energy (Klemeš et al., 2016), and affects sustainable development (Imasiku and Ntagwirumugara, 2020). Using fossil fuels for energy generation exhausts the supply of non-renewable resources; and emissions from burning the fuel cause environmental damage (Owusu et al., 2016). Apart from the industrial sector, the construction sector has a significant share in global energy consumption (32 %) and is one of the largest contributors to climate change and CO_2 emissions (Abikoye, 2019). In this regard, the relevance of developing the technologies to minimize the use of energy and water, wastes and emissions is growing (Klemeš, 2013). The demand for the use of heating and cooling in the residential sector for 165 countries was investigated, and global maps were built (Sach et al., 2019). The mathematical methods of investment planning (Vrionis et al., 2020) in the technology of using renewable energy sources (wind, solar, and biomass) are actively being developed. The energy of the sun reaching the earth is most widely used to generate heat and power, including a combined generation (Tang et al., 2019). The global potential of solar energy is huge (Dupont et al., 2020), and its use does not depend on the borders of countries (Haukkala, 2015). Technologies are being developed to incorporate the solar fraction into hybrid systems using traditional fuels (Wang et al., 2016). In the study (Redpath, 2012) the author demonstrates the effectiveness of solar water heaters with thermosyphon heat pipes for the northern marine climate. It was shown that for any of the two types of residential buildings studied, from April to August, the solar fraction was not lower than 70 %. Most of the published papers deal with the development of new solar energy

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facilities and analysis of existing ones is not addressed enough. The difference between designed and achieved an efficiency of such systems have to be additionally investigated to find disadvantages, loss of opportunities and improve the installed solar systems.
The current paper presented an approach to the analysis of the installed solar systems in a Russian permafrost region. The territory of Russia with permafrost is approximately 65 % (Permafrost Russia, 2020) and it is extremely vulnerable to emissions of harmful substances. The sparse population of this huge territory with small settlements were provided with thermal and electric energy utilising outdated diesel stations. The potential of renewables for such territories (Kenden, 2015) is being analysed and the systems for their use are being developed (Marchenko, 2017). In recent years, solar and wind stations have been actively built to replace the old diesel stations. The city of Yakutsk can be considered the centre of the territory with permafrost. In this city, from 2013 to 2017, a major pilot project was implemented. In this demonstrates the approach that was applied as a software. It was used for the analysis of the built energy-efficient district with three-storey residential houses and a kindergarten. All buildings were equipped by hybrid solar hot water systems (HHWSs) as a part of the roof boiler houses were built. Detailed annual performance analysis of the two systems used, compare the obtained results with the data of design solutions and outline the ways of their reconstruction were necessary to carry out. Based on the analysis of these data, recommendations are provided to increase the efficiency of the system and increase the solar fraction. An automated application has been developed for managing and analysis the operation of solar hot water systems in the permafrost regions of Russia, which uses internal and external heterogeneous communication. The application provides scheduling and safety of water heating systems. A one-year cycle of collecting and transmitting data on the operation parameters are performed by an automated processing and data representation with any measurement intervals. The application can be used to analyze the efficiency of the developed hot water supply systems to identify the drawbacks. The ways of improving the hardware-software application are outlined. The software may be used for the analysis and improvement of existing solar heating system and making the recommendation of new solar energy construction in northern territories.

2. Methods

The methodology is based on the installation of additional measurement equipment and analysis of experimental and calculated data. The first system, placed on the building of the kindergarten, includes two groups of tubular evacuated collectors and three storage tanks. An additional source of thermal energy in this system is heated water for heating and ventilation of the kindergarten building in a block-type gas boiler installed at the required distance from the kindergarten building. Using the hardware-software application developed for these purposes allowed to carry out the required experimental study (Krivoshein, 2020a) for the first system in 2018. The second system includes three groups of evacuated collectors, three header tanks and a gas boiler. Storage tanks and a gas boiler are located in a room built on the roof of each apartment building. Two more gas boilers and equipment for providing heating energy to the heating and ventilation systems of a residential building are located in this room. Metering of consumed natural gas is carried out on a common gas pipeline for three boilers. This did not allow obtaining data on the consumption of natural gas and the generation of thermal energy by the gas boiler of the hot water supply system. To analyse the receipt of thermal energy from the gas boiler, metering equipment for this energy was installed, integrated into the upgraded software and hardware application. In this study, for the second system, experimental data on hourly, daily (on workdays, weekends and holidays), monthly and annual operation modes for 2019 are given.
In the experimental annual performance analysis of a solar water heating system with an evacuated tubular collector (Ayompe et al., 2013) the developed automated subsystem was used to control the parameters. This work shows the need to control the circulating pump on cloudy days. In the developed hardware-software application circulating pumps of each group of collectors (Figure 1) switch off when reaching the temperature differential in the average temperature of collectors and the temperature of water in the corresponding storage tank of less than 10 °C and they switch on when this differential is more than 10 °C.
The performance of U-tube vacuum collectors was studied during daytime under different mass flow rates: 0.03 kg/s, 0.05 kg/s and 0.08 kg/s (Bhowmika et al., 2019). The results revealed that the coolant flow through the collectors influences the effectiveness of the system insignificantly. The measured values were recorded every 15 min. Measurements also showed that the effectiveness of three series-connected collectors and the obtained thermal energy change significantly during the time and they qualitatively reproduce the solar insolation curve. The annual analysis (Maraj et al., 2019) was performed to investigate the energy characteristics of a solar water heating system with forced circulation equipped with an evacuated collector for Mediterranean climate conditions. Data from sensors and instruments were recorded with a minute interval. It was established that the average monthly efficiency of the collector and the system efficiency during the annual period varies insignificantly. In the developed application, the values of the measured parameters are observed on the

mnemonic diagram (Figure 1) in real-time for the city of Yakutsk (Krivoshein, 2020b). The developed hardware-software application is part of the elaborated three-level dispatch and energy management system of a single-entrance residential house, built-in 2013 in the energy-efficient district “Zhatay” in Yakutsk on 3 Komsomolskaya Street.

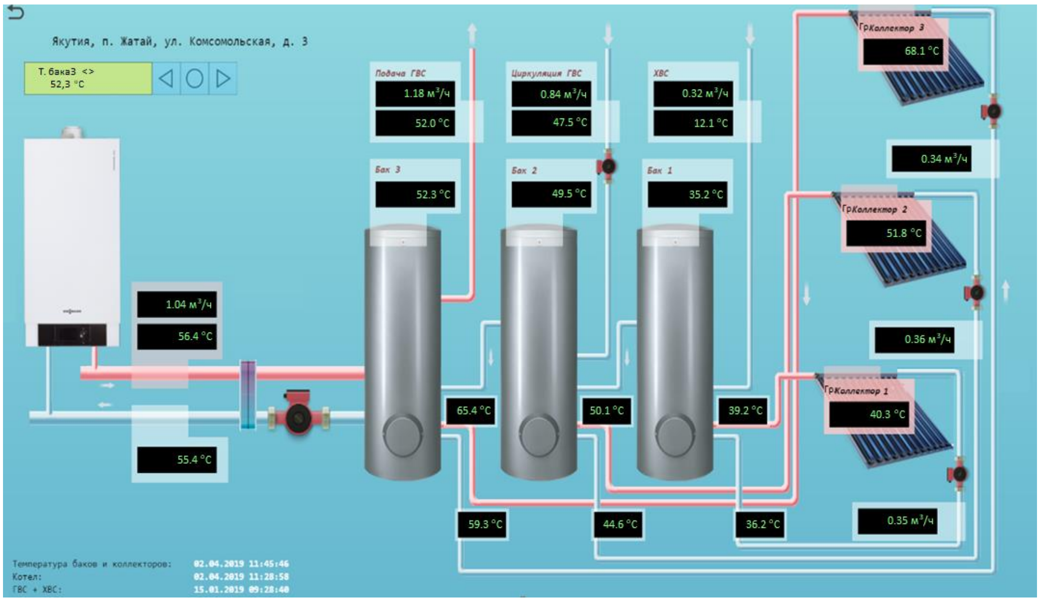

Figure 1: Mnemonic diagram of hardware-software application for field studies of solar hot water supply systems of the residential house in 3 Komsomolsayai Street in the city of Yakutsk

The application has remote access and provides collection, storage, transmission over long distances and processing of data received from all the installed sensors and devices at any given time (Prokhorov et al., 2019). Data received during any hour of any day is stored within 90 d, and then automatically transferred to the server. Averaging of all the obtained hourly and daily data is performed using numerical integration employing the trapezium method. These data remain in the memory of hardware-software application for a year (from January 1 to December 31) and within 15 d of the next year. Then the data are automatically transferred to the server. The averaged data for each month and a year are always stored in the application memory and are transferred only to the person having the respective access. Storage of accumulated information in special microelectronic components can reach 10 y with the power off. Since synergic interaction between consumers and suppliers has become the inevitable trend (Xia et al., 2019), presentation of measured data for any period is provided by the application in the required table or graphic form, convenient for residents of the house and organizations providing services and supplying resources for the given house. To ensure the reliability of data transmission in the application at any of the three levels, it is necessary to provide heterogeneous communication.

3. Results and discussion

Some results of the conducted study are demonstrated in Figures 2-4.

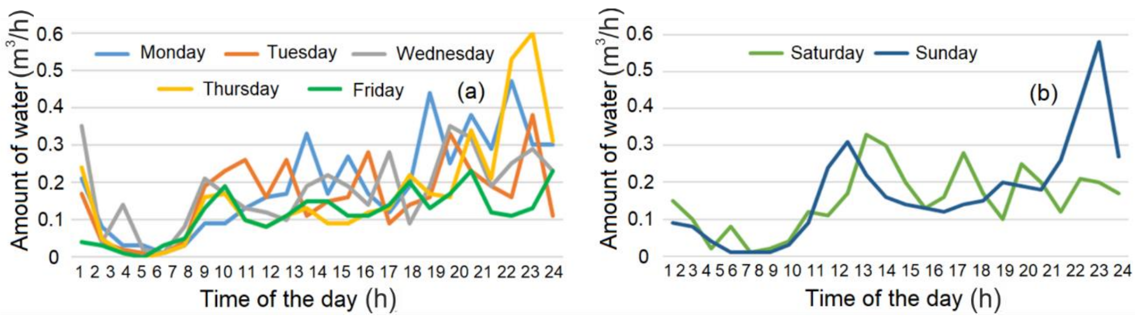

Figure 2: Typical graphs of hourly hot water consumption in workdays (a) and weekends (b)

Typical graphs of hot water flow rate (Figure 2) illustrate that in the middle of the day and the evening hours higher hot water consumption is observed. The system should provide the design values for the temperature of the water supplied to the consumer. Typical averaged data on the daily hot water flow rate is given in Figure 3. On Mondays, Thursdays and Sundays, hot water consumption was higher than it was considered in the project (4 m^3/d). The observed average values of hot water consumption for all weeks of the year are below the design value of 4 m^3/d, except for one week on New Year's holidays (Figure 4a). At the design daily consumption of hot water, fluctuations in its temperature in the delivery pipeline to the consumer should be within 57 ± 2.5 °C under the total absence of the solar fraction. With daily consumption of 4 m^3/d from January to March and from November to December, temperature fluctuations were recorded within 47 ± 3.1 °C. With daily consumption of 5 m^3/d temperature fluctuations were recorded within the range of 43 ± 4.2 °C. The greatest decrease in the studied temperature (up to 34.8 °C) was observed on December 31, 2018 (Figure 4b). Hourly supply water flowrate (V_1) and return one (V_2) from the circulation loop with the generation of thermal energy by the gas boiler are shown in Figure 5a. It should be noted that according to calculations the gas boiler generates 3.63 times more thermal energy Q during 3 h at night than it is necessary to compensate the heat losses in the circulation pipeline. Thermal losses in the storage tank No 1 without cold water input due to lack of hot water consumption increased by 2.6 times as compared to the calculated values.

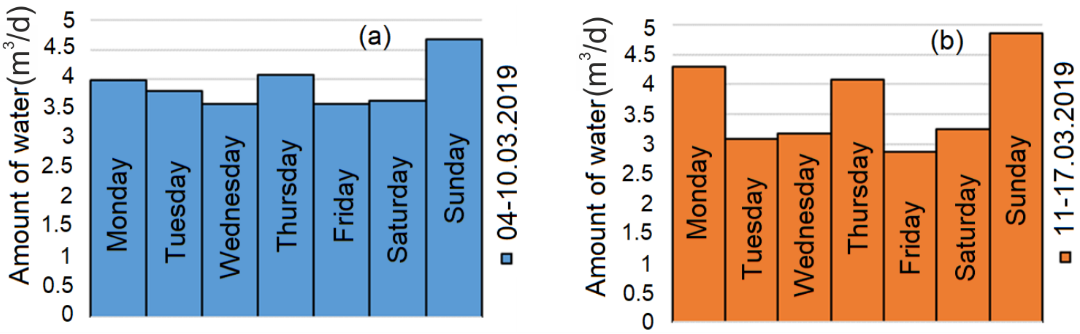

Figure 3: Typical data on hot water consumption during the day of the week 11 - 17 March 2019

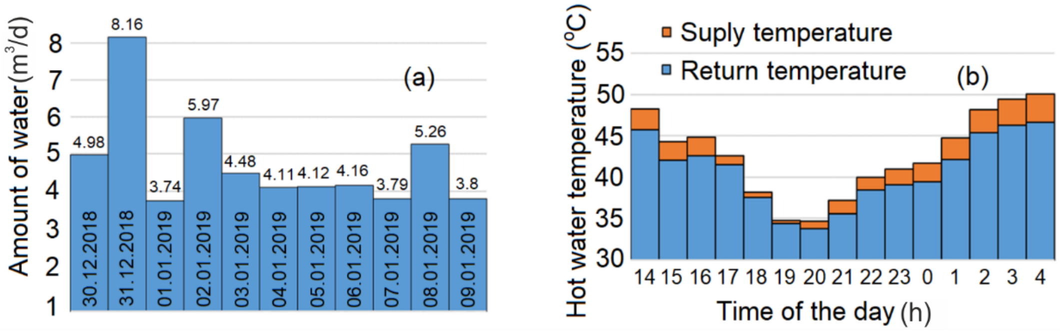

Figure 4: Hot water consumption during New Year Holidays (a) and changing the temperature of water delivered to the consumer and returned in the system at the maximum daily flow rate (b)

Typical data on the generation and consumption of thermal energy during the month are presented in Figure 5b from April 1 to 23. Due to the failure of the automation system of the gas boiler from April 24 to 29, an electric boiler was connected to the hot water supply system, the power of which was half of the gas boiler. The failed gas boiler was replaced on April 30. Table 1 presents monthly data and the data for the year 2019 showing the thermal energy produced by the gas boiler and collectors, data on the solar fraction of the system are presented. The design annual value of the solar fraction is 0.51. The experimentally obtained low value of the solar fraction of 0.29 does not reflect its actual capabilities. This is attributed to the fact that at night due to the occurrence of natural convection in hydraulic circuits of collectors, additional heat losses occur from the storage tanks, which are not always compensated by a gas boiler. For this reason, natural gas is unproductive and harmful emissions are unreasonably increasing. The exclusion of these phenomena is extremely important for permafrost territories.

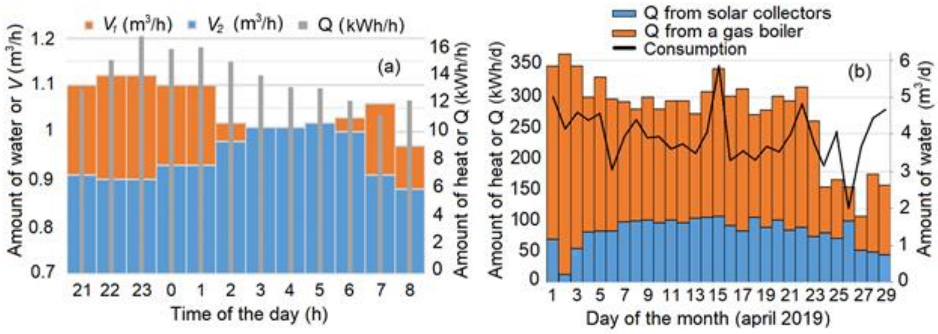

Figure 5: Hourly supply flowrate V_1 and return flowrate V_2 from the circulation circuit using the generation of thermal energy by a gas boiler (a), typical monthly data of the system operation (b)

Table 1: Solar fraction during different months in 2019

Month of the year	Thermal energy from a gas boiler, kWh	Thermal energy from the collectors, kWh	Used heat energy for domestic hot water, kWh	Solar fraction
January	8,379	894	9,274	0.0965
February	9,843	1,441	11,284	0.1277
March	6,764	2,196	8,960	0.2451
April	6,136	2,661	8,797	0.3025
May	6,264	2,940	9,204	0.3194
June	4,695	6,915	11,610	0.5955
July	2,963	6,915	9,878	0.7004
August	5,253	7,124	12,377	0.5759
September	6,345	2,893	9,239	0.3132
October	8,228	871	9,100	0.0958
November	8,565	267	8,832	0.0303
December	8,236	352	8,588	0.0409
Total	82,016	35,121	117,138	0.2869

When retrofitting the system under study, it is necessary to consider how to exclude natural convection in hydraulic circuits of the collectors at night time. Thermal energy in the storage tanks will significantly reduce the proportion of energy produced by a gas boiler. This will approximate the achievement of the design water temperature in the delivery pipeline to a consumer of 57 ± 2.5 °C at a flow rate of 4 m^3/d of hot water per day. It is expected that the solar fraction will be increased, and the energy accumulated in storage tanks during the day will not be emitted through the same collectors at night.

4. Conclusions

Using the developed hardware-software application allowed carrying out a detailed study in the city of Tomsk remotely to investigate the effectiveness of hybrid solar hot water system used in residential houses in Yakutsk. It was established that the hot water supply temperature of 47 ± 3.1 °C in cold 6 months does not correspond to the designed temperature in the project of 57 ± 2.5 °C. The annual solar fraction of 0.29 does not correspond to the design one of 0.51. The identified shortcomings of the system design are removable in the process of low-cost reconstruction. This will increase the efficiency of the system, reduce operating costs and unjustified emissions of natural gas combustion products. The developed computer application will need to be supplemented with a device control program that excludes the occurrence of natural convection in the hydraulic circuit of collectors at night.

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