Model and simulation of temperature changes in the buffer tank cooperating with the greenhouse heating system

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Abstract. The paper presents a mathematical model describing the water temperature change in a buffer tank. The buffer tank is an integral part of modern greenhouse heating systems. The model includes heat fluxes from the heating boiler, heat fluxes transferred to the greenhouse interior and heat losses from the system (tank, pipes connecting the tank with the heating system). The differential method was used to determine the temperature value in the tank. Verification tests carried out in a real facility showed that the mean square error is 0.14K.

1. Introduction

Increasing production cost and care for the natural environment stimulate the search for solutions that meet these conditions. One of such solutions in heated greenhouses is the use of heat accumulators. The necessity to use batteries results from several reasons: legal regulations (EP directives on the limitation of the fossil fuels use, energy efficiency, industrial emissions), ensuring optimal boiler efficiency (and thus reduction of fuel consumption) and environmental protection, thanks to reduced emissions of harmful substances into the atmosphere. This issue is particularly important during the boiler's operation in the summer period, where the demand for thermal power is many times lower than in the winter period, and it leads as a consequence to a reduction of the boiler efficiency [1]. Apart from efficiency reducing, the risk of boilers corrosion is a disadvantageous phenomenon, because the corrosion intensity, apart from its proper structure, depends on the water temperature returning from the heating system [2]. These unfavourable phenomena can be prevented by installing buffer tanks in the system. Their installation is treated as an innovative method which, based on the production experience, leads to the improvement of the system operating conditions, i.e.: the economics of heat production, reduction of pollutant emissions and increased security of energy supply [3]. The issue of heat storage in energy accumulators is intensively analyzed in numerous research centres however the Authors mainly focus on storage of energy from renewable sources.

Kalder et al. [4] analyzed the problem of heat from solar collectors stored in a thermally insulated water tank in the summer, taking into account the balance of thermal energy during the heating period. The authors determined the percentage share of heat accumulated in the tank in the expenditure on object heating and the efficiency of the entire system. Glebin et al. [5] using the TRNSYS simulation program, they analyzed standard systems using a heat pump for the heating needs of a facility, which included the cooperation of the pump with any buffer tank and various types of heating systems. The Authors concluded that the elaborated algorithms can be used to design various heating systems consisting of a heat pump and diverse types of storage tanks. Another work of these authors [6] presents
the results of simulation tests in which the connection of heat pumps and buffer tanks was examined. Bai and Hu [7] investigated the effects of using two energy accumulators in the solar system: a concrete tank and a filled water-steam tank. The energy effects of the system were analyzed based on numerical simulation experiments, indicating the factors determining heat storage. Sarbu and Dorca [8] reviewed the technologies and materials used to store thermal energy in batteries in terms of their use for heating and cooling objects (cooperating with a heat pump). Marini et al. [9] analyzed the dimensioning of thermal energy storage systems consisting of a heat pump operating according to different electric load tariffs. In the analyzed scenarios, they assumed the diversified households energy demand. Li et al. [10] considered a system consisting of a reservoir and solar collectors. In the TRNSYS software, they conducted simulation experiments in which they analyzed the influence on the average temperature in the tank of the tank volume, temperature difference in the tank (tank without mixing) and the heat amount from the system. They also determined the recommended tank capacity depending on the collector area.

Taki et al. [11] reviewed the possibilities of saving heat for the greenhouses heating needs using the existing technical solutions: PV modules, solar collectors, heat accumulator filled with Phase Change Material (PCM) integrated with the heating system, heat pumps, covering materials with increased thermal insulation, and underground heat storage. As a result of the analysis, they found that the application of these solutions brings almost 70% savings in heat consumption. Yang and Svendsen [12] analyzed the effectiveness of the municipal heating installation delivering domestic hot water from the buffer tank to individual recipients. The proposed hot water flow control strategy used in two systems with an external heat exchanger and a heat pump allowed to reduce the peak heat demand and the achieved savings, compared to the reference case, amounted to 8–28%. Kuravi et al. [13] analyzed the effects of the heating system work equipped with a tank filled with PCM material, the structure of which was made of independent macrocapsules. Another work of this author [14] presents an overview of the methodology of designing thermal energy storage systems in a solar concentrating power plant (CSP). The Authors, based on the available studies, discussed the existing thermal energy storage systems together with analysis of thermal and exergy efficiency and economic effects. Guo et al. [15] presented the results of the analysis of space heating with the use of a heat pump equipped with a buffer tank. Using two simulation programs, they analyzed the impact of tank capacity on the energy efficiency of the heating system. Kurpaska and Latała [16] developed guidelines for the use of system components (including a tank with a different volume) cooperating with a heat pump for heating a foil tunnel. Based on the conducted experiments, they determined the variability of the COP coefficient depending on the input variables. Li et al. [17] analyzed the modified structure of the storage tank in the installation with solar collectors, concluding that the modification in the number of outlet pipes had a positive effect on the amount of useful heat from solar radiation conversion. Lu et al. [18] analyzed the thermal effects of a system consisting of a tank of variable volume cooperating with solar collectors in which heat was supplied to the greenhouse. They chose the optimal capacity of the tank depending on the collectors’ area and the heated greenhouse areas. Sun et al. [19] developed and verified a mathematical model in which the dosing of water at reduced temperature to the storage tank in a heating system with a heat pump was analyzed.

Mavrogianopoulos and Kyritsis [20] examined the possibilities of greenhouses heating using passive heating of water heated by sunlight in a storage tank. The issue of heat storage for the greenhouse heating was analyzed, among others by Gasia et al. [21]. The authors use to heat the water a system of PE pipes placed between the rows of plants. In the work, they analyzed the energy effects of the modified heat exchanger structure in the storage tank and the PCM material, concluding that the use of the exchanger increases the intensity of heat reception. Van Beveren et al. [22] developed a decision-making system for a greenhouse heating, in which a boiler cooperating with an accumulation tank and a Combined Heat Power system with an additional tank were considered. The research showed that as a result of the optimal control of the tank loading and unloading process, savings in heating costs compared to a system without a tank amounted to 20%. The research [23], in which the PCM accumulator was used in the heating system, showed that it is possible not to accumulate excess heat but also to improve the efficiency of the entire system. Using the CFD program, El-Amin and Al-Ghamdi [24] simulated the influence of water with variable temperature injected into the tank, concluding that the is differential
compatibility (depending on the water temperature) between the measured and calculated values. The presented literature review indicates that the problem of heat storage in batteries is interesting, having both cognitive and application values.

Therefore, the main purpose of the work is an analysis of a system consisting of a boiler cooperating with an accumulation tank in which hot water is used for greenhouse heating needs.

2. Materials and methods

The analysis was carried out for the system presented in Figure 1.

The considered system consists of:

a) two gas boilers with a peak power of 3.5 MW,

b) hot water storage tank with a capacity of 1000 m³,

c) a greenhouse with a cultivation area of 3.5 ha.

The water temperature was measured using PT1000 meters. As it was not possible to determine the stream of water injected into the buffer tank and heating systems, the inverse method was used to determine these values. It consists of a selection of installation operating states without boiler operation and heat consumption.

The analyzed system is described by the balance equation:

\[ V_{\text{acc}} \rho_w c_w \frac{dT_w}{d\tau} = q_b - q_h - q_{\text{loss}} \]  

It can be seen that the change in water temperature in the tank \((T_w)\) depends on the heat flux supplied by the boiler \((q_b)\) reduced by heat loss flows through the heating system \((q_h)\) and heat transferred from the pipes supplying hot water from the boiler to the tank and from the tank to the environment \((q_{\text{loss}})\). These streams can be determined based on the measurement of heating water parameters, based on the equations used to determine the intensity coefficients of heat transfer from the analyzed system's components to the environment (surrounding air, the air inside the greenhouse) and the geometric parameters of the system. Having the values and dependencies, the equation (1) was solved by the differential method.

The starting point is the assumption of the initial temperature in the tank \((T_w^0)\), and after finding the time step value, the water temperature is automatically calculated \((T_w^{n+\Delta})\). The calculated new temperature in the tank becomes the temperature of the medium fed to the greenhouse heating system in the next time step.

To evaluate the difference between the measured value \((T_{\text{mea}})\) and that calculated \((T_{\text{calc}})\) making \((n)\) comparisons, mean square error was used, defined as:
\[ \sigma = \left[ \sum_{i=1}^{n} \left( \frac{T_{\text{meas}} - T_{\text{calc}}}{n} \right)^2 \right]^{0.5} \]  

(2)

3. Results

The described algorithm for finding water temperature in the tank is shown in figure 2.

![Diagram of the simulation procedure](image)

Figure 2. Diagram of the simulation procedure.

Examples of test results are shown in figure 3.

![Time course of temperature](image)

Figure 3. Time course of temperature in the heating system and the ambient temperature (a) as well as the boiler operation status and the boiler water temperature (b).

The analysis of the boiler operation shows (Figure 3b) that the total operation time in 6 cycles is 430 minutes, and the time of individual cycles ranged from 13 to 203 minutes. The maximum water temperature from the boiler supplied to the buffer tank was 90 °C, and the return temperature was 84°C. During the analyzed day of system operation, the range of ambient temperature changes (Figure 3a) was between 3.4 °C and 12.5°C, and the maximum temperature of the heating water (with the assumed temperature inside the greenhouse in the daily cycle at the level of 14/21°C, respectively night/day) was 51oC (system supply) and 45°C (heating water return), respectively.
Figure 4 shows the course of the measured and calculated water temperature in the buffer tank.

The average water temperature was around 86.2°C. The relatively low value of the mean square error equal to 0.14K proves the correctness of the water temperature simulation process. Such a high value of the indicator results from the adopted simulation period equal to 1 hour. This means that in the adopted procedure, a maximum of 60 simulations were performed (with the adopted step equal to 1 minute), and after 1 hour it was assumed that the temperature of the water in the tank in the next 1-hour simulation period was the measured temperature.

4. Conclusion

The proposed model defining the change of water temperature in the tank, with the adopted assumptions, correctly describes the analyzed parameter value. However, the assumptions made (constant temperature of the environment and inside the greenhouse) impose the necessity to expand research. After these modifications, the proposed model can be used to find the optimal capacity of the hot water storage tank. It is assumed to adopt two criteria: minimization of heat loss from the tank to the environment and minimization of the difference between the water temperature in the tank and the required operating temperature of the heating system. The model including these postulates and the simulation experiments will allow to minimizing the operating costs of the greenhouse heating system.

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