MIDDLE POMERANIAN SCIENTIFIC SOCIETY OF THE ENVIRONMENT PROTECTION
ŚRODKOWO-POMORSKIE TOWARZYSTWO NAUKOWE OCHRONY ŚRODOWISKA
Annual Set The Environment Protection
Rocznik Ochrona Środowiska
Volume/Tom 18. Year/Rok 2016 ISSN 1506-218X 758-769

Experimental and Theoretical Studies of Heat Losses from the Hot Water Storage Tank

Kinga Dopieralska, Alicja Siuta-Olcha,
Tomasz Cholewa, Monika Studzińska
Politechnika Lubelska

1. Introduction

Thermal energy storage tanks form a crucial element in solar usable hot water systems, which can considerably improve their efficiency and profitability by enabling a more efficient use of solar collectors, and by adjusting solar energy resources to the actual demand. Thermal stratification is a significant aspect of the heat efficiency of both the tank itself and the entire system. It refers to the occurrence of a vertical temperature gradient in the tank, which makes it possible to divide water by temperature level, whereby hot water is placed in the upper section and cold water in the lower part of the heat storage facility (Pluta 2000). The entire system efficiency grows with an increased degree of thermal stratification. In contrast to full-mixing tanks, this solution enables the delivery of the higher-temperature water to recipients, whereas the lowest-temperature water returns to the collectors, increasing their efficiency.

Heat losses from the tank to the surroundings have the strongest impact on establishing and maintaining thermal stratification. The underlying causes of heat energy losses from tanks include the insufficient thickness of the thermal insulation, and its ruptures and damage, as well as the high conductivity of the material used to build storage tank walls (Furbo 2005). Extensive heat losses are likely to result in the diminished stratification and levelled-off temperature of the stored water.

2. Heat loss determination methods

The amount of heat losses from storage tanks is often used in projecting the heat efficiency of solar systems. The simulation method involves developing a mathematical model which is intended to accurately reflect the physical and thermal conditions found inside the tank. One can distinguish complex multi-dimensional models which enable the demonstration of the tank functioning, along with simpler one-dimensional models that are more common, given their shorter calculation time (Oliveski et al. 2003). In many cases, due to the lack of detailed information, a number of simplifying assumptions are usually made in the model, which can lead to erroneous heat loss calculations. Experimental methods, in contrast, deliver more accurate results, as heat loss values are determined on the basis of measurements obtained through the conducted studies.

3. Testing methodology

Tests were conducted on a usable hot water storage tank located in the laboratory of the Faculty of Environmental Engineering at the Lublin University of Technology. The tank in question forms one of the elements of a solar usable hot water system, and is indirectly connected to a solar collector supplying water to the system. The solar system schema is shown in Figure 1.

The tank is a pressure vessel with a total volume of 350 dm^3 and a fineness ratio of about 3.4. It was planned and constructed according to an individual design, for the purpose of accommodating immersion temperature sensors. The upper part of the tank features a heat exchanger which is a steel spiral heating coil with a diameter of 26.9 x 2.3 mm and a length of 18 m. The internal surface of the tank was coated with epoxy paint suitable for contact with potable water. Type-S235JRG2 4-mm-thick steel sheet was used to construct the tank body, whereas end caps were made of 8-mm-thick steel sheet. The lateral tank surface was thermally insulated with a 10-cm-thick mineral wool layer, and surrounded with an external coating made of 1-mm-thick galvanised steel sheet, covered with polyurethane paint. The upper end cap was insulated with 32-mm-thick lagging, while the lower end cap was left non-insulated.

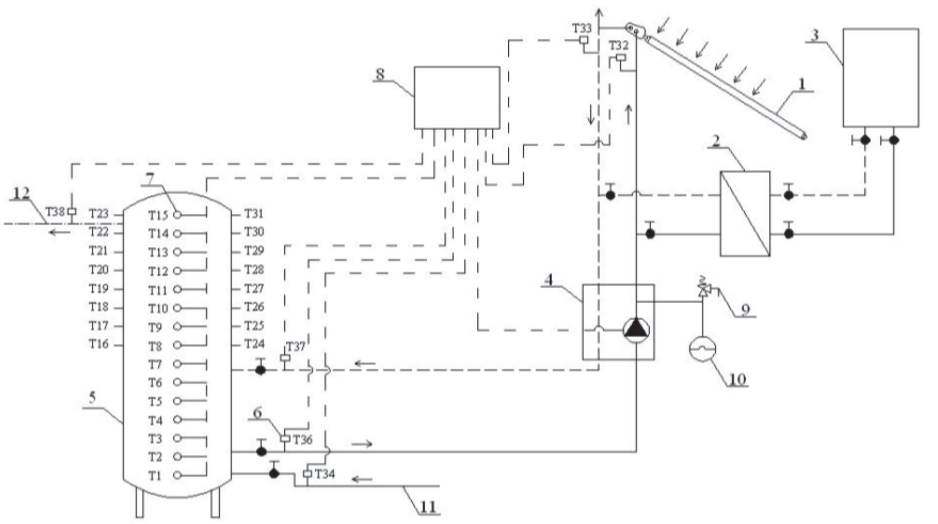

Fig. 1. Schema of solar domestic hot water system, 1 – solar collector, 2 – heat exchanger 3 – ultrathermostat, 4 – pump set, 5 – hot water storage tank, 6 – medium temperature sensor in pipes, 7 – temperature sensor in the tank, 8 – master control, 9 – safety valve, 10 – expansion tank, 11 – cold water inlet, 12 – the flow of hot water

Rys. 1. Schemat badawczej słonecznej instalacji ciepłej wody. 1 – kolektor słoneczny, 2 – wymiennik ciepła 3 – ultratermostat, 4 – zestaw pompowy, 5 – zbiornik magazynujący ciepłą wodę, 6 – czujnik temperatury czynnika w przewodach, 7 – czujnik temperatury wody w zbiorniku, 8 – sterownik, 9 – zawór bezpieczeństwa, 10 – naczynie wzbiorcze, 11 – doprowadzenie wody zimnej, 12 – pobór ciepłej wody

Thirty-one type-Pt500 class-A temperature sensors manufactured by the Alf Sensor company were placed inside the tank, serving the purpose of measuring water temperature. The thermometer was tightly fixed to the measuring plug using a pressure tap. The temperature sensors were divided into three columns at a distance of 120° between them, measured on a horizontal plain. In the first column, holes for 15 sensors were made at the entire container height, at intervals of 10 cm (T1-T15 starting with the bottom of the tank), with a 50-mm-long cover and a diameter of 6 mm.

In other cases, sensors were placed only in the upper section of the container, above the internal heat exchanger level. The second and third column featured 8 sensors (in each case) situated at intervals of

10 cm. In the case of the second column, these were T16-T23 sensors, placed towards the upper tank cover, with a 150-mm-long cover and a diameter of 6 mm. The last column included T24-T31 sensors, placed towards the upper tank cover, with a 250-mm-long cover and a diameter of 6 mm. Another 6 sensors manufactured by the same company, and of the same type, were used to measure the water temperature inside the pipelines. They were placed in the solar pipelines at the inlet to and outlet from the solar collector (T32 and T33), in front of and behind the heating coil (T37 and T36), and at the cold water pipeline (T34), as well as at the hot water pipeline (T38). Together with the sensors listed above, a type-AF11.PT500.Cu. ambient temperature sensor was also used to measure the air temperature around the tank.

Measuring data recorded by the sensors were sent to the computer, which made their monitoring, archiving and visualisation possible. All temperature measurements, conducted round the clock, were recorded every 5 minutes.

The values of the ambient temperature and the temperature of the water stored in the tank, obtained through sensors T1 to T15, were used to determine both heat losses from the accumulation tank and the UA heat loss coefficient. In this way the tank was divided into 15 sections, with sensor numbers corresponding to section numbers. Temperature values were averaged on an hourly basis.

Only the temperature measures during the night, i.e. between 7.00 pm and 6.00 am, were taken into consideration. For this reason, both the heat flux from the solar collector and the heat flux collected by the user were excluded from the tank-specific heat balance, as neither of them occurred during the night-time hours $\rho_{w,i}$ – water density in the section i, [kg/m^3].

4. Results and discussion

Three nights were selected for analytical purposes, i.e. the night of 18-19 June 2011, the night of 10-11 July 2011, and the night of 7-8 August 2011. Based on the measuring data, the dynamics of the stored water temperature changes occurring between 7.00 pm and 6.00 am could be determined.

During the night of 18-19 June, the average water temperature in the lowest tank section dropped at night from 31.29°C to 30.38°C, while in the topmost section it fell from 40.78°C to 35.71°C, which is shown in Figure 2.

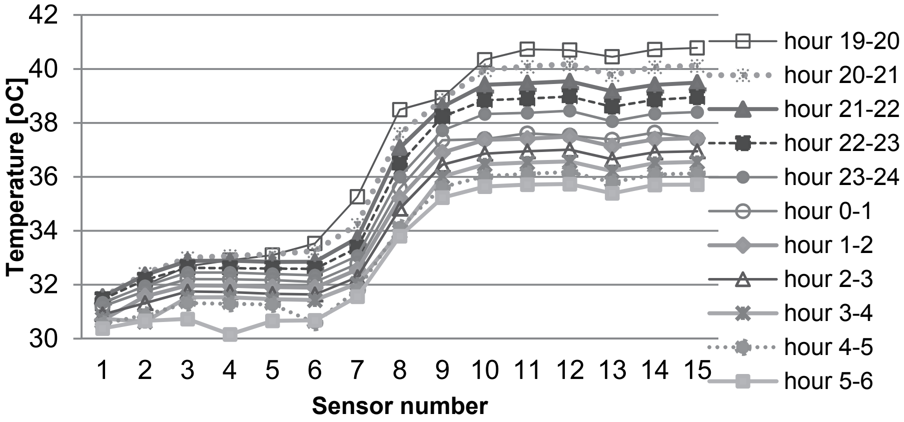

Fig. 2. The development of stored water temperature values during the night of 18-19 June 2011
Rys. 2. Rozkład temperatury wody w zbiorniku w nocy z 18 na 19 czerwca 2011 roku

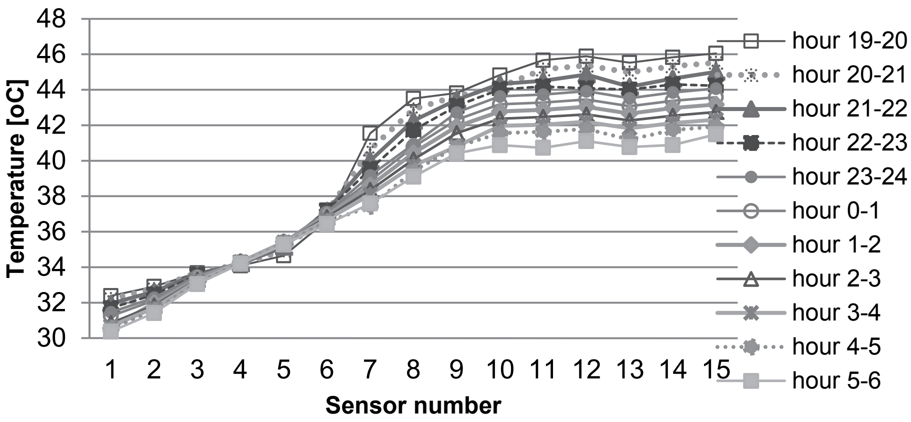

Fig. 3. The development of stored water temperature values during the night of 10-11 July 2011
Rys. 3. Rozkład temperatury wody w zbiorniku w nocy z 10 na 11 lipca 2011 roku

During the night of 10-11 July, the average water temperature in the lower tank section dropped from 32.39°C to 30.37°C, while in the upper section it fell from 46.05°C to 41.49°C (Fig. 3).

As regards the night of 7-8 August, the average water temperature in the lowest section reached 33.08°C at the start of the analysed period, eventually falling to 32.08°C, whereas in the topmost section it fell from 45.89°C to 41.43°C. The above mentioned relations are displayed in Figure 4.

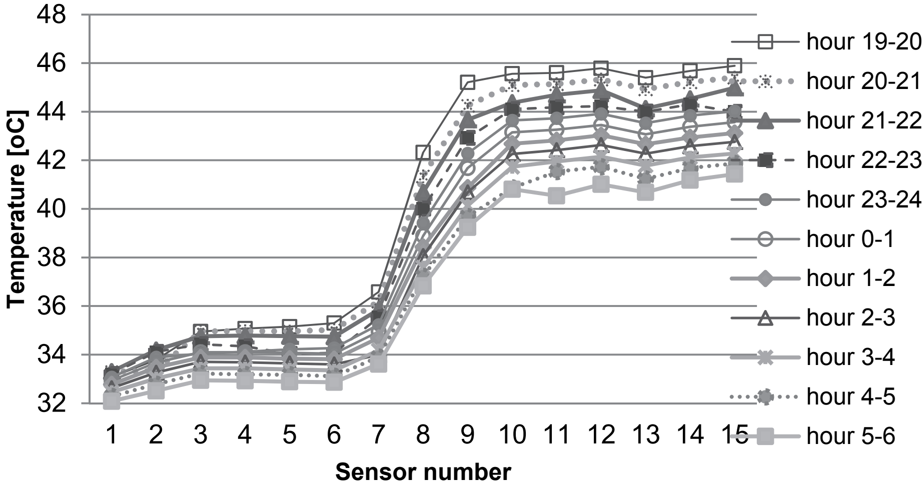

Fig. 4. The development of stored water temperature values during the night of 7-8 August 2011
Rys. 4. Rozkład temperatury wody w zbiorniku w nocy z 7 na 8 sierpnia 2011 roku

Based on the above data, it can be inferred that the cooling rate was the fastest in the upper tank section, in which the water temperature dropped during the night by an average of 5°C, whereas in the lower section the temperature drop ranged between 1-2°C.

Having compared the three nights under analysis, it was noted that the highest heat loss values pertained to the uppermost and lowermost tank sections, and in the case of the June and the August nights also to the central sections: 6 and 7, respectively. Such considerable heat losses through the outermost tank sections could have resulted from the fact that they also comprise the upper and lower end caps, which make the heat exchange area in these sections much bigger than in the remaining ones. The lack of insulation in the lower end cap, and the insufficiently thick insulation layer of the upper end cap, are also not to be disregarded. Thermal heat bridges formed by screws going through the upper end cap, as well as pipelines feeding cold water to the tank and supplying hot water to users, also contribute significantly to the actual heat loss. As regards the central sections, heat loss can stem from the heating coil placement.

Figure 5 presents the aggregated values of heat losses through the tank for individual hours. Based on these data, it can be inferred that neither the heat losses nor the UA coefficient values are constant. The tank loses its heat in an uneven manner. The highest heat loss through the tank occurred in June, and the lowest in July. This leads to the conclusion that the falling water temperature levels also make the loss values drop, though in an uneven manner.

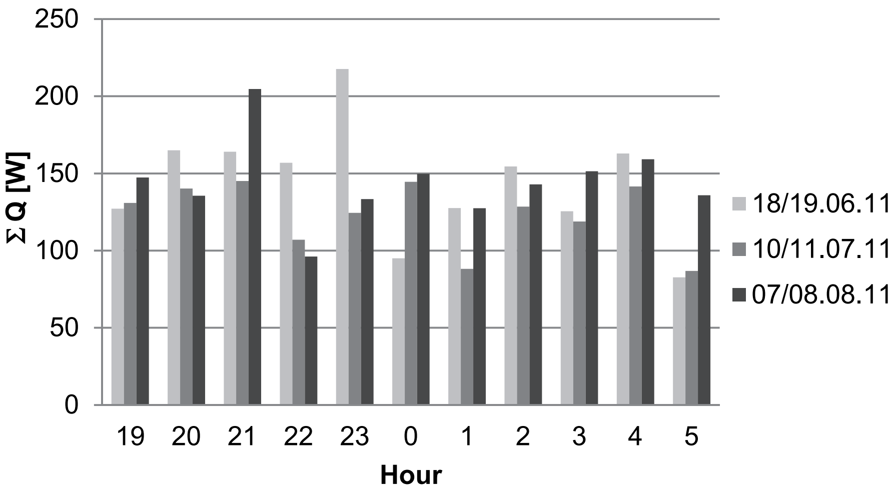

Fig. 5. Total heat losses values for a given hour, for the hot water tank
Rys. 5. Całkowite wartości strat ciepła dla danej godziny dla zasobnika ciepłej wody

With a view to comparing the values of the calculated heat loss coefficient, reference can be made to the studies by Fan and Furbo. In order to analyse the influence of heat losses by means of an experimental method, they made use of a fine 150-litre tank with a diameter of 0.34 m and a height of 1.68 m. The tank was made of stainless steel and insulated with a 5-cm-thick mineral wool layer. The temperature development in the tank was measured using 14 copper/constantan thermocouples (type TT) equally placed from the bottom to the top of the tank. During the measurements, the tank was heated by an electric heating element to a uniform constant temperature. The electric heating element was placed at the very bottom of the tank. The authors determined the heat loss coefficient for three tank sections; for the lower section it amounted to 0.48 W/K, for the upper section to 0.19 W/K and for the lateral surface to 1.83 W/K. The overall heat loss coefficient for the tank was also calculated, amounting to 2.51 W/K (Fan & Furbo 2012).

One can also refer to the studies by Fernández-Seary et al., in which the UA coefficient value for the tank was given as 2.1 W/K. It is a vertical cylindrical tank with a storage capacity of 150 dm^3. The storage tank consists of a vertical cylindrical body and caps of the Klopper type made of 2 mm thick stainless steel sheets. The height and diameter are 870 mm and 480 mm, respectively. The tank is insulated with polyurethane foam (type S Spray). The thickness on the cylindrical surface is of 32 mm and on the upper cap varies according to the cap geometry. The lower cap is only partially insulated because the electric heater is placed vertically at the centre of this cap. The space without insulation corresponds to a circle with 32 cm diameter. The insulation on the lateral, on the top and on the bottom surfaces is covered with plain carbon steel sheets. The thickness of the steel sheets is 1 mm and they are lacquered white externally. The commercial tank is equipped with an electric heater of 2.2 kW. The water temperature distribution inside the tank is measured by using 11 temperature sensors distributed uniformly along the height of the tank (Fernández-Seary et al. 2007).

Figure 6 presents a comparison of the average UA coefficient values with the corresponding values quoted by Fan and Furbo. It can be noted that for the lower and upper tank sections the UA values obtained through our measurements are several times higher than the coefficients presented by the said researchers. This results from the fact that both the lower and upper surface of the tank analysed by Fan and Furbo were insulated with a 50-mm-thick mineral wool layer, whereas the lower end cap of the tank referred to in this study was left non-insulated, and the insulation layer of the upper end cap was 18 mm thinner. Furthermore, the tank analysed by Fan and Furbo had no thermal heat bridges, unlike the other tank being compared, where such bridges were formed by screws going through the upper end cap and significantly increasing heat losses through the tank. As regards the lateral surface, the average UA coefficient values were smaller than the values given by Fan and Furbo, which might have stemmed from the fact that the lateral surface insulation of the tank analysed by the researchers was weaker. Specifically, the insulation layer was 50% thinner and was not covered by an external coating, in contrast to the other storage tank under comparison.

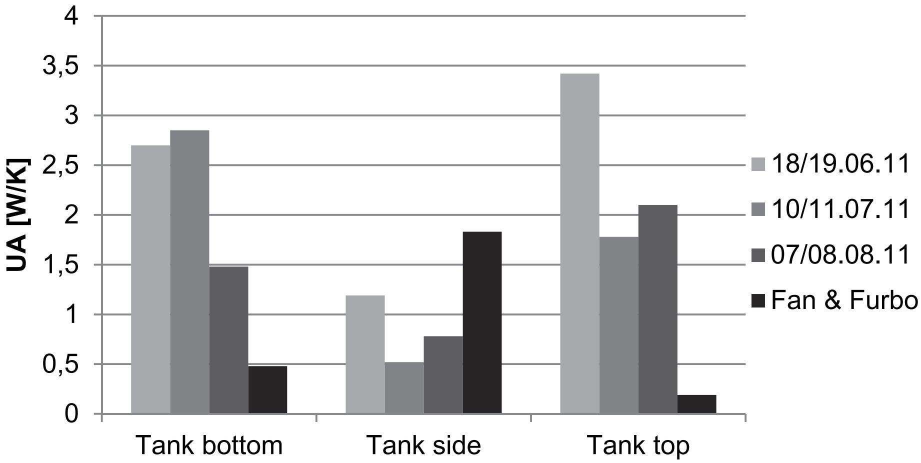

Fig. 6. A comparison of the UA heat loss coefficient values for various tank sections
Rys. 6. Porównanie wartości współczynnika strat ciepła UA dla różnych części zbiornika

Figure 7 shows a comparison of the total UA coefficient values for the tank analysed by Fan and Furbo, as well as by Fernández-Seara et al., with the highest average values of the UA coefficient of the model in question. It reveals that the average heat loss coefficients for the entire tank under analysis were lower than the values quoted both by Fan and Furbo, and by Fernández-Seary et al. This difference can be explained by the fact that these authors made use of smaller tanks, with a volume of 150 dm^3, in the case of which the cooling speed was higher than for the 350 dm^3 tank discussed in this study. Furthermore, the thinner insulation layers used in the smaller tanks also justify such observations.

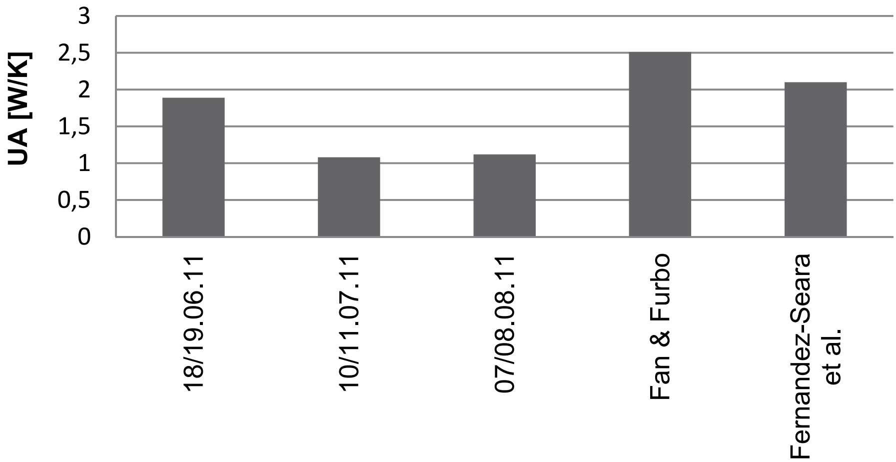

Fig. 7. A comparison of the overall heat loss coefficient values for the tank
Rys. 7. Porównanie wartości ogólnego współczynnika strat ciepła dla zbiornika

5. Conclusions

The study focused on the night-time functioning of the tank, considering the lack of water movement and heat energy supplies during the night hours, which allowed gradual and uninterrupted tank cooling, heat losses and the establishing of thermal stratification. Most of the heat was lost through the upper and lower tank sections, mainly due to thermal heat bridges and insufficient insulation. The heat losses in the central section of the tank might have been caused by the factor flowing through the heat exchanger with a temperature lower than that of the water stored in the tank, being heated up at the cost of the heat energy gathered in the tank. The tank lost its heat in an uneven manner, with the fastest cooling rate observed in the upper section. During the night, water temperature in this section dropped by an average of 5°C, whereas in the lower tank section the temperature drop fell within the range of 1-2°C. The UA coefficient values, calculated as part of the study, amounted to 3.42 W/K, 1.78 W/K and 2.10 W/K for the upper section, and to 2.70 W/K, 2.85 W/K and 1.48 W/K for the lower one. Lower differences between the coefficient values were found for the lateral tank section, which might prove its good insulation. The UA coefficient for the reference section amounted to 1.19 W/K, 0.52 W/K and 0.78 W/K. However, the UA coefficient for the entire tank was lower than the values given by other researchers which might have stemmed from the fact that tanks of various capacities were compared, displaying different cooling rates. The highest average UA coefficient value for the entire tank reached 1.89 W/K, 1.08 W/K and 1.12 W/K. Based on the analysis conducted, it can be inferred that in all cases heat losses increased along with the increasing water temperature levels.

The research was funded by the project No. S-130/M/WIŚ/2014

References

Fan, J., & Furbo, S. (2012). Buoyancy driven flow in a hot water tank due to standby heat loss. *Solar Energy, 86,* 3438-3449.

Fernández-Seara, J., Uhía, F. J., Sieres, J. (2007). Experimental analysis of a domestic electric hot water storage tank. Part I: Static mode of operation. *Applied Thermal Engineering, 27,* 129-136.

Fernández-Seara, J., Uhía, F. J., Sieres, J. (2007). Experimental analysis of a domestic electric hot water storage tank. Part II: dynamic mode of operation. *Applied Thermal Engineering, 27*, 137-144.

Furbo, S. (2005). *Heat Storage for Solar Heating Systems. Educational Note*. Department of Civil Engineering. Technical University of Denmark.

Oliveski, R. D. C., Krenzinger, A., Vielmo, H. A. (2003). Cooling of cylindrical vertical tanks submitted to natural internal convection. *International Journal of Heat and Mass Transfer, 46,* 2015-2026.

Pluta, Z. (2000). *Podstawy teoretyczne fototermicznej konwersji energii słonecznej*. Warszawa: Oficyna Wydawnicza Politechniki Warszawskiej (in Polish).

Badania eksperymentalne i teoretyczne strat ciepła zasobnika ciepłej wody

Streszczenie

Efektywność magazynowania ciepła ma wpływ na efektywność energetyczną instalacji ciepłej wody. Do jej zwiększenia przyczynia się utrzymanie rozwarstwienia termicznego w zasobniku ciepłej wody. Zaburzenie stratyfikacji termicznej może być spowodowane między innymi stratami ciepła ze zbiornika do otoczenia.

W pracy przedstawiono dynamikę zmian temperatury wody w zasobniku o pojemności 350 dm^3, podczas jego wychładzania w godzinach nocnych, na podstawie przeprowadzonych pomiarów temperatury wody magazynowanej na 15 wyróżnionych poziomach.

Dla zasobnika obliczono współczynniki strat ciepła dla części górnej, bocznej oraz dolnej, jak również dla całego zasobnika. Uzyskane wyniki odniesiono do wyników badań innych autorów.

Słowa kluczowe:
współczynnik strat ciepła, zbiornik ciepłej wody, stratyfikacja termiczna

Keywords:
heat loss coefficient, hot water tank, thermal stratification