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Improving Energy Efficiency of Hot Water Storage Tank by Use of Obstacles

Tomasz Cholewa
Lublin University of Technology

1. Introduction

In the present world the deficit of nonrenewable raw materials, particularly energy carriers may be noticed [16], what is caused, among others, by the crisis-generating development of modern civilization [12, 17, 18]. On the other hand the development of new energy sources creates new technical, economic and ecological challenges [2, 5, 7–10, 20]. The residential sector constitutes one of the most important sectors of the economy, which uses about 40% of produced energy. Therefore, the rationalization of energy consumption and the efficient use of renewable energy sources, exactly in this sector, create significant technical problems [4, 26].

As far as the popularity and the continuous growth of number of small solar installations for hot water preparation are concerned, there have been many studies conducted on the optimization of conversion and later storage of energy obtained from solar radiation [21–24] as well as the environmental effects of solar system usage in a detached house [27].

According to [6, 13, 25], the installation equipped with the thermal stratification tank is 5–20% more efficient than a fully mixed water storage tank system, that is the system with uniform stored water temperature in the whole volume of the tank.

The application of suitable cold water inlet [3, 14] and the horizontal obstacle situated inside the tank [1, 11, 19] have the large influence on thermal stratification in water storage tank.

However, there is still a lack of experimental and numerical research presenting the influence of the use of obstacles on thermal stratification in the most often used water storage tank with the spiral-tube heating coil.

Thus, in the present article the experimental research was done. Its aim was to show the influence of the usage of different obstacle constructions in water storage tank on energy efficiency of process of hot water preparation.

2. Materials and methods

The experimental research was made on the laboratory stand located in Faculty of Environmental Engineering at Lublin University of Technology. A cylindrical steel water storage tank (Figure 1) was the main element of the laboratory stand. The volume of the tank is equal to 350 dm^3 and the height to diameter ratio (1.7/0.5 m) is equal to 3.4. In order to reduce the heat losses to the laboratory room (indoor air temperature equal to 20°C), the tank was insulated with mineral wool (10 cm thick). Inside the tank, in its lower section, there is a steel 26.9×2.3 mm spiral-tube heating coil with the length of 18 m.

Fig. 1. Water storage tank in the laboratory
Rys. 1. Widok zbiornika magazynującego w laboratorium

For continuous measurement of water temperature in the tank, 15 class-A resistance sensors Pt500 (5 cm length) were installed every 10 cm (from top to bottom of the tank), what is presented in Figure 2.

Inside the water storage tank (43 cm above the top of the tank – see Figure 2) different kinds of obstacles were placed (Figure 3), which are made of steel (0.7 cm thick).

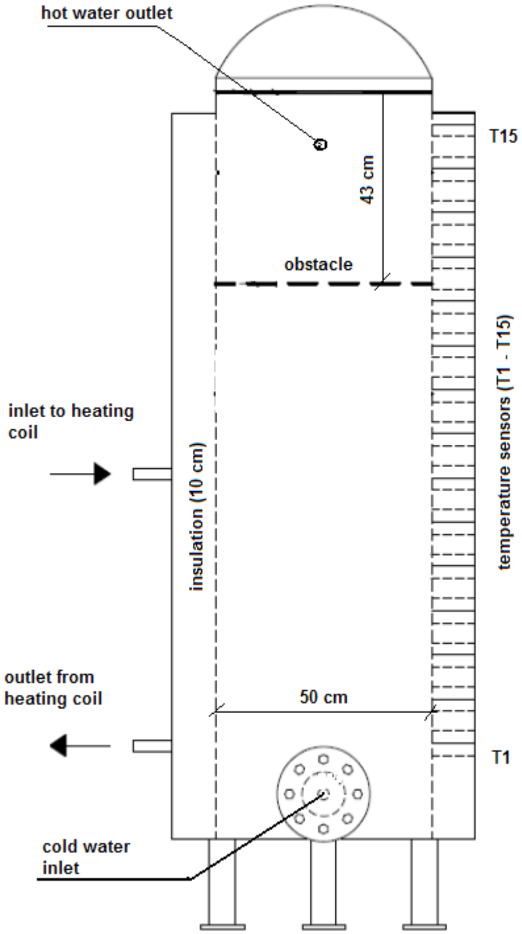

Fig. 2. Schema of analyzed water storage tank
Rys. 2. Schemat analizowanego zbiornika magazynującego

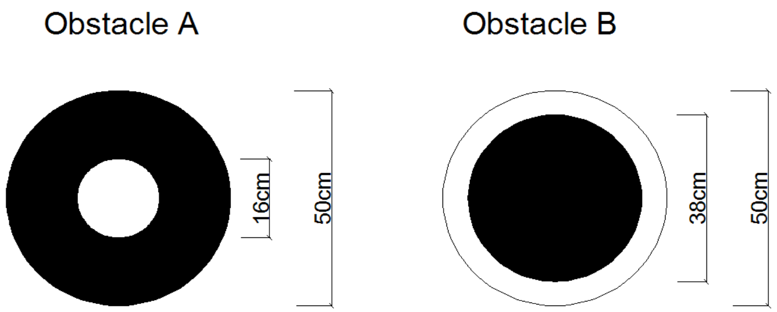

Fig. 3. Schema of two analyzed obstacles inside the tank
Rys. 3. Schemat dwóch analizowanych przegród poziomych umieszczanych wewnątrz zbiornika

In case of *obstacle A* the flow of heated water into upper parties of storage tank takes place through its centre and not at the sides of the tank.

However, when it comes to the *obstacle B* the flow of heated water takes place at sides of the storage tank and not through its centre.

The heat source for the analysed system was ultrathermostat, which allow to maintain constant temperature on supply during each experiment.

The flow of working medium was forced with the use of pump with regulated performance. But the volume flow rate in the circulation was constant and equal to about $5.56 \cdot 10^{-5}$ m^3/s.

The system works with a special computer program for monitoring, archiving and data visualization. All parameters are being recorded every 5 minutes.

Research methodology consisted in supplying the spiral heating coil located inside the water storage tank with heating factor at constant temperature equal to 55°C during 6 hours.

The power of the water storage tank with the heating was turned on at about 8.30 am and turned off at about 2.30 pm. Directly before switching the power of the water storage tank with heating factor on, the water temperature in the tank was constant and equaled to 11°C during all experiments.

To evaluate the influence of the use of obstacles inside the storage tank on energy efficiency of hot water preparation system, four measuring series for each of two analysed obstacles and for the tank without obstacle were done. Moreover, the hot water consumption profile was changed in all measuring series.

Analysed profiles of hot water consumption are the following:

- profile 1 – water was not being taken;
- profile 2 – water was being taken four times a day (9 am, 12 am, 3 pm, 7 pm) 50 dm^3 each time;
- profile 3 – water was being taken seven times a day (9 am, 10 am, 11 am, 12 am, 1 pm, 2 pm, 7 pm) 50 dm^3 each time;
- profile 4 – water was being taken three times a day (12 am – 100 dm^3, 2 pm – 50 dm^3, 7 pm – 80 dm^3).

Together with hot water draw-offs, the inlet of cold water into the lower layers of storage tank took place. The temperature of cold water during each experiments ranged from 10.5 to 11.0°C.

For below analyses was calculated among other things the stratification number (*Str*), which allows for the assessment of thermal stratification inside the accumulation water tank.

The stratification number (*Str*) is defined as the ratio of the mean of the temperature gradients at each time interval to that of the beginning (t = 0) and may be calculated with the use of Equations 1 and Equations 2 [15].

$$Str = \frac{\left(\overline{\frac{\partial T}{\partial z}}\right)_t}{\left(\overline{\frac{\partial T}{\partial z}}\right)_{t=0}} \tag{1}$$

$$\overline{\frac{\partial T}{\partial z}} = \frac{1}{J-1} \cdot \left[\sum_{j=1}^{J-1} \left(\frac{T_{j+1} - T_j}{\Delta z} \right) \right] \tag{2}$$

where:

j – water layer,
J – number of water layers, J = 15,
t – time (s),
T – water temperature in the tank (˚C),
z – height of the storage tank (m),
Δz – distance between temperature sensors (m), Δz = 0.10 m.

In order to compare the energy efficiency of analyzed obstacles, the amount of energy needed (E_{HW}) to heating up the amount of consumed hot water to the temperature equal to 55°C was calculated by use of Equation 3.

$$E_{HW} = \left(V \cdot \rho \cdot c_p\right) \cdot \left(T_{HW} - T_{stored}\right) \text{ (MJ)} \tag{3}$$

where:

c_p – water specific heat ($Jkg^{-1}K^{-1}$),
T_{HW} – hot water temperature (˚C), T_{HW} =55°C,
T_{stored} – mean temperature of water draw from the tank during each draw offs, (˚C),
V – volume of consumed hot water (m^3),
ρ – water density (kgm^{-3}).

3. Results and discussion

During the heating of water stored in the tank (Fig. 4), without draw-offs (profile 1), it may be noticed, that the use of the *obstacle A* causes the considerable increase of stratification number in the water storage tank. The *Str* is even two times greater on end of water heating process inside the tank than for the tank without the obstacle.

The use of *obstacle B* increases the stratification number only during the final phase of the water heating process inside the tank, what may be caused by free flow of the warm water at sides of the tank into its upper parties.

In Figures 5–7 temperatures of stored water draw from the storage tank during every draw-offs of hot water are presented.

Taking into consideration the values of temperature of water draw from the tank, which are presented in Figures 5–7, it may be noticed that the use of obstacles inside the storage tank contributes to the increase of the temperatures of stored water, which is taken from the tank in comparison to the tank without the obstacle. It is caused by the decrease of influence of incoming cold water to the storage tank on the temperature of stored water in upper parties of the tank.

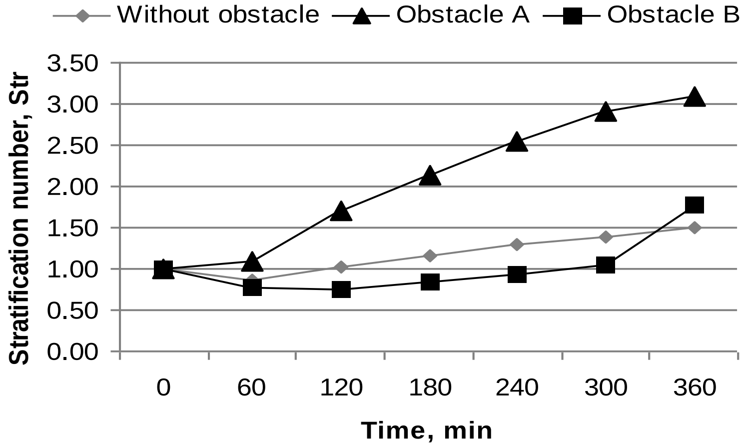

Fig. 4. Thermal stratification in the storage tank during profile 1 of draw-offs
Rys. 4. Stratyfikacja termiczna wewnątrz zbiornika magazynującego podczas rozbiorów ciepłej wody dla profile 1

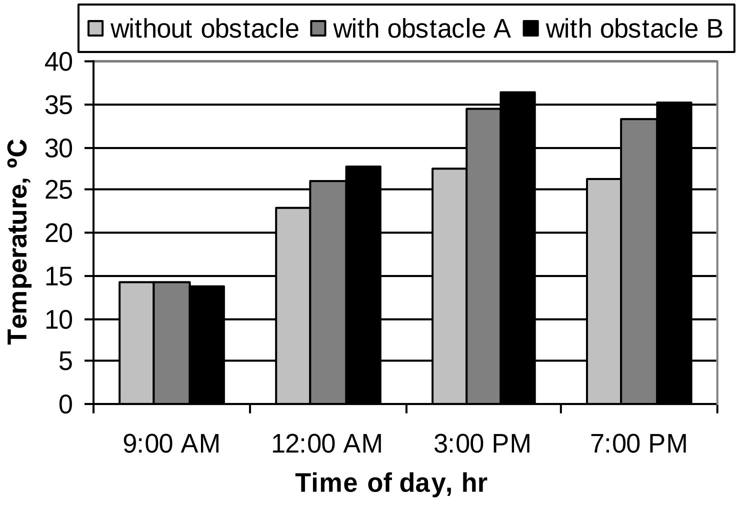

Fig. 5. Temperature of water draw from the tank during each draw-off in profile 2
Rys. 5. Temperatura wody pobieranej ze zbiornika podczas poszczególnych rozbiorów wody w profilu 2

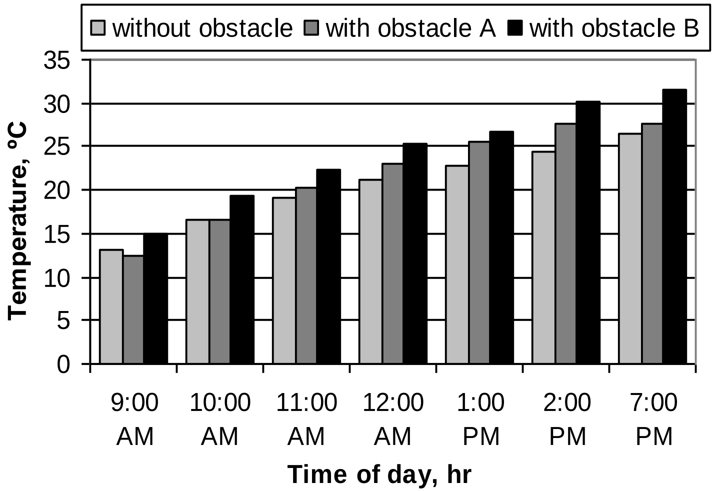

Fig. 6. Temperature of water draw from the tank during each draw-off in profile 3
Rys. 6. Temperatura wody pobieranej ze zbiornika podczas poszczególnych rozbiorów wody w profilu 3

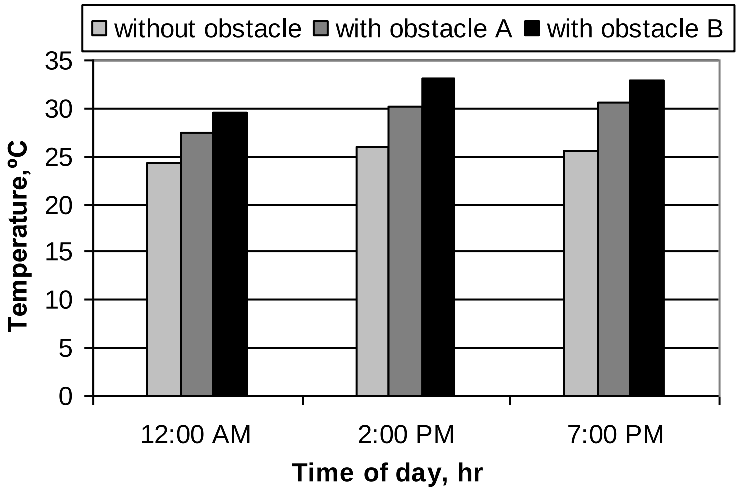

Fig. 7. Temperature of water draw from the tank during each draw-off in profile 4
Rys. 7. Temperatura wody pobieranej ze zbiornika podczas poszczególnych rozbiorów wody w profilu 4

The highest temperatures of drawn water were reached for the *obstacle B* and they were getting greater, in comparison to the storage tank without the obstacle, when the amount of the single draw-off of stored water was getting higher.

Differences in temperature of stored water create differences in the amount of energy, which is necessary to heat up the stored water to the temperature required by the user (55°C), what can be seen in Figure 8 for the profile 4.

On the basis of Figure 8 it may be stated that the use of obstacles allow to decrease the energy consumption for heating up stored water to the temperature required by the user (55°C), even of about 14% and 20% in comparison to the tank without the obstacle, respectively with the use of *obstacle A* and *obstacle B.*

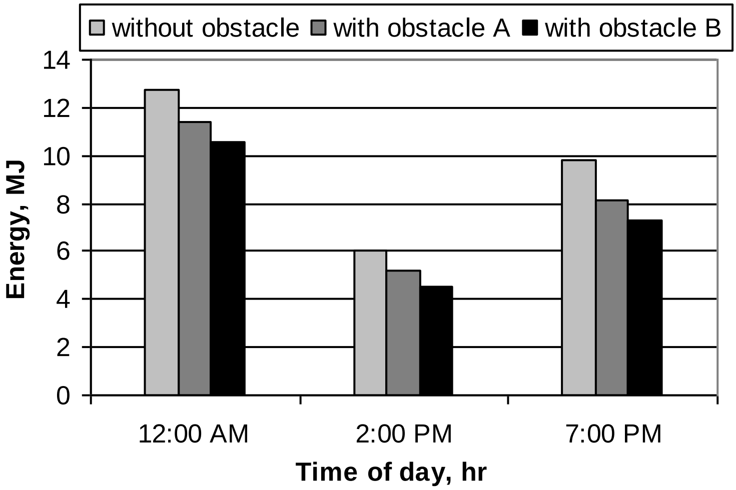

Fig. 8. Amount of energy used for heating up the drawn water from the tank to 55°C during each draw-off in profile 4

Rys. 8. Ilość energii potrzebnej do podgrzania pobieranej ze zbiornika wody do temperatury 55°C podczas każdego rozbioru w profilu 4

4. Conclusions

Experimental research done on the laboratory stand allowed for the estimation of the influence of horizontal obstacles inside water storage tank on thermal stratification inside the tank and the energy efficiency of process of hot water preparation.

It was noticed that the use of obstacles inside the tank facilitated the increase of temperature of water drawn from the storage tank even of about 9°C, in comparison to the variant without the obstacle. The use of obstacle (*obstacle B*), which makes impossible the flow of the water through centre of the tank to its upper parties, seems to be the most profitable in respect of energy efficiency because the water flow is at sides of the tank. It contributes to the reduction of energy needed for heating up of stored water to the temperature required by the user of the system, even of about 20% in comparison to the variant without the obstacle.

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Wpływ umieszczenia przegród poziomych wewnątrz zbiornika magazynującego na zwiększenie jego efektywności energetycznej

Streszczenie

Sektor gospodarki komunalnej zużywa znaczne ilości energii na cele ogrzewania i przygotowania ciepłej wody użytkowej. Dlatego też ważnym zagadnieniem staje się między innymi właśnie zwiększenie sprawności systemów przygotowania ciepłej wody użytkowej.

Dlatego też w tym artykule zaprezentowano wyniki badań eksperymentalnych procesu przygotowania ciepłej wody użytkowej w wodnym zbiorniku magazynującym.

Głównym celem badań była ocena wpływu umieszczenia dwóch różnych przegród poziomych wewnątrz zbiornika na zjawisko stratyfikacji termicznej oraz sprawność energetyczną układu przygotowania ciepłej wody użytkowej.

Badania były prowadzone w skali półtechnicznej na stanowisku badawczym, które jest zlokalizowane w jednym z laboratoriów Wydziału Inżynierii Środowiska Politechniki Lubelskiej.

Głównym elementem stanowiska badawczego był wodny, zaizolowany termicznie zbiornik magazynujący o pojemności 350 dm^3, w którym przygotowywana była ciepła woda użytkowa. W dolnej części zbiornika umieszczona

jest stalowa wężownica grzewcza (26,9×2,3 mm) o długości 18 m za pomocą której następował podgrzew magazynowanej wody. Wężownicę grzewczą wewnątrz zbiornika zasilano czynnikiem grzewczym o stałej temperaturze równej 55°C przez 6 godzin podczas każdej z serii pomiarowych.

Na wysokości 43 cm (poniżej góry zbiornika) umieszczano w zbiorniku przegrody poziome wykonane ze stali o grubości 0,7 cm.

Badane dwie przegrody różniły się między sobą sposobem ukierunkowania przepływu magazynowanej wody wewnątrz zbiornika.

Przy zastosowaniu jednej z badanych przegród (przegroda A) przepływ magazynowanej wody wewnątrz zbiornika odbywał się jego środkiem. Natomiast przy zastosowaniu drugiej przegrody (przegroda B) przepływ był możliwy przy ściankach zbiornika.

W celu oceny wpływu zastosowania przegród wewnątrz zbiornika na efektywność energetyczną systemu przygotowania ciepłej wody użytkowej wykonano po 3 serii pomiarowe dla każdej z analizowanych dwóch przegród oraz dla zbiornika bez przegrody, w których zmieniano profil rozbioru ciepłej wody użytkowej.

Stwierdzono, że zastosowanie przegrody poziomej wewnątrz zbiornika magazynującego prowadzi do zwiększenia temperatury magazynowanej wody, która jest pobierana ze zbiornika w porównaniu do zbiornika bez przegrody. Jest to spowodowane zmniejszeniem oddziaływania napływającej wody zimnej do zbiornika na temperaturę magazynowanej wody w górnych partiach zbiornika. Najwyższe temperatury pobieranej wody osiągnięto dla przegrody z przepływem przy ściankach zbiornika (przegroda B) i były one tym większe w porównaniu do zbiornika bez przegrody im większy był jednorazowy pobór magazynowanej wody.

Dlatego też zastosowanie przegród wewnątrz zbiornika pozwala zmniejszyć zużycie energii do podgrzania magazynowanej wody do temperatury wymaganej przez użytkownika (55°C), nawet o 14% i 20% w porównaniu do zbiornik bez przegrody, odpowiednio przy zastosowaniu przegrody A oraz przegrody B.