The impact of inflow velocity on thermal stratification in a water storage tank

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Abstract. The paper presents the analysis of thermal processes occurring in thermal energy storage tanks used for heating hot water systems. Three-dimensional Computational Fluid Dynamics (CFD) methods were used. The standard buffer charging stage was modelled for three tank inlets’ diameters DN20, DN40 and DN80. With a constant charging water flow and temperature the port diameter affects inlet velocity, heat storage dynamics, thermal stratification and thermocline thickness in storage tank. The smallest diameter causes unfavourable thermal mixing of accumulated water, and the largest diameter supports thermal stratification

1 Introduction

Thermal energy storage (TES) in heating hot water systems allows the stabilization between the variable heat demand and heat production. TES tank in water heating systems has two basic tasks: to store the required amount of heat, and to deliver the required water temperature to heat exchangers. The influence of TES tank volume and water temperature on thermal storage capacity is widely known and understood. The TES tank charge-discharge dynamic and the impact of water stratification is little known among engineers, and rarely considered in the design. Designers use TES tanks in many systems of different characteristics and design parameters. In TES design process the storage volume, water flow and water temperature are determined by heat source and heat demand characteristics. The water inlet velocity of charging water is determined by diameter of TES tank connection ports. The higher inflow velocity is commonly interpreted as the possibility of faster charging of TES tank. High inlet velocity causes however water turbulence and disturbances inside the TES, which affect thermal stratification [1]. The inlet velocity impact on stratified heat storage should be therefore defined and investigated in every project.

2 Thermal stratification

The thermal stratification is a layering of water of different temperatures at different depths of the tank. In undisturbed conditions stratification maintains two temperature zones separated by a transient layer, the so-called thermocline. The thermal stratification phenomenon is beneficial for an effective work of heating system. It increases the amount of

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available heat during TES tank charging and it accelerates start-up on heat demand side. High stored water temperature is achieved faster in stratified TES tank than in the tank in which water is mixed. Lack of stratification extends the time of reaching the desired supply temperature on the demand. In this case only a fully charged TES tank provides the required temperature. Stratification in the charging stage is the most important during the TES tank dynamic work cycle. A stream of high temperature medium falling into the tank at high speed disturbs the system of water temperature layers, disperses and mixes with the low temperature water [2]. The impact of inlet water velocity on thermal stratification in TES tank will be investigated below, using CFD simulations.

### 3 CFD modelling and analysis

In order to illustrate and define the impact of charge flow velocity on heat storage, the thermal stratification phenomenon was analysed using a validated CFD model. Laboratory tests consisted in measurement of in- and outflow temperatures during cyclic charging and discharging of TES tank. The thermal imaging supplemented and confirmed changes of temperature layers in TES tank (Figure 1). The obtained values were used to verify the correctness of the CFD model.

![Image](https://example.com/image1)

**Fig. 1.** The thermovision images of 200 dm³ TES tank charging and discharging test.

The charging stage in a typical 200 dm³, four ports water TES tank was tested, modelled and analysed. The CFD analysis assumes a charging stage with constant water stream and temperature on heat source side, and three diameters of inlet port: DN20, DN40 and DN80 (table 1). The increase of port diameter at a constant flow results in a decrease of inflow velocity and change of stratification conditions in TES tank.

| Ports size       | DN20     | DN40     | DN80     |
|------------------|----------|----------|----------|
| Tank capacity (volume) | 200 dm³ |          |          |
| Temperature range | <60°C; 80°C> |          |          |
| Inflow stream    | 0.75 m³/h |          |          |
| Inflow speed     | 0.663 m/s | 0.166 m/s | 0.041 m/s |
| 3D CFD model     | ![Image](https://example.com/image2) | ![Image](https://example.com/image3) | ![Image](https://example.com/image4) |
Heat transfer as well as fluid flows in the TES tank were simulated using the ANSYS Fluent program. All performed simulations are transient simulation with a total run time equal to fully tank charging time. The modelling parameters applied to the CFD simulation of the tank are as follows: the fluid is water with constant properties, density was calculated through the Boussinesq approximation, turbulence is modelled using the k-ε turbulence model and time step is 0.1s [3]. The referenced temperature inside the tank is set to 60°C, the temperature of charging water is set to 80°C.

The numerical CFD simulations allowed to illustrate and evaluate the six following features and parameters of analysed charging stage [2, 4]:

1. Graphical illustration of water temperature distribution in storage tank during charge stage in sequent snapshot steps.
2. The full charge time as the time from the beginning of charging with an initial tank temperature of 60°C, to 100% filled tank with design temperature of 80°C.
3. The time needed to achieve the design water temperature in heat demand port, as the time needed to achieve the water design temperature in outlet port on heat demand side.
4. Percentage of partial charge at set intervals, as a percentage of tank filled with design temperature of 80°C in sequent time steps.
5. The size of the thermocline, as a the thickness of the thermocline at specific intervals.
6. The amount of stored thermal energy - as a percentage of stored thermal energy (heat) in specified time steps.

### 3.1 Graphical illustration of stored water temperature distribution

Table 2 presents graphical illustrations of TES tanks charging. Numbers on TES tank graphics represent the percentage of stored thermal energy. Dynamic changes that take place inside the charged tanks are clearly visible. The simulations indicate contrast in the stratification process depending on inlet stream velocity (changed by port diameter). One should pay attention to the thermocline formation and height, the turbulence caused by the inlet stream and the water temperature available on the demand side [4, 5].

The increase of inlet port diameter improves water stratification and thermocline formation. The formation of turbulent flows is prevented when reducing the inlet velocity, and thus it minimises the mixing of water. In the TES tank with the smallest inlet diameter measured (DN20) the stream crosses the tank and hits the opposite wall. The DN80 diameter supports the convective movement of the hot water stream towards the TES tank slope. There are also clear differences in the height of the thermocline, as a temperature zone between the 80°C (hot) and 60°C (cold) water zones. In the case of diameter DN20, at each time stage, this border is practically blurred. This is caused by mixing of water. In the tank with the largest inlet port diameter, the mixing phenomenon is considerably limited, which reduces the thermocline height.

### 3.2 The full charge time

The full charge of a storage tank is achieved when the TES tank has an average temperature of accumulated water at design water temperature. Due to the tank construction, it was assumed that the full charge temperature is 79°C. The CFD analysis allows to define and compare the charging times for three analysed TES tank port sizes (figure 2). Increasing the diameter to DN80 from slightly changes the full charge time, up to 3 minutes from 38 to 35 minutes. The reduction of 3 minutes is important when the TES tank serves the very dynamic needs, like supplying hot water.
Table 2. Charging the water TES tank in identical thermal conditions equipped with port size DN20, DN40 and DN80, in consecutive simulation steps.
### 3.3 The time needed to achieve the design temperature in heat demand port

Figure 3 shows the time periods needed to achieve the design water temperature in the heat demand side port, with a charging limit of 79°C. In order to reach the limitation temperature in the TES tank with DN20, it is necessary to wait as much as half-hour and at while using the inlet port of DN80 this time is 30% shorter than for DN20. This is due to the stratification or mixing of stored water. This causes delay in achieving the design water temperature in heat demand port, which has a direct impact on the dynamics and thermal comfort of the supplied heating system.

![Fig. 3. Time required to reach the temperature of 79°C at the height below of discharge outlet port for analyzed TES tank ports’ diameters - time in minutes.](image)

### 3.4 Percentage of heat tank charge

The figure 4 shows the charging dynamics, illustrated by the percentage filling of analysed TES tanks volume with the design water temperature. The charging rate increases with the diameter of the port. The most significant differences are visible at the beginning and middle section of charging stage. At the first 20 minutes in the TES with DN20 diameter it was not possible to obtain the design temperature. Whereas the DN40 tank was filled in 38% and DN80 over 50% after the same amount of time. In the case of 200 dm³ tank, in 30th minute the DN80 tank inlet ports offers 20 litres more of > 79°C water compared to DN20 ports. The differences decrease and finally disappear in the following minutes of charging.

![Fig. 4. The percent of buffer filled with near-design temperature of 79.5°C in time steps.](image)
3.5 Occurrence and the size of thermocline

Defined graphs in figure 5 show stored water temperature distribution in relation to set time steps. In assessing the formation of the thermocline the most important is the angle of inclination of a given curve to the axis of the abscissa of the graph. From the presented data it is clear that the thermocline occurs in each case. The easiest way to describe angles is to evaluate the temperature distribution at 10 minutes charging. The stratification process takes place in the tank with the inlet diameter DN80. It can be seen from the charts below that the curves are the steepest for the vessel with DN80 diameter inlet port. The volume of water that achieved design water temperature can also be read from the diagrams below.

For example, the expected temperature (> 79°C) in tank with DN80 inlet ports is reached between 10 and 20 minutes, while in DN20 such a temperature is not yet available. In DN20 the temperature profile breaks down at the 0.8 to 1.1 m due to high water inlet velocity. In other cases, the inlet velocity is much lower.

Fig. 5. The temperature profile in TES tank with inlet diameters DN20, DN40, DN80, in consecutive simulation steps.

The low height of the forming thermocline is advantageous for thermal energy storage process and it shows good stratification. To assess the thermocline thickness, the dimensionless method was used. The non-dimensional coefficients were used to draw the graphs. And so the dimensionless height of the TES represents the dependence [6]:

\[ h^* = h / H; [-] \]  \hspace{1cm} (1)

where \( h \) represents height at the point and \( H \) represents the total height of the tank. Similarly, the dimensionless storage water temperature was defined. The thermocline is defined as the region in which the temperature meets the dependence [7]:

\[ \Theta = (T - T_c)/(T_H - T_c); [-] \]  \hspace{1cm} (2)

where \( T_H \) is the temperature on the hot side and \( T_c \) on the cold side. The temperature \( \Theta \) is determined according to the following relation [7]:

\[ 0.1 \leq \Theta \leq 0.9; [-] \]  \hspace{1cm} (3)

From the graphical data presentation in figures 6 (10th minute of charging) and 7 (30th minute), the thermocline at the tank with DN20 inlet ports has the greatest height compared to other inlet ports. Large thermocline thickness means the unfavourable mixing of stored water. The thinnest thermocline occurs in a vessel with DN80 inlet ports. It indicates a more complete, advantageous stratification. This relationship applies to the entire TES tank charging cycle. On simplified illustrations of the thickness of the thermocline the orange thermocline separates the top layer of hot water (red) and bottom layer of cold water (blue).
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3.6 The amount of stored thermal energy

All analysed TES tanks have the same thermal capacity. The size of inlet port affects increase in the amount of available thermal energy during charging process. The fastest charging occurs in DN80 tank, slower in DN40, and the slowest in DN20. Figure 10 presents the diagram of thermal energy surplus in specified time steps, in TES tank for diameters DN40 and DN80 with respect to the DN20 tank. It is noticeable that from the first minute, bigger diameters give measurable energy benefits They reach a gain of about 280 kJ higher for DN40 and about 550 kJ higher for DN80 after 20 minutes of charging. These differences decrease in time, and finally they disappear completely so that they level up when TES tank fully charged.

Fig. 6. Dimensionless estimation (left) and thermocline thickness (right) in 10th minute of charging. Thermocline (orange) separates layers of hot (red) and cold water (blue).

Fig. 7. Dimensionless estimation (left) and thermocline thickness (right) in 30th minute of charging. Thermocline (orange) separates layers of hot (red) and cold water (blue).

Fig. 8. Energy surplus for diameters DN40 and DN80 with respect to the DN20.
4 Conclusions

CFD transient 3D simulations can be successfully used as an effective tool to analyse and optimize the parameters of a water TES tank at a very early stage of design. The results of numerical analysis indicate that the adjustment of water inlet port diameter significantly improve the thermal stratification in charging stage. It appears that the increase in inlet port size supports the stratification layering and even distribution of water in the tank. Even such small structural change in TES tank design can improve working conditions of the entire heating hot water system.

Thermal stratification in TES tank brings many thermal, energy and comfort benefits in thermal energy storage systems. It increases TES dynamics and it accelerates the start-up of installation, which effectively results in cost savings. The results show that time of full charge is similar for all inlet ports’ diameter. The partial charge rate differ in analysed variants. The higher inlet velocity, the bigger increase the partial charge time. The available water temperature on the demand side significantly differs in analysed tanks. In each case the thermal stratification was achieved in charging stage in different dynamics and sizes. It has been proven that stratification at the lower water inlet velocity is fuller, with clearer division into temperatures layers and minimized mixing. The thermocline thickness changes among individual cases. It can be observed that the thermocline height in the DN80 tank gradually decreases with time, whereas in the tanks with smaller diameters this phenomenon is limited. Summarizing, as the inlet velocity increases, it is harder to create conditions that favour stratification.

The CFD analysis allows to perform the same analyses for stages of accumulating and discharging TES water tank. Simultaneous charging and discharging in various proportions can also be analysed. The thermal energy storage CFD analysis should become an essential element of design, especially due to the wide range of applied design water temperatures in modern heating systems. The thermal energy storage tank can become low-, medium- or high-temperature and therefore they can be used in various installations such as renewable energy systems, conventional heating systems or systems using waste heat, This makes the TES tanks a useful piece of equipment that can effectively lead to better operation of system and cost savings.

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