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Analysis of thermal stratified storage tank

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Abstract: The basic aim of the task is to compile a temperature stratification system in an accumulation tank. The range of the thesis concerns the shape and dimensions of a stratification system for an accumulation tank. Thermal stratification is a process that comprises the maintaining of temperature stratification at different levels of an accumulation tank which reduce to a minimum the process of temperature equalization. It results from the fact that the thermal stratification in a tank significantly increases the installation efficiency and improves the process of energy storing. It is connected with a thermodynamic element quality, that is the higher the temperature, the higher the energy, and, thus, the thermosdynamic element quality. In this phenomenon, thanks to the same amount of accumulated thermal energy and average temperature, as in a fully mixed tank, the user has a higher temperature in the upper part of the tank at his disposal. It has significant importance in the case when there is a low-temperature heating medium that transfers heat to the accumulation tank. Such a situation occurs when heat is absorbed from synthetic freons used in cooling and air-conditioning systems.

Key words: temperature stratification, thermal energy, heat recovery, convection

1. Introduction

Providing vertical stratification of temperature in a tank is extremely important from the perspective of energy effectiveness of the process of utilising waste energy. It is connected with proper location of inlet and outlet ports, sizes, shape, the method of distributing hot water within a tank, as well as the placement of elements that potentially interfere with temperature stratification, such as heat exchangers, booster heaters etc. It requires proper configuration of the stratification system elements so as to reduce mixing of cold and hot water in a tank. The application of the stratification system enables 'direct' transfer of heated water to upper parts of a tank, without mixing with cold water, which increases the effectiveness of the heat recovery system. Fig. 1 presents three cases of the accumulation of the same value of thermal energy, but with different levels of stratification. The first case corresponds to the highest level of the temperature stratification and is the most beneficial one. It is determined by the fact that the share of the zone of the highest temperatures in an accumulation tank is the greatest. With the increase of the mixing level, the zone of thermoclines expands until full mixing.

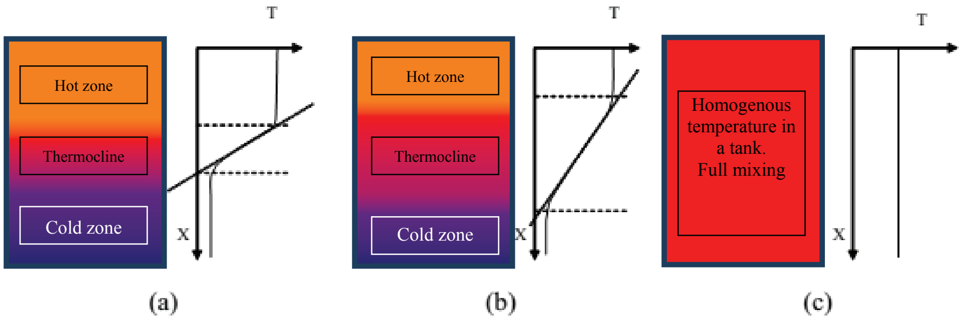

Fig. 1. Different levels/layers of temperature stratification by the same amount of the accumulated thermal energy

Providing vertical stratification of temperature in a tank is important and its quality is connected with sizes, the shape of a tank, the method of distributing hot water in a tank, as well as the arrangement of elements that may potentially interfere with temperature stratification. It requires proper configuration of the stratification system elements so as to reduce mixing of cold and hot water in a tank.

Heat, mass and momentum exchange are the basic instrumental processes that influence the processes taking place inside an accumulative tank.

The main factors destabilizing thermal stratification are:

– Forced convection inside a tank, caused by supplying cold water and reception of warm water by the external hydraulic system. The streams of supplying and receiving water while filling the tank induce mixing of water in a tank.
– Free convection that is a result of the density difference between cold and warm zones in an accumulative tank.
– Heat conductance between levels of water with different temperatures.

2. Virtual/real model

The subject of the analysis is an accumulation tank without a stratification system (Fig. 2) and with the stratification system (Fig. 3).

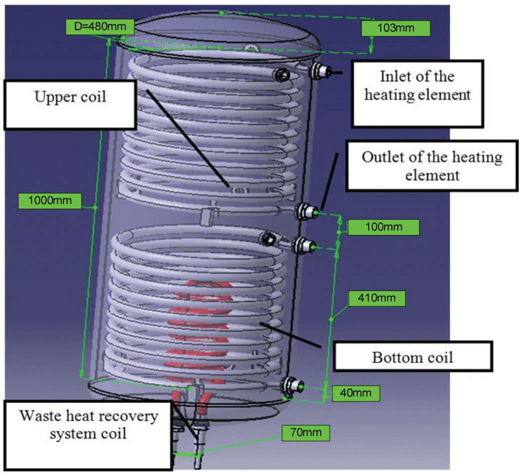

Fig. 2. 3D visualization of an accumulation tank

There are three heating coils inside the tank: the upper one, the bottom one and the coil of waste heat recovery system. The high-temperature heating element flows through the upper coil, the bottom one is used by the thermal solar collectors system [1]. The coil of the waste heat recovery system is used for receiving heat from a cooling/air-conditioning element. According to the assumption, water (high-temperature heating element) from the central heating system is the heating element flowing through the upper coil. The heating element flowing through the bottom coil is the liquid solution of propylene glycol. The working element flowing through the coil of the heat recovery system is R143a Freon. The geometric sizes of the coils are presented in Fig. 1, and the tank in Fig. 2.

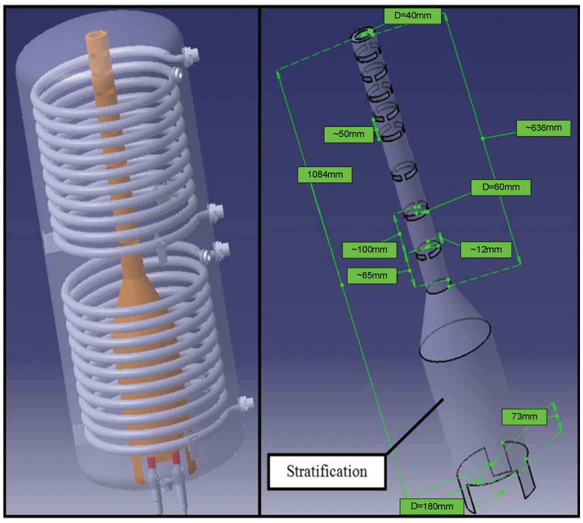

Fig. 3. 3D visualization of an accumulation tank with a stratification system

Table 1. Geometric sizes of coils

Description	Upper/bottom coil	Waste heat recovery system coil	Unit
coil average diameter	385	126	mm
coil pitch *p*	41	31	mm
coils number	10	10	–
internal diameter	16.5	12	mm
wall thickness	1	1	mm
material	copper	copper	–

Table 2. Geometric shapes of a tank

Description	Value	Unit
external diameter of the tank jacket	480	mm
wall thickness	2.5	mm
height of jacket/boiler casing	1 000	mm
height of boiler end plate	103	mm
type of boiler end plate	cage boiler end plate DIN 28013	–
material	stainless steel	–

3. Physical model

From the mathematical perspective, the phenomena occurring in fluid filling of an accumulation tank may be modelled by means of the equations of energy, momentum and mass exchange [2] as

– mass conservation equation – continuity equation:

$$\nabla(\rho w)+\frac{\partial \rho}{\partial t}=0, \tag{1}$$

– movement equation:

$$\rho\frac{\mathrm{d}w}{\mathrm{d}t}=\rho g-\nabla p+\nabla\tau_{ij}, \tag{2}$$

– energy equation:

$$\rho c\frac{\mathrm{d}T}{\mathrm{d}t}=\nabla(k\ \nabla T)+\Phi, \tag{3}$$

where: ρ is the density, c is the specific heat, w is the velocity, p is the pressure, T is the temperature, g is the acceleration of gravity, τ_{ij} is the stress tensor, k is the coefficient of conductivity, Φ is the dissipation function.

In the analysed case the following assumptions were assumed:
- the fluid that flows in a tank is incompressible, turbulent and unsteady,
- the fluid is Newtonian,
- the properties of the fluid are constant and do not depend on temperature, except for the density,
- the influence of a dissipation function on the energy equation is significantly small,
- there is no radiative heat exchange within the fluid (the fluid is transparent in infrared radiation),
- the configuration is 2D-axisymetrical,
- inside the coils, convective boundary conditions take place (Newton's Law of Cooling),
- there is no heat exchange between the external boiler casing/jacket and exterior,
- the initial temperature of the cold water in the tank: 20°C,
- the water temperature in the upper coil: 75°C,
- the temperature of the water solution of glycol in the bottom coil: 60°C,
- the freon temperature in the coil of heat recovery system: 50°C,
- the coefficients of heat transfer for water glycol solution and freon were determined from correlation equations (presented in a separate part of this report).

For the previously presented assumptions the equations of mass, momentum and energy exchange take the following form:

$$\frac{\partial\rho}{\partial t}+\frac{\partial}{\partial z}(\rho w_z)+\frac{\partial}{\partial r}(\rho w_r)+\frac{\rho w_r}{r}=0, \tag{4}$$

$$\frac{\partial}{\partial t}(\rho w_z)+\frac{1}{r}\frac{\partial}{\partial z}(r\rho w_r w_z)+\frac{1}{r}\frac{\partial}{\partial r}(r\rho w_r w_z)=-\frac{\partial p}{\partial z}+\frac{1}{r}\frac{\partial}{\partial z}\left[r\mu\left(2\frac{\partial w_z}{\partial z}-\frac{2}{3}(\nabla w)\right)\right]+ \\ +\frac{1}{r}\frac{\partial}{\partial r}\left[r\mu\left(\frac{\partial w_z}{\partial r}+\frac{\partial w_r}{\partial z}\right)\right]+F_z, \tag{5}$$

$$\frac{\partial}{\partial t}(\rho w_r)+\frac{1}{r}\frac{\partial}{\partial z}(r\rho w_r w_z)+\frac{1}{r}\frac{\partial}{\partial r}(r\rho w_r w_z)=-\frac{\partial p}{\partial r}+\frac{1}{r}\frac{\partial}{\partial r}\left[r\mu\left(2\frac{\partial w_r}{\partial r}-\frac{2}{3}(\nabla w)\right)\right]+ \\ +\frac{1}{r}\frac{\partial}{\partial z}\left[r\mu\left(\frac{\partial w_r}{\partial z}+\frac{\partial w_z}{\partial r}\right)\right]+F_r-2\mu\frac{w_r}{r^2}+\frac{2}{3}\frac{\mu}{r}(\nabla w)+\rho\frac{w_w^2}{r}+F_r, \tag{6}$$

$$\frac{k}{\rho c}\left(\frac{\partial^2 T}{\partial r^2}+\frac{\partial^2 T}{\partial z^2}+\frac{1}{r}\frac{\partial T}{\partial r}\right)=\frac{\partial T}{\partial t}+\frac{\partial T}{\partial r}w_r+\frac{\partial T}{\partial z}w_z, \tag{7}$$

where: r is the radial coordinate, z is the axial coordinate,

$$\nabla w=\frac{\partial w_z}{\partial z}+\frac{\partial w_r}{\partial r}+\frac{w_r}{r},$$

w_w is the swirling velocity, F is the mass forces, c is the specific heat.

On the basis of the assumed assumptions and the Reynolds hypothesis (which enables one to write down speed vector constituencies and the pressure field as a sum of averaged values and fluctuations) and time average to model the turbulent flow, the RANS model (Reynolds-averaged Navier-Stokes equations) was applied:

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i}\left(\rho w_i\right) = 0, \tag{8}$$

$$\frac{\partial}{\partial t}\left(\rho w_i\right) + \frac{\partial}{\partial x_j}\left(\rho w_i w_j\right) = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial w_i}{\partial x_j} + \frac{\partial w_j}{\partial x_i} - \frac{2}{3}\delta_{ij}\frac{\partial w_i}{\partial x_i}\right)\right] + \frac{\partial}{\partial x_j}\left(-\rho\overline{w_i^{'} w_j^{'}}\right), \tag{9}$$

where: i, j are the indices defining directions (r, z), δ_{ij} is the Kroneker delta,

$$\left(-\rho\overline{w_i^{'} w_j^{'}}\right)$$

is the tensor of Reynolds' turbulent stresses.

In order to solve Reynolds' equations for the process of fluid flow in a tank, a turbulence model k-ε was applied, due to the fact that it provides more realistic results by the higher Reynolds numbers in the areas significantly far from channel walls [4]. Moreover, the k-ε model describes better the flow through a cylindrical hole with recirculation, which takes place in the case of using a stratification system. Additionally, it is the turbulence model that is the most verified, and gives the most realistic description of turbulences [3].

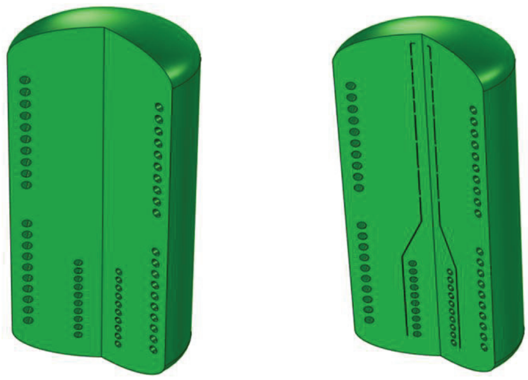

Fig. 4. Calculation model: without stratification system (a); with stratification system (b)

In the analysed case, a process of unsteady heating of water that fills the tank by means of coils was discussed. No-stationary free convection of external surfaces of coils takes place in the tank.

4. Results and conclusions

In the analysed model, we concentrated on defining the level-distribution of heat in a tank during heat recovery system coil operation and its interaction with other elements, as well as defining proper geometrical dimensions/sizes of a stratification system in order to minimize the process of cold and hot water mixing. In the first variant, the calculations were made for the operating coil of a waste heat recovery system without a stratification unit, Fig. 4a, in the second variant, the influence of different geometric variants was analysed and described in Fig. 5. This geometry includes a stratification unit for temperature stratification in an accumulation tank.

The parameters that changed during the simulation were:
– diameters – D_1, D_2, D_3,
– heights – H_0, H_1, H_2, H_3, H_4,
– an angle of the conical shape of part of stratification device – α.

Different geometrical configurations were analysed, and the final version of the stratificator is presented in Figs. 4b and 3. The values of geometric parameters are presented in Table 3. The height of the H_4 gap in the calculation model was assumed to be equal to 10 mm. In the real construction presented in Fig. 3, however, the H_4 height was increased to 12 mm, so as to maintain an unchanged cross section area for the fluid flowing out. In a similar way, the height H_0 was increased.

Table 3. Geometric shapes of a tank

Symbol	Value	Unit
D_1	180	mm
D_2	60	mm
D_3	40	mm
H_0	70	mm
H_1	412	mm
H_2	1 084	mm
H_3	50/100	mm
H_4	10	mm
α	12	°

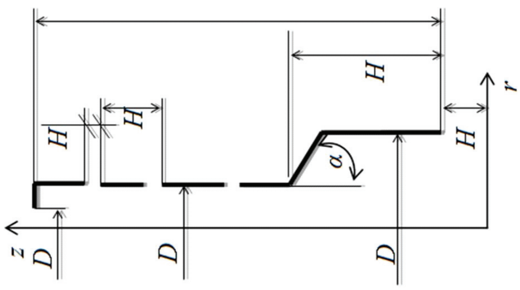

Fig. 5. Stratification system diagram

Numerical simulations were made by using the COMSOL Multiphysics commercial software. In the model presented in Fig. 4a, 798 220 finite elements were applied (675 870 three-node triangular elements, 122 350 four-node square elements as well as 26 990 and 1 260 boundary and apex elements. For the model presented in Fig. 4b, 1 774 510 finite elements were applied (152 951 three-node triangular elements, 245 000 four-node square elements as well as 53 690 and 1 888 boundary and apex elements) [5].

For the needs of the following report, water temperature distribution in the tank, as well as speed distributions for selected time points, i.e. 5, 10, 20 minutes from the moment of the initiating coil operation of the heat recovery system were presented.

For the aim of quantitative evaluation of the stratification process, non-dimensional temperature was defined:

$$\Theta = \frac{\overline{T} - T_{\min}}{T_{\max} - T_{\min}}, \tag{10}$$

where : $T_{\min}$ is the minimal temperature of water in the tank, $T_{\max}$ is the maximal temperature, which is equal to the freon temperature, $\overline{T}$ is the average integral temperature on a particular height of the tank, R is the external radius of a tank.

$$\overline{T}(z,t) = \frac{1}{R}\int_0^R T(r, z = \text{idem},\ t = \text{idem})\, \mathrm{d}r. \tag{11}$$

Moreover, in order to define the level of accumulated energy at particular time, the average temperature in the tank was defined in the form:

$$T_{av}(t) = \int T(r,z,t)\, \mathrm{d}A, \tag{12}$$

where: A is the area of the computational domain.

Fig. 6 shows non-dimensional temperature in a relative height function for time points: 5, 10, 20 minutes. The characteristic feature is that the temperature increase occurs starting from the tank's bottom, and water temperature stabilizes at the level of 60%, 50% and 40% of the tank's height. The maximal temperature values for z/H = 1 amount to 0.025, 0.042, 0.068, respectively. The average values of the temperatures calculated from relation (12) amount to 20.49°C, 20.98°C, 21.85°C, respectively. There occurs the process of “natural stratification” in the tank, where intensive mixing of hot and cold water takes place, higher temperature water flows toward the upper stream and cold water stays in inertia, which is visible in Figs. 8-10. One may notice strong circulation of water particles in the upper part of the tank, which contributes to intensification of cold and hot water mixing.

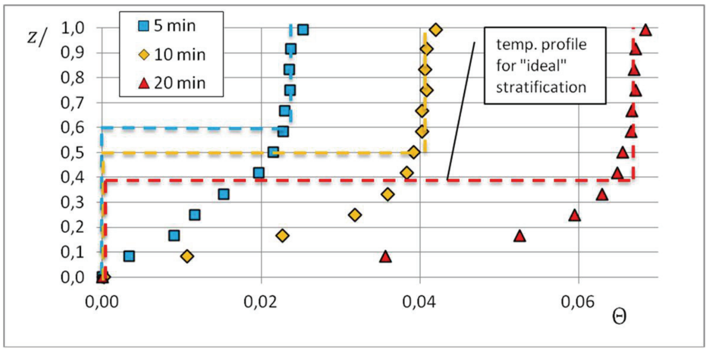

Fig. 6. Non-dimensional temperature in relative height function – without stratification system

Fig. 7 shows distribution of non-dimensional temperature as the function of relative height, for a tank with a stratification system installed. For the first 5 minutes of the heat exchange, there was no increase in the water temperature up to the level of 60% of the relative height of the tank, which is a radical change in comparison to the case of a tank without stratification.

The highest temperature for *z*/H = 1 amounted to 0.07 and it was only 6.8% higher than in the case of a system without stratification. The average temperature in the tank after 5 minutes was 20.75°C and it is only 12% higher, which corresponds to the increase of the amount of accumulated thermal energy of 53%.

For the time point of 10 minutes after starting the heat recovery system, the temperature at the highest point of the tank reached a value of 0.081 and it was 5.5% higher than in analogical time, but without stratification. Moreover, the average temperature in the tank reached a value of 21.32°C, which corresponds to the increase of the amount of the accumulated energy by about 35%.

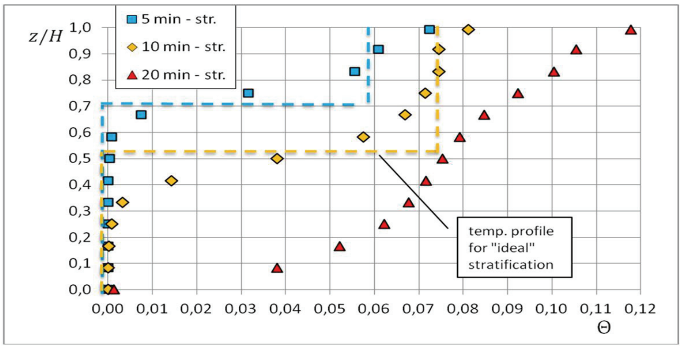

Fig. 7. Non-dimensional temperature in a relative height function – with a stratification system

After 20 minutes the temperature at the highest point of the tank, the average temperature and the increase of the amount of the accumulated thermal energy in comparison to analogical time, but without stratification equal to 0.188, 22.50°C and 35%, respectively.

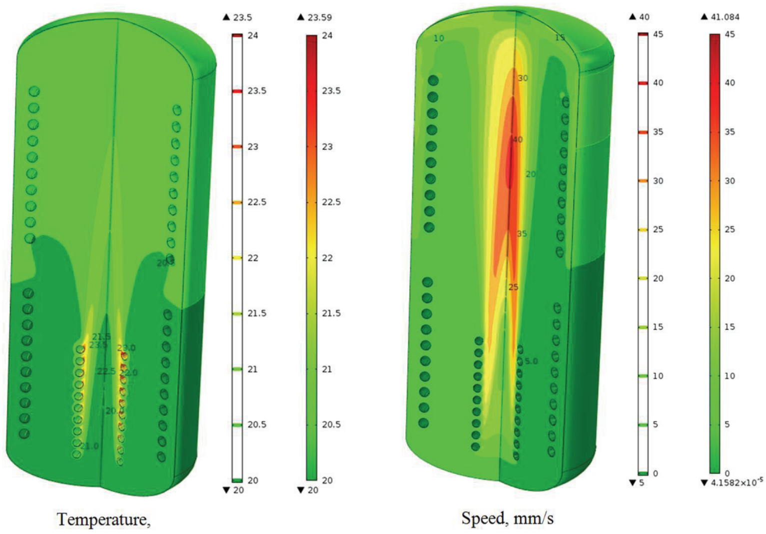

Fig. 8. Temperature distribution and speed after 5 minutes

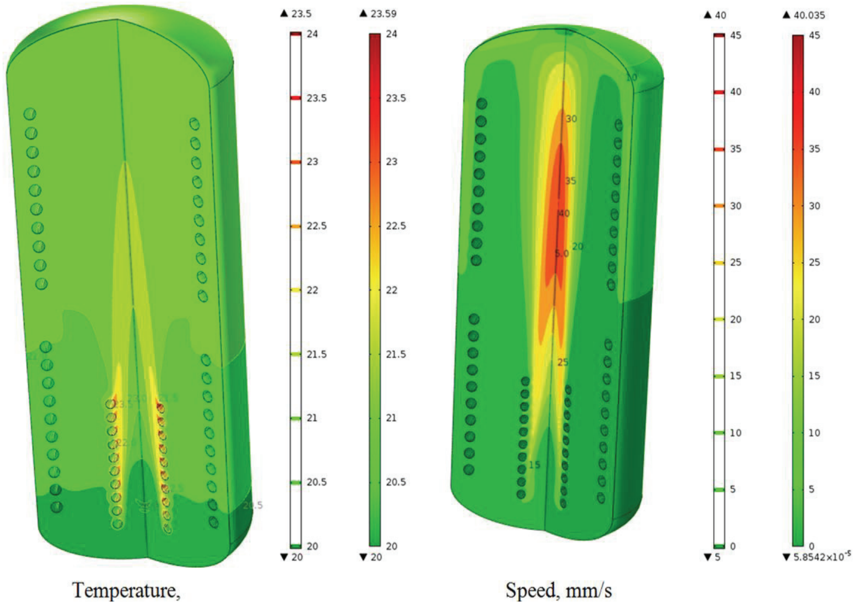

Fig. 9. Temperature distribution and speed after 10 minutes

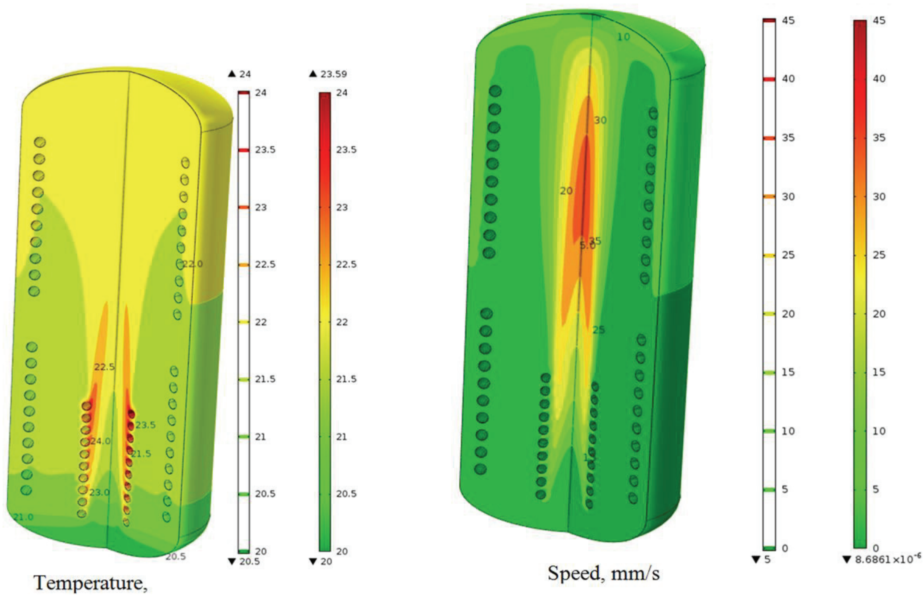

Fig. 10. Temperature distribution and speed after 20 minutes

In the light of the results presented above, it should be stated that the application of the stratification system has positive influence not only on temperature leveling in a tank, which can be clearly seen in Figs. 11-13, but also on the amount of accumulated energy. It is the result of separating heated and cold water streams by means of a wall, and radial gaps, through which the heated water flows, reducing the rate of mixing.

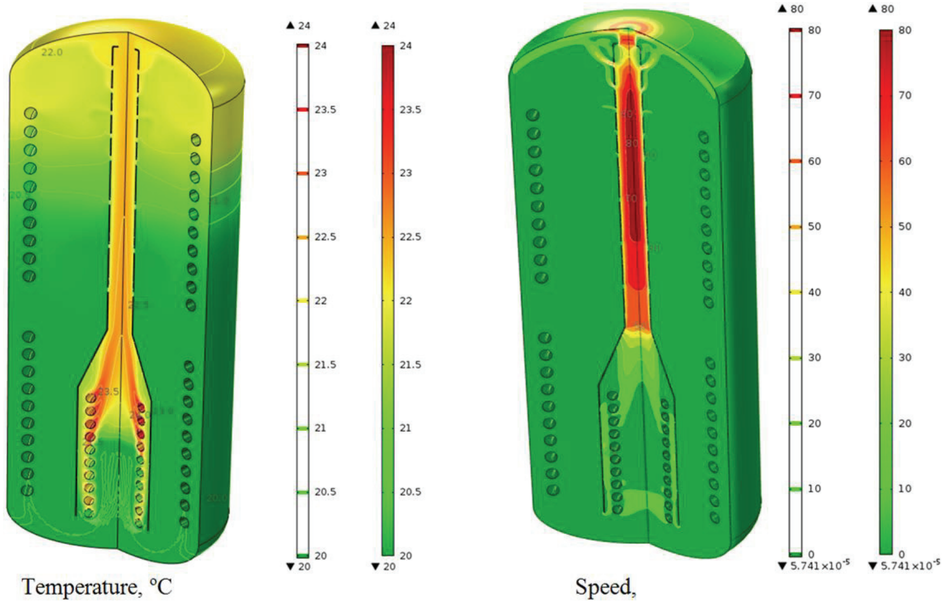

Fig. 11. Temperature distribution and speed after 5 minutes

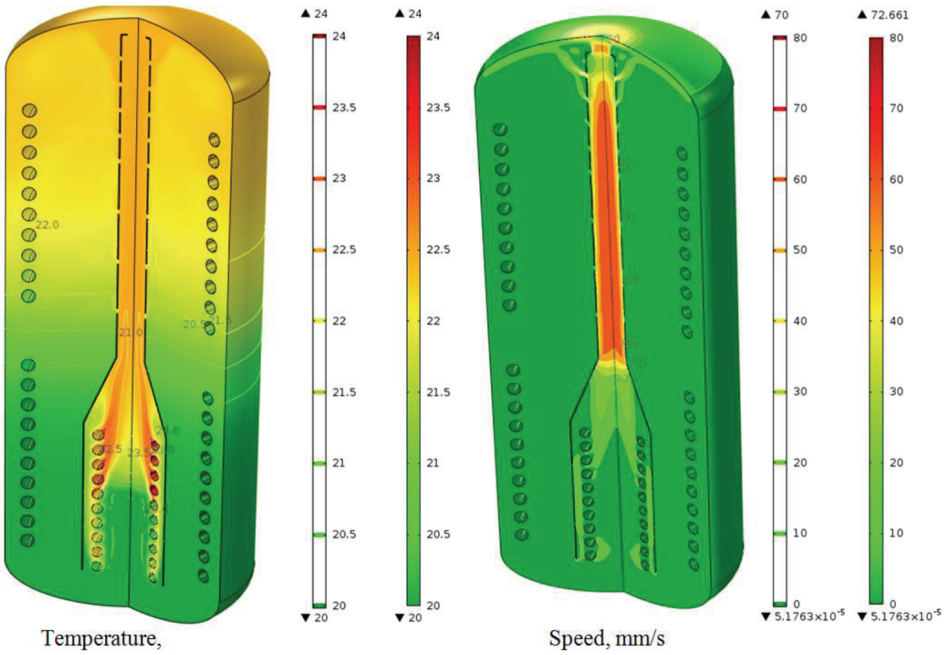

Fig. 12. Temperature distribution and speed after 10 minutes

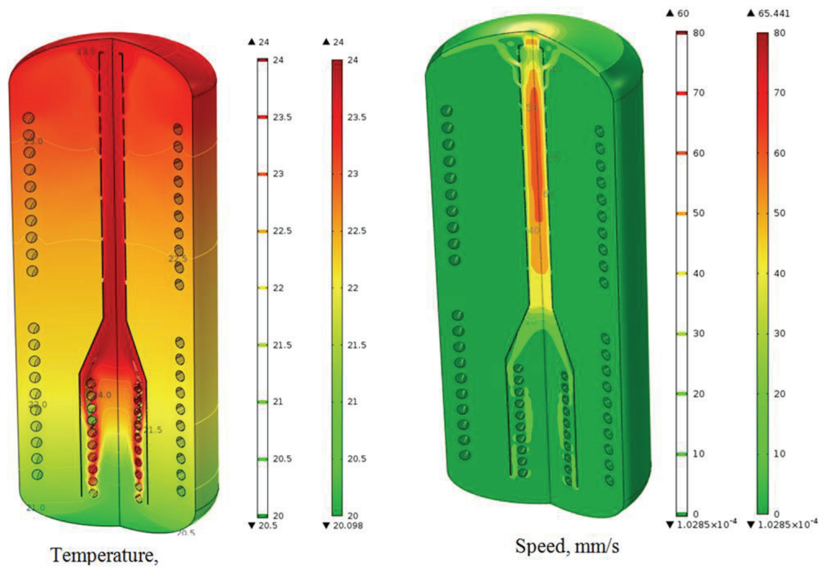

Fig. 13. Temperature distribution and speed after 20 minutes

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