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The Impact of Tube Arrangement in Latent Heat Thermal Energy Storage on the Melting Rate of Phase Change Material

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ABSTRACT

This paper analyses the impact of tube arrangement in a latent heat thermal energy storage (LHTES) system on the melting rate of phase change material (PCM). Numerical model was created in ANSYS Fluent 2023 R2, considering natural convection, to investigate the PCM melting process in LHTES. To validate the numerical model, a simulation of the PCM melting process around a single tube was conducted, and the obtained results were compared with experimental findings from other researchers. The validation showed good agreement, confirming the model's accuracy. Next, the melting process of PCM in a latent heat thermal energy storage system constructed of 9 tubes arranged inline was examined. The effect of the distance between the axes of the heating tubes and the distance from the axis of the tubes in the lower row to the bottom edge of the LHTES was investigated to understand the impact of these parameters on the melting dynamics of the PCM. The study showed that lowering the tubes in the LHTES improves natural convection in the PCM, thereby accelerating the melting process, especially in the final stage. For the exchanger with lowered tubes, charging times were reduced by up to 53.7%, and the heat flux was more than twice as high compared to the classic inline tube arrangement. Within the tested range of tube distances, increasing the spacing between the tubes in the inline arrangement decreases the average heat flux, whereas for the lowered tube arrangements, increasing the distance between the tubes does not affect the average heat flux. The conclusions drawn from this research can be used to optimize LHTES designs, contributing to the enhanced performance of thermal energy storage systems. These findings are particularly relevant for applications in renewable energy systems, where efficient thermal management is crucial for overall system performance.

Keywords: melting process, phase change material, PCM, thermal energy storage, TES, LHTES, time to completely melt; heat exchanger.

INTRODUCTION

Thermal energy storage (TES) is increasingly recognized as a critical component in the transition to renewable energy systems, primarily due to its ability to bridge the temporal gap between energy supply and demand [1]. This is particularly relevant for renewable energy sources such as solar and wind, which are inherently intermittent [2]. TES systems enhance the reliability and efficiency of renewable energy integration by storing excess thermal energy during periods of low demand and releasing it when demand is high [3].

Among various TES technologies, latent heat thermal energy storage (LHTES) systems, which utilize phase change materials, are gaining attention due to their high energy storage density and ability to operate within a narrow temperature range. PCMs absorb and release significant amounts of latent heat during phase transitions, making them ideal for maintaining stable temperatures and improving energy efficiency in various applications [4].

Phase change material (PCM) plays a crucial role in applications related to thermal energy storage and energy management strategies. The low thermal conductivity of PCMs is a major issue in the construction of LHTES. This results in low heat exchange rates and, consequently, extends the charging and discharging times of PCM heat storage systems [5-7]. Numerous articles [8-10] have highlighted various methods and techniques to improve heat exchange rates in LHTES.

The main methods to enhance the heat exchange rate in LHTES include expanding the heat exchange surface in the form of fins. Al-Abidi et al. [11] developed a numerical simulation for eight different configurations of triplex tube heat exchangers (TTHX). These exchangers were constructed with three tubes having the same axis of symmetry (a concentric arrangement). Water flowed in the inner and outer tubes, while the PCM was placed in between. The results showed that the impact of fin thickness was less significant than its length. It was demonstrated that the proposed variant type G achieved complete solidification 35% faster than other variants with the same fin thickness of 1 mm.

Liu et al. [12] examined the temperature distribution, solid fraction, and solidification time of two innovative fin geometries, types B and C, and compared them with conventional rectangular fins, type A. It was found that the innovative longitudinal triangular fins significantly improved the solidification characteristics of the PCM. The type C fins (with triangular fins decreasing in height from the tube axis) had the highest solidification efficiency among the studied geometries, and the solidification time was minimized by 38.3% in this variant compared to the conventional rectangular fin, type A.

An interesting solution investigated by Sciacovelli et al. [13] involved Y-shaped fins with single and double branching. It was found that the application of Y fins with double branching improved heat storage efficiency by 24%. Optimization analysis also showed that for long operation times, Y fins with smaller angles were preferred, while for short times, Y fins with wide angles between branches were preferred.

Another method to improve the heat exchange rate in LHTES is the use of modified PCMs to enhance their thermal conductivity or the amount of energy stored per unit mass. A good review of such solutions can be found in [14].

Alizadeh in study [15], investigated the melting of a phase change material enriched with nanoparticles. These results showed that increasing the nanoparticle volume fraction, due to increased thermal conductivity and decreased latent heat, caused an increase in the melting rate and the amount of absorbed energy. Based on the study of various volume fractions, he concluded that using a higher volume fraction of 3% was more appropriate both in terms of energy and melting rate. However, he also pointed out that if the volume fraction exceeds this value, it could cause agglomeration and deposition of nanoparticles, reducing system efficiency.

The main conclusions of the review performed by Han [16] in 2022 are that the spatial structure of carbon nanomaterials has a greater degree of influence on the phase change material. The more complex the spatial structure of the carbon nanomaterial, the more significant the increase in thermal conductivity of the phase change material. Of the seven properties of nano-phase change materials, the one that has the most significant influence on the phase change material is the concentration, followed by size, shape, and type.

Furthermore, to improve heat exchange in PCM, porous materials or metallic foams are used. Wu and Zhao [17] conducted experimental studies on improving heat exchange in a cylindrical PCM storage unit using materials with different porosities. The experiments were conducted for three cases: without metallic foam, with metallic foam, and with expanded graphite. $NaNO_3$ was used as the PCM. The results showed a significant increase in the heat transfer coefficient (about 2.5 times) when using porous materials compared to the case with pure $NaNO_3$.

Yu et al. [18] numerically studied the impact of using metallic foam on the behaviour of PCM during solidification in a horizontal shell and tube heat exchanger (STHX). They found that the addition of metallic foam significantly improved the effective thermal conductivity of the PCM, which accelerated the discharging process and improved the uniformity of the PCM temperature. Moreover, metallic foam with lower porosity achieved a higher solidification rate and a more uniform temperature distribution.

Gong et al. [19] prepared an innovative PCM composite made of octadecane ($C_{18}H_{38}O$) combined with Al_2O_3 and expanded graphite. They found that the thermal conductivity of octadecane improved 4.5 times after dispersing Al_2O_3

with expanded graphite in it. The PCM material proved to be more stable and homogeneous.

Some researchers also employ hybrid techniques involving combining the expansion of heat exchange surface with the addition of nanoparticles to the PCM material. Mahdi and Nsofor [20] analysed the impact of using only fins, only nanoparticles, and a combination of both on the efficiency of TTHX. According to them, introducing only nanoparticles or a combination of nanoparticles with fins significantly improves the solidification process, but much better results can be achieved by using only fins with the same PCM volume.

Mahdi et al. [21] investigated the improvement of heat exchange through TTHX containing longitudinal fins and PCM material enriched with nanoparticles. The fin geometry in the upper and lower parts of TTHX was different to further enhance heat exchange in each area. The results showed that the use of well-designed fins inside the storage unit can significantly accelerate the PCM melting process compared to using only nanoparticle modified PCM without additional fins.

Darzi et al. [22] studied the loading and unloading processes of PCM using fins, as well as using nanoparticles in a tubular storage unit. They considered the influence of changing the geometry of the annular container, the number of fins, and the concentration of nanoparticles used. The results showed that doping nanoparticles into pure PCM improved both the loading and unloading speeds, but it proved impossible to ensure heat transfer stability in the lower part of the section. Adding fins, on the other hand, significantly improved both the loading and unloading speeds.

The influence of flow rate and temperature of the heat transfer fluid (HTF) on the heat exchange process in LHTES was also studied. The results of several studies [5, 6, 23] indicate a minimal effect of the heat transfer fluid (HTF) flow rate on reducing the charging and discharging time of LHTES.

The temperature of the heat transfer fluid (HTF) has a significantly greater impact on the melting process of the PCM material. In [6], an experimental and numerical investigation of a sebacic acid/expanded graphite composite phase change material in a double-spiral coiled heat exchanger was conducted. The authors found that increasing the inlet temperature by 40 °C shortened the charging time by 60%, and the thermal power transferred from HTF to the composite PCM increased by more than 50%. Jesumathy et al. [24] investigated heat transfer in a horizontal double pipe heat storage unit in which the phase change material was paraffin wax. They found that increasing the inlet temperature from 70 to 74 °C decreased the total melting time by 31%.

Similar conclusions were presented by Szajding et al. [3] in a study of the LHTES charged with a photovoltaic installation. The product from Rubitherm Technologies GmbH with the trade name RT54HC was selected as the phase change material characterized by a phase transition temperature of 53–54°C. They found that the shortest charging time and the amount of stored energy occurred at a heater surface temperature of 80°C. At a heater surface temperature of 60°C, 12% less energy per mass unit was stored, and the charging time increased more than threefold.

When studying the design of the heating element in LHTES to improve heat exchange rates, researchers often consider only a segment of the storage unit and focus on a single heating element. These studies lack information about the mutual interaction of neighbouring heating elements and TES walls. In this paper, the scope of the research was extended to examine the melting process of PCM in a latent heat thermal energy storage system consisting of 9 tubes arranged inline. The effect of the distance between the axes of the heating tubes and the distance from the axis of the tubes in the lower row to the bottom edge of the LHTES was investigated to understand the impact of these parameters on the melting dynamics of the PCM. It was found that lowering the tubes in the TES (construction B) led to a significant reduction in the charging time of the LHTES. Using TES construction type B, compared to type A, resulted in a reduction of the charging time by up to 53.7%.

PHYSICAL MODEL

For the analysis, a heat storage model consisting of 9 heating tubes with a diameter of $d = 10$ mm was constructed. Two heat storage geometries (A and B) shown in Figure 1 were considered. Geometry A represents the classical serial arrangement, while geometry B is a serial arrangement shifted downwards so that the distance from the bottom edge of the heat storage to the axis of the tubes placed at the bottom was constant and equal to 7.5 mm (which is 3/4 d). In both cases, the dimension x, representing the distance between the axes of adjacent tubes, was varied. To make the obtained results more universal, the dimension x was varied relative to the diameter of the tube d = 10 mm. Distances x of 1.5d, 2.0d, 2.5d, and 3.0d were analysed, allowing for the examination of 7 heat storages (arrangement A for x = 1.5d, 2.0d, 2.5d, 3.0d, and arrangement B for the same values of x, with arrangement A and B being the same for x = 1.5d). By changing the dimension x, the size of the heat storage also changed. The larger the x, the greater the proportion of the phase change material volume and the smaller the proportion of the heating tube volume, as shown in Figure 2 for arrangement A.

The phase change material used was paraffin wax, whose properties are shown in Table 1 based on S.P. Jesumathy et al. [24].

NUMERICAL MODEL

To build the numerical model, the commercial software ANSYS Fluent 2023 R2 was used. Due to the complexity of the model and the non-stationarity of the heating process (which generates very long computation times), a decision was made to use a 2D model representing the cross-section of the heat storage under consideration.

Table 1. Physical properties of paraffin wax [24]

Physical property	Paraffin wax (PCM)
Melting temperature, °C	58
Latent heat, kJ/kg	210
Solid density, kg/m^3	860
Liquid density, kg/m^3	780
Specific heat, kJ/(kg K)	2.9 (*s*) 2.1 (*l*)
Thermal conductivity, W/(m K)	0.24 (*s*) 0.15 (*l*)
Dynamic viscosity (N s/m^2)	0.205

The temperature of the heating tubes was set to 70 °C, and the initial temperature of the phase change material was 40 °C. The insulation condition has been considered for the outer surface of the heat storage as the boundary condition. The calculations

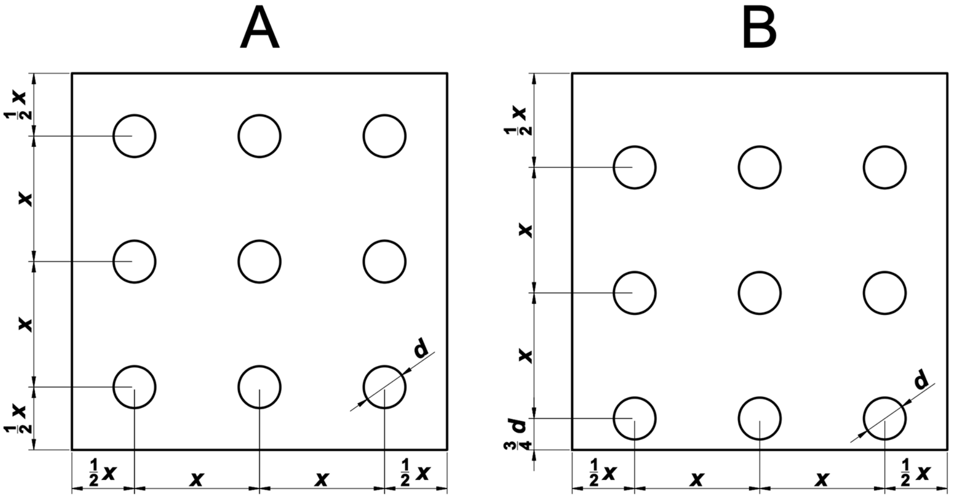

Figure 1. The geometry of the analysed heat storage for x = 3d (arrangement A and B)

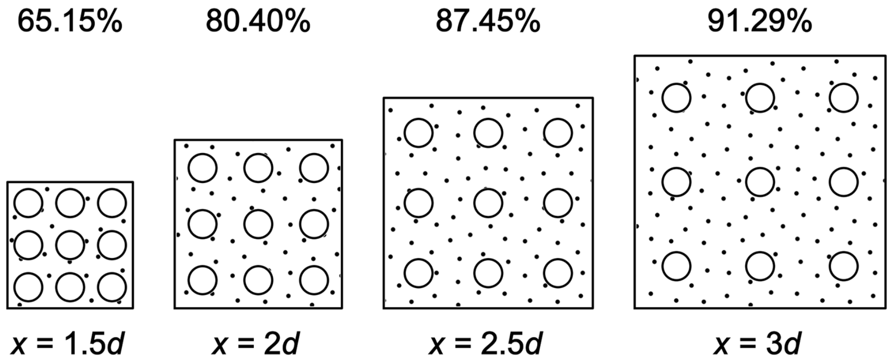

Figure 2. The volume fraction of the phase change material to the total volume of the heat storage (arrangement A)

were terminated when the temperature of the phase change material at the coldest location (the bottom corner of the heat storage) reached 60 °C.

In the simulations, phase change processes were included, using the Solidification and Melting Model embedded in ANSYS Fluent. The model also takes into account Viscous laminar and energy. The system's governing equations have been solved using the SIMPLE algorithm. To discretize the energy and momentum equations, the QUICK differentiation scheme has been applied. The pressure equation was adjusted with the PRESTO scheme like M. Kazemi et al. [25]. To ensure a stable solution, under-relaxation factors were used, set at 0.3 for pressure, 0.7 for velocity, 1 for energy, and 0.9 for the volumetric liquid fraction. The convergence criteria are set at 10^{-4} for both the continuity and momentum equations, and 10^{-6} for the energy equation.

The numerical mesh was generated in ANSYS Meshing, and then improved in Fluent so that the mesh had at least 0.9 minimum Orthogonal Quality, which indicates excellent mesh quality.

To verify the accuracy of the numerical solution, the calculation results were compared with the experimental results of S.P. Jesumathy et al. [24]. They conducted experimental studies on a simple double pipe heat exchanger. Paraffin wax was present in the outer tube, while water flowed through the inner tube. The water had a temperature of 70°C, and the initial temperature of the paraffin wax was 34°C. Figure 3 shows the comparison of the temperature calculation results obtained at two points in the heat exchanger: T3 (15 mm above the inner tube) and T9 (15 mm below the inner tube) with the research results presented in [24]. The Figure 3 demonstrates a good match between the simulation results and the experimental results of Jesumathy et al.

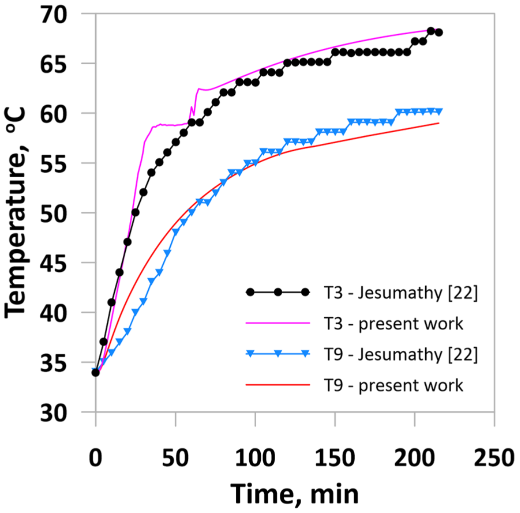

Figure 3. The comparison of temperature profiles at different locations between this study and Jesumathy et al. [24]

RESULTS AND DISCUSSION

The melting process in storage units A and B for a distance of $x = 3d$ is shown in Figure 4 for three times: 20, 50 and 90 minutes. The diagram also illustrates the proportion of the liquid phase. In the initial stage, the melting of the phase change material occurs concentrically around the heating tubes. At this stage, conduction is the dominant heat exchange mechanism. Over time, the volumetric proportion of the liquid phase increases, leading to an increased buoyancy effect of the hot liquid rising upward, with natural convection becoming the dominant heat exchange mechanism. This effect has been observed by many researchers, including [26]. Due to the occurrence of natural convection directing the hot fluid upwards, the loading process

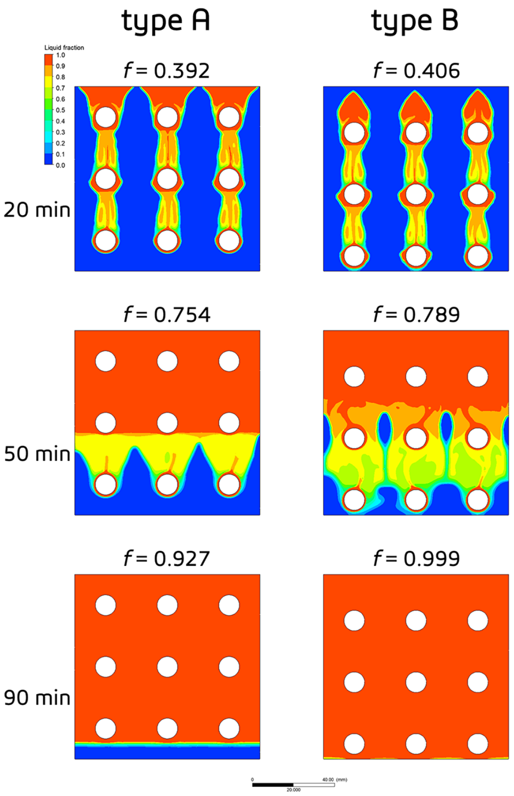

Figure 4. Distribution of the liquid phase during the melting of the PCM material in LHTES A and B for x = 3d

of the latent heat thermal energy storage (LHTES) with lowered tubes is faster than in the case of a classical arrangement of tubes in a serial layout. At the 90-minute mark, the proportion of the liquid phase in exchanger A is 0.927, and in exchanger B it is 0.999, representing an increase in the proportion of the liquid phase by 7.8%.

In Figure 5, the loading times of all considered LHTES systems are shown. The termination of the TES loading process occurred when the temperature of the phase change material at the coldest location (the bottom corner of the TES) reached 60°C (indicated by the dashed line in Fig. 5). In all considered cases, reaching this temperature resulted in the LHTES being charged to approximately 99%. Naturally, the loading process was fastest in the TES with $x = 1.5d$, and slowest in the TES with $x = 3d$, due to the larger volume of PCM in the TES with larger x values, with the same surface area of the heating tubes. It is worth noting here that the material costs of TES in relation to the stored energy quantity are higher for smaller storages than for larger ones. In the thermal energy storage with $x = 1.5d$, the volume of PCM accounts for only 65% of the total volume of the storage, while for $x = 3d$, it already accounts for 91% of the volume. It is also observed here that lowering the tubes (construction B) results in a significant reduction in the loading time of LHTES, especially in the final stage of the process. In the considered range of distances between the heating tubes, the larger the parameter x, the greater the reduction in the loading time of LHTES. The use of construction B compared to A resulted in a reduction in the loading time for $x = 2d$ by 36.8%, and for $x = 3d$ by as much as 53.7%.

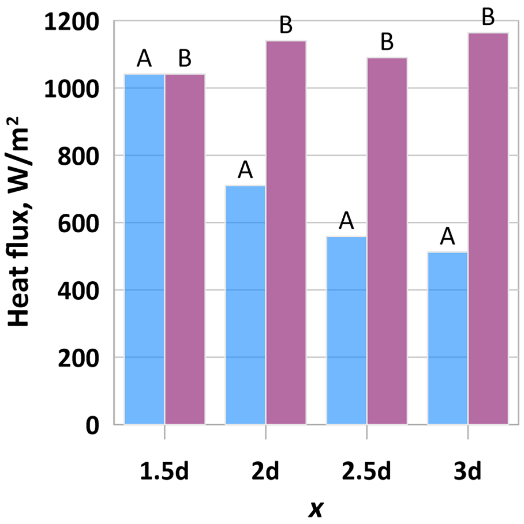

Figure 6. Average heat flux for different LHTES geometries during loading

Figure 6 shows the average heat flux obtained for different LHTES geometries during its loading. In the case of LHTES type A, a noticeable decrease in heat flux is observed with increasing distance between the heating tubes. For $x = 1.5d$, the average heat flux is 1041.1 W/m², while for $x = 3d$, it drops to 512.5 W/m², representing a decrease of 50.8%. However, in the case of LHTES with lowered tubes (type B), it remains at a similar level for all considered values of the parameter x. The use of construction type B instead of A for $x = 3d$ results in an increase in the average heat flux from 512.5 W/m² to 1164.2 W/m², which is more than double.

Fully charging the LHTES from 40 °C to 70 °C with paraffin wax as the PCM allows storing approximately 287.4 kJ/kg of energy. Figure 7 shows the total amount of stored energy in each

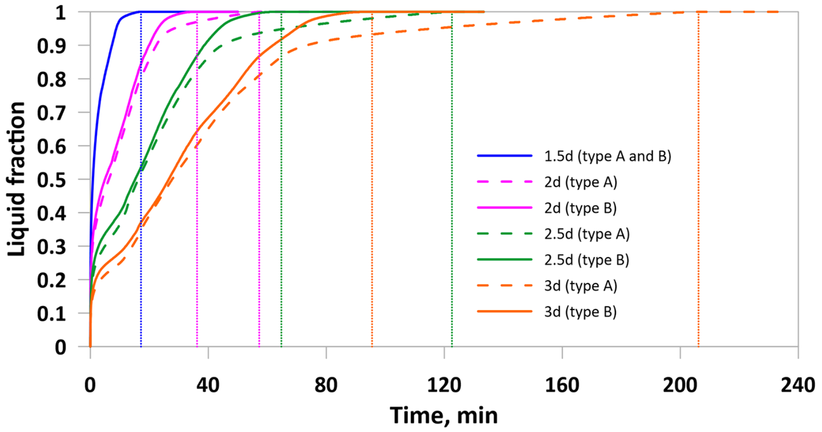

Figure 5. Liquid fraction of PCM during TES charging process depending on the geometry of the heat storage unit

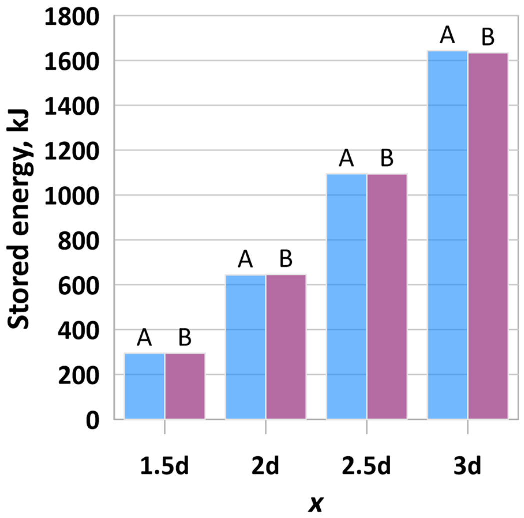

Figure 7. Stored energy for different LHTES geometries

energy storage unit. The greater the value of parameter *x*, the greater the volume of PCM in the heat storage, and consequently, the amount of stored energy. The use of construction A or B for the same parameter *x* values had no effect on the amount of stored energy, as both constructions contained the same amount of PCM. However, it is worth emphasizing that in the case of construction type B, the charging time of LHTES was significantly shorter with the same material costs as construction type A.

CONCLUSIONS

In this paper, the melting process of phase change material (PCM) in a latent heat thermal energy storage (LHTES) constructed with 9 tubes arranged in series was investigated. The influence of the distance between the axes of the heating tubes and the distance from the axis of the lower row tubes to the bottom edge of the LHTES was examined to understand the impact of these parameters on the PCM melting dynamics. Based on the analysis of the obtained results, the following conclusions were formulated:

- In the initial stage of PCM melting, the dominant heat exchange mechanism is conduction. As time progresses and the volumetric fraction of the liquid phase increases, natural convection becomes the dominant heat exchange mechanism.
- Due to the presence of natural convection directing the hot fluid upward, the charging process of LHTES with lowered tubes is faster than in the case of the classical arrangement of tubes in series. For thermal energy storage (TES) with $x = 3d$, at the 90th minute, the liquid phase fraction in construction A is 0.927, while in construction B, it is 0.999, representing an increase in the liquid phase fraction by 7.8%.
- Lowering the tubes in TES (construction B) leads to a significant reduction in the charging time of LHTES, especially in the final stage of the process. In the considered range of distances between the heating tubes, the greater the distance between them, the greater the reduction in the charging time of LHTES. The use of TES construction type B compared to A resulted in a reduction in the charging time for $x = 2d$ by 36.8%, and for $x = 3d$ by as much as 53.7%.
- In the case of LHTES with a classical series arrangement of tubes (type A), there is a noticeable decrease in heat flux with an increase in the distance between the heating tubes. For $x = 1.5d$, the average heat flux is 1041.1 W/m^2, and for $x = 3d$, it drops to 512.5 W/m^2, which represents a decrease of 50.8%. However, in the case of LHTES with lowered tubes (type B), it remains at a similar level for all considered values of the parameter *x*. Using type B construction instead of A for $x = 3d$ results in an increase in average heat flux from 512.5 W/m^2 to 1164.2 W/m^2, or by 127.1%.
- The use of LHTES type A or type B constructions for the same values of the parameter *x* did not affect the amount of stored energy, as it results from the same amount of PCM material in both constructions. However, it should be emphasized that in the case of type B construction, the charging time of LHTES was significantly shorter with the same material costs as type A construction.
- The material costs of TES in relation to the amount of stored energy are higher for smaller storages than for larger ones. In the thermal energy storage with $x = 1.5d$, the volume of PCM material constitutes only 65% (the rest is the volume of tubes) of the total storage volume, whereas for $x = 3d$, it already constitutes 91% of the volume.

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