# Numerical Simulation of the Heat Storage and Release Processes in an Innovative Aluminum-Silicon Phase Change Energy Storage System

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**Abstract.** As traditional fossil energy sources become depleted and the global energy structure undergoes transformation, the installed capacity of renewable energy—primarily wind and solar power—continues to expand rapidly. This necessitates the use of energy storage devices as a buffer to ensure effective energy utilization. In this study, we present a novel aluminum-silicon phase change energy storage device, with simulations of heat storage and release processes conducted using Fluent software. We analyzed the effects of heating rod arrangement and power on the heat storage process, as well as how variations in heat exchange fluid pipe diameter and flow rate influence the heat release process. The results indicate that internal temperature distribution is more uniform, leading to a 38% increase in heating efficiency for individual heating rods. Under specified design conditions, various combinations of heat exchange pipe diameters and inlet fluid velocities were examined; it was found that at a pipe diameter of 20mm, the outlet temperature of the heat exchange fluid met design specifications. Furthermore, when operating at a flow rate of 0.5m/s under this diameter condition, latent heat utilization during phase transformation reached its peak efficiency. Both parameters can be adjusted according to actual requirements to derive optimal solutions based on demand. Additionally, these findings provide a robust foundation for further device development and experimental investigations.

**Keywords:** Aluminum-silicon phase change heat storage; Fluent; Heat storage; Exothermic

## 1 Introduction

With the swift development of China's economy, a set of issues such as energy shortage and environmental pollution have become increasingly salient. To achieve the goals of "carbon peak" and "carbon neutrality", China has embarked on vigorously developing new energy [1]. Nevertheless, the upsurge of unstable electricity connected to the power grid is bound to exert a considerable negative impact on the stability and security of the power grid system. Energy storage will play a vital role in the flexible adjustment of


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the power balance of the high-proportion new energy power system and support the dynamic matching of supply and demand [2]. The current energy storage approaches mainly encompass mechanical energy storage, electrochemical energy storage, and electric heat storage boilers [3]. Mechanical energy storage fails to align with the flexibility of new energy [4]. Electrochemical energy storage is prone to safety concerns due to its inherent shortcomings [5]. The energy storage density of solid thermoelectric storage boilers is relatively low [6], while phase-change boilers can handle the coordinated regulation of large-scale and multi-type energy storage more effectively [7].

The selected phase change material—Al-Si alloy—is characterized by moderate pricing coupled with abundant availability; it boasts advantages including elevated thermal density capacity, favorable operational temperature ranges during cycles, superior thermal conductivity alongside excellent cost-performance ratios—all non-flammable and non-toxic—which holds significant promise for alleviating contemporary challenges faced by renewable energies[8]. This paper presents a design for an aluminum-silicon shell-based phase change energy storage device aimed at partially substituting traditional boiler water circulation while enabling collaborative power generation alongside conventional thermal plants. Heat is directly supplied via electric heating rods utilizing low-cost grain electricity; during discharge phases, condensate from condensers enters this device where it is heated up to boiler feedwater temperatures. The study investigates how variations in heating rod configurations along with applied power influence heating dynamics as well as how changes in fluid pipe diameters affect flow rates during discharge processes—laying foundational groundwork for practical applications involving phase change boilers.

## 2 Numerical Modeling of an Aluminum-Silicon Phase Change Energy Storage System

The physical model utilized in the numerical simulation is illustrated in Figure 1.

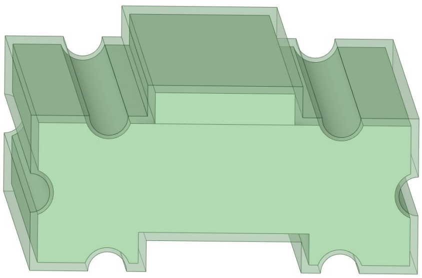

**Fig. 1.** Physical model

The physical model utilized in the numerical simulation is illustrated in Figure 1. The dimensions of the model are 2000 mm in length, 500 mm in width, and 240 mm in height, with a shell thickness of 10 mm. By elevating the central section of the shell by 40 mm, a self-supporting structure is created to facilitate the stacking of thermal energy storage blocks while simultaneously reducing stress on the shell. Additionally, this design allows for protective gas to be introduced into the upper portion of the space, safeguarding the aluminum-silicon material from oxidation during both melting and solidification processes. The phase change material (PCM) occupies the lower section of the housing, whereas protective gas fills its upper section. A semi-cylindrical notch with a diameter of 50 mm is incorporated; heating rods are positioned at both ends while fluid pipes run along its top and bottom *edges*. The model employs Al-Si12 alloy as PCM encased within a package made from 310 stainless steel, with nitrogen serving as the protective gas.

## 3 Results and Discussion

### 3.1 Numerical Simulation of Heat Storage Process

In this model, the positions designated for heating rods are fixed; however, the distinction lies in whether heat is dissipated during the heat storage process with fully engaged heating rods. The varying number of heating rods influences both heating efficiency and melting duration.

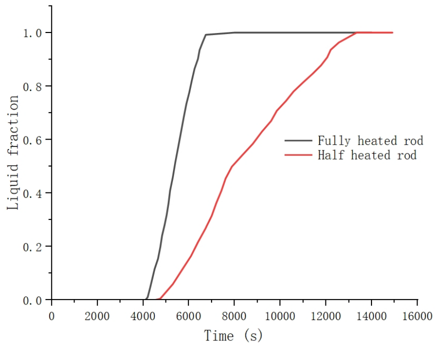


**Fig. 2.** Influence of heating rod arrangement on melting time under the same power

In comparison to the liquid phase rate curve depicted in Figure 2, it is observed that from the moment the liquid phase rate began to alter, the time difference between the two configurations was merely about 500 seconds. This indicates that the phase transition initiates from the inner two columns, suggesting that the outer heating rod exerts minimal influence on the timing of this transition. Notably, at the conclusion of phase transformation, there is a significant acceleration in the rate of phase change following the introduction of an outermost heating rod, with its power increasing by *36%*. The slope of the liquid phase rate curve serves as an indicator of phase transition velocity; thus, it can be seen that for full heating rod implementation, a steep and relatively constant slope signifies a rapid and uniform process. Conversely, in scenarios lacking an external heating rod, a generally shallow slope suggests a comparatively slower phase transition process. Furthermore, after reaching a certain threshold point on this curve, changes in slope indicate variations in melting speed for the phase change material. As these alterations cannot be adequately represented within Figure 2 itself, we introduce thermal imaging captured post-heating under identical power conditions over 1.5 hours for further analysis (refer to Figure 3).

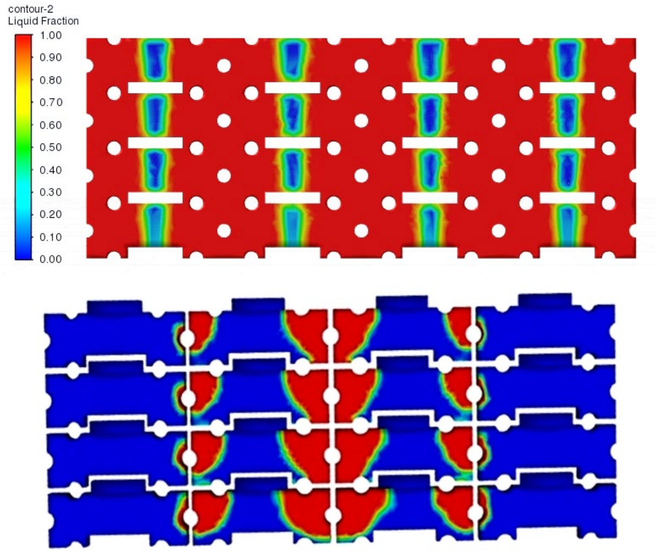


**Fig. 3.** Melting cloud image at 1.5h with the same heating power a) full heating rods b) no heating rods arranged on both sides

As illustrated in Figure 3, the *phase* transition of the fully heated rod is nearly complete at 1.5 hours, whereas it has only just commenced in the absence of an external heating rod. The alteration in slope observed in Figure 2 can also be elucidated by examining the right cloud image. The temperature of the outer phase change material (PCM) is lower than that of the inner test sample, leading to a greater heat flow from the inner side to the outer side due to a larger temperature gradient; consequently, this delays the onset of phase change. When there is a change in slope, melting within the two inner columns of PCM occurs instantaneously, while for the remaining outer PCM, only half is subjected to heating via a rod. At this juncture, as the temperature difference diminishes and unilaterally induced thermal resistance increases due to extended heat transfer distance, further reduction in melting speed ensues—this phenomenon is reflected in Figure 2 as a continued decrease in curve slope during its latter half.

In addition to the configuration of heating rods, the power output of these rods is a critical factor influencing the thermal storage efficiency of aluminum-silicon phase-change energy storage systems. This study simulated the phase change process of PCM within the heat storage device under four distinct heating rod power levels. The variations in average temperature and liquid phase fraction of PCM at different heating rod powers are illustrated in Figure 4.

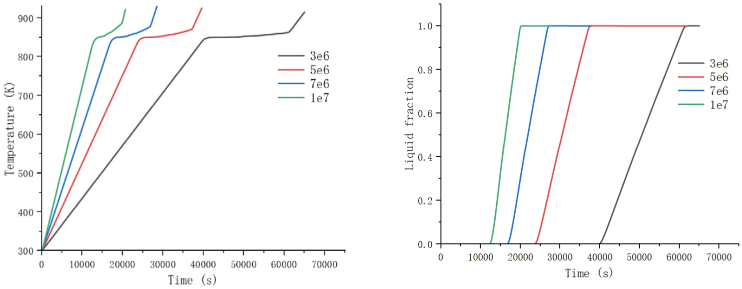


**Fig. 4.** Influence of heating rod power on the temperature and phase transition time of PCM

It can be seen from the temperature change of the phase change material on the left of Figure 4 that the temperature of the phase change material rises uniformly during the whole phase change process. It took 1.5, 1.9, 2.7 and 4.6h to heat the phase change material from normal temperature to the initial temperature of hot start temperature 520K, and 4, 5.6, 7.5 and 12.4h to complete the heating under normal hot start, respectively. According to the liquid phase rate curve on the right, the phase transition starts at 3.5, 4.7, 6.6 and 11h, and ends at 5.5, 7.5, 10.2 and 17h, respectively. The heating time of normal use of valley electric heating should be controlled within 6-8h, so the heating rod power is selected as 5e6W/m³.

## 3.2 Numerical Simulation of Heat Release Process

The main factors influencing the heat release performance of the aluminum-silicon phase change energy storage device are the flow rate of the heat exchange fluid and the diameter of the heat exchange pipe. To cooperate with traditional thermal power generation, it is necessary to heat the normal-temperature water to approximately 550K and then enter the boiler evaporation tube to participate in the boiler steam circulation. Referring to the boiler design manual [9], three pipe diameters of 10mm, 20mm, and 30mm, and five flow rates of 0.5, 1, 3, 5, and 10m/s were selected here for arrangement and combination to find the best pipe diameter and flow rate matching the working conditions.

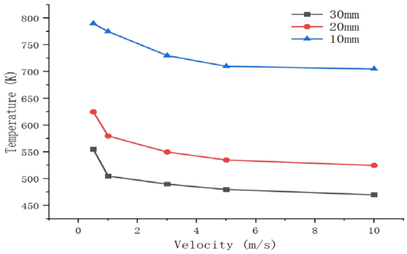


**Fig. 5.** Fluid outlet temperature corresponding to different pipe diameters and flow rates near the phase transition point

As illustrated in Figure 5, the outlet temperature of the heat exchange fluid exhibits a direct correlation with pipe diameter; specifically, a reduction in the diameter of the heat exchange pipe results in an increase in the outlet fluid temperature. Furthermore, a decrease in flow rate corresponds to an elevation in outlet fluid temperature. Notably, when the pipe diameter is larger and the fluid flow rate falls below 1 m/s, the influence of flow rate on outlet temperature becomes more pronounced. At a pipe diameter of 20 mm, the outlet fluid temperature approaches 550 K, thereby meeting design specifications; consequently, this scenario involving a 20 mm pipe diameter is selected for further investigation into heat release processes.

When the diameter of the pipe is 20mm, the temperature of the PCM and the outlet temperature of the heat exchange fluid under five flow rates are monitored, and the results obtained are shown in Figure 6.

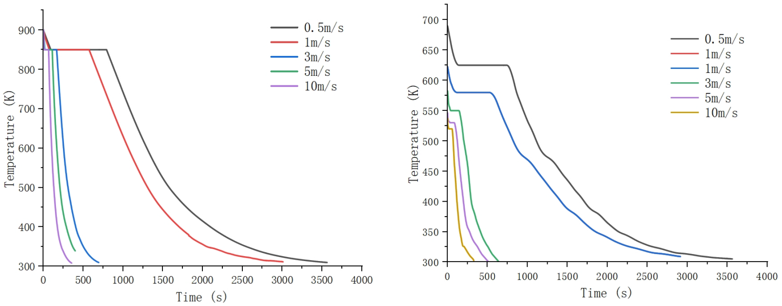


**Fig. 6.** a) PCM temperature and b) outlet temperature of heat exchange fluid at different flow rates with pipe diameter of 20mm

The heat release duration of the phase change latent heat storage device can be broadly categorized into two segments: latent heat release duration and sensible heat release duration. The latent heat release duration refers to the period during which the liquid phase fraction of the phase change material (PCM) begins to transition until all solidification is complete, at which point the liquid phase fraction reaches zero. Although sensible heat storage occurs during this interval, its contribution is significantly lower than that of latent heat and can therefore be disregarded. The sensible heat release duration encompasses all time outside of the latent heat release period within the total thermal discharge timeframe (when PCM average temperature decreases to 520K). Figure 7 illustrates the corresponding durations for latent heat release, sensible heat release, total thermal discharge time, and utilization efficiency across varying inlet velocities.

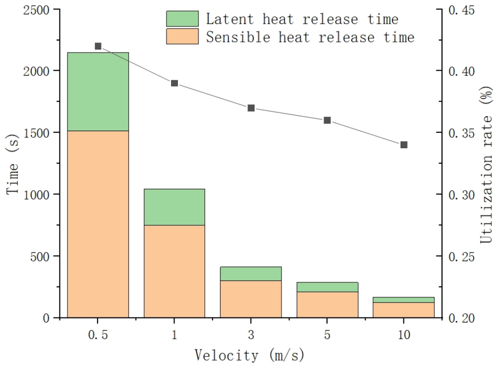


**Fig. 7.** Latent heat, sensible heat release time and latent heat utilization rate at different flow rates at pipe diameter of 20mm

As illustrated in Figure 7, the duration of latent heat release constitutes a significant portion of the total heat release time. Furthermore, it is observed that the total heat release time diminishes with an increase in inlet velocity, primarily attributed to a reduction in latent heat release duration. Although variations in flow rate substantially impact the device's heat release timing, the ratio of sensible to latent heat release remains relatively constant. The duration of latent heat release is crucial for influencing overall heat release time, maintaining approximately 40%. When the inlet velocity escalates from 0.5 m/s to 10 m/s, the utilization efficiency declines from 42% to 34%. As inlet speed increases, this efficiency gradually decreases due to a reduced proportion of outlet temperature aligning with the threshold temperature for available output; consequently, availability rates diminish. Therefore, in practical applications—considering factors such as power consumption, thermal transfer efficiency, and utilization rates—the optimal inlet flow rate is determined to be 1 m/s.

## 4 Conclusion

This paper establishes a three-dimensional model of an aluminum-silicon phase change energy storage device and analyzes the impact of various factors on the heat storage and release processes through numerical simulations. By examining indicators such as system heat exchange efficiency, heat release utilization rate, and heat release power, we investigate how variables including heating rod power and arrangement mode, heat exchange pipe diameter, and inlet flow rate affect the system's thermal storage and discharge performance. The conclusions drawn are as follows:

In comparison to the scenario where only the inner heating rod is utilized, the implementation of an outer heating rod results in a more uniform internal temperature distribution. Additionally, the heating efficiency of a single heating rod is enhanced by 38%, with an optimal power selection for the heating rod set at 5e6 W/m$^3$. Under these design conditions, various diameters of heat exchange pipes and inlet fluid velocities were systematically analyzed; it was determined that when the pipe diameter is 20 mm, the outlet temperature of the heat exchange fluid meets specified requirements. Taking into account both heat release duration and utilization rate comprehensively, it was found that at a flow rate of 1 m/s under this pipe diameter, the latent heat utilization rate achieves 40%, resulting in optimal heat transfer performance.

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