Numerical study of liquid medium based packed bed cold storage in liquid air energy storage system

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Abstract. Liquid air energy storage (LAES) represents a promising large-scale energy storage technology that supports renewable electricity integration and reduces carbon emissions. The cold energy storage unit plays a critical role in determining the efficiency of the LAES system. Currently, solid-phase packed beds are commonly used as cold energy storage units in LAES due to their safety and ease of arrangement. However, the thermocline effect within packed beds significantly reduces cold energy storage efficiency. To address this issue, this study introduces an innovative cold storage device employing a liquid heat transfer fluid in a packed bed. This study conducts a numerical analysis based on a porous media model to investigate the impact of internal packed bed structures on heat transfer and fluid flow. Through optimization of the packed beds' aspect ratio (length-to-diameter), considering both efficiency and pressure drop parameters, the study determines optimal aspect ratios of 3 and 2 for the first-stage and the second-stage packed beds, respectively. These results contribute to the advancement of packed bed cold storage technology, thereby promoting the large-scale application of LAES systems.

1. Introduction

The International Energy Agency (IEA) projects that renewable energy will account for over 42% of global electricity supply by 2028, with wind and solar photovoltaic power constituting 25% of this share [1]. However, inherent uncertainties such as intermittency and volatility pose significant challenges to the reliability and stability of renewable power generation. Energy storage systems present a promising solution to these challenges. Among emerging technologies, Liquid Air Energy Storage (LAES) offers distinct advantages in deployment flexibility, environmental compatibility, and cost-effectiveness for long-duration, large-capacity applications [2]. These characteristics position LAES as a highly promising large-scale energy storage technology.

The fundamental principle of LAES involves liquefying air during off-peak periods (energy storage) and generating electricity during peak demand periods (energy release). As shown in Figure 1, the packed beds cold storage based LAES system employs the two-stage packed beds configuration. Notably, the cold storage unit constitutes the core component of LAES, significantly determining the system's round-trip efficiency [3].

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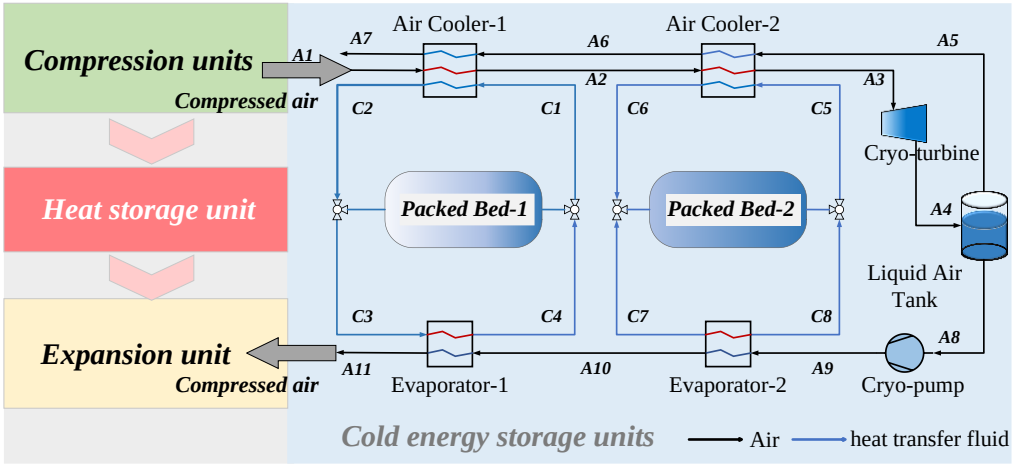

Figure 1. Schematics of the LAES based on packed bed cold storage.

LAES primarily utilizes two cold storage methods: solid phase and liquid phase systems. As the cryogenic liquid medium primarily comprises alkane-based substances, liquid phase cold storage demonstrates advantages in component compactness and thermodynamic efficiency, yet faces challenges regarding operational costs and safety in large-scale implementations [4]. In comparison, solid phase systems generally adopt packed bed configurations using rock based particulate materials, offering benefits in safety, cost-effectiveness, and deployment flexibility. Morgan et al. [5] constructed a 350 kW/2.5 MWh pilot scale LAES facility utilizing quartzite as the cold energy storage medium and air as the heat transfer fluid to evaluate packed bed performance. Chai et al. [6] created a cryogenic energy storage test rig employing liquid nitrogen and granite pebbles (solid particles), conducting parametric studies under various temperature and pressure conditions. In numerical research, Elouali et al. [7] implemented four distinct computational models to examine packed bed thermal behavior, with experimental data verifying the numerical predictions. Wang et al. [8] established that continuous solid phase models provide superior accuracy compared to single phase approximations in characterizing essential heat transfer mechanisms. Regarding structural design, Qu et al. [9] demonstrated that implementing two-stage cascaded packed beds for storing cryogenic energy across temperature ranges enhances overall system efficiency in LAES applications.

Current research predominantly employs gaseous heat transfer fluids (HTF) in packed bed cold storage systems. However, the relatively low thermal conductivity and prolonged heat exchange duration associated with gaseous HTF result in pronounced thermal gradient development that adversely constrains cold storage efficiency. This study proposes an innovative packed bed configuration utilizing liquid-based HTF to enhance thermal exchange dynamics, thereby achieving enhanced efficiency and cost-effectiveness in cold storage units. Furthermore, we conduct a comprehensive investigation into the geometric configurations of the proposed packed bed structure, elucidating their impacts on heat transfer characteristics and system performance. The findings facilitate the development of advanced cold storage solutions for LAES systems, offering valuable insights for both academic research and industrial applications.

2. System Description

The system implements a two-stage packed bed architecture comprising basalt particles as solid packing material, with methanol (Bed 1) and propane (Bed 2) serving as respective heat transfer

fluids. The two-stage packed beds are designed with specific operating temperature ranges and capacity specifications based on the system's cold energy requirements. Operating parameters for the heat transfer fluids are determined through pinch point temperature difference analysis and thermal compatibility requirements. As detailed in Table 1, the packed beds' operational parameters include material properties of basalt particles obtained from Guo et al. [10], while the liquid media properties are derived from Aspen HYSYS simulations.

Figure 2 illustrates the cold storage mechanism where energy exchange is achieved through convective heat transfer between fluid and solid particles, complemented by thermal conduction within the particle matrix. During the charging phase, subcooled liquid enters the packed bed bottom, transfers its cold energy to the solid particles through a counter-current flow, and exits as warmer fluid from the top. Conversely, in the discharging process, relatively warm liquid enters from the top, undergoes cooling via energy absorption from the packed bed, and discharges chilled fluid through the bottom outlet.

Table 1. Parameters of packed beds.

Items	Unit	Bed1	Bed2
Operating temperature(T)	K	185.55-302.15	95.15-177.85
Liquid media		Methanol	Propane
Fluid mass flow (m)	kg/s	0.95	4.42
Specific heat of solid material ($c_{p,s}$)	J	702	504
Thermal conductivity of solid materials (k_s)	W/(m·K)	3.07	3.45
Density of solid material (ρ_s)	Kg/m^3	2688	2688
Diameter of solid particles (d_p)	m	0.01	0.01
Packing porosity (ε)		0.4	0.4

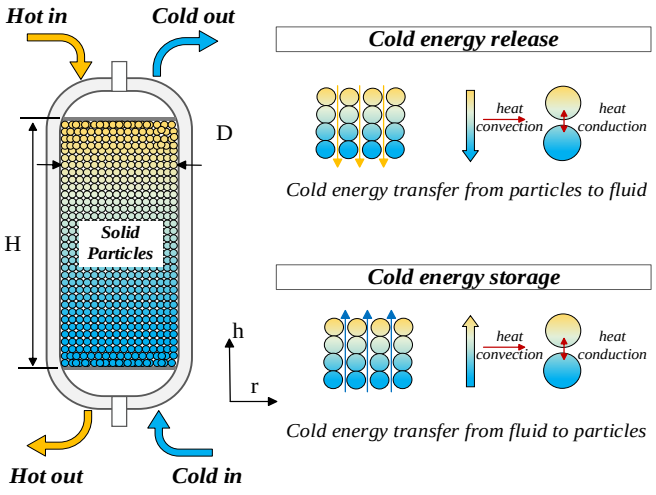

Figure 2. Schematic diagram of the packed bed.

3. Process Calculation

In this study, the flow dynamics and heat transfer processes within the packed bed are modeled using a porous media approach. A 2-D axisymmetric computational model is developed in

COMSOL Multiphysics software for numerical simulation. For thermal characterization, the continuous solid-phase formulation is adopted. The model is simplified using the following assumptions:

(1) The flow is a one-dimensional Newtonian plug flow.

(2) The porosity inside the packed bed is uniform.

(3) The solid rock particles are isotropic with the same diameter.

(4) Adiabatic boundary conditions eliminate heat loss while radiation heat transfer is disregarded.

For solid particles, the energy equation is:

$$(1-\varepsilon)\rho_s c_{p,s}\frac{\partial T_s}{\partial t} = \nabla\cdot[(1-\varepsilon)k_s\nabla T_s] + q_v(T_f - T_s) \tag{1}$$

For fluid medium:

$$\varepsilon\rho_f c_{p,f}\frac{\partial T_f}{\partial t} + \varepsilon\rho_f c_{p,f}u_f\cdot\nabla T_f = \nabla\cdot(\varepsilon k_f\nabla T_f) + q_v(T_s - T_f) \tag{2}$$

Where ε is the porosity of the solid particles, and ρ (kg/m^3) is the density. T (K) is temperature, and$t$ (s) is time. c_p (J/kg·K^{-1}) and k (W/m·K^{-1}) are the specific heat capacity and thermal conductivity. The u_f is the velocity vector. The subscripts s and f stand for solid and fluid.

The interstitial convective heat transfer coefficient q_v is expressed as [3]:

$$q_v = \frac{6(1-\varepsilon)}{d_p}h_{sf} \tag{3}$$

h_{sf} is the interstitial heat transfer coefficient which satisfies the relation [8]:

$$\frac{1}{h_{sf}} = \frac{d_p}{k_f Nu} + \frac{d_p}{10k_s} \tag{4}$$

$$Nu = 2.0 + 1.1Pr^{\frac{1}{3}}Re^{0.6} \tag{5}$$

$$Pr = \frac{\mu_f c_{p,f}}{k_f} \tag{6}$$

$$Re = \frac{||u_f||d_p\rho_f}{\mu_f} \tag{7}$$

Where μ_f is the dynamic viscosity of the fluid.

The pressure drop in packed beds is characterized using the Ergun equation [9]:

$$\frac{\Delta P}{H} = 150\frac{(1-\varepsilon)^2\mu_f}{{d_p}^2\varepsilon^3}u + \frac{1.75(1-\varepsilon)\rho_f}{d_p\varepsilon^3}u^2 \tag{8}$$

The performance of packed beds is characterized by three key efficiency metrics. The charging efficiency (η_{CES}) is quantified as the ratio of cooling energy retained within the packed bed to the input cooling energy during the charging phase. Similarly, the discharging efficiency (η_{CER}) is expressed as the proportion of stored cooling energy released during the discharging process relative to the total stored energy.

$$\eta_{CES} = \frac{m_{ch}\int_0^{t_{ch}}(h_{ch,out} - h_{ch,in})dt}{m_{ch}\int_0^{t_{ch}}(h_{ch,amb} - h_{ch,in})dt} \tag{9}$$

$$\eta_{CER} = \frac{m_{dis}\int_0^{t_{dis}}(h_{dis,in} - h_{ch,out})dt}{m_{ch}\int_0^{t_{ch}}(h_{ch,out} - h_{ch,in})dt} \tag{10}$$

h is the specific enthalpy, t_{ch} is the charging time, t_{dis} is the discharging time, the subscripts ch and dis indicate the charging and discharging process, respectively, and the subscripts in and out indicate the inlet and outlet, respectively.

The round-trip efficiency of cold storage is defined as the ratio of the cold energy released during the discharge phase to the cold energy absorbed by the packed bed during the charging

phase, which equals the product of the charging and discharging efficiencies.

$$\eta_{CSR} = \eta_{CES} \cdot \eta_{CER} \tag{11}$$

To validate the accuracy of the proposed model, we compared its results with experimental data reported in the literature [11]. The geometric dimensions, thermal properties of air and solid materials, and boundary condition parameters were set identically to those in the reference study, as shown in Figure 3. The maximum deviation between our simulation and the experimental data was 5.48%, indicating strong agreement. This model developed in this study demonstrates high accuracy and is capable of reliably predicting the performance of the packed bed.

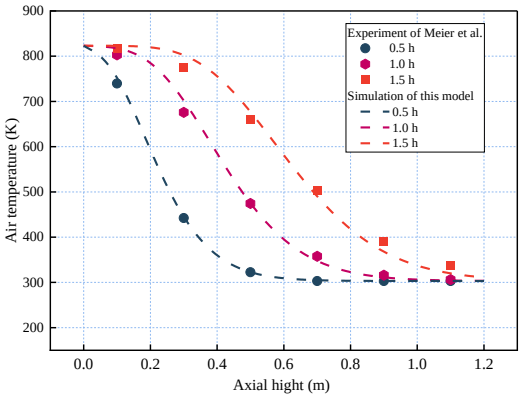

Figure 3. Comparison of temperature distribution between simulation and experimental data.

4. Result Discussion

4.1 Structural design of the packed beds

Based on calculations, the volume of the first-stage cold storage unit is 40.5 m^3, while the volume of the packed bed in the second-stage unit is 169.6 m^3.

$$V_{tot} = \frac{E}{[\varepsilon\rho_f c_{p,f} + (1-\varepsilon)\rho_s c_{p,s}](T_{top} - T_{bot})} \tag{12}$$

V_{tot} is the volume of the cold storage unit. E is the capacity of the cold energy storage system, while T_{top} and T_{bot} are the top and bottom temperatures of the packed bed.

The packed beds are designed with varying aspect ratios according to their respective volumes. Table 2 presents the packed bed dimensions under different aspect ratios for a constant volume. The thermodynamic performance of packed beds with different structural parameters will be analyzed and compared in the following sections.

Table 2. Packed bed dimensions with varying aspect ratios.

	Bed1		Bed2	
Aspect ratio	Diameter (m)	Height (m)	Diameter (m)	Height (m)
1	3.72	3.72	6.00	6.00
2	2.96	5.19	4.76	9.52
3	2.58	7.75	4.16	12.48
4	2.38	9.38	3.78	15.12
5	2.18	10.89	3.51	17.54
6	2.05	12.29	3.30	19.81

4.2 Effect of structural parameters on the performance of first-stage packed bed

First-stage packed bed (bed1) uses methanol as the heat-transfer fluid and operates between 185.55 K and 302.15 K. Figure 4 illustrates how varying aspect ratios affect cold storage and release in the first-stage packed bed. As shown in Figure 4(a), during the charging phase of bed 1, the stored cold energy first increases and then decreases with increasing aspect ratio, reaching a maximum at an aspect ratio of 5. This trend arises from changes in the average outlet temperature: higher outlet temperatures correspond to greater storage capacity. In Figure 4(b), the release profile of bed 1 follows the same pattern as storage, with lower outlet temperatures yielding higher released cold energy.

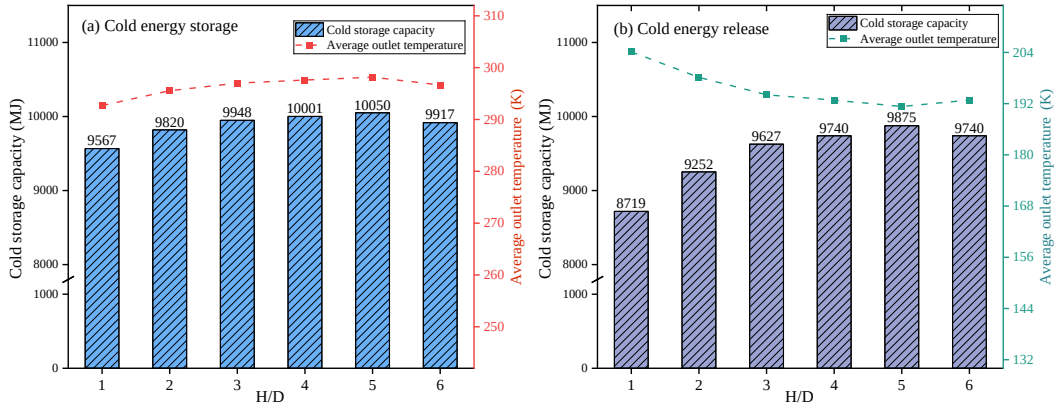

Figure 4. Effect of aspect ratio on the cold storage capacity of the bed1.

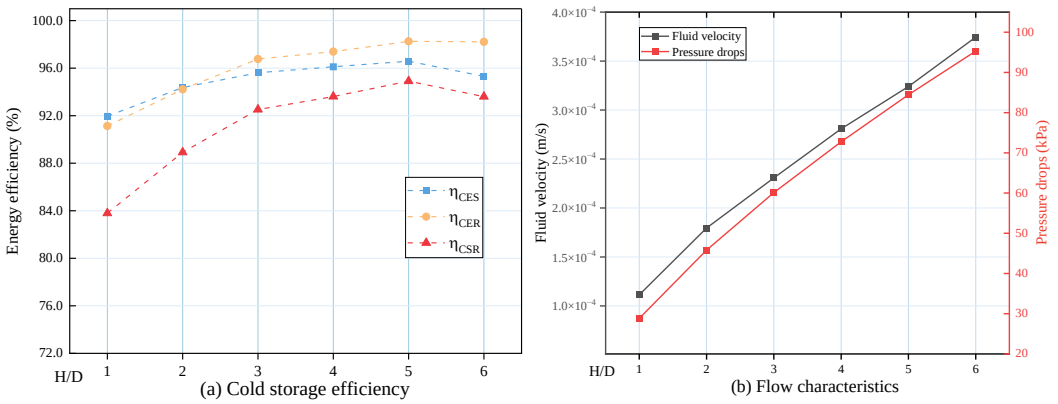

Figure 5. Effect of aspect ratio on the cold storage efficiency and flow characteristics of bed 1.

Figure 5(a) shows that charging efficiency, discharging efficiency, and round-trip efficiency exhibit the same dependence on aspect ratio, peaking at 5. When the aspect ratio increases from 1 to 3, the round-trip efficiency of bed 1 rises most sharply, from 83.79 % to 92.52 %; further increasing the ratio from 3 to 6 changes efficiency by only about 1 %.

The aspect ratio also significantly affects the internal flow characteristics within the packed bed. For a constant fluid flow rate, increasing the aspect ratio narrows the flow channels and thus increases the flow velocity. As shown in Figure 5(b), the fluid velocity in bed 1 rises with aspect ratio. Moreover, higher velocities and greater bed heights markedly increase the pressure drop across the packed bed. When the aspect ratio increases from 1 to 6, the pressure drop through

bed 1 grows from 28.8 kPa to 95.3 kPa. Excessive pressure losses are detrimental to system performance, as they incur additional energy consumption.

4.3 Effect of structural parameters on the performance of second-stage packed bed

The second-stage packed bed (bed2) utilizes propane as the heat transfer fluid to store cold energy at lower temperatures. The aspect ratio significantly influences its thermal performance. As illustrated in Figure 6, the interstitial heat transfer coefficient exhibits a stepwise distribution along different axial positions. With increasing aspect ratio, the axial average interstitial heat transfer coefficient within bed 2 increases, indicating enhanced heat exchange between the fluid and solid surfaces. This stepwise pattern is attributed to the temperature distribution; higher temperatures correspond to higher interstitial heat transfer coefficients. Additionally, the increase in average interstitial heat transfer coefficient with aspect ratio is due to the elevated flow velocity.

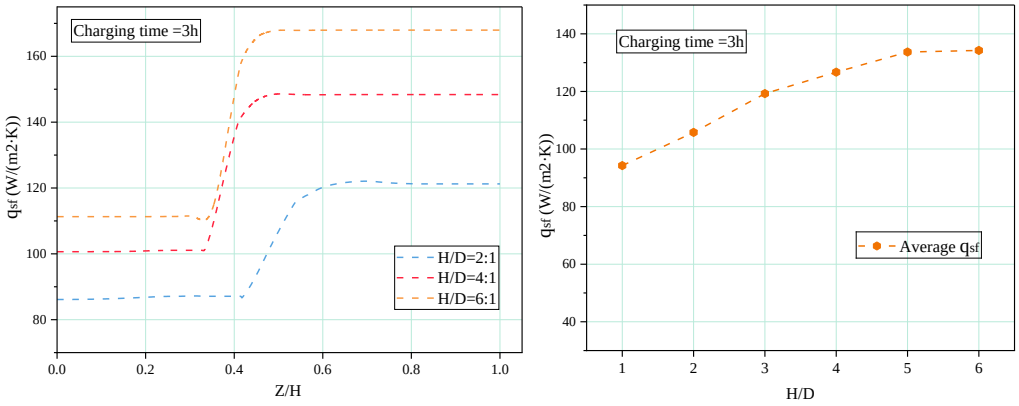

Figure 6. Effect of aspect ratio on the interstitial heat transfer coefficient in bed 2.

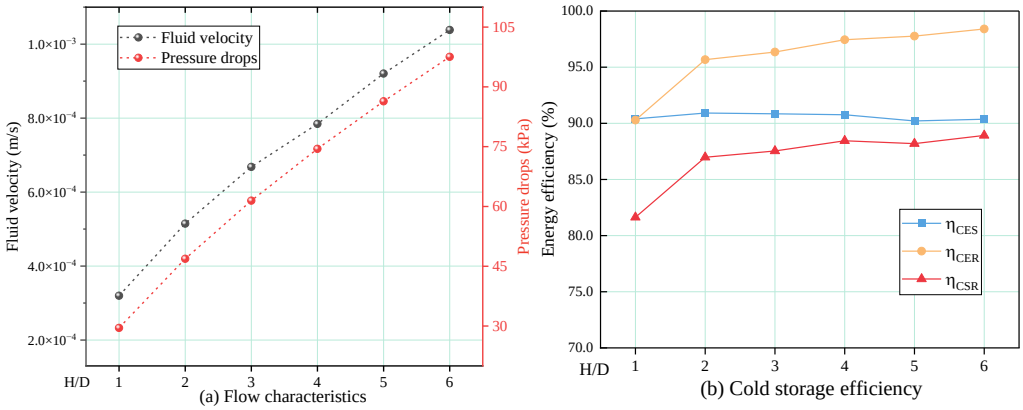

Figure 7. Effect of aspect ratio on the cold storage efficiency and flow characteristics of bed 2.

As shown in Figure 7(a), when the aspect ratio increases from 1 to 6, the fluid velocity in bed 2 triples. Consequently, the interstitial heat transfer coefficient in bed 2 is influenced by both temperature and flow velocity—higher velocities and temperatures lead to higher coefficients. However, higher flow velocities also result in greater pressure drops. Specifically, as the aspect ratio increases from 1 to 6, the pressure drop in bed 2 rises from 29.5 kPa to 95.3 kPa.

The flow and heat transfer characteristics within bed 2 significantly influence its cold storage efficiency. As illustrated in Figure 7(b), the charging efficiency remains relatively constant between 90% and 91% as the aspect ratio increases. In contrast, the discharging efficiency improves with higher aspect ratios, rising from 90.29% to 98.40%. Notably, the round-trip efficiency exhibits a substantial increase when the aspect ratio increases from 1 to 2 but remains nearly unchanged with further increases. Considering both efficiency and pressure drop, an aspect ratio of 2 is identified as optimal for bed 2.

5. Conclusion

LAES face challenges related to energy efficiency and safety, which hinder their widespread adoption. This study introduces an innovative two-stage packed bed cold storage unit utilizing liquid media: methanol serves as the HTF in the first stage and propane in the second. A numerical model was developed to investigate the impact of structural parameters, particularly the aspect ratio, on internal heat transfer and fluid flow characteristics. Findings indicate that increasing the aspect ratio enhances the flow velocity of the heat transfer fluid, thereby improving internal heat transfer performance. However, this also leads to a significant rise in pressure drop within the packed bed, tripling as the aspect ratio increases from 1 to 6.

For bed 1, the most notable improvement in round-trip cold storage efficiency occurs as the aspect ratio increases from 1 to 3, with efficiency rising from 83.79% to 92.52%. Beyond an aspect ratio of 3, efficiency gains plateau, showing only about a 1% increase up to an aspect ratio of 6. In bed 2, round-trip efficiency significantly improves when the aspect ratio increases from 1 to 2, but further increases yield negligible benefits. Considering both efficiency and pressure drop, the optimal aspect ratio is determined to be 3 for bed 1 and 2 for bed 2. This research provides valuable insights for the design and application of cold storage units in LAES systems, aiming to enhance performance while addressing efficiency and safety concerns.

Acknowledgments

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