Energy Proceedings
Vol 44, 2024
ISSN 2004-2965

Improved Rock-based Thermal Energy Storage (RTES) with Perforated Plate Based on Double Thermocline Design

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ABSTRACT

Advancing the transition to renewable energy necessitates significant investments, especially in energy storage solutions to mitigate the variability and intermittency of renewable electricity generation. Rock-based Thermal Energy Storage (RTES) offers the vital adaptability needed to incorporate significant amounts of renewable energy by harnessing excessive energy and storing it in rocks or geological formations. This stored energy can then be used for various applications like heating or generating electricity, providing a reliable and sustainable energy source. One of the main challenges in the widespread use of RTES is the thermal losses (mainly because of the diffusion of thermocline) and the high pressure drop in the packed beds. Hence, a novel RTES system is proposed to overcome these limitations. The design has a perforated plate that delivers air in a certain length from the inlet. The fluid flow and heat transfer inside the packed bed are studied using a 2D Computational Fluid Dynamics (CFD) model considering the local thermal non-equilibrium (LTNE) at the air-rock interface. For the optimal case (perforated length to bed length of 0.7), the proposed design is shown to increase the charging efficiency of the conventional RTES by 14 percent by decreasing the fan power requirement and increasing the stored thermal energy. This improvement is due to the emergence of a secondary thermocline that bypasses the main thermocline, and hence, utilizes the packed bed more efficiently while also reducing the fan power requirement.

Keywords: thermal energy storage, packed bed of rocks, thermocline, thermal efficiency, bed utilization.

NOMENCLATURE

Abbreviations

CFD	Computational Fluid Dynamics
LR	Length Ratio ($l_{\text{perforated}} / l_{\text{bed}}$)
LTNE	Local Thermal Non-Equilibrium
RTES	Rock-based Thermal Energy Storage
TES	Thermal Energy Storage

Symbols

$\dot{m}$	Mass flow rate (kg/s)
κ	Permeability (m^2)
μ	Dynamic viscosity (Pa.s)
ρ	Density (kg/m^3)
ε	Porosity
A	Specific surface area (1/m)
c_p	Specific heat (J/kgK)
D	Packed bed diameter
E	Energy (kJ)
d_p	Particle diameter (m)
g	Gravitational acceleration (m/s^2)
H	Height of the packed bed (m)
h	Heat transfer coefficient (W/m^{2}K)
I	Identity matrix
l	Length (m)
p	Pressure (Pa)
T_f	Fluid temperature (K)
T_s	Solid temperature (K)
t	Time (s)
u	Superficial velocity (m/s)
Nu	Nusselt Number

This is a paper for 15th International Conference on Applied Energy (ICAE2023), Dec. 3-7, 2023, Doha, Qatar.

1. INTRODUCTION

Thanks to the increased adoption of renewable energy sources, our dependence on fossil fuels has been significantly reduced in recent years. To completely detach our power grid from non-renewables, however, energy storage becomes necessary due to the variability and unreliability of renewables[1]. The current energy storage trend is not sustainable though, jeopardizing the transition to a green energy future.

Thermal Energy Storage (TES) has emerged as one of the most sustainable storages because of their affordability[2], eco-friendliness[3], and long life cycle[4]. Among various TES systems, sensible-based TES such as Rock-based TES (RTES) offers one of the most practical solutions to address the energy storage issues[5]. In RTES systems, air is heated by the electricity from renewables which is then blown through a packed bed of rocks to complete the so-called “charging” state. The heated rocks can then store energy for either short-term[6,7] or long-term applications[8]. Using packed of rocks as the storage medium, however, poses its own challenges.

One of the main drawbacks of current RTES design is the thermocline losses[9,10]. The delivery of air behind the thermocline also threatens the affordability of such systems due to the reduction in the storage utilization, which increases the specific material cost of a TES[9]. Although, many studies have targeted TES improvement by incorporating different storage medium[11] and different particle shapes[12], few studies have addressed this issue by modifying the geometry of the RTES[13,14] maintaining the simplicity and reliability of the design.

The objective of this work is to address the concerns regarding the widespread adoption of RTES which is the low efficiency and utilization factor of packed beds. For this, a novel double thermocline system is proposed in which a perforated plate is used to partially deliver the hot air to the RTES system bypassing the main thermocline in the conventional ones. The implication of this study is also crucial for different engineering applications such as wastewater treatment[15], filtration and separation [16], and carbon capture and storage[17], highlighting the importance of developing efficient packed bed systems in various industrial applications.

2. MODEL

2.1 Materials and methods

The proposed packed bed is placed vertically as this alignment exhibits the most efficient operation thanks to the geometrical and buoyancy effect of the flow[18]. A perforated pipe is designed in the center of the packed bed to provide a secondary mass flow rate. Air is considered as the heat transfer fluid and bauxite is used as the storage medium. Also, the packed bed is insulated with refractory brick to minimize the heat loss. The schematic of the proposed design is shown in Fig. 1.

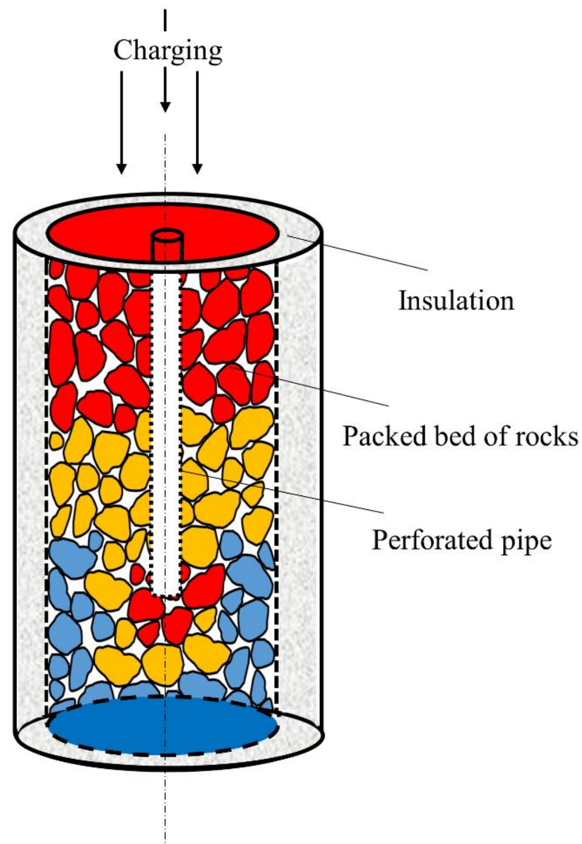


Fig. 1 – Schematic of the proposed RTES system with perforated pipe.

2.2 Theory

Fluid flow and heat transfer in packed bed of rocks can be defined by the volume-average theories behind flow inside porous media[19]. From the continuity equation, one can write:

$$\partial(\varepsilon\rho_{\mathrm{f}})/\partial t+\nabla\cdot(\rho_{\mathrm{f}}u)=0 \tag{1}$$

The conservation of momentum in the fluid region yields:

$$\partial(\varepsilon\rho_{\mathrm{f}}u)/\partial t+(\nabla\cdot u)(\rho_{\mathrm{f}}u)=-\nabla pI \tag{2}$$
$$+\nabla\cdot\left[\mu_{\mathrm{f}}(\nabla u+(\nabla u)^{\mathrm{T}})-\frac{2}{3}\mu_{\mathrm{f}}(\nabla\cdot u)I\right]+\rho_{\mathrm{f}}g-\frac{\mu_{\mathrm{f}}}{\kappa}u$$

Two different energy equations are solved for the solid and fluid regions to include the effect of local thermal non-equilibrium. For the solid and fluid regions, respectively, energy conservation yields:

$$\partial[(1-\varepsilon)\rho_{\mathrm{s}}c_{p,\mathrm{s}}T_{\mathrm{s}}]/\partial t=\nabla\cdot[(1-\varepsilon)k_{\mathrm{s}}\nabla T_{\mathrm{s}}]+h_{\mathrm{fs}}A_{\mathrm{fs}}(T_{\mathrm{f}}-T_{\mathrm{s}}) \tag{3}$$

$$\partial(\varepsilon\rho_{\mathrm{f}}c_{p,\mathrm{f}}T_{\mathrm{f}})/\partial t+\nabla\cdot(\rho_{\mathrm{f}}c_{p,\mathrm{f}}uT_{\mathrm{f}})=\nabla\cdot(\varepsilon k_{\mathrm{f}}\nabla T_{\mathrm{f}})+h_{\mathrm{fs}}A_{\mathrm{fs}}(T_{\mathrm{s}}-T_{\mathrm{f}})$$

where the heat transfer coefficient is defined as:

$$h_{fs} = \frac{k_f}{d_p} Nu \quad (4)$$

in which, the Nusselt number for the gas-solid is estimated by the correlation proposed by Wakao et al.[20]:

$$Nu = \left[2.0 + 1.1 \left(\frac{\rho_f u d_p}{\mu_f} \right)^{0.6} \left(\frac{\nu_f}{\alpha_f} \right)^{1/3} \right] \quad (5)$$

The specific area in the packed bed is also found by:

$$A_{fs} = 6(1-\varepsilon)/d_p \quad (6)$$

In order to solve the above governing equations, ANSYS FLUENT software is used. For this purpose, the 2D domain, as shown in Fig. 2, is considered. The domain is discretized with structured mesh and appropriate boundary conditions are applied as discussed in Refs. [8,18]. In the model, an identical mass flow rate is considered for the perforated plate and the porous zone ($\dot{m}_1 = \dot{m}_2$). This assumption is not the optimal mass flow rate distribution in the proposed design. However, it was used as an initial value to verify the efficiency of this design. Different values of perforated plate length to the packed bed length (LR) is considered ($l_{perforated} / l_{bed}$ = 0.1, 0.3, 0.5, 0.7, and 0.9), to find the optimal length ratio for the perforated RTES system. The novel design is compared to the conventional RTES system where LR=0.

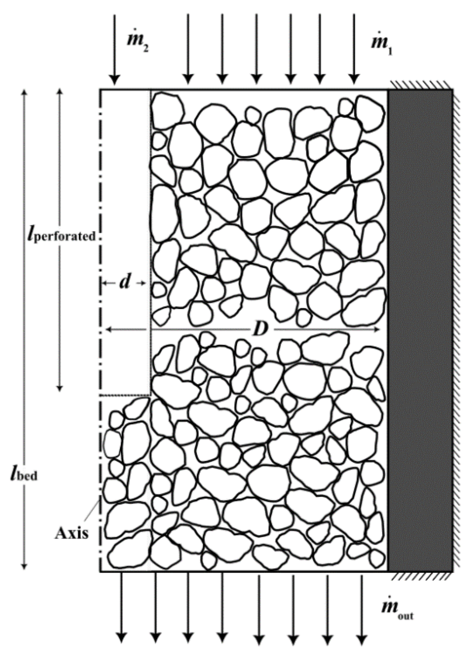
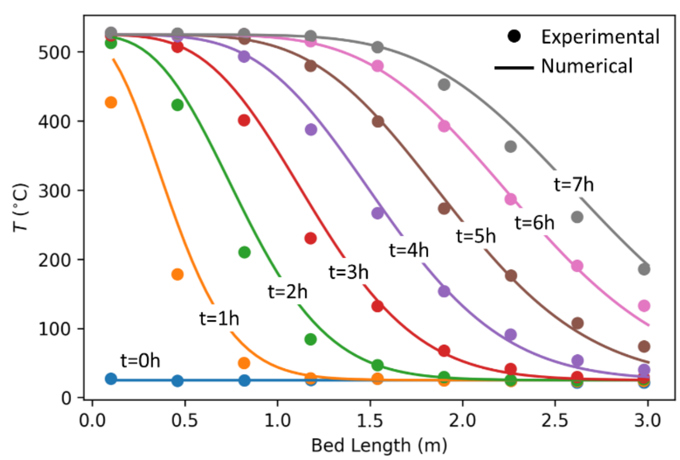


Fig. 2 – Domain of the thermocline RTES system during the charging state.

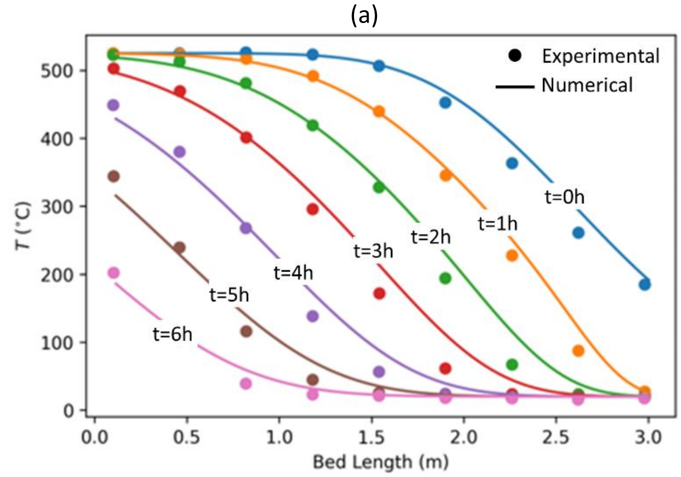
3. VALIDATION

For the validation, an identical geometry to that of Touzo et al.[6] is considered. The TES entails a square cross-section of 1.7 m^2 extended by 3.08 m in length. The bed contains 16 tons of bauxite rubbles. The bed porosity is 0.4 and insulated on the outside with a layer of 200 mm-thick refinery brick. During the charging and discharging phases, the system delivers air at mass flow rates of 0.58 and 0.65 kg/s and temperatures of 525 and 20 °C, respectively. The thermophysical properties of bauxite, air, and the refractory brick are available in Touzo et al[6].

Fig. 3 shows the validation of the volume-average method, where the temperature distributions is validated against benchmarked experimental results for both charging and discharging cases. The results are compared in Fig. 3(a) for the charging cycle, with a maximum error of 34% and an average error of 3.28 % for all thermocouple reads. The results for the discharging cycle show a maximum error of 36% and an average error of 3.08 %, which show an acceptable average error for both charging and discharging cycles.



(a)



(b)

Fig. 3 – Validation of the present numerical study with the experimental result of Touzo et al.[6] in the (a) charging cycle and (b) discharging cycle.

Table 1. Efficiency of different RTES designs.

LR	Charging time (h)	Total Fan Work (kJ)	Total Input Energy (kJ)	Total Stored Energy (kJ)	Charging Efficiency (%)
0	4.52	1210.760	5109885	3299559	64.6
0.1	4.47	1070.375	5045562	3227241	63.9
0.3	4.47	870.672	5042061	3260642	64.7
0.5	4.72	779.413	5322752	3579021	67.2
0.7	**5.76**	**815.529**	**6519571**	**4739633**	**72.7**
0.9	7.31	768.685	8300338	5923558	71.4

4. RESULTS AND DISCUSSIONS

A cut-off temperature of 80% of the inlet temperature is considered for the charging of the RTES, meaning that the system is considered fully charged when the volume average temperature of the rock zone reaches to 365°C. The consideration of a cut-off temperature is necessary for the operation of RTES application as a thermal battery when combined with the upstream (the receiver) and downstream elements (the turbine) of the plant[21].

With the intention of a preliminary efficiency evaluation of the proposed design, only the charging state is considered. The charging efficiency is defined by the ratio of stored energy in the rocks at the end of the charging cycle to the net input and fan power requirement[22–24]:

$$\eta_{\text{charging}} = \frac{E_{\text{stored}}}{E_{\text{input}} + E_{\text{fan}}} \quad (7)$$

Table 1 compares the charging efficiency of conventional RTES systems (LR=0), with the proposed perforated RTES design for different values of perforated plate length to the bed length. The charging efficiency of the proposed design is around 14% higher than the conventional design when LR=0.7, highlighting the superior thermos-fluid performance of perforated RTES.

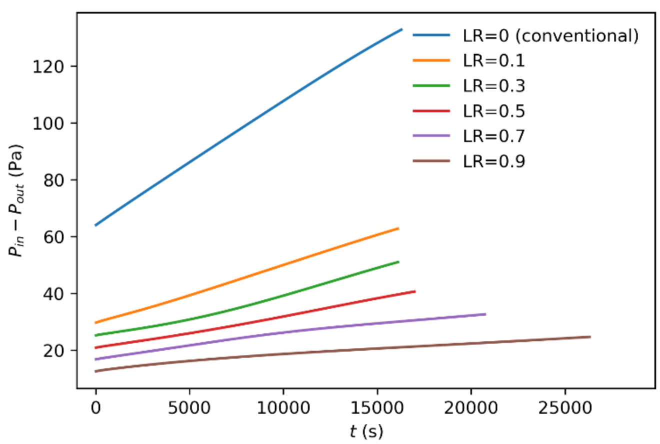


Fig. 4 – Pressure drop along the packed bed in the charging cycle of the RTES.

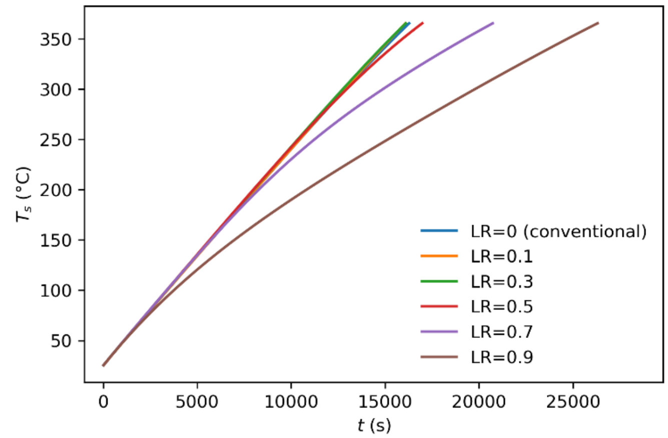


Fig. 5 – Volume-average temperature of the storage medium in the charging cycle of the RTES.

The higher efficiency in the proposed design is due to the reduced fan work requirement in the perforated design (as shown in Fig. 4) as well as the higher energy stored for the double thermocline RTES. The latter is attributed to the higher utilization of the packed bed and the emergence of a secondary thermocline (bypass of the main thermocline) as shown in Fig. 6.

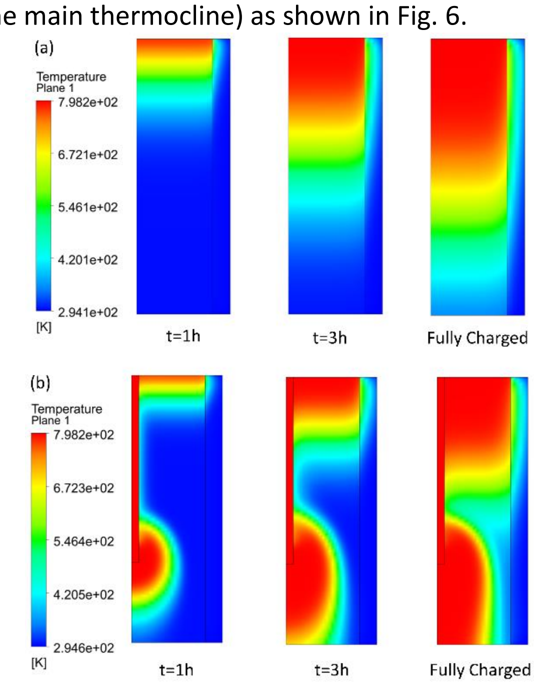


Fig. 6 - Temperature distribution at different times for (a) conventional and (b) proposed design when LR=0.7.

5. CONCLUSIONS

One of the main problems in the widespread application of thermocline based RTES is the relatively low utilization factor and high pressure drop in such systems. In this work, a novel RTES with perforated plate is proposed to improve the utilization of the packed bed and reduce the fan power requirement.

Computational Fluid Dynamics (CFD) based on local thermal non-equilibrium (LTNE) is used to predict the fluid flow and thermal performance of the RTES, with the results showing an average error of 3 % for the charging and discharging cycle.

The proposed design is shown to benefit the system due to the emergence of a secondary thermocline which bypasses the main thermocline observed in the conventional RTES. For the optimized perforated length to packed bed length ratio of 0.7, the charging efficiency is shown to increase by 14 percent, storing 4739633 kJ of energy during 6 hours of charging cycle.

Overall, perforated RTES systems are shown to be a promising energy storage solution offering a higher utilization of the packed bed, higher energy storage capacity, and a lower fan power requirement.

Meanwhile, this study encourages more multi-objective optimization works on finding the global optimum mass flow distribution as well as perforated to bed length ratio for different aspect ratios of the storage container and storage materials for various temperature range applications.

ACKNOWLEDGEMENT

HE and APS gratefully acknowledge the financial support from Natural Sciences and Engineering Research Council of Canada and Fond de Recherche du Quebec Nature et Technologies. LA would like to thank the Department of Mechanical Engineering, University of Sherbrooke, for its financial support.

DECLARATION OF INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. All authors read and approved the final manuscript.

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