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Numerical study of the improvement of an indirect contact mobilized thermal energy storage container

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HIGHLIGHTS

- The phase change behaviours in indirect contact M-TES container were investigated.
- Three options were analyzed for the improvement of container performance.
- The optimal parameters of options described above were discussed and given.

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ABSTRACT

In this paper, the melting and solidification behaviours of the PCM in an indirect contact mobilized thermal energy storage (ICM-TES) container were numerically investigated to facilitate the further understanding of the phase change mechanism in the container. A 2D model was built based on the simplification and assumptions of experiments, which were validated by comparing the results of computations and measurements. Then, three options, i.e., a high thermal conductivity material (expanded graphite) addition, the tube diameter and the adjustment of the internal structure of the container and fin installation, were analyzed to seek effective approaches for the improvement of the ICM-TES performance. The results show that the optimal parameters of the three options are 10 vol.% (expanded graphite proportion), 22 mm (tube diameter) and 0.468 m^2 (fin area). When the three options are applied simultaneously, the charging time is reduced by approximately 74% and the discharging time by 67%.

1. Introduction

The energy consumption of the industrial sector accounts for 37% of global energy consumption [1]. It was reported that 33% of this industrial energy was released as waste heat [2,3]. How to efficiently recover and utilize waste heat is of importance to improving energy efficiency while reducing emissions, including CO_2. The residential sector is also energy-intensive, representing 16–50% of the total national energy consumption [4–6]. For community users, district heating (DH) is often used. However, due to its high initial cost and heavy infrastructure requirements, it is unreasonable and uneconomic to expend the DH network to detached users. Doing so will restrict the delivery of heat for emergency use, e.g., pipeline maintenance or field operations.

With the consideration of above two issues, mobilized thermal energy storage (M-TES), combining waste heat recovery and heat transport for distributed users, was proposed [7,8]. The concept of M-TES is illustrated in Fig. 1. The M-TES system consists of a waste heat source, transport container and distributed users. The whole operational process is composed of two steps: charging and discharging. In charging, the container filled with a phase change material (PCM) is transported to the waste heat source by a lorry. Because of the thermal energy storage technology, the waste heat can be stored in a container. After charging, the container is sent to distributed users and releases heat at the user's demand. Then, the container is carried back to the waste heat source and replenished for the next cycle.

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Nomenclature

Abbreviation	
CHP	combined heat and power
DCM-TES	direct contact mobilized thermal energy storage
HTF	heat transfer fluid
ICM-TES	indirect contact mobilized thermal energy storage
M-TES	mobilized thermal energy storage
PCM	phase change material
Symbols	
A	area
A_{mush}	constant
C	cost (€)
C_P	special heat of PCM (J kg^{-1} K^{-1})
h	total enthalpy (J kg^{-1})
h_{ref}	reference enthalpy (J kg^{-1})
h_s	sensible enthalpy (J kg^{-1})
g	gravitational acceleration (m s^{-2})
k	heat transfer coefficient (W m^{-2} K^{-1})
L	latent heat capacity of PCM (J kg^{-1})
min	minutes
M	mass (kg)
M_{PCM}	mass of PCM (kg)
P	pressure (Pa)

Pr	price (€ kg^{-1})
q_{wall}	heat flux of wall (J m^{-2} s^{-1})
S	energy source term (W m^{-3})
S_u	momentum source term in X axis direction (N m^{-3})
S_w	momentum source term in Z axis direction (N m^{-3})
t	time (s)
T	temperature of PCM (K)
T_l	melting temperature of PCM (K)
T_{ref}	reference temperature (K)
T_s	solidification temperature of PCM (K)
u	velocity magnitude in X coordinate (m s^{-1})
w	velocity magnitude in Z coordinate (m s^{-1})
α_{1-3}	thermal resistance
β	liquid fraction
δ	thickness of wall (m)
Δh	latent heat of PCM (J kg^{-1})
ΔT_{PCM}	temperature difference of PCM (K)
ΔT_O	temperature difference of HTF (K)
ε	constant
λ	thermal conductivity of PCM (W m^{-1} K^{-1})
μ	dynamic viscosity (kg m^{-1} s^{-1})
ρ	density of PCM (kg m^{-3})
ρ_{ref}	reference density (kg m^{-3})

Several studies were conducted on M-TES in recent years. Among the storage materials, erythritol was tested and reported to be an appropriate candidate for M-TES [9–11]. A few other inorganic salts and organic composite materials were also prepared and assayed [12–15]. In terms of the behaviour of the material in the container and the performance of the system, laboratory-scale experiments with direct and indirect contact containers were conducted [16–18]. Moreover, the integration of the combined heat and power (CHP) plant with the M-TES was investigated [19].

As mentioned above, the characteristics of the M-TES system with direct contact and indirect contact containers have been studied. The direct contact M-TES (DCM-TES) showed a better performance than the indirect [20]. However, its disadvantages, including the chemical reaction and decomposition of the PCM due to directly contacting the heat transfer fluid (HTF) at a high temperature [9], restrict its extensive application. At present, high thermal stability candidates for most users have not been found. Therefore, the indirect contact M-TES (ICM-TES) shall also be investigated. Improvements shall be implemented for both the direct and indirect contact containers to enhance the efficiency of the M-TES. The optimization of the DCM-TES container was conducted by experimental and numerical studies [21–23]. The model established in the previous work was valid for simulation with forced convection in a container. However, conductive heat transfer and natural convective heat transfer dominate in the ICM-TES container. According to the best knowledge of the authors, few models have considered the improvement of the ICM-TES container. The purpose of this paper is to investigate how to improve the performance of the ICM-TES container using numerical simulation. The results show that the optimal solutions cause a significant improvement in the performance of the ICM-TES, which provides guidelines for the design and optimization of the ICM-TES container.

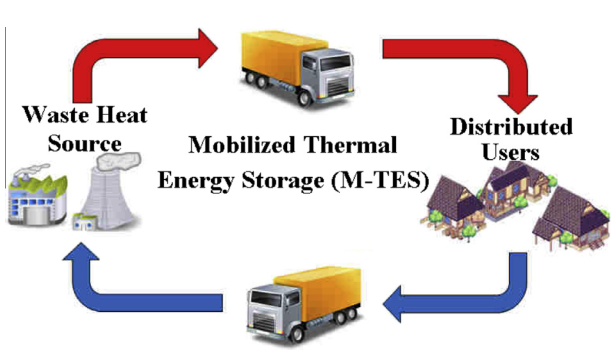

Fig. 1. Schematic diagram of the M-TES system.

2. Description of the ICM-TES experiment

As shown in Fig. 2, the lab-scale ICM-TES experimental system is mainly composed of three parts: a heat source site, container and

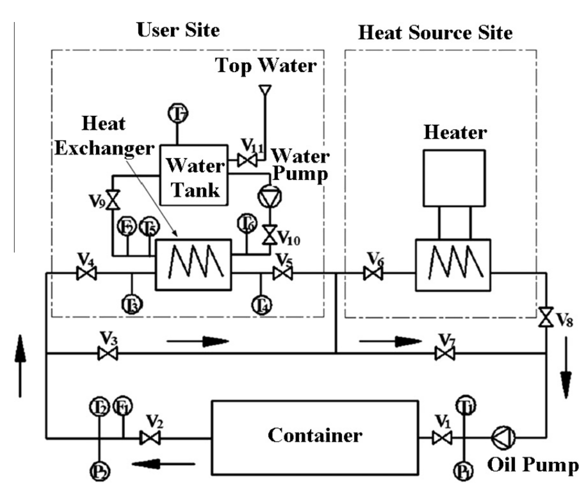

Fig. 2. Schematic diagram of the ICM-TES system.