Energy xxx (2015) 1–12

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Thermodynamic analysis and optimization of cascaded latent heat storage system for energy efficient utilization

H.J. Xu [a, b], C.Y. Zhao [a, *]

[a] Institute of Engineering Thermophysics, Shanghai Jiao Tong University, Shanghai 200240, China
[b] College of Pipeline and Civil Engineering, China University of Petroleum, Qingdao 266580, China

ARTICLE INFO

Article history:
Received 9 February 2015
Received in revised form
23 May 2015
Accepted 22 June 2015
Available online xxx

Keywords:
Cascaded heat storage
Phase change
Entransy dissipation
Thermodynamic optimization
Heat transfer
Energy efficiency

ABSTRACT

CHS (cascaded heat storage) plays a significant role in the improvement of thermal efficiency and the utilization of multi-graded thermal energies. This work presents thermodynamic modeling of the CHS for direct thermal utilization purpose with the lumped parameter method employed for the PCMs. The optimization of temperatures of HTF (heat transfer fluid) and multistage PCMs (phase change materials) is performed based on the entransy theory. Analytical solutions for optimal temperatures of HTF and PCMs are obtained with heat optimization for fixed entransy dissipation and entransy optimization for fixed heat. The existence conditions of the two optimizations are put forward with corresponding critical stage numbers proposed. The results show that CHS can extend applicable temperature scope for multi-graded thermal energies. Heat transfer enhancement is essential for multistage heat storage. The uniform distribution of parameter C in each stage is beneficial for thermal efficiency improvement. The present thermodynamic optimization and solutions can guide the selection of PCMs, and establish a benchmark for similar research in CHS.

1. Introduction

Energy conservation is an important solution for energy crisis and environment degradation. As a good manner for energy conservation, thermal storage can be used to maintain the balance between the thermal energy demand and the supply, which can substantially improve the thermal energy utilization efficiency and reduce the waste heat discharged to the environment. In general, heat can be stored with sensible [1], latent [2] and chemical [3] manners. Amongst these heat storage technologies, the solid–liquid latent heat storage is the most commonly used heat storage form for high storage density, almost isothermal characteristics and good safety [4]. Owing to these advantages, phase-change heat storage can find its applications in solar thermal power [5], off-peak electric storage [6], waste heat recycling [7], thermal environment for buildings [8], thermal management of electronics [9], and so on.

Much interest is paid on the research of phase-change heat storage and the main contents are focused on the preparation of appropriate PCM (phase change materials) with stable property, good conduction performance and high energy density [10], phase-change heat transfer enhancement techniques [11], thermodynamic evaluation and optimization of phase-change heat storage systems [12], and so on. However, for the SHS (single heat storage) with one-stage PCM, the outlet temperature of HTF (heat transfer fluid) is high and the driving force of phase-change heat transfer is reduced due to the sharply decreased HTF temperature. This remarkably restricts the efficiency of thermal energy utilization. In this condition, the CHS (cascaded heat storage) system can be employed to improve the thermal efficiency [13], especially for the thermal energy with broad temperature band. In the CHS system, multiple PCMs with different phase-change temperatures are used to store thermal energies with different grades. Compared with SHS, CHS owns the advantages of high thermal efficiency, good thermal storage ability, and efficient heat transfer rate.

The concept of CHS was firstly put forward by Farid and Kansawa [14] and was experimentally investigated by Farid et al. [15]. They indicated that the appropriate combination of PCMs can effectively improve the exergy efficiency of thermal storage system. Lim et al. [16] performed thermodynamic optimization for two-stage and multi-stage heat storage system and pointed out that CHS with multiple PCMs can reduce the irreversible exergy loss and improve the heat transfer rate. Adebiyi et al. [17] theoretically investigated the high-temperature cascaded thermal storage

* Corresponding author.
E-mail address: changying.zhao@sjtu.edu.cn (C.Y. Zhao).

http://dx.doi.org/10.1016/j.energy.2015.06.131
0360-5442/

Nomenclature

A	convective heat transfer area, m^2
Ac	Crossectional area, m^2
c_p	heat capacity at constant pressure, J kg^{-1} K^{-1}
E	entransy, W K
F	Lagrange function, W
G	Lagrange function, W K
h	convective heat-transfer coefficient, W m^{-2} K^{-1}
H	height of the rectangular, m
L	length of the rectangular, m
$\dot{m}$	mass flow rate, kg s^{-1}
n	stage number of the cascaded heat storage system
Nu	Nusselt number
Pe	Peclect number
Q	heat, W
T	temperature, K
T_{in}	inlet temperature, K
T_0	surrounding temperature, K

Greek symbols

η	thermal efficiency
Θ	fixed value of heat, W
κ	ratio of temperature drop
λ	Lagrange multipler, K^{-1}
μ	Lagrange multipler, K
φ	entransy dissipation, W K
Φ	fixed value of entransy dissipation, W K

Subscripts

in	inlet
m	melting/mean
max	maximum
min	minimum
opt	optimal
pr	practical
tot	total

system with multiple PCMs and found that the increase in thermal efficiency by using CHS is from 13% to 26% compared with SHS. Watanabe et al. [18] performed theoretical investigation on the three-stage tubular phase change thermal storage device and found that the CHS can obviously improve the heat transfer rate. Watanabe and Kanzawa [19] conducted optimization for the cascaded thermal storage system based on the second law of thermodynamics and the results shows that appropriate temperature distribution of multiple PCMs in CHS systems is very important for exergy efficiency and the measures promoting the heat storage rate can also improve the thermal efficiency. Gong et al. [20] presented the 1D model on heat storage and release with multiple PCMs with the finite element method and the research focuse was emphasized on the effects of PCM temperature distribution, thermo-physical properties and boundary conditions on the unsteady heat transfer process. The results show that the stable and reversible state can obviously improve the heat storage/release rates. Aceves et al. [21] simplified the thermodynamics analysis on cascaded thermal storage system and obtained the optimum phase change temperatures of PCMs based on the second law. Shaikh and Lafdi [22] performed numerical simulation on CHS in a 2D enclosure filled with multiple PCMs based on the finite volume method and indicated that the CHS form can enhance the heat transfer in thermal storage. Michels and Pitz-Paal [23] studied the three-stage thermal storage device for parabolic trough solar power plant. They showed that the corresponding PCMs own relatively low heat capacity, low thermal conductivity and serious corrosive characteristic, which restricts the application of CHS. Seeniraj and Narasimhan [24] numerically simulated the cascaded thermal storage module with extended fins for solar energy utilization and found that the employment of multiple PCMs can obviously promote the thermal storage rate and make the outlet HTF temperature more uniform. Rady [25] experimentally and numerically investigated the cascaded thermal storage characteristics of PCMs with granular particles and indicated that the employment of multiple PCMs can obviously reduce the exergy loss for thermal storage. Cui et al. [26] theoretically investigated the cascaded thermal storage for solar receiver and found that the cascade thermal storage can lower the temperature fluctuation of working fluid and decrease the weight and scale of solar receiver. Fang et al. [27] performed an experiment for the effect of PCM fraction on three-stage thermal storage system and found that a maximum thermal storage rate exist for an optimal PCM fraction. Tian et al. [28] investigated the metal-foam enhanced three-stage thermal storage system and indicated that the heat transfer rate of cascaded thermal storage is 30% higher than the single-stage thermal storage.

Overall, nearly all the thermodynamic analyses for cascaded thermal storage systems are based on either the first law of thermodynamics or the traditional balance equation of exergy (also known as available energy) in thermodynamic second law. For thermal storage systems, the minimization of exergy loss is usually an important criterion for optimization and design, which is closely connected with entropy generation minimization. There are mainly two purposes for heat storage: storing useful work and temporarily storing heat for subsequent direct thermal utilization. The entropy generation minimization theory plays an important role in the thermodynamic evaluation of heat-work conversion [29], which was extended to heat transfer by Gyarmati [30] and Bejan [31]. Charach and Rubinstein [32] also used the entropy generation minimization method to optimize the melting and solidification heat transfer with conduction. However, in optimizing the heat transfer with entropy generation minimization theory, the entropy generation paradox in heat exchanger optimization was realized by many investigators, such as Bejan [33], Hesselgreaves [34], and Shah and Skiepko [35]. To make this problem clear, Guo et al. [36,37] proposed the concept of entransy and its dissipation, which is successfully applied in optimization of heat transfer with heat conduction. The entransy dissipation can be treated as an effective evaluation and optimization criterion for irreversibility of heat transfer, including heat storage. The researches on the thermodynamic optimization of thermal storage with entransy theory were reported by only a few scholars, such as Xia et al. [38], Wang et al. [39], and Tao et al. [40]. Xia et al. [38] performed entransy minimization analysis for 1-D melting process in a solid–liquid interface problem. Wang et al. [39] established the entransy balance equations for the closed unsteady system for melting process with solid–liquid interface and obtained the expressions for entransy and its dissipation. Tao et al. [40] numerically simulated the two-stage thermal storage device and obtained the optimum temperature with the entransy theory for the two-stage thermal storage system. It can be seen that CHS plays a significant role in the improvement of thermal efficiency and multi-graded thermal energy utilization, but using entransy dissipation theory to optimize heat storage is still in its early age. Thermodynamic modeling of CHS system for thermal

Please cite this article in press as: Xu HJ, Zhao CY, Thermodynamic analysis and optimization of cascaded latent heat storage system for energy efficient utilization, Energy (2015), http://dx.doi.org/10.1016/j.energy.2015.06.131