ARTICLE IN PRESS

Applied Energy xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Applied Energy

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

Thermodynamic analysis and optimization of multistage latent heat storage unit under unsteady inlet temperature based on entransy theory

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HIGHLIGHTS

- Optimization model for LHS with unsteady inlet temperature was proposed.
- Performance optimizations of multistage LHS unit were performed.
- Expressions of optimum PCM melting temperatures were derived.
- Effects of geometric parameters were investigated.
- Results are significant for PCMs selection.

ARTICLE INFO

Keywords:
Multistage latent heat storage
Entransy theory
Unsteady state
Performance optimization

ABSTRACT

An optimization model for a multistage latent heat storage (LHS) unit with unsteady heat transfer fluid (HTF) inlet temperature was proposed. Thermodynamic analysis and optimization were performed based on the entransy theory. The expressions of the optimum phase change material (PCM) melting temperatures ($T_{m,opt}$) were derived. The effects of geometric parameters and unsteady HTF inlet temperature on the optimum phase change temperatures were investigated. The results indicate that with the increase of stage number (n), $T_{m1,opt}$ increases and $T_{mn,opt}$ decreases, which is beneficial to extend the selection range of PCM. For fixed entransy dissipation condition, increasing n will not change the fluctuation of the HTF outlet temperature; however a nearly uniform HTF outlet temperature can be obtained by increasing unit length (L). The unsteady HTF inlet temperature has great effects on the optimum phase change temperature. For a 3-stage LHS unit, the optimum phase change temperature of each stage increases by 14.9 K, 26.4 K and 38.0 K respectively with respect to the values obtained by steady method, which causes the heat storage capacity decreases by 6.1% and entransy dissipation decreases by 10.6%. The present work can provide guidance for the design of the multistage LHS unit with unsteady HTF inlet temperature.

1. Introduction

Thermal energy storage (TES) technology is an effective way to improve energy efficiency, which can resolve the contradiction between energy supply and demand. At present, the major thermal energy storage methods include sensible heat storage, latent heat storage and chemical heat storage, among which latent heat storage (LHS) is found to be particularly attractive, because of its high energy storage density and constant phase change heat storage temperature.

However, the phase change material (PCM) used in LHS system usually has a disadvantage of low thermal conductivity [1], which reduces the efficiency of the LHS system. Hence heat transfer enhancement techniques for LHS system are necessary. A lot of performance enhance methods have been developed, such as enhancing heat transfer surface using fins [2,3] and encapsulated PCM [4], enhancing PCM thermal conductivity with metal foams [4] and nanomaterial [5,6]. Another effective method to improve LHS performance is using multiple PCMs to form multistage LHS system. In a single-stage LHS system, the temperature difference between the heat transfer fluid (HTF) and PCM decreases along the HTF flow direction, which weakens the LHS unit performance, especially for the later part. However, in multistage LHS system, the temperature difference is more uniform due to the high melting temperature PCM near the inlet of the HTF and the low melting temperature PCM near the outlet. Thus the performance

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http://dx.doi.org/10.1016/j.apenergy.2017.10.021
Received 6 January 2017; Received in revised form 11 September 2017; Accepted 5 October 2017

Nomenclature

A	a constant defined in the text
a	coefficient of sine function, K
B	a constant defined in the text
b	coefficient of sine function, K
C	a constant defined in the text
c_p	specific heat, J kg^{-1} K^{-1}
F	Lagrange function
G	entransy, J K
h	heat transfer coefficient, W m^{-2} K^{-1}
L	length of the PCM unit, m
M	a constant defined in the text
$\dot{m}$	mass flow rate, kg s^{-1}
n	stage number of the multistage LHS unit
Q	thermal storage capacity, J
q_i	heat transfer rate, W
R_i	the radius of the inner tube, m
R_o	the radius of the shell side, m
t	time, s
T	temperature, K
T_e	environmental temperature, K
T_{in}	inlet temperature, K
T_m	melting temperature of PCM, K
v	HTF inlet velocity, m s^{-1}
x	axial coordinate, m
Greek symbols	
Θ	the given heat storage capacity, J
λ	Lagrange multiplier
ρ	density, kg m^{-3}
τ	thermal storage time, s
φ	entransy dissipation, J K
Φ	the given entransy dissipation, J K
ϕ	entransy dissipation rate, W K
Subscripts	
cr	critical
i	the *i*th-stage
max	maximum
min	minimum
opt	optimal

can be effectively improved through the reasonable arrangement of PCMs.

Many researchers have studied the multistage LHS system through numerical or experimental methods [7–13]. Seeniraj et al. [7] numerically investigated the LHS unit employing multiple PCMs and fins. The results show a considerable enhancement in the melting rate of PCMs and nearly uniform exit temperature of HTF. Tao and He [8] proposed a compound enhancement method to improve the LHS performance of a shell-and-tube LHS unit, which consists of internal enhanced tube and multiple PCMs. The results show that the compound enhancement method can further reduce the PCM melting time and total charging time compared with simple enhancement method. Cui et al. [9] presented a new solar receiver thermal storage model consisting of multiple PCMs and found that the multistage system has a higher heat transfer rate and a smaller fluctuation of the outlet temperature compared with the single-PCM system. The results show that the cascaded PCM structure has a higher latent heat utilization rate; however, this benefit was found to be highly sensitive to the selected melting temperatures. Mosaffa et al. [11,12] numerically investigated a free cooling system with a multistage LHS unit by the effective heat capacity method. The optimum geometry of the PCM slabs corresponding to the optimum coefficient of performance was obtained. Peiró et al. [13] explored a two-PCM unit experimentally, which introduced an effectiveness enhancement of above 19% if compared with a single-PCM configuration and a higher uniformity of the HTF temperature difference.

However, in those studies, the selection of PCMs was mostly based on arbitrary choice and the order of PCMs was just linearly arranged according to their melting temperatures. In order to achieve the best performance of the multistage LHS system, it's essential to find the optimum PCMs properties, which largely depends on the theoretical analysis.

Li et al. [14] developed a mathematical model of a two-stage LHS system and indicated that the melting temperature of each PCM influence the overall exergetic efficiency in different patterns. Finally, an optimum melting temperature range for PCMs was recommended. Xu et al. [15] performed an exergy optimization for cascaded latent cold/heat storage and the optimal PCM temperature was derived. They found that the multistage LHS with large stage number can not only extend temperature band but also reduce the outlet HTF exergy. And the heat transfer enhancement is necessary for a cascaded thermal storage system. Ezra et al. [16] numerically solved a mathematical model of a multistage LHS unit. An optimal way was found to achieve the shortest melting (charging) time.

Throughout the process of the research on the multistage LHS system, it can be concluded that most of the early work is performed on the basis of the First Law of Thermodynamics, exergy theory and entropy theory. In recent years a new concept called entransy was proposed by Guo et al. [17,18] to describe the heat transfer ability in the heat transfer process. The entransy dissipation was derived to measure the irreversibility of an arbitrary heat transfer process. And the entransy dissipation extremum theory has been used to optimize the heat transfer process [19–22]. However, there are only a few articles on phase change heat transfer optimization, especially on LHS system.

Xia et al. [23] optimized the liquid-solid phase change process of a simple one-dimensional slab taking entransy dissipation minimization as optimization objective. Cheng et al. [24,25] extended the entransy theory to analyze and optimize the performance of evaporative cooling systems. Tao et al. [26] analyzed and optimized the performance a two-stage LHS unit based on the entransy theory. The formulas for the optimum PCMs melting temperatures of the two-stage LHS unit was derived. Xu et al. [27] extended Tao [26]'s formula to the *n*-stage LHS system and found that the uniform distribution of parameter *C* is beneficial to the thermal efficiency improvement.

So far, all the theoretical research on the multistage LHS system based on entransy theory is basically conducted under steady state conditions [26,27]. However, in the practical application, the HTF inlet temperature is usually unsteady. Tao et al. [28] numerically studied a two dimensional shell-and-tube LHS unit, regarding the non-steady-state boundary. They found that even when the average HTF inlet temperature in an hour is fixed at a constant value, PCM melting time is influenced by the variation forms of the HTF inlet temperature. Therefore, the optimization of the multistage LHS system under unsteady state conditions is very necessary. In present paper, the optimization of the multistage LHS system with unsteady HTF inlet temperature is performed based on the entransy theory. And the expressions of the optimum phase change temperatures under different constraint conditions are given. The influence of various parameters on the optimization results and system performance are discussed.

2. Physical model and governing equations

2.1. Physical model

The physical model of multistage LHS unit is shown in Fig. 1. The unit consists of an inner tube and a shell. HTF flows in the inner tube