International Journal of Heat and Mass Transfer 114 (2017) 1013–1024

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Optimization of double-stage latent heat storage unit in whole cycle with entransy analysis

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ARTICLE INFO

Article history:
Received 3 December 2016
Received in revised form 20 June 2017
Accepted 20 June 2017

Keywords:
Entransy
Optimization
Double-stage
Latent heat storage (LHS)
Phase-change materials (PCMs)
Cycle

ABSTRACT

Double-stage latent heat storage (LHS) unit is believed as a valid design to improve performance by separating LHS unit into two portions filled with different phase-change materials (PCMs). In this paper, double-stage LHS unit is optimized with entransy analysis. Different from those in references, optimization is conducted for LHS unit in whole cycle, i.e. charging and discharging process. Charging rate and inlet temperature of heat transfer fluid (HTF) are constrained constant. All the heat stored in charging process is released in discharging process. The criterion formulas of optimum melting temperature match is derived. The performance, i.e. discharging rate and entransy dissipation of double-stage LHS unit optimized in whole cycle, is compared with those of single-stage LHS unit and those of double-stage LHS unit optimized in only charging process. It is concluded that optimum melting temperature match exists in double-stage LHS unit in whole cycle. Performance is enhanced in double-stage LHS unit optimized in whole cycle. Constraint of discharging rate equal to charging rate is not favored in entransy analysis. Comparing with those in single-stage LHS unit, discharging rate of double-stage LHS unit optimized in whole cycle is always larger and entransy dissipation is always smaller. The difference of entransy dissipation between that of double-stage LHS unit optimized in whole cycle and that of single-stage LHS unit increases with coefficient *c*. It is also concluded that the double-stage LHS unit optimized in whole cycle is not the same as that optimized in only charging process. Comparing with those in double-stage LHS unit optimized in only charging process, entransy dissipation of double-stage LHS unit optimized in whole cycle is smaller, but discharging rate is also smaller. The difference of entransy dissipation between that of double-stage LHS unit optimized in whole cycle and that of double-stage LHS unit optimized in only charging process decreases with coefficient *c*. Optimization results are discussed in typical heat storage cases. The results are helpful to optimal design and performance improvement of LHS unit.

1. Introduction

Latent heat storage (LHS) is a kind of thermal energy storage technology, based on melting and solidification of phase-change materials (PCMs). It has been widely researched [1–14], due to its advantages, such as high energy storage density and constant phase-change temperature. Operation of LHS unit includes charging process and discharging process. In charging process, heat is stored in melting PCMs; in discharging process, heat is released from solidifying PCMs.

Uniformity of temperature difference between PCMs and HTF is favored for LHS unit. Therefore, transforming single-stage unit into double-stage, as well as multi-stage, by adopting PMCs with different phase-change temperatures, is believed as a valid method to improve performance of LHS unit [15–19]. Moreover, entransy dissipation extremum theory is considered to judge, investigate and optimize performance of LHS unit, because only heat transfer, rather than conversion between heat and work, is involved in operation of LHS unit.

Entransy is a physical quantity measuring the ability of one matter to transfer heat to the other [20], due to temperature difference of two matters [21]. It is always dissipated in irreversible heat transfer process [22,23]. Therefore, entransy dissipation extremum theory is the optimization criterion for heat transfer process [24–29]. It has been successfully used in optimization of conductive [30–32], convective [33–35] and radiative heat transfer process [36–38]. Besides single-phase convective heat transfer in tube, entransy dissipation extremum theory is also used in optimization of phase-change heat transfer process in LHS unit [39–42].

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http://dx.doi.org/10.1016/j.ijheatmasstransfer.2017.06.085
0017-9310/

Nomenclature

A	surface area for convective heat transfer, m^2
c	coefficient
C_p	specific heat, J kg^{-1} K^{-1}
E	entransy dissipation, J K
$\dot{G}$	entransy, J K s^{-1}
i	index number
K	convective heat transfer coefficient, W m^{-2} K^{-1}
$\dot{m}$	mass flow of HTF, kg s^{-1}
M	parameter
N	parameter
$\dot{Q}$	heat transfer rate, W
T	temperature, K
Y	parameter

Greek symbols

α	parameter
β	parameter
δ	parameter
Δ	Logarithmic Mean Difference, LMD
Φ	entransy dissipation rate, J K s^{-1}
τ	period in process
χ	parameter
Θ	constraint value of heat transfer rate, W

Subscripts

0	total value of c
1	inlet value of HTF in 1st-portion; value of c in 1st-portion; index of Y
2	outlet value of HTF in 1st-portion; value of c in 2nd-portion; index of Y
c	value of double-stage LHS unit optimized in only charging process
i	index number
i + 1	index number
in	inlet value
m	melting temperature
out	outlet value
s	value of single-stage LHS unit
w	value of double-stage LHS unit optimized in whole cycle

Superscripts

c	value in charging process; value of double-stage LHS unit optimized in only charging process
d	value in discharging process
e	temperature corresponding to equal discharging rate to charging rate
s	value of single-stage LHS unit
w	value of double-stage LHS unit optimized in whole cycle

Formulas of melting temperature match in double-stage LHS unit has been derived [1] for the first time by Tao et. al. This is a great step in practice, which is important as guidance for optimal design of LHS unit, without complex simulation or calculation case by case. It is concluded that entransy dissipation rate of double-stage LHS unit, optimized with PCMs melting temperature match, is always lower than that of single-stage LHS unit, under the constraint of constant heat transfer rate.

However, optimization in references is usually conducted with melting temperature match in only charging process of LHS unit, where PCMs is melting and is heated by hot heat transfer fluid (HTF). Therefore, optimization results only correspond to least entransy dissipation rate in charging process. Is it also the criterion for optimization of LHS unit in whole cycle? If not, what is the optimization criterion of double-stage LHS unit, from the viewpoint of entransy dissipation extremum theory, with whole cycle under consideration? This is usually found in those cases, in which the operation conditions are pre-set, e.g. inlet HTF temperatures in both charging and discharging process are prescribed. Then, the optimization in whole cycle is more important than that in only charging process.

The objective of this paper is further to conduct optimization of double-stage LHS unit in whole cycle with entransy analysis, under the constraint of constant heat transfer rate in charging process. Equal separation of c for LHS unit is considered. Optimization criterion formulas on match of PCMs melting temperature is derived. The effects of optimization in only charging process on performance of LHS unit in whole cycle is also discussed.

2. Entransy analysis on double-stage LHS unit

2.1. Double-stage LHS unit

A shell-and-tube configuration of double-stage LHS unit in whole cycle is depicted in Fig. 1. HTF is flowing at the tube-side, and PCMs is filled at the shell-side. Charging process is shown in Fig. 1a and discharging process is shown in Fig. 1b. The tube between PCMs and HTF is not shown. It is transformed from single-stage LHS unit, by equally separating it into two portions filled with PCMs at different melting temperatures. This means that the volume of PCMs, as well as the surface area for convective heat transfer, in two portions are the same.

As shown in Fig. 1, along with the flow direction of HTF in charging process, LHS unit is separated into two portions, naming as 1st- and 2nd-portion. The melting temperatures of PCMs in 1st- and 2nd-portion are defined as T_{m_1} and T_{m_2}, respectively. During discharging process, cold HTF flows in reverse direction. PCMs is solidified and HTF is heated.

To simplify the problem and to derive optimization criterion formulae, following hypothesis is assumed in this paper:

(1) inlet temperature of HTF in charging process is kept constant at T_1^c;
(2) convective heat transfer coefficient K in whole cycle is assumed constant and the same for two portions;
(3) thermal-physical properties of HTF are independent of temperature;
(4) mass flow rate in charging process is the same as that in discharging process;
(5) PCMs temperature in each portion is kept constant and uniform at its melting and solidification temperature in charging and discharging process, respectively;
(6) solidification temperature of PCMs in each portion is equal to its corresponding melting temperature;
(7) thermal resistance of tube and thermal leakage are neglected;
(8) PCMs is thermally insulated between portions.

2.2. Heat transfer in double-stage LHS unit

Based on assumptions above, heat transfer in double-stage LHS unit is equivalent to accumulation of convective heat transfer in