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Electrical circuit analogy for analysis and optimization of absorption energy storage systems

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ABSTRACT

Due to the rapid development of renewable energy and waste energy recovery, absorption energy storage is an important technology with promising future. However, because most researches focus on working fluid flow rather than energy flow used in electric power systems, it is hard to analyze the entire systems as a whole. This contribution introduces the electrical circuit analogy to analyze absorption energy storage systems from the perspective of energy flow. It turns the energy storage and release processes to their corresponding electrical circuits, which are described by Kirchhoff's laws in circuitous philosophy instead of complex component analysis. On this basis, optimization of an absorption energy storage system is converted to a conditional extremum problem, and applying the Lagrange multiplier method offers the optimization equations to directly obtain the optimal structural and operating parameters with the best performance. In this contribution, the optimized results offer 13% and 25% higher power in the storage and release cases, respectively, compared to existing experimental results. Besides, inspired from the batteries connected in parallel and series, the design of a multi-stage absorption energy storage system could store low-grade heat but provide high-grade heat, which further reveals the superior of the newly proposed approach.

1. Introduction

Due to high energy storage density, low heat loss and environmental friendliness, absorption energy storage technology favors to energy conservation and environment protection. Hence, it attracts more and more attentions and has increasingly widespread applications. During the past several years, a large number of researches aim to find the variation law and design pattern for absorption energy storage systems with different goals and thereafter build advanced absorption energy storage systems for different applications.

Experimental researches came first among all studies. For short-term energy storage in solar air-conditioning systems, in order to match solar energy incoming to cooling load and consequently increase the solar energy utilization efficiency, Grassie et al. [1] added a solution container to an absorption energy storage system as a buffer pool to maintain the concentration of working solution stable to ensure the operation of the entire refrigeration cycle [2]. Sheridan et al. [3] optimized the capacity of fluid reservoir to prevent the cycle from being interrupted by over concentrated solution in the generator. Wilbur et al. [4,5] analyzed a solar air-conditioning system with an absorption energy storage facility and suggested setting up a reservoir as a buffer device to lower the temperature of driving heat source, which made it possible to use low-grade heat. On the other hand, for long-term solar energy storage, Weber et al. [6] established a closed absorption energy storage system with NaOH-H_2O working pair. Generator and condenser in the system during the energy storage process in summer turned to be evaporator and absorber, respectively, during the energy release process in winter. The results showed that the solar energy stored in summer ensured the heating requirement in winter, and they also improved the system to two-stage, which applied a plate solar collector to drive the system.

Besides, absorption energy storage technology could not only work alone but also cooperate with other energy storage technologies. For instance, the absorption energy storage system could work with heat pumps. Rizza [7] proposed a lithium bromide absorption energy storage system combined with a regular

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Nomenclatures

A	area, m^2
c_p	constant pressure specific heat, J kg^{-1} K^{-1}
K	heat transfer coefficient, W m^{-2} K^{-1}
KA	thermal conductance, W K^{-1}
m	mass flow rate, kg s^{-1}
p	pressure, Pa
P	energy storage/release power, W K
Q, q	heat transfer rate, W
R	entransy dissipation-based thermal resistance, K W^{-1}
T	temperature, K
U	electrical potential, V
X	concentration, %
ξ	fluid arrangement factor of heat exchanger
Φ	entransy dissipation rate, W K
λ	Lagrange multiplier
Π	Lagrange Function
γ	latent heat of vaporization of water, kJ kg^{-1}
ε	voltage in thermal circuit diagram, also temperature difference, K

Subscripts

a	absorber
c	condenser
e	evaporator
g	generator
i	inlet, internal
o	outlet
s	solution
v	vapor
w	water
1	system 1
2	system 2

refrigerator and the heat for generator was supplied by an electric heat pump. In this case the energy is stored through heat pump at the times of low electrical demand, and cooling is supplied with stored cryogen at the times of peak electrical demand. The absorption system could also combine with other systems using different working materials. Rizza [8] later combined an R123 vapor refrigerator with another lithium bromide absorption energy storage system to build an energy storage air-conditioning system. Experimental researches, however, only gave specific data sets for a certain system, but were hard to reveal the relation between system performances and operation conditions.

Apart from experimental researches, theoretical studies contributed a lot to analyze and optimize absorption energy storage systems in detail. For steady-state simulation, Sheridan et al. [3] established a mathematical model to analyze the performance of an absorption energy storage system used in Brisbane. Kaushik et al. [9] built a dynamic mathematical model for a system using NH_3-H_2O working pair and found that the combination of cryogen storage and other energy storage technologies leaded to better performance, where the optimal match of the system was important. Le Pierres et al. [10] analyzed a long-term absorption energy storage system with LiBr-H_2O working pair. The analysis showed that it needed two containers both 20 m^3 for the heating load of a 120 m^2 room, and the energy storage density of the system ranged from 180 to 310 kWh/m^3. Xu et al. [11] established both a dynamic mathematical model and an operating parameter determination model for an absorption energy storage system using LiBr solution, and the models gave the relation between the operating parameters of each device and the system performances under different operating conditions. N'Tsoukpoe et al. [12] established a dynamic simulation model for an absorption energy storage system, and found that the solution flow rate was a critical parameter influencing the process performance and crystallization in the solution storage tank would increase the storage density more than three times. Mazloumi et al. [13] built a dynamic thermodynamic model to simulate an absorption cycle throughout the whole day, and found that the mass flow rate in the collector had a negligible effect on the minimum required collector area, but had a significant effect on the optimal capacity of the storage tank.

Theoretical researches on absorption energy storage systems have not been fully developed yet. First, most theoretical researches are based simply on energy conservation principle and heat transfer analysis, which means their perspectives are locked on working fluid flow. Next, since there are always several working fluids in a certain absorption energy storage system and not all fluids flow through each component during a complete cycle, it is inevitable to introduce many intermediate unknown variables to analyze each component separately, which could be avoided by treating the system as an ensemble. Therefore, the global relation between system performance and design parameters, which is of great importance for energy conservation, is still hidden. Most importantly, it is because that the analysis perspective of absorption energy storage systems is different from that of electric power systems, thermal energy systems are hard to be comprehended and analyzed with electric energy systems as a whole for further energy conservation. Therefore, it is desired to introduce a new analysis perspective to focus on the energy flow in the system instead of the traditional working fluid flow in components and further globally not locally matching the system parameters for the best performance.

Recently, Guo et al. [14] introduced the concepts of entransy and entransy dissipation in heat transfer analysis, and defined the ratio of entransy dissipation rate to squared heat flow rate as the entransy dissipation-based thermal resistance (EDTR). Based on the definition of EDTR together with the energy conservation and heat transfer equations, Chen [15] derived the expressions of EDTR for several different kinds of heat exchangers. Meanwhile, Chen et al. [16] introduced an electrical circuit analogy method to reveal the inherent global relations of different decision parameters in heat exchanger networks, and proposed a theoretical method to optimize the system performance as a whole under some constraints. However, this method was strictly restricted to pure heat transfer processes in heat exchanger networks, which means any system with energy storage or energy conversion is not compatible with this method yet. It is natural to wonder whether the method extends to analyze absorption energy storage systems including both heat and mass transfer processes.

Based on this idea, this contribution aims to extend the electrical circuit analogy method to analyze and optimize absorption energy storage systems. First, a typical absorption energy storage system is introduced and analyzed based on the electrical circuit analogy, which converts the system into its equivalent electrical circuit to describe the combination of evaporating and condensing processes. On this basis, the governing equations of the entire energy storage system can be directly obtained through circuit laws instead of coupled energy conservation and heat transfer equations. Then, the