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Cumulative exergy analysis of ice thermal storage air conditioning system

Jing Pu [a,b], Guilian Liu [a,*], Xiao Feng [a]

[a] Department of Chemical Engineering, Xi'an Jiaotong University, Xi'an 710049, Shaanxi Province, China
[b] Taiyuan Institute of Architecture Design & Research, Taiyuan 030002, Shanxi Province, China

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ABSTRACT

Based on the cumulative exergy analysis method, the effect of incorporating the Ice Thermal Storage (ITS) air conditioning system in power supply is analyzed. Not only the cumulative exergy of air conditioning system is considered, but also that of the processes consuming the power generated by the same peak regulating unit. The results show that the total cumulative exergy consumption of all processes consuming the power supplied by the peak generating unit, increases as the ITS system is applied. However, the average cumulative exergy variation, which is the ratio between the increment of the cumulative exergy consumption (ΔCEx) and the cooling load of the ITS system (Q_{ITS}), decreases slightly as Q_{ITS} increases. It exhibits a linear relationship with the operating load of the power generating unit and Q_{ITS}. And, it decreases as either of the two parameters increases. These results are verified by two case studies.

1. Introduction

Along with the fast-paced development of modern construction in China, the energy consumption of air conditioning increases rapidly and is fast approaching the international level. As the environmental temperature changes, the cooling load and the electricity consumption change correspondingly. During the periods of high outdoor temperatures, they are much higher than those during the periods with lower outdoor temperatures. Hence, the use of residential air conditioning equipment combined with other residential, commercial and industrial usage creates a high peak electricity demand in the summer. While during the off-peak hours, the power demand is far lower than that in the peak periods.

To meet the peak electricity demand, utilities are forced to introduce new power generating unit, which is termed as peak regulating unit. Since these requirements typically occur for only peak period, which is relatively short in comparison to the overall time period during which energy is consumed, the peak regulating unit can only be operated at the design load during these short periods. While during the off-peak periods, it is operated at a load that is far lower than the design value. Although the peak regulating unit has good operating characteristics under different loads, it has low efficiency when it is not operated under design load and its coal consumption for generating a kW h electricity will increase as its load decreases. This will increase the natural resource consumption significantly.

Ice Thermal Storage (ITS) system stores energy by producing ice during off-peak periods and releases the stored energy during the peak periods. It is an effective measure for shifting peak period power demand to the off-peak nighttime hours [1–4]. Since the electricity price during off-peak hours is lower than that in peak hours, applying ITS in the air conditioning system is a cost-effective measure, and its application is increasing [5,6]. However, ITS may consume more natural resources because of the following two reasons. First, the performance coefficient of the ice production process is lower than that of the conventional air conditioning. Second, the natural resource (such as coal) consumption for generating a kW h electricity during off-peak periods is higher than that in the peak periods. On the other hand, applying the ITS air conditioning system will increase the load of the peak generating unit during the off-peak periods, and decrease the coal consumption for generating a kW h electricity. From this perspective, applying ITS air conditioning system will decrease the natural resource consumption of the system which consumes the electricity supplied by the peak regulating unit. Therefore, it is necessary to quantitatively evaluate the effect of applying ITS air conditioning system on the natural resource consumption with all the factors introduced above considered.

Most of the previous studies evaluated the ITS air conditioning system according to the operating costs and economic benefits, while the raw material consumption aspect is often ignored. For example, Chaichana et al. [7] developed a model for comparing the conventional air cooling systems and ITS systems based on the energy cost. The results show that at most 55% of the electricity cost can be saved by applying the ITS system. To minimize the operating cost and shorten the payback period, Liu and Wang [8] designed an optimal scheme for ITS air conditioning system. With both life-cycle cost and payback period considered, Chen et al. [9] optimized an ITS air conditioning system by the dynamic programming algorithm. Ashok and Banerjee [10] presented a method for

* Corresponding author. Tel.: +86 (0) 29 8266 8980.
E-mail address: guilianliui@mail.xjtu.edu.cn (G. Liu).

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Nomenclature

b	the coal consumption for generating per kW electricity (g/kW h)
B	daily coal consumption (kg/day)
CEx	daily cumulative exergy consumption (kJ/day)
COP	the performance coefficient of refrigerating system
D	the operating load of the peak regulating unit (kW)
E	total electric consumption per day (kJ/day)
$q(t)$	the hourly cooling load at time t (kW)
Q	daily cooling load (kJ/day)
R	the cumulative exergy of coal (kJ/kg)
t	time (h)
ΔCEx	the variation of the cumulative exergy consumption when the ITS is applied (kJ/day)

Greek letters

ε	the increase of the coal consumption per kW h electricity when the operating load of the power generating unit decreases by 1 MW (g/kW h)

Subscripts

AC	air conditioning system
d	equipment
design	design parameter
e	energy
i	item *i* in the system
ITS	ice thermal storage system
m	raw material
off	off-peak hours
on	peak hours
other	processes consume the electricity generated by the peak regulating unit exclude the air conditioning system

Superscripts

$'$	the parameter of the air conditioning system with ITS

identifying the optimal chilled water storage capacity and corresponding operating strategy. Lee et al. [11] adopted particle swarm algorithm to design the optimal operating strategy for ITS air conditioning systems. The objective of this method is to minimize the life-cycle cost, and the results show that the power consumption rises with the increase of ITS capacity. Habeebullah [12] made an economic feasibility analysis for ITS system.

Furthermore, Wang et al. [13] developed a fuzzy multi-criteria model for designing the optimal cool storage system. In this model, the subjectivity of the decision-maker can be combined with the objectivity of numerical data. Soltan and many other researchers studied the water solidification process by either numerical simulation or experiments [14–21].

To evaluate the effect of ITS on the basis of resource utilization, cumulative exergy analysis can be an effective approach. The cumulative exergy consumption of a product is the total exergy of all the consumed natural resources [22,23]. Yang et al. [24] compared the expanded cumulative exergy consumption of two residential heating systems. One is a hot-water heating system with mechanical ventilation; the other is a forced-air heating (FAH) system. Feng et al. [25] studied the cumulative exergy consumption of a heat exchange process. Pu et al. [26] compared the cumulative exergy consumption of different air conditioning systems. These studies show that cumulative exergy analysis is a valuable analysis method based on the concept of resource consumption. However, there are no studies evaluating the ITS air conditioning systems based on the cumulative exergy consumption in the open literature.

In this paper, the cumulative exergy analysis model will be built for ITS air conditioning systems with all the processes consuming the energy supplied by the peak regulating unit considered.

2. Background

2.1. Peak regulating unit

To meet the peak electricity requirements during the peak periods, utilities are hard pressed to adopt the peak regulating unit. Since the operating load of the peak regulating unit decreases significantly from the peak periods to off-peak periods, its coal consumption for generating a kW h electricity will increase significantly. Generally, the coal consumption for power generation has a linear relationship with the operating load [27]. If the operating load decreases by 1 MW, the coal consumption for power generation will increase by ε (kg/kW h). Take a 300 MW facility as example, the coal consumption per kW h electricity will increase by 0.18 g/kWh as its operating load decreases by 1 MW, i.e. (ε = 0.18 g/kW h) [27]. Thus, the coal consumption for power generation during the peak and off-peak periods, b_{on} and b_{off}, satisfies following equation:

$$b_{off} = b_{on} + \varepsilon(D_{design} - D_{off}) \quad (1)$$

where D_{design} and D_{off} represent the design load and operating load of the peak regulating unit, respectively.

2.2. The ice thermal storage system

The ice thermal storage systems use the latent heat of ice to store cooling energy. In these systems, ice is generated in the off-peak hours, and the stored cooling energy is used to meet the air conditioning requirements during the peak periods. Thus, part of the power demand is shifted from peak daytime periods to off-peak night time periods [28].

There are different types of ice storage devices, such as the solid ice brine coil, ice in containers and ice slurry system [29]. In ice slurry system shown in Fig. 1, brine is pumped from storage to the top of an ice generator where it flows as a thin film down the inside surface of tubes whose outside surfaces are cooled by evaporating refrigerant. When the brine is cooled to its freezing point, discrete ice crystals form in the fluid film. The resultant slurry is pumped to storage, where the ice crystals form a floating porous ice pack.

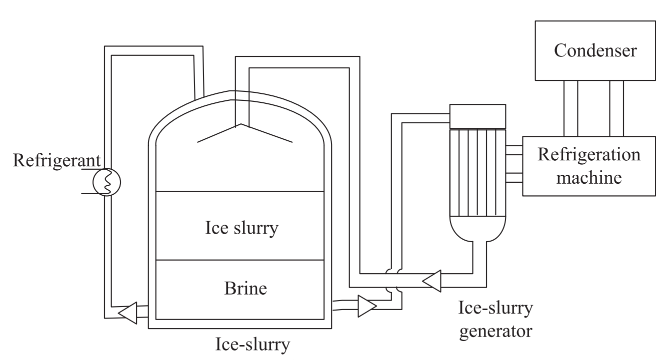

Fig. 1. The cycle of the ice-slurry storage system [29].