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# Four E analysis and multi-objective optimization of an ice thermal energy storage for air-conditioning applications

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ABSTRACT

One method to reduce the peak electrical demand of air-conditioning (A/C) systems is incorporating an ice thermal energy storage (ITES) with the A/C system. In this paper, an ITES system was modeled for A/C applications and analyzed from energy, exergy, economic, and environmental aspects (4E analysis). Applying the genetic algorithm optimization technique, multi-objective optimization of the system was performed and the optimum values of system design parameters were obtained. The exergy efficiency and total cost rate were considered as objective functions. The performance of modeled ITES system was also compared with a conventional system. The results indicated that electricity consumption in ITES system was 10.9% lower than that of the conventional one. Furthermore, $0.659 \times 10^6$ kg of $CO_2$ was prevented from emitting into the atmosphere in comparison with the conventional system. The extra capital cost associated with using ITES system was paid back with savings in electricity consumption in 3.39 years.



# Système à accumulation thermique de glace pour les applications en conditionnement d'air : Analyse tenant compte des aspects énergétiques, exergétiques, économiques et environnementaux et optimisation à objectifs multiples

Mots clés : Accumulation thermique de glace - système ; Énergie ; Exergie ; Économie ; Environnement ; Optimisation à objectifs multiples

## 1. Introduction

A major part of electricity consumption in residential, commercial, administrative, and industrial sectors is related to A/C systems. With increasing the electricity consumption for this type of demand, the capacity of power plants as well as their fuel consumption has to increase and the major portion of $CO_2$ emissions is allocated to the fossil fuel consumption for electricity generation. In addition, it is noteworthy that the main cause of global warming and climate change is due to

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**Nomenclature**

| | |
|---|---|
| $A$ | heat transfer surface area ($m^2$) |
| $c_{elec}$ | electricity cost (US$ k W $h^{-1}$) |
| COP | coefficient of performance |
| $c_p$ | specific heat at constant pressure (kJ $kg^{-1}K^{-1}$) |
| CRF | capital recovery factor |
| $E$ | exergy (kWh) |
| $\dot{E}$ | exergy flow rate (kW) |
| $F$ | logarithmic mean temperature difference correction factor |
| $h$ | specific enthalpy (kJ $kg^{-1}$) |
| $i$ | interest rate (%) |
| $i_{ph}$ | melting latent heat (kJ $kg^{-1}$) |
| $k$ | specific heat ratio |
| $m$ | mass (kg) |
| $\dot{m}$ | mass flow rate (kg $s^{-1}$) |
| $N$ | operational hours in a year |
| $n$ | system life time (year) |
| NTU | number of transfer unit |
| $p$ | pressure (Pa), extra cost payback period (year) |
| $\dot{Q}$ | the time rate of heat transfer (kW) |
| $Q_C$ | cooling load (kWh) |
| $\dot{Q}_C$ | cooling load (kW) |
| $R_{th}$ | total thermal resistance ($m^2$ K k $W^{-1}$) |
| $s$ | specific entropy (kJ $kg^{-1}K^{-1}$) |
| $T$ | temperature (K) |
| $U$ | overall heat transfer coefficient (kW $m^{-2}$ $K^{-1}$) |
| $u$ | specific internal energy (kJ $kg^{-1}$) |
| $V$ | volume ($m^3$) |
| $\dot{V}$ | volumetric flow rate ($m^3$ $s^{-1}$) |
| $\dot{W}$ | the time rate of energy transfer by work (kW) |
| $Z$ | capital cost (US$) |
| $\dot{Z}$ | capital cost rate (US$ $s^{-1}$) |

*Greek symbols*

| | |
|---|---|
| $\eta$ | isentropic efficiency |
| $\mu_{CO_2}$ | $CO_2$ emission factor (kg k $Wh^{-1}$) |
| $\nu$ | specific volume ($m^3$ $kg^{-1}$) |
| $\rho$ | density (kg $m^{-3}$) |
| $\Phi$ | maintenance factor |
| $\phi$ | relative humidity |
| $\psi$ | exergy efficiency |
| $\omega$ | absolute humidity (kg water vapor $kg^{-1}$ dry air) |

*Subscripts*

| | |
|---|---|
| a | air |
| AHU | air handling unit |
| amb | ambient |
| C | cooling load |
| CH | chemical |
| ch | charging |
| Comp | compressor |
| Cond | condenser |
| CT | cooling tower |
| cv | control volume |
| CW | chilled water |
| D | destruction |
| dc | discharging |
| EV | evaporator |
| EX | expansion valve |
| f | final |
| FP | freezing point |
| g | gas |
| i | inlet |
| int | initial |
| inv | investment |
| l | leakage |
| LMTD | Logarithmic Mean Temperature Difference |
| main | maintenance |
| o | outlet |
| op | operation |
| PH | physical |
| r | refrigerant |
| ST | storage tank |
| suc | suction |
| sv | salvage value |
| t | time |
| tot | total |
| w | water |
| WB | wet-bulb |

the fact that the rate of $CO_2$ emissions is increasing tremendously (Habeebullah, 2007; UNEP, 2000). Thus, in order to preserve fossil fuel sources and also to decrease $CO_2$ and other greenhouse gases emissions, finding an appropriate way to reduce electricity consumption is necessary.

Using cold thermal energy storage (CTES) system is one way to reduce electricity consumption of A/C systems during on-peak hours. The operating principle of these systems for A/C applications is to store cooling energy in a cooling medium during off-peak hours for utilization in space conditioning during on-peak hours (Dincer and Rosen, 2011). In other words, CTES systems shift the electricity peak load associated with A/C cooling of buildings from on-peak hours (during daytime) to off-peak hours (during nighttime). The cooling medium may be chilled water, ice, or eutectic salts. Among the mentioned cooling mediums, ITES systems use smaller tanks for a given amount of cooling energy. This is why ITES systems have been receiving much more attention in recent years for use in A/C applications (Dincer, 2002). In general, CTES systems operate on either full storage or partial storage scenarios. For full storage strategy, the total cooling energy used during on-peak hours is supplied by the storage tank while the ice maker operates only at nighttime. Therefore, the ice maker (and the whole charging cycle) is turned off during on-peak hours. For partial storage scenario, only a part of on-peak load is covered by the storage tank while a chiller provides the rest of the cooling load. In this strategy, the chiller (refrigeration system) operates continuously during the day (mostly at the rated capacity). During off-peak hours, the excess energy is stored, which is utilized later to cover the on-peak load (Habeebullah, 2007). Although the use of CTES systems and their auxiliary equipment incur extra initial costs, these additional costs are paid back in a short time because of reduction in the consumption of electricity (as compared to conventional systems).