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Design and operation methodology for active building-integrated thermal energy storage systems

Yuxiang Chen*, Khaled E. Galal, Andreas K. Athienitis

Concordia University, 1455 De Maisonneuve Blvd. W., Montreal, Quebec, Canada H3G 1M8

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ABSTRACT

A methodology is presented for integrating the design and operation of active building-integrated thermal energy storage (BITES) systems to enhance their thermal and energy performance. A bounding-condition based design approach is proposed in conjunction with predictive control strategies. The predictive control uses frequency domain models and room air temperature set-point profile as input. The set-point profiles and BITES design are improved in a holistic manner according to the thermal dynamic response of active BITES systems and their thermal zones. The dynamic response is obtained from the transfer functions of frequency domain models. The methodology is demonstrated on ventilated systems. The results show that the methodology can significantly improve the design and operation of active BITES systems, and hence improve their thermal and energy performance. The dynamic response of different sizes of systems is presented to provide useful information for design selection. It is shown that concrete thickness of 0.2–0.3 m is a good value to initiate design. Other important application considerations are also discussed.

1. Introduction

Building-integrated thermal energy storage (BITES) systems use building fabric (e.g. masonry block walls and concrete slabs) as thermal storage mass. They are considered as active BITES if they embody internal charging system, such as hydronic, air-based or electric systems. They are sometimes referred to as fabric thermal storage [1], fabric energy storage [2], or thermo-active (or thermally activated) building systems (TABS) [3]. Active charging enhances the engagement of core mass for thermal energy storage by utilizing core area for heat transfer.

Primary space conditioning can be supplied through active BITES systems. The active charging systems may heat/cool the building fabric (wall, floor or ceiling), which in turn heat/cool their zones through radiation and convection, like large radiant heating/cooling panels [4] integrated with storage mass. Using active BITES systems with proper control can provide low energy space conditioning with relatively flat profile of power demand, while maintaining or improving thermal comfort. The demand of space conditioning and the supply of ambient renewable energy and off-peak power can also be well matched [5,6].

Fig. 1 shows two configurations of such active BITES systems. They will be used for demonstration in this paper. In the without-airflow-to-zone configuration (Fig. 1a, e.g. hydronic floor heating/cooling systems), the only function of heat transfer fluids (e.g. air or water passing through the BITES) is to heat or cool the BITES mass. In the with-airflow-to-zone configuration (Fig. 1b, only for air-based systems), the airflow enters the room and mixes with room air after passing through the BITES. It can provide ventilation and space conditioning to the zone, besides exchanging heat with the BITES mass.

There are two main criteria for the thermal functions of such active BITES systems. First, they can provide sufficient space thermal conditioning to their thermal zones. Second, they can store ideal (sometimes large) amount of thermal energy for appropriate operating temperature ranges and time. The acceptable thermal comfort range offers flexibility but also imposes limits on their operations.

Since an active BITES systems has a considerable amount of thermal storage mass, its thermal response is slow. Its time constant is of the order of hours. To achieve their functionality, predictive control has to be implemented. Different predictive control strategies for BITES systems have been proposed in the literature [4–12].

* Corresponding author. Dept. BCEE, Rm: EV-6.139, Concordia University, 1455 de Maisonneuve Blvd. West, Montréal, Québec, Canada H3G 1M8.
Tel.: +1 514 848 2424x7244; fax: +1 514 848 7965.
E-mail address: yuxia_ch@hotmail.com (Y. Chen).

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Nomenclature

Symbols

~	oscillatory value/response
≅	approximately equal to
Δ	difference or potential
←	order of layers in an assembly. $1 \leftarrow N$ means the assembly contains layers from 1 to N, and the excitations are on surface l of layer N
Area	surface area
Arg{}	argument (phase angle) of the complex number
B	total number of bounding surfaces, or BITES
c	specific heat capacity (J/kg/K)
CR	combined convection and radiation
d	mathematical symbol for differential
e	TES capacity per unit area (J/m^2) or exponential base
E	energy (J)
f	fluids (air for with-airflow-to-zone configuration, and air or water for without-airflow-to-zone configuration)
h	convective heat transfer coefficient (W/m^2/K) or harmonic index
$\boldsymbol{M}$	matrix of transfer functions
P	heat power (W) or period in seconds
Q	volumetric flow rate (m^2/sec)
rm	room or room air
sc	source or source layer
slr	solar
t	time or duration (second/sec unless specified)
ttl	total
T	temperature (°C)
ΔT	temperature difference or potential (°C)
Th	thickness or equivalent thickness (m)
u	heat transfer coefficient per unit area (W/m2/K)
Y	self-/transfer-admittance, transfer function in frequency domain

Greek

ρ	density (kg/m^3)
ρc	volumetric heat capacity (J/m^3/K)
ω	angular frequency (rad/s), $\omega_f = 2\pi/P$ and $\omega_h = h \cdot \omega_f$
ϕ	phase angle of complex number

Acronyms

ACH	air changes per hour (air flow rate in terms of how many times of room volume in 1 h)
AHU	air handling unit
BITES	building-integrated thermal energy storage
CHTC	convective heat transfer coefficient
DFS	discrete Fourier series
TES	thermal energy storage

Variables

${}_{0\leftarrow rm}a21$	the element at the second row and the first column of the admittance matrix ${}^{0\leftarrow rm}_{adm}M$ of the assembly between node "0" and room air nodes
${}_{sc}h$	CHTC between the path inner surface and the airflow
${}_{top}h$	combined heat transfer coefficient on BITES top surface
${}_{0\leftarrow rm}p$	heat exchange between the room air and the other side of the BITES (node "0" in this case)
${}_{A.B}p$	advective thermal output of BITES
${}_{B}p$	total thermal output of BITES to the room (i.e. ${}_{CR.B}p + {}_{A.B}p$)
${}_{CR.B}p$	combined convective and radiative thermal output of BITES
${}_{cs}Ratio$	area ratio of internal heat transfer surface to room-side surface
${}_{0\leftarrow rm}t12$	the element at the first row and the second column of the transmission matrix ${}^{0\leftarrow rm}_{trs}M$ of the assembly between node "0" and room air nodes

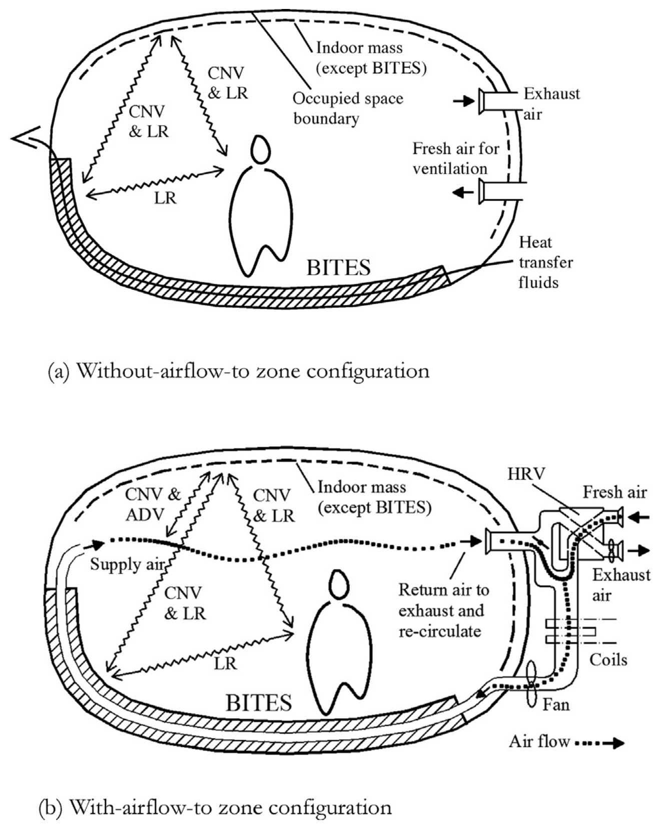

Fig. 1. Conceptual schematics of active BITES systems and their thermal coupling with the interior space: (a) without-airflow-to-zone configuration, and (b) with-airflow-to-zone configuration ("Indoor mass" includes room air, wallboards and furniture; CNV: convection; ADV: advection; LR: long-wave radiation; HRV: heat recovery ventilator).

Some guidelines for design and operation are provided in literature. Ma and Wang [13,14] and Athienitis and Santamouris [15] investigated the dynamic response of common building fabric components and provided some sizing guidelines for passive storage. Athienitis and Chen [16] studied the thermal performance and control strategies of an electric radiant heating floor with thermal storage. Howard and Fraker [17] reviewed the design principals of ventilated BITES systems that use concrete masonry units. Simplified mathematical models and graphical methods are developed in the literature for sizing the active charging system of hydronic BITES [4,18,19]. Similar approach is provided for ventilated BITES system by Fort [20].

The design and operation of buildings are interrelated, and the operation should be taken into account in the design as a primary consideration. Frequency domain thermal modeling of active BITES systems provides a promising approach to integrate design and predictive operation. It offers a convenient means for analyzing the