Energy and Buildings 84 (2014) 651–661

Contents lists available at ScienceDirect

Energy and Buildings

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

A charging control strategy for active building-integrated thermal energy storage systems using frequency domain modeling

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

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

ARTICLE INFO

Article history:
Received 18 August 2014
Accepted 2 September 2014
Available online 16 September 2014

Keywords:
Predictive control
Frequency domain model
Transfer function
Thermal energy storage
Building-integrated thermal energy storage

ABSTRACT

Primary space conditioning can be provided through active building-integrated thermal energy storage (BITES) systems, such as radiant space heating through concrete slabs. This approach can reduce peak space conditioning demand and energy costs while satisfying thermal comfort. However, thermal charging rates need to be predictively controlled due to the slow thermal response of BITES systems. This paper presents a charge control strategy using frequency domain models and room air temperature set-point profile as input. The models were previously verified with full-scale experiment data. The calculation procedures are demonstrated on active BITES systems with and without airflow to zone. Results show that the calculated charging rates satisfy the desired room air temperature set-point profiles. This control strategy is important for integrating the design and operation of active BITES systems because frequency domain models also provide important design information.

1. Introduction

Effective utilization of thermal energy storage for ambient renewable energy (e.g. solar heat for heating and cool outdoor air for free cooling) with proper design and control has proven promising in reducing peak demand and energy costs associated with space conditioning [1]. Building-integrated thermal energy storage (BITES) systems, which use building fabric (e.g. concrete slabs or masonry walls) as storage mass, have recently attracted significant research interest (e.g. [2–4]). Building fabric can provide a large effective thermal storage capacity. Savings in room space and material can be achieved in comparison with conventional centralized and thermally isolated storage systems (e.g. water/ice tanks). One unique characteristic of BITES systems is their strong thermal coupling with thermal zones due to large exposed surface areas.

Active BITES systems are conventionally passive building fabric (e.g. solid concrete slabs) embedded with active charging systems (Fig. 1). The charging systems can be hydronic, air-based (i.e. ventilated) or electric. Active BITES systems have larger and faster charge and discharge, as compared to passive BITES systems. Furthermore, primary space conditioning can be supplied through active BITES systems and hence significantly enhance thermal comfort due to enhanced radiant effect [1,5]. Active BITES systems can be located in ceilings, floors, or walls.

Fig. 1 depicts two main types of active BITES configurations – without airflow to zone (Fig. 1a and b) and with airflow to zone (Fig. 1c). In the configuration without airflow to zone, the charging systems can be hydronic or air-based. Heat transfer fluids have only one function – charging the storage mass. The charging systems heat or cool the building fabric, which in turn heats or cools their thermal zones through radiation and convection. The active BITES systems are like large radiant heating/cooling panels integrated with storage mass. For the configuration with airflow to zone, the heat transfer air is released to the room after passing through the BITES. It provides additional heat exchange between the BITES and the room – advection, implying a stronger thermal coupling. Ventilation can also be provided through the airflow.

Suitable room air and BITES surface temperatures profiles are critical in satisfying thermal comfort requirements. They also bound the operations of active BITES systems, and hence bound their energy performance. The following considerations are essential in the charging controls of BITES systems:

(1) A thermal zone's operative temperature [6] is significantly influenced by the temperature of its active BITES system due to their strong thermal coupling;
(2) Slow thermal response of BITES systems due to high thermal inertia;

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

http://dx.doi.org/10.1016/j.enbuild.2014.09.004
0378-7788/

Nomenclature

List of symbols

ˆ	DFS or complex frequency form
–	(overhead bar) mean value/response
_	(underscore) a_b means from a to b
~	oscillatory response
←	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

Greek

ρ_c	volumetric heat capacity (J/m^3/K)

English

a	admittance matrix element or a numerical value or
A	advective/advection or a numerical value
Area	surface area
Arg{}	argument (phase angle) of the complex number
B	BITES in subscript
c	coefficients, combined, or convective
C	thermal capacitance (J/K)
CR	combined convection and radiation
f	fluids (air for with-air-to-zone configuration, and air or water for no-air-to-zone system in this study)
i	index of time step
k	thermal conductivity (W/m/K)
h	convective heat transfer coefficient or harmonic index
hx	heat exchange
H	total number of harmonics used in the modeling
M	matrix of transfer functions
p	heat flux or power per unit area (W/m^2)
P	power (W)
Q	volumetric flow rate (m^3/s)
r	thermal resistance per square meter (m^2 K/W)
rm	room or room air
Re{}	real part of the complex number
sc	source layer
trs	transmission matrix
t	time (s) or transmission matrix element
T	temperature (°C)
U	conductance (W/K)
Y	admittance

Acronyms

ACH	air change per hour. Air flow rate in terms of how many times of room volume in one hour
AHU	air handling unit
AZ	with airflow to zone
BITES	building-integrated thermal energy storage
CHTC	convective heat transfer coefficient
DFS	discrete Fourier series
TES	thermal energy storage
NAZ	with-no-airflow-to-zone

Key variables

${}^{soil\leftarrow rm}a21$	the element at the second row and first column of the admittance matrix ${}^{soil\leftarrow rm}_{adm}\boldsymbol{M}$ of the assembly between soil and room air nodes
${}_{c}a12$	the element at the first row and second column of the combined admittance matrix ${}_{adm.c}\boldsymbol{M}$
${}_{hx}c$	heat exchange coefficient ${}_{hx}c = {}_{sc}U/{}_{f}Qc$
${}_{top}h$	combined heat transfer coefficient on BITES top surface
${}^{1\leftarrow N}_{adm}\boldsymbol{M}_h$	admittance matrix of the hth harmonic for an assembly composed of layers 1 to N
${}_{adm.c}\boldsymbol{M}$	combined admittance matrix, for simplified models of with-airflow-to-zone configuration
${}_{path}N$	quantity of air paths for the whole floor
${}_{A.B}p$	advective thermal output of BITES system
${}_{CR.B}p$	combined convective and radiative thermal output of BITES system
${}_{B}p$	thermal output of the BITES to the room (i.e. ${}_{CR.B}p + {}_{A.B}p$)
${}_{load}p$	space conditioning load or required thermal output from the BITES systems
${}_{sc}p$	charging rate at source layer, from embedded active charging system
${}_{slr}p$	transmitted solar radiation absorbed by BITES top surface
${}_{slr\text{-}rm}p$	heat flux to room air from solar radiation absorbed by the floor surface
${}_{soil\text{-}top}p$	heat flux following to the floor top surface due to temperature difference between top surface and soil
${}_{add}P$	thermal energy injection rate (W) at external heat exchanger, AHU in this case
${}_{f}Qc$	${}_{f}Qc = {}_{f}Q \cdot {}_{f}\rho c$
${}_{Qc}r$	convective resistance, ${}_{Qc}r = {}_{floor}Area/({}_{f}Qc \cdot {}_{path}N)$
${}^{soil\leftarrow top}r$	thermal resistance between soil and floor top surface
${}^{sc\leftarrow rm}_{c}r$	combined thermal resistance between source layer and room air
${}^{sc\leftarrow rm}t11$	the element on the first row and first column of the transmission matrix ${}^{sc\leftarrow rm}_{trs}\boldsymbol{M}$ of the assembly between source layer and room air node
${}^{1\leftarrow N}_{trs}\boldsymbol{M}_h$	transmission matrix of the hth harmonic for an assembly composed of layers 1 to N
${}_{trs.c}\boldsymbol{M}$	combined transmission matrix, for simplified models of with-airflow-to-zone configuration
${}_{f}T$	fluid temperature (airflow temperature in with-airflow-to-zone system)
${}_{inlet}T$	BITES system inlet fluid temperature
${}_{outlet}T$	BITES system outlet fluid temperature
${}_{rm}T$	room air temperature
${}_{sc}T$	floor source layer temperature
${}_{soil}T$	soil temperature
${}_{top}T$	BITES top surface temperature
${}_{sc}U$	total heat transfer conductance between each air path and the fluids (W/K)
${}_{Re}No$	Reynolds number

(3) Enhancing the energy performance of buildings through the suitable charging/discharging of active BITES systems, such as to condition and pre-condition BITES using renewable and off-peak energy as much as possible while satisfying comfort constraints.

Conventional feedback control strategies aim to keep room air temperature within a comfort range without considering energy performance [7–9]. To take better advantage of building fabric for thermal storage to improve energy performance, predictive control is needed. Athienitis and Chen [10] and Athienitis [11] proposed control strategies using time-varying (e.g. sinusoidal or ramp) set-points for the room air temperature. Recently, model-based predictive control (MPC) has attracted significant attention in building studies [12–15]. Charging rates are optimized according to