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Development of a thermal energy storage model for EnergyPlus

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Abstract

A module for ice-based thermal energy storage (TES) systems has been developed and integrated within EnergyPlus. The TES module uses building load and system thermodynamics (BLAST) models for two direct ice systems (ice-on-coil external melt and ice harvester) and one indirect ice system (ice-on-coil internal melt). The TES systems are integrated as part of the EnergyPlus cooling plant components and are able to operate for any charge/discharge rates provided as input data. In this paper, the structure of the TES module as implemented in EnergyPlus is described. In addition, typical input–output variables from the added TES module are illustrated. Moreover, the operation of the TES systems is discussed for various conventional control strategies.

Keywords: EnergyPlus; Thermal energy storage (TES) system

1. Introduction

Thermal energy storage (TES) is an electrical load management and building equipment utilization strategy, which can reduce utility electricity demand and equipment first-costs. Indeed, TES systems have been utilized as a demand-side management (DSM) strategy by several utilities to shift electricity use associated with cooling from on-peak periods to off-peak periods. For building managers and owners, TES systems are designed to avoid high utility demand and energy charges from cooling during on-peak periods associated with time-of-use (TOU) rates or real-time pricing (RTP) rates. In addition, TES systems have been promoted as a means to reduce installed chiller capacity. Typical applications of TES systems include medium-size to large office buildings, hotels, and retail stores.

The main obstacle that hinders a wider acceptance of TES systems is the lack of understanding among HVAC designers and facility operators of the proper operation and control that improve the cost-effectiveness of TES systems [1,2]. Several studies have proposed improved optimal control strategies for TES systems [3–5]. However, almost all of these studies are based on either simplified TES models or sole analysis of the cooling plant without considering the impact of the entire building operating and design conditions such as building thermal mass and internal gains effects. In this paper, realistic models for TES systems are integrated within the state-of-the-art whole-building simulation program, EnergyPlus, to allow for future analysis of the performance of TES systems under various control strategies and design options.

The TES model is based on a steady-state plant model developed by King and Potter [5] using algorithms adapted from the building load and system thermodynamics (BLAST) energy simulation program [6]. The model was designed to meet building cooling load directly and was used in evaluating optimal control of ice thermal energy storage systems [4]. The TES model was developed as a packaged unit system containing zone fan-coil unit, chiller, pump, and cooling tower. Unfortunately, the model cannot be used in EnergyPlus directly due to the optimal control methodology employed and the fan-coil unit system which is already contained in EnergyPlus. The new TES plant module, presented in this paper, is developed to work as an integral part of EnergyPlus plant equipment and to accommodate the entire continuum of charge/discharge rates given as user input data.

This paper describes the structure of the TES plant module as integrated within EnergyPlus. In addition, typical input–output variables from the added TES module are illustrated. Finally, the operation of the TES systems is evaluated for conventional control strategies including chiller-priority and storage-priority using a small office building.

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2. TES model description

As in BLAST, TES systems are modeled as heat exchangers with the charging/discharging rates as functions of the state-of-charge and the log-mean temperature difference between the ice and brine side. The dependence on the state-of-charge is determined using a fifth-order polynomial fit to manufacturers' data. Three ice storage systems are considered in the TES module implemented in EnergyPlus: ice-on-coil internal melt, ice-on-coil external melt, and ice harvester. The details of the TES models and the polynomial fits are described in King and Potter [5].

When modeling TES system in EnergyPlus, two chillers are considered in addition to the TES system: a base-load chiller to directly meet the building cooling load either during on-peak or off-peak periods, and a dedicated TES chiller to charge the TES system. The TES chiller cannot be utilized to directly meet building cooling load. The TES module integrated in EnergyPlus includes all ice-making equipment such as TES chiller, pumps, and associated cooling tower as well as the TES system. Fig. 1 illustrates how the base-load chiller, the TES chiller, and the TES system are modeled as part of the Plant Supply Side Cooling Loop within EnergyPlus.

A TES system is continuously operating over the entire range of designed charging/discharging rates. Its capacity is generally characterized by a charge/discharge rate as expressed in Eq. (1):

$$\dot{Q}_{\text{ice}} = u\frac{Q_{\text{TES}}}{\Delta t} \tag{1}$$

where $\dot{Q}_{\text{ice}}$ is the TES charge(+)/discharge(−) rate (kW), Q_{TES} the TES capacity (kWh), u the charge/discharge rate (fraction), and Δt the simulation time interval (hour).

Three basic operation modes can be conveniently considered over the continuum of charge/discharge rates:

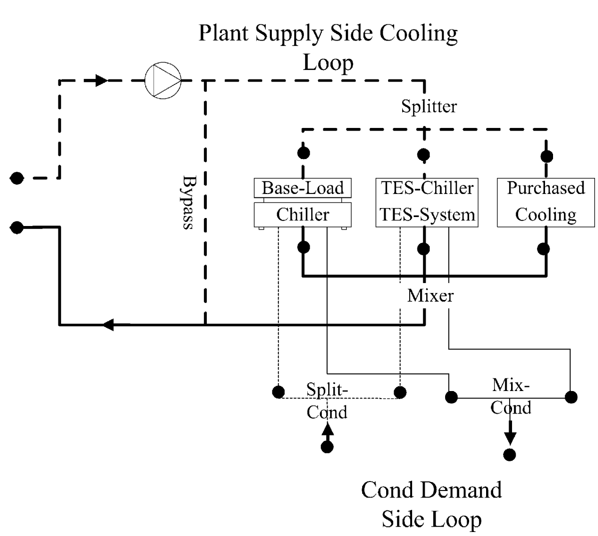

Fig. 1. Integration of base-load chiller, TES chiller, and TES system models within EnergyPlus Plant Supply Side Cooling Loop.

- dormant mode: $u = 0$;
- charging mode: $u > 0$; and
- discharging mode: $u < 0$.

2.1. Dormant mode

When the TES system is not operating, the charge/discharge rate is set to zero ($u = 0$) in an hourly schedule defined specifically for the TES operation. In the dormant mode, the TES module assumes that TES mass flow rate is zero, and that the outlet water temperature is the same as the inlet water temperature. In summary, there is no TES capacity to handle building cooling loads or to make ice.

2.2. Charging mode

In charging mode, the dedicated TES chiller integrated in the TES module produces ice at the charging rate, u, as long as it has sufficient ice-making capacity. After every time step, Δt, the level of ice in the TES system, x, is increased according to Eq. (2). It should be noted that the actual value of the charging rate, u, used in Eq. (2) may be different from user input data since it is adjusted every time step based on the thermal and physical operational constraints of the chiller and TES system. In particular, the actual value for u is calculated by taking into account the maximum TES plant charging capacity and the maximum TES chiller capacity to charge the TES system.

$$x_t = u\,\Delta t + x_{t-\Delta t} \tag{2}$$

where x_t is the current state-of-charge (fraction) and $x_{t-\Delta t}$ the previous charging level (fraction).

Based on the actual charge rate and the estimated ice level, the TES chiller inlet water temperature is calculated every time step using a set of user-defined outlet water temperatures in an hourly schedule. Once the inlet water temperature is calculated given the ice-making load and outlet water temperature, the electricity consumption of the TES chiller is calculated.

2.3. Discharging mode

The TES system provides cooling capacity to meet the cooling demand calculated by the supply side in EnergyPlus. The cooling capacity from the TES system is determined from the discharge rate, u ($u < 0$) set by a user-defined hourly schedule. If the user-input discharge rate cannot be provided by the TES system due to, for instance, insufficient available capacity, an actual discharging rate, u, is determined based on the existing ice level in TES system and on the current inlet water temperature from EnergyPlus. The mass flow rate through TES is then calculated using Eq. (3) from the cooling load to be met by the TES system and the temperature difference between inlet water temperature and supply loop water setpoint temperature. Outlet water temperature is equal to the supply loop water outlet setpoint temperature. The ice level of TES plant is also adjusted using Eq. (2).

$$\dot{m}_{\text{ice}} = \frac{\dot{Q}_{\text{ice}}}{c_{p,\text{water}}(T_{\text{inlet}} - T_{\text{Loop setpoint}})} \quad (3)$$

where $\dot{m}_{\text{ice}}$ is the TES water mass flow rate (kg/s), $\dot{Q}_{\text{ice}}$ the TES cooling load (W), $c_{p,\text{water}}$ the specific heat of water (J/kg °C), T_{inlet} the inlet water temperature from EnergyPlus (°C), $T_{\text{Loop setpoint}}$ the supply loop setpoint water temperature (°C).

3. Implementation of TES module

Fig. 2 illustrates the three TES operating modes described above as implemented in EnergyPlus. In addition, Fig. 2 indicates the interactions between the TES system and other existing systems in the EnergyPlus environment [7,8].

In particular, "*PlantLoopSupplySideManager*" module calculates the demand on the plant loop, selects the equipment that is available to meet the demand based on the plant operation scheme, and calls the equipment simulation modules (including the new TES module) to operate each piece of equipment on the loop.

The subroutine "*ManagePlantSupplySides*" in "*PlantLoopSupplySideManager*" is the main driver routine for the plant equipment simulation. Its main function is to determine which pieces of plant equipment are operating and to call the appropriate equipment simulation managers. Then, each element of plant equipment is simulated with the priority set by a user-defined building load range. After each plant simulation is completed, the loop properties such as mass flow rate, inlet water and outlet water temperatures are updated and reported as node properties in EnergyPlus.

4. Structure of the ice thermal energy storage module

This section provides a more detailed description of the input variables as well as the general structure of the TES module.

4.1. Input data

As required by the EnergyPlus programming standard, model input data are supplied by means of ASCII (text) files. Specifically, there are two files: the Input Data Dictionary

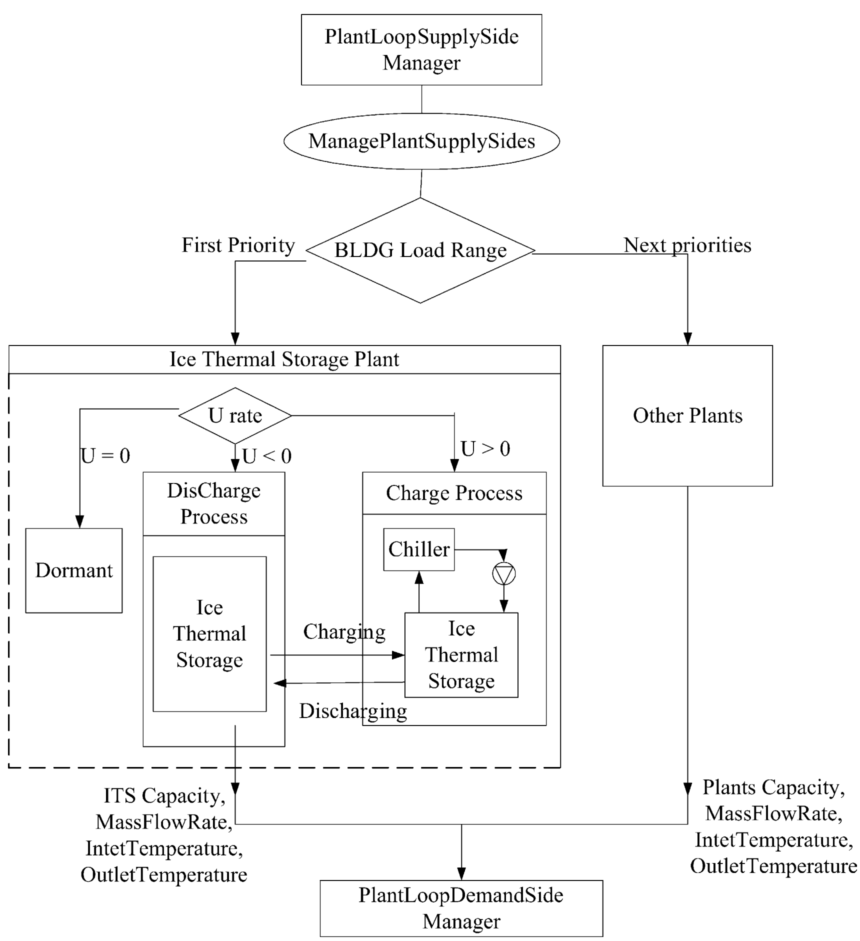

Fig. 2. Flow chart of operating processes and implementation of ice thermal storage plant model in EnergyPlus.

(IDD) and the Input Data File (IDF). For the TES module, the input variables include the following:

- [Name]—Less than 40 characters can be used as the name for a particular TES system.
- [TES Type]—Type of the TES system. Currently, there are three ice storage types that can be modeled including ice-on-coil internal melt, ice-on-coil external melt, and ice harvester systems. The regression coefficients for the charging/discharging rate curves as well as the head loss for each TES system are integrated in the module to calculate the ice storage overall heat transfer coefficient.
- [TES Urate Schedule] is a charging/discharging rate schedule. The values for the charge/discharge rates should be between −1 and 1 as fractional values prescribed in a daily schedule.
- [TES Capacity (kWh)] is the nominal TES system capacity.
- [Plant Loop Inlet Node] is a node name for the inlet side of the TES system.
- [Plant Loop Outlet Node] is a node name for the outlet side of the TES system.
- [TES Chiller Type]—Type of the TES chiller. Currently, there are three electrical compressor types for the TES chiller including centrifugal, reciprocating, and screw. The TES chiller coefficients and nominal full-load power ratio are integrated in the module to obtain full-load capacity ratio, full-load power ratio, and fraction of full-load power.
- [TES Chiller Outlet Temp Schedule]—Schedule to set the chiller outlet temperature. In the charging process, it is used to calculate the charging capacity for the TES system.
- [TES Chiller Capacity (W)]—The nominal TES chiller capacity to make ice during the charging process.
- [TES Chiller Nominal Outlet Temperature for Ice Harvester (°C)]—When ice harvester system is selected, a nominal value for chiller outlet temperature needs to be provided in order to calculate the overall heat transfer coefficient for the ice harvester under the charging mode.
- [TES Chiller Nominal Inlet Temperature for Ice Harvester (°C)]—When ice harvester system is selected, a nominal value for chiller inlet temperature needs to be provided in order to calculate the overall heat transfer coefficient for the ice harvester under the charging mode.
- [TES Pump Nominal Head Loss (m)] is the nominal value for pump head loss to calculate energy consumption for the pump dedicated to the TES module.
- [TES Pump Efficiency (fraction)] is the nominal pump efficiency to calculate pump energy consumption.

4.2. TES module structure

The TES module consists of several subroutines that are called from EnergyPlus or from other internal calculation routines within the TES module. Major subroutines within TES module are briefly described below.

4.2.1. IceThermalStorage module

The module *IceThermalStorage* simulates the performance of the TES system to meet the building cooling load from the cooling plant. This module can be included into the main program if it is to be used.

4.2.2. SimIceStorage

The subroutine *SimIceStorage* is called by *PlantLoopSupplySide* module, which contains all of the plant modules for EnergyPlus. Access to the module and its data elements are only allowed through this subroutine. All other routines, except the routine *CalcIceStorageCapacity*, are accessed from the main driver routines.

4.2.3. GetIceStorageInput

The input data for TES system and TES chiller are read by routine *GetIceStorageInput*. The read data are then delivered to other subroutines within the *IceThermalStorage* module.

4.2.4. CalcIceStorageCapacity and CalcUAIce

These two subroutines are called at each "time step" to calculate current minimum and maximum TES system capacity and the overall TES heat transfer coefficient. Every time step, the TES capacity is updated to estimate current values for the ice level, discharging rate, and chiller outlet temperature. The routine *CalcIceStorageCapacity* is called from the module *PlantLoopSupplySideManager* to calculate the maximum and minimum TES system capacity before simulating one of the charging/discharging modes (i.e., dormant, charging, discharging).

4.2.5. CalcIceStorageDormant, CalcIceStorageCharge, and CalcIceStorageDischarge

These subroutines are the main subroutines of the simulation TES module. The three subroutines are called from the subroutine *SimIceStorage* depending on user's hourly input data for charging/discharging rates.

4.2.6. UpdateNode

After simulating the performance of the TES system, the subroutine *UpdateNode* updates outlet side node properties for the TES plant, which includes outlet water temperature and mass flow rate.

4.2.7. RecordOutput

The subroutine *RecordOutput* provides the results from the TES module to be reported in an EnergyPlus output file.

5. Results

To test the TES module as implemented in EnergyPlus, the performance of an ice storage system is evaluated under two conventional operating strategies: chiller-priority and storage-priority. A three-zone building with a variable air volume (VAV) system is considered. Fig. 3 illustrates the

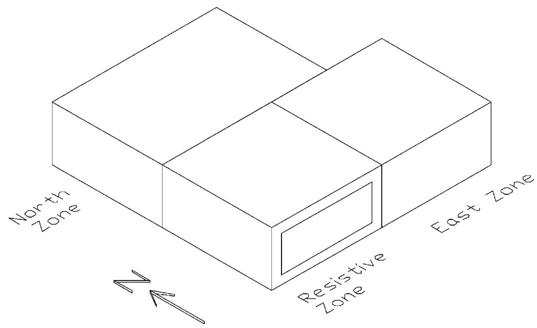

Fig. 3. Illustration of three-zone building model.

building and its zones. The building is located in Phoenix, Arizona. The three zones have a floor area of, respectively, 18 m^2 (200 ft^2), 18 m^2 (200 ft^2), and 27 m^2 (300 ft^2) with a ceiling height of 3 m (9 ft). The lighting and equipment power density for each zone is set to be 22 W/m^2 (2 W/ft^2) and 54 W/m^2 (5 W/ft^2), respectively. A centrifugal TES chiller with a capacity of 24 kW (6.76 t) and an ice-on-coil internal melt ice storage system with a capacity of 80 kWh (22.5 t h) are added to the building cooling plant which includes a centrifugal base-load chiller with a capacity of 40 kW (11.4 t).

Table 1 provides the schedules for the indoor temperature set-point and the electricity charges considered in the analysis. Various 1-day simulations are performed using EnergyPlus to determine the energy use and energy cost of cooling the building on 21 July with and without the TES system. Table 2 illustrates a typical output report generated by EnergyPlus to assess the performance of the TES system.

Figs. 4 and 5 present the hourly variations of TES inventory level, charge/discharge rate, and chiller electricity use for chiller-priority control and storage-priority control, respectively. The chiller electricity use is attributed to the TES chiller during unoccupied period and to the base-load chiller during occupied period. For both control strategies, the TES ice level increases up to about 90% during unoccupied period (from 1 to 7 a.m.). During on-peak period, chiller-priority control decreases the ice level since the TES system is used to partially meet building cooling load. As depicted in Fig. 4, the remaining ice level is about 63% at the end of the day. The ice tank is recharged during the off-peak period so that excess storage capacity remains at the end of the day.

In the case of storage-priority control, the ice is completely melted at the end of the on-peak period. As depicted in Fig. 5, the chiller has to be operated to meet a portion of building cooling load during all hours of the on-peak period due to the limited storage capacity of the TES system. It should be noted that to be effective, storage-priority control requires some forecasting of building cooling load.

The impact of EnergyPlus simulation time step is evaluated using storage-priority control. Table 3 summarizes the building energy use and energy cost obtained for various simulation time steps. The results indicate that both energy use and energy cost increase slightly when EnergyPlus simulation time step is decreased. However, the selection of the

Table 1
Daily schedule for building cooling temperature setpoint and energy and demand charges

Period	Cooling setpoint (lower limit, °C)	Cooling setpoint (higher limit, °C)	Demand charge rate ($)	Energy charge rate ($)
Off-peak: 6 p.m.–7 a.m.	15	45	0	0.05
On-peak: 8 a.m.–5 p.m.	20	24	10	0.20

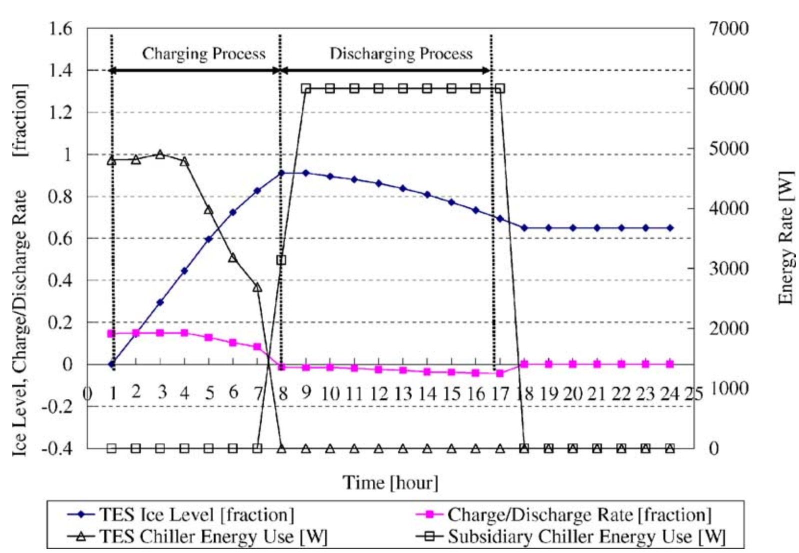

Fig. 4. Performance of the TES system using chiller-priority control: charge/discharge rate, ice level, and chiller energy use.

Table 2
Typical EnergyPlus output report for the TES module using a chiller-priority control

Hour	Xact	Uin	Uact	Mdot, CH	Tinlet, CH	Toutlet, CH	CPP	CP	CTP	TotPower	TotEnergy	Mdot, ITS	Tinlet, ITS	Toutlet, ITS	Qdot, ITS	Energy, ITS
1	0	0.150	0.145	0.7131	−0.10	−4	329	4808	4117	5548	19973188	0	7.00	7.00	0	0
2	0.145	0.150	0.150	0.9421	−0.95	−4	435	4819	420	5674	20426774	0	7.00	7.00	0	0
3	0.295	0.150	0.150	0.9396	−2.27	−4	434	4904	423	5761	20738605	0	7.00	7.00	0	0
4	0.445	0.150	0.150	0.7725	−3.45	−4	357	4789	420	5565	20034574	0	7.00	7.00	0	0
5	0.595	0.150	0.129	0.6170	−3.99	−4	285	3984	357	4626	16654024	0	7.00	7.00	0	0
6	0.724	0.150	0.103	0.4914	−3.99	−4	227	3183	285	3694	13299244	0	7.00	7.00	0	0
7	0.827	0.150	0.084	0.4011	−3.99	−4	185	2692	235	3112	11203541	0	7.00	7.00	0	0
8	0.911	−0.100	−0.014	0.0000	0.00	0	0	0	0	0	0	0.0184	21.75	19.39	1097	3947697
9	0.911	−0.100	−0.016	0.0000	0.00	0	0	0	0	0	0	0.0223	20.13	6.67	1253	4511971
10	0.895	−0.100	−0.015	0.0000	0.00	0	0	0	0	0	0	0.0210	20.19	6.67	1186	4267875
11	0.880	−0.100	−0.018	0	0	0	0	0	0	0	0	0.0258	20.16	6.67	1455	5238941
12	0.862	−0.100	−0.025	0	0	0	0	0	0	0	0	0.0354	20.12	6.67	1989	7161720
13	0.837	−0.100	−0.029	0	0	0	0	0	0	0	0	0.0413	20.14	6.67	2327	8375593
14	0.808	−0.100	−0.036	0	0	0	0	0	0	0	0	0.0517	20.10	6.67	2905	10457480
15	0.772	−0.100	−0.038	0	0	0	0	0	0	0	0	0.0532	20.20	6.67	3011	10838433
16	0.734	−0.100	−0.041	0	0	0	0	0	0	0	0	0.0579	20.21	6.67	3277	11798900
17	0.693	−0.100	−0.043	0	0	0	0	0	0	0	0	0.0614	20.22	6.67	3477	12518844
18	0.650	−0.100	0	0	0	0	0	0	0	0	0	0	7.00	7.00	0	0
19	0.650	−0.100	0	0	0	0	0	0	0	0	0	0	7.00	7.00	0	0
20	0.650	−0.100	0	0	0	0	0	0	0	0	0	0	7.00	7.00	0	0
21	0.650	−0.100	0	0	0	0	0	0	0	0	0	0	7.00	7.00	0	0
22	0.650	−0.100	0	0	0	0	0	0	0	0	0	0	7.00	7.00	0	0
23	0.650	−0.100	0	0	0	0	0	0	0	0	0	0	7.00	7.00	0	0
24	0.650	−0.100	0	0	0	0	0	0	0	0	0	0	7.00	7.00	0	0

Here, Xact: ice thermal storage starting fraction (fraction); Uin: ice thermal storage discharge(−)/charge(+) *U* input hour (fraction); Uact: ice thermal storage discharge(−)/charge(+) *U* current hour (fraction); Mdot, CH: ice thermal storage chiller water mass flow rate (kg/s); Tinlet, CH: ice thermal storage chiller water inlet temperature (°C); Toutlet, CH: ice thermal storage chiller water outlet temperature (°C); CPP: ice thermal storage chiller pump power (W); CP: ice thermal storage chiller chiller power (W); CTP: ice thermal storage chiller tower power (W); TotPower: ice thermal storage chiller total power (W); TotEnergy: ice thermal storage chiller total power consumption (J); Mdot, ITS: ice thermal storage water mass flow rate (kg/s); Tinlet, ITS: ice thermal storage water inlet temperature (°C); Toutlet, ITS: ice thermal storage water outlet temperature (°C); Qdot, ITS: ice thermal storage cooling rate (W); Energy, ITS: ice thermal storage cooling energy (J).

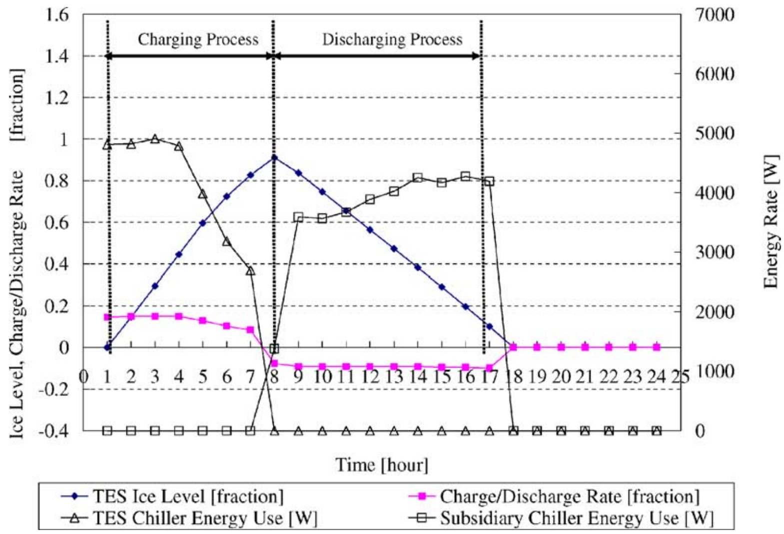

Fig. 5. Performance of the TES system using storage-priority: charge/discharge rate, ice level, and chiller energy use.

Table 3
Building energy use and energy cost for the three-zone building with TES system operated using storage-priority control for various simulation time steps during 21 July, in Phoenix, Arizona

Time interval	Energy use (kWh)	On-peak demand (kW)	Total cost ($)
60 min	141.91	11.43	26.64
30 min	144.68	12.72	27.47
20 min	144.97	12.98	27.64
15 min	144.83	13.07	27.66
10 min	144.78	13.13	27.68

time step has a minimal effect on estimating building energy use and energy cost.

Fig. 6 compares the hourly variation of the chiller electricity use to cool the three-zone building with and without the TES system (operated with storage-priority control). Three sizes for TES storage system and TES chiller are considered in the analysis: 80 kWh (22.5 t h) and 24 kW (6.8 t), 140 kWh (39.4 t h) and 42 kW (11.9 t), and 200 kWh (56.3 t h) and 60 kW (17.0 t). Fig. 6 clearly shows that chiller electricity demand can be reduced significantly during on-peak period by increasing the capacity of the TES plant.

Table 4 lists the building energy use and energy cost for various control strategies and TES system sizes. As indicated in Table 4, the use of a TES system increases the energy use but decreases on-peak demand. Storage priority control leads to more savings than chiller-priority control. In particular, the total electricity charges for the building can be reduced by 45% when storage-priority control is applied to operate sufficiently large TES system.

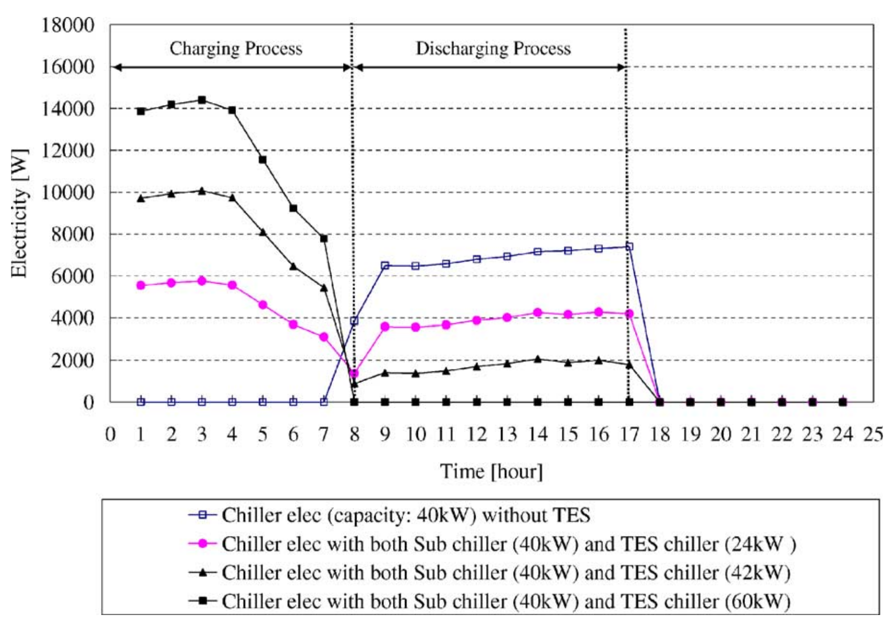

Fig. 6. Chiller electricity use for with/without TES plant on 21 July in Phoenix, Arizona.

Table 4
Building energy use and energy cost for the three-zone building with and without TES system during 21 July, in Phoenix, Arizona

Control	Sub/TES chiller (kW)	TES tank (kWh)	Energy use (kWh)	On-peak demand (kW)	Total cost ($)	Savings (%)
Without TES	40/na	n/a	139.29	14.63	32.05	n/a
Chiller-priority	40/24	80	164.19	13.24	31.47	2
Storage-priority	40/24	80	141.91	11.43	26.64	17
Storage-priority	40/42	140	147.76	9.22	23.04	28
Storage-priority	40/60	200	144.27	6.23	17.51	45

6. Summary

A thermal energy storage module based on BLAST models for three ice storage systems has been developed and integrated into EnergyPlus. The subroutines as well as the input–output variables of the TES module have been described in this paper. The developed TES module was tested and evaluated using a three-zone building model. The potential cost savings attributed to the use of TES system are evaluated for various conventional control strategies and TES chiller and storage tank sizes. While conventional controls can save energy cost, better control strategies should be considered and evaluated for TES systems. The integration of TES module in combination with the integration of optimization routines within EnergyPlus, as described in Zhou et al. [9], provides HVAC designers and facility operators with an effective simulation environment to determine the best control strategy for a building equipped with a TES system.

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