



# Integrating hollow-core masonry walls and precast concrete slabs into building space heating and cooling



Yuxiang Chen<sup>a,\*</sup>, Khaled E. Galal<sup>b</sup>, Andreas K. Athienitis<sup>b</sup>

<sup>a</sup> University of Alberta, 116 St & 85 Ave, Edmonton, AB, Canada T6G 2R3

<sup>b</sup> Concordia University, 1455 De Maisonneuve Blvd. W., Montreal, Quebec, Canada H3G 1M8

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## ABSTRACT

Hollow-core masonry block walls and precast concrete slabs can be used for active thermal energy storage to assist space heating and cooling by circulating air through their hollow-core space. This Building-Integrated Thermal Energy Storage (BITES) approach can provide a significant amount of effective mass for relatively fast thermal energy storage and release. Furthermore, it integrates several building functions into one building fabric component. Hence, it can significantly improve buildings' thermal performance while saving overall cost and room space. This study explains the benefits of using ventilated BITES systems, such as effective use of materials and enhanced thermal performance. The characteristics and thermal performance of three system configurations that have airflow to zone are presented. These three configurations can significantly enhance the thermal coupling between a ventilated BITES and its zone, and hence can enhance the thermal performance of the zone. Qualitative and quantitative comparisons of thermal performances between different configurations with and without airflow to zone are presented. This study also investigates a practical approach for applying ventilated BITES in buildings-using standard hollow-core masonry blocks and precast concrete slabs. The thermal properties of these standard construction units and their potential variations are investigated, and some design considerations are presented. The walls and slabs of interest include structural or non-structural masonry block walls and structural precast concrete slabs.

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## 1. Introduction

Thermal Energy Storage (TES) systems such as ice or water tanks, ground storage, and thermally massive walls and slabs, have been widely used in building applications [1,2]. The thermal energy stored in TES systems needs to be released to occupied space in an appropriate manner (e.g. rate and location) to moderate its mechanical space conditioning (i.e. heating or cooling) demand [3,4]. Effective TES systems with proper operations can significantly improve the thermal performance of buildings. The improvements include enhanced thermal comfort by reducing room temperature fluctuations, higher efficiency and smaller capacities of mechanical equipment (e.g. chiller, air ducts), reductions of peak demand and energy procurement from utilities, more effective utilization of renewable thermal energy, and offsetting the mismatch of demand and different energy supplies [5–8].

Building fabric (i.e. structure skeleton, partitions, and envelope)

constitutes a significant portion of a building's thermal storage capacity. Braun [9] stated that the thermal storage capacity of a typical concrete building is in the order of 0.1 kWh/K per m<sup>2</sup> of gross floor area, equivalent to that of a 0.2 m thick concrete slab. The normal thickness of concrete slabs ranges from 0.15 to 0.4 m [10,11]. Due to masonry and concrete's long term chemical and physical stability, fire resistance, and availability of raw materials, they are among the world's most widely used building materials. These characteristics promote concrete and masonry building fabric as effective means for TES in a wide range of buildings. Using building fabric for TES can be referred to as Building-Integrated Thermal Energy Storage (BITES).

Given BITES' high thermal storage capacity, it can absorb and release significant amount of thermal energy from and to its zone to modulate the zone temperature [3,12,7]. Successful modulation requires sufficient thermal coupling between BITES and the rest of its room [13]. BITES with exposed room side surfaces inherently has strong thermal coupling with its zone due to its large surface area. Therefore, for space conditioning loads with moderate amplitudes, simply exposing the surfaces of walls and floors (i.e. passive BITES) will create sufficient thermal coupling. Passive

\* Correspondence to: Innovation Center for Engineering (ICE), Rm 7-203, 9211-116 Street NW, Edmonton, AB, Canada T6G 2G6.

E-mail address: [yuxiang.chen@ualberta.ca](mailto:yuxiang.chen@ualberta.ca) (Y. Chen).

## Nomenclatures

$Ratio_{cr}$  area ratio of core surface to room-side surface  
AHU air handling units

BITES Building-Integrated Thermal Energy Storage  
PID proportional, integral and derivative  
TES thermal energy storage

BITES has been widely applied [9,14,15]. However, when amplitudes are high, such as passive solar heating on a cold and clear winter day, stronger thermal coupling is needed so that more thermal energy can be stored and released timely [8,13,16]. Furthermore, stronger thermal coupling increase the effective use of thermal storage mass, since heat can penetrate deeper into BITES' core area.

Alongside passive BITES, active BITES have also attracted significant research interest [1,4,7,8,17–19]. Charging systems of active BITES are normally embedded into building fabric. These systems can be hydronic, air-based (i.e. ventilated) or electric. The advantages of using active BITES include the following:

- Internal active charge engages core storage mass for heat exchange. Together with charge on the exposed surfaces, they result in larger effective storage mass and heat exchange area. Hence, faster and larger thermal energy storage/release is possible when needed. They promote the utilization of renewable energy that is only available intermittently and/or of low-grade (i.e. solar energy, nighttime cool air) [18];
- Energy from detached sources, such as ground heat and thermal energy collected by solar devices, can be stored in the BITES through heat transfer fluids;
- Active charge improves the control of charge/discharge. The BITES temperature, heat transfer rate, and amount of storage can be controlled more easily than that of passive systems;
- Instead of acting passively, active BITES can be used to regulate the zone temperature proactively, like large radiant panels with significant thermal storage mass [20];
- Larger thermal storage capacity and more controllable charge/discharge result in better demand-side management than passive BITES [4];
- Using active BITES, savings in room space and construction (material and installation) can be achieved in comparison with conventional centralized and thermally isolated storage systems (e.g. water/ice tanks).

Building fabric components that have hollow cores, such as hollow core slabs and concrete masonry block walls, can be easily used as ventilated BITES systems by connecting their hollow cores to form air channels (Fig. 1). Air as heat transfer fluid is circulated through the air channels to charge and discharge the core mass of the BITES systems. If room space is part of the air circulation path (the options of having return and/or supply air into zone as shown in Fig. 1), this type of BITES system can be referred to as ventilated BITES with airflow to zone. In addition to the above mentioned advantages, one unique advantage of ventilated BITES with airflow to zone is that stronger thermal coupling between the BITES and the rest of the room can be provided. This advantage will be further explained in the next section. The air channels can be used as ventilation ducts. Wires and pipes can also be incorporated in them. By eliminating the conventional space required for service systems, the floor-to-floor height will be reduced. Hence, the possibility of having additional floors for a given permitted building height is increased.

BITES systems combine thermal and building fabric/structural functions. These functions share some common design parameters, such as the overall thickness and the hollow core diameter. Therefore, the designs of these functions interact with each other. Take a concrete slab for example, larger hollow core diameter increases the heat transfer area between the core air and the cores, but it reduces the net cross sectional area and hence reduces the shear strength of the slab. In order to take full advantages of BITES systems, i.e. offer multiple functions with effective use of the material and the architectural space, an integrated design is needed. In current research and development activities, there exists a disconnection between structural and thermal designs. Methodology and guidelines for the integrated design of ventilated BITES systems are needed [20].

Ventilated BITES can provide a significant amount of effective mass for relatively fast thermal energy storage and release. Compared to BITES without airflow to zone such as hydronic floors, ventilated BITES with airflow to zone can significantly enhance the thermal coupling between a BITES and the rest of its room. These

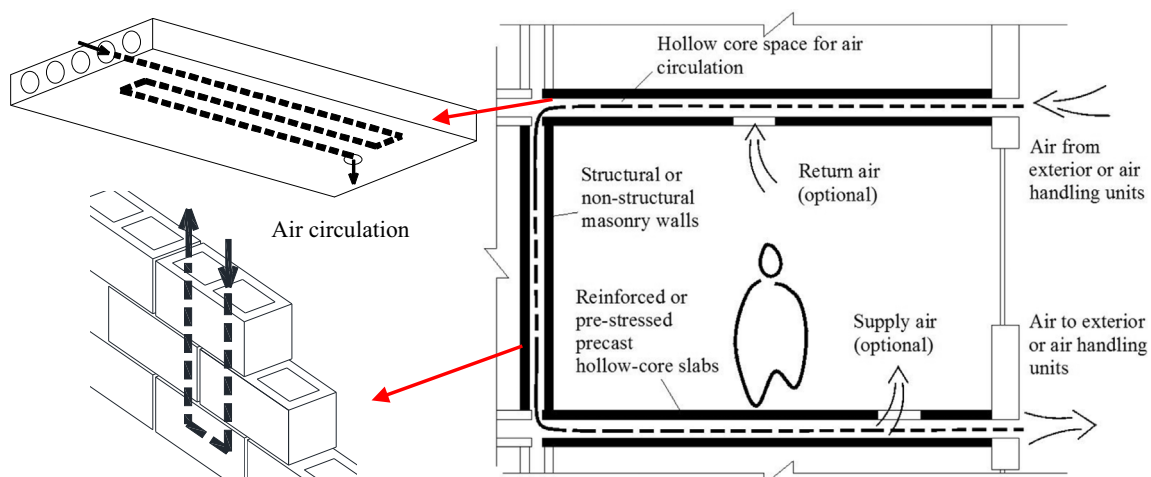


Fig. 1. Scheme illustrating use of hollow-core walls and slabs for ventilated BITES (connections between walls and slabs are optional).

features can significantly improve buildings' thermal performance while saving overall cost and room space. This study explains the main benefits of using hollow-core masonry walls and concrete slabs as ventilated BITES with airflow to zone. Three system configurations and their technical characteristics and typical thermal behavior are presented. Comparisons of simulated thermal performance between the three configurations and against “no airflow to zone” BITES configurations are also presented. Utilization of standard construction units for ventilated BITES are also discussed. This approach can facilitate the integrated design process of ventilated BITES by avoiding substantial alterations in practices such as re-design for the structural aspects. The TES properties of standard hollow-core masonry wall and concrete slabs are investigated. In the end, some practical design considerations are also presented.

The energy performance of ventilated BITES systems (e.g. consumption of fan energy, heating and cooling energy) is not presented in this study, because it is out of the scope of this study – application concepts and qualitative evaluation of ventilated BITES systems, and it would require a whole topic on its own. In general, the energy performance heavily depends on the built environment (e.g. building usage and envelope types), and operation strategies (e.g. charging with renewable energy). However, it is worth studying and valuable for operation cost references.

## 2. Materials and methods

In this section, explanations of the main benefits of using hollow-core masonry walls and concrete slabs as ventilated BITES will be first described. Then, three system configurations with airflow to zone are proposed. Their technical characteristics and typical thermal behavior are presented. Utilization of standard construction units for ventilated BITES are also discussed.

### 2.1. Effective use of materials

Using hollow-core design for a BITES component can enhance its structural and thermal performance and use material effectively at the same time. The structural and thermal capacities of a BITES component are greatly affected by its geometry. For example, when flexural strength (i.e. resistance to bending forces) is the governing factor for structural stability (e.g. large span slabs and tall walls), the core mass contributes negligibly to this strength [11]. In the example of a reinforced concrete slab with given material properties and placement of reinforcement (location and amount), the flexural strength is mainly influenced by the thickness of the slab, not the amount of mass. Hollow core concrete slabs and masonry block walls have significant reduction in their self-weight, and hence benefits structural design.

The nominal TES capacity of a BITES per unit room side surface area is determined by its net cross-section area, but its charging rate is highly influenced by its boundary area (room side and core surfaces). The comparison between the conceptual cross sections

of two reinforced concrete slabs (Fig. 2) is used here as an example. Their geometric difference is that slab (b) has hollow cores, in which air is circulated to charge the slab. Their flexural strengths are about the same. However, slab (b) is much lighter (smaller self-weight) than slab (a), and hence has more effective use of material for flexural strength. Furthermore, even though the nominal TES capacity of slab (a) is higher than that of slab (b) due to larger net cross-section area, slab (b) is able to store and release more thermal energy within a couple of hours (for a practical thickness of 0.1–0.4 m). This improvement is due to its extra boundary surface at the core and the core mass (e.g. point P) is closer to the boundary (i.e.  $Db$  is smaller than  $Da$ ) – smaller characteristic length for heat conduction [21]. BITES with faster storage and release is more useful in building applications, especially for peak space conditioning load reduction and utilization of renewable energy [18].

### 2.2. Configurations with airflow to zone to enhance thermal coupling

As previously mentioned, even fully exposing passive BITES may not be able to provide sufficient thermal coupling between a BITES and its zone when the amplitude of space heat gain and loss is high, such as on a cold winter day with strong solar heat gain [16]. On the room side, passive thermal coupling is mainly attributed to natural convection on the exposed BITES surfaces and long-wave radiative heat exchange between the exposed surfaces and the rest of the room. The natural convection heat transfer coefficient is about 1–4 W/m<sup>2</sup>/K depending on the heat flow direction and surface location, and the radiative heat exchange is about 5 W/m<sup>2</sup>/K [22]. This passive coupling may be weakened by surface coverings such as furniture, carpet or wooden flooring.

Fig. 3 conceptually compares the typical dynamic thermal response of a room with different thermal coupling levels in the presence of high amplitude of space heat gain and loss. In situation (a), there exists insufficient thermal coupling, and hence the BITES is not able to moderate the room air temperature fluctuation. The fluctuation is large while the temperature of the BITES barely changes. Space cooling is needed during the daytime and possibly heating for the night time. In situation (b), the BITES is strongly coupled with the rest of the room. The temperature amplitude of the room air is significantly reduced, while that of the BITES system is increased. The temperature of the room air closely follows that of the BITES system. The time lag between the peak temperatures of the room air and the BITES system is shortened. The heat stored in the BITES during the daytime is able to keep the room warm for the rest of the day.

In order to increase thermal coupling and reduce the impact of surface coverings, ventilated BITES with airflow to zone can be used. Fig. 4 shows three configurations with different air paths. In configuration (a) “local circulation”, room air is drawn through the ventilated BITES and then released back to the room. In configuration (b) “BITES then room”, air for space conditioning and ventilation (for fresh air) from the air handling unit (AHU) passes through the ventilated BITES before entering the room. In

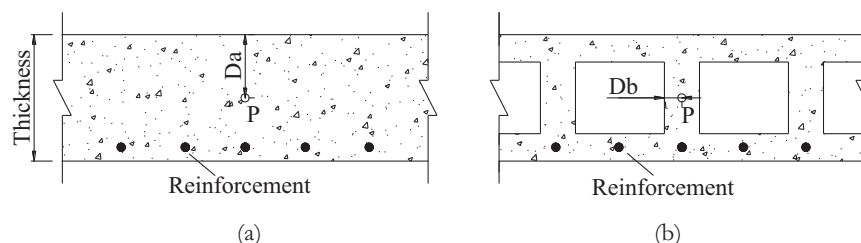


Fig. 2. Schematics of the conceptual cross sections of two reinforced concrete slabs. (a) Solid BITES slab. (b) Hollow-core BITES slab.

configuration (c) “room then BITES”, air from AHU is delivered to the room first and then to the ventilated BITES before returning back to AHU. Additional thermal coupling, as compared to passive

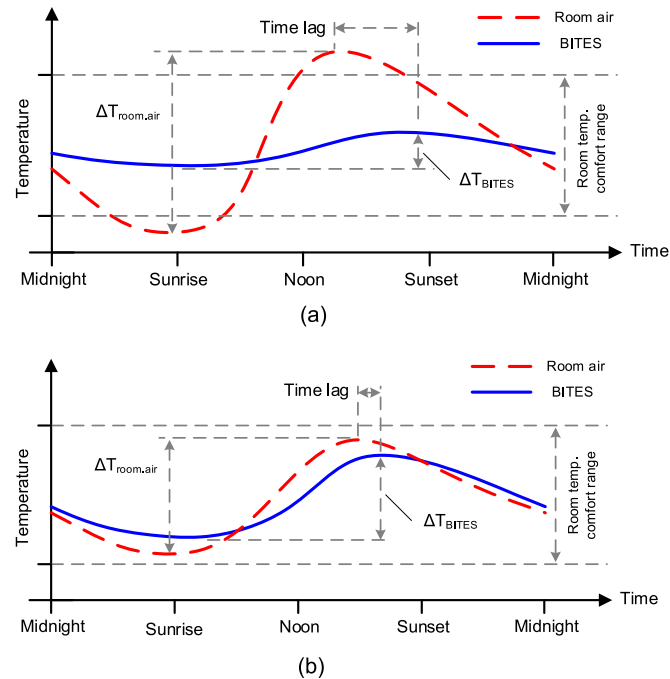


**Fig. 3.** Conceptual thermal response of a zone with different levels of BITES applications under high solar/internal heat gains. (a) Typical response with a low thermal storage BITES or weak interior thermal coupling. (b) Passive measures: strong thermal coupling between passive BITES and the thermal zone.

BITES, is provided in these three configurations – circulation air extracts heat from the cores of the BITES and mixes with room air. Potential surface coverings will not have effect on this coupling. This air circulation also increases the effective use of thermal storage mass by thermally coupling the core mass with room air directly.

Operation wise, “local circulation” is more flexible – its circulation operation is independent from that of ventilation. The circulation can be halted regardless of the space conditioning and ventilation needs of the room. While for the other two configurations, space conditioning and ventilation air has to pass through the BITES at all times. For room temperature regulation speed, “local circulation” and “room then BITES” configurations are almost as fast as conventional forced-air systems. “BITES then room” is relatively slow-BITES will be conditioned first and air will be attenuated to near BITES temperature.

In the case of storing useful passive solar heat gain, “room then BITES” and “local circulation” configurations are preferable because excess thermal energy will be immediately transferred into the BITES without being attenuated by ventilation and/or AHU. For building cooling and precooling through mechanical ventilation, if “room then BITES” and “local circulation” are used, the supply air cannot be cooler than room temperature setpoint during occupied periods and it will be attenuated by the room mass before entering the BITES, making the BITES charge less effective. Using “BITES then room”, the supply air can be cooler than room temperature setpoint since it will be warmed up by the BITES before entering the room space. Hence more coolness can be stored more effectively without overcooling the room. This advantage was also investigated by Corgnati and Kindinis [18]. In a natural ventilation scenario, the three configurations will perform approximately the same since mechanical ventilation and space cooling will be

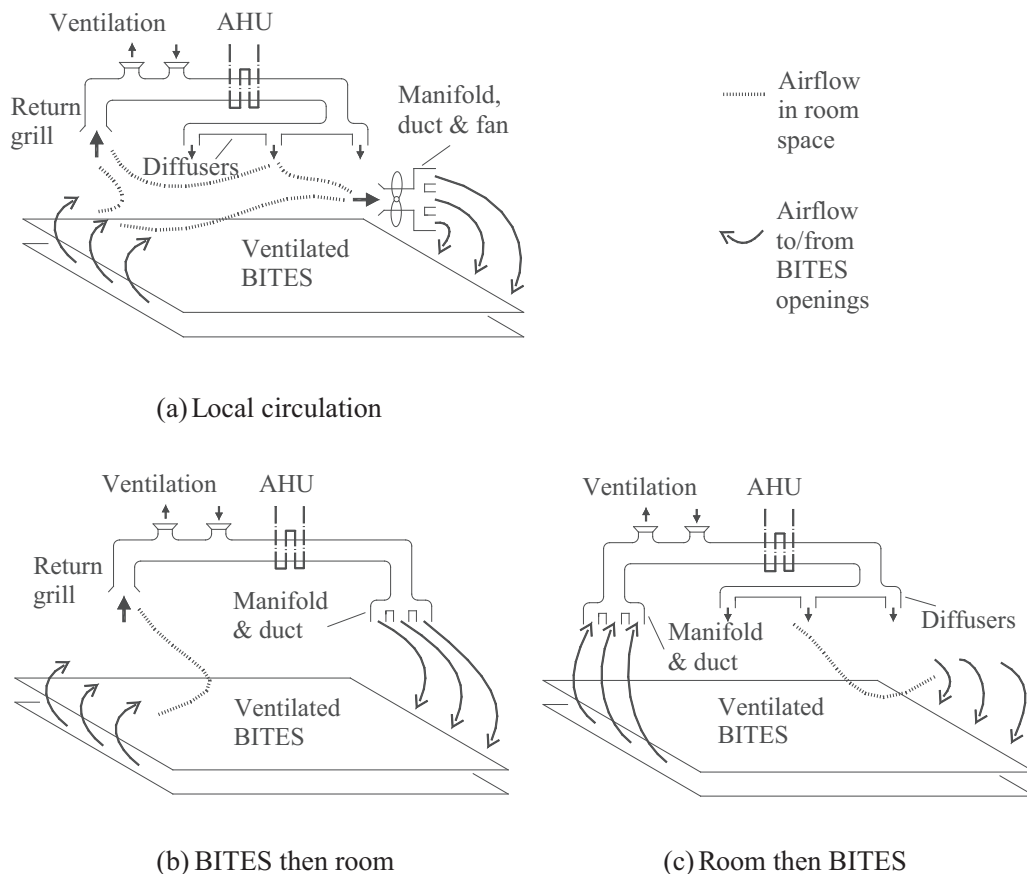


**Fig. 4.** Conceptual configurations of ventilated BITES with airflow to zone.

**Table 1**  
Thermal properties related dimensions of standard precast hollow core slabs [23] and their variations.

| Slab depth<br>m (in.) | Equivalent slab thickness<br>m (in.) | No. of cores | Core diameter<br>m (in.) | $Ratio_{cr}$ |
|-----------------------|--------------------------------------|--------------|--------------------------|--------------|
| 0.102 (4.0)           | 0.082 (3.2)                          | 12           | <b>0.051 (2.0)</b>       | 1.6          |
|                       | 0.090 (3.5)                          | 8            | 0.049 (1.9)              | 1.0          |
| 0.152 (6.0)           | 0.100 (3.9)                          | 8            | <b>0.101 (4.0)</b>       | 2.1          |
|                       | 0.140 (5.5)                          | 8            | 0.049 (1.9)              | 1.0          |
|                       | 0.128 (5.0)                          | 4            | 0.097 (3.8)              | 1.0          |
| 0.203 (8.0)           | 0.113 (4.5)                          | 6            | <b>0.153 (6.0)</b>       | 2.4          |
|                       | 0.187 (7.3)                          | 6            | 0.065 (2.5)              | 1.0          |
|                       | 0.171 (6.7)                          | 3            | 0.129 (5.1)              | 1.0          |
| 0.254 (10.0)          | 0.137 (5.4)                          | 5            | <b>0.191 (7.5)</b>       | 2.5          |
|                       | 0.235 (9.2)                          | 5            | 0.078 (3.1)              | 1.0          |
|                       | 0.222 (8.7)                          | 3            | 0.129 (5.1)              | 1.0          |
| 0.305 (12.0)          | 0.153 (6.0)                          | 4            | <b>0.243 (9.6)</b>       | 2.5          |
|                       | 0.217 (8.6)                          | 4            | 0.184 (7.3)              | 1.9          |
|                       | 0.281 (11.0)                         | 4            | 0.097 (3.8)              | 1.0          |
|                       | 0.256 (10.1)                         | 2            | 0.194 (7.6)              | 1.0          |

Note:

1. The values in the hatched area are for standard components.
2. Core diameters in bold are the maximum allowable values.
3.  $Ratio_{cr}$  is based on one side of the slab.
4. 0.102 m thick slab is not common in practices.

halted. These characteristics are demonstrated by a theoretical case study presented in the following subsection.

For the configurations shown in Fig. 4, the space conditioning energy is delivered through local AHU's. Local air recirculation flow rates and AHU coil temperature are adjusted according to space conditioning load. The ventilation airflow rate does not depend on the space conditioning load. For small buildings (e.g. houses), local AHUs are generally not adopted. The space conditioning and mechanical ventilation are accomplished by one common air circulation. In this case, in order to reduce fan energy consumption, it is ideal that the flow rate required for ventilation can also satisfy that for BITES storage and space conditioning. Ideal ventilated BITES system can integrate building fabric (structural/non-structural), BITES, and ventilation functions together. Further study is needed.

In terms of construction and operation costs, "BITES then room" configuration is most equipment saving. The hollow cores of the BITES are used to distribute air. As compared to "BITES then room", "room then BITES" requires extra duct work and diffusers for even air distribution to room space (Fig. 4). This extra requirement means more fan power consumption. For "local circulation" configuration, further additional diffusers, manifolds, air filters, and fans are needed to collect and circulate room air through BITES.

In order to investigate the impacts of different system configurations on a zone's thermal performance, simulations are conducted on a simple room equipped with different BITES systems. A typical space heating scenario is chosen to compare the ventilated BITES slabs with airflow to zone (Fig. 4) and a normal solid concrete floor. Then, a high-demanding space cooling scenario is used to compare a ventilated BITES slab with airflow to zone and a hydronic BITES floor (i.e. no airflow to zone BITES). The simulated thermal performance and their comparison are presented in section "Results and discussion".

### 2.3. Integrated design using standard construction units

The geometry (e.g. thickness) and material properties of a ventilated BITES system significantly influence its structural and thermal functions. Constructability should also be considered in the integrated design process. Therefore, there are many parameters to consider when designing ventilated BITES systems that

aim for a high level integration of structural and thermal functions. Using standard wall and slab construction units with minor modifications is practical.

The design parameters of standard masonry walls and precast concrete slabs are presented in this section. Their different equivalent thicknesses (i.e. net cross section area per meter length) and corresponding  $Ratio_{cr}$  (area ratio of core surface to room-side surface) are listed since these two design parameters are critical. Equivalent thickness defines nominal storage capacity, and  $Ratio_{cr}$  indicates how much core area is available for active charge per unit surface room-side area. Faster storage and/or higher space conditioning loads requires larger  $Ratio_{cr}$ . For a given  $Ratio_{cr}$ , fewer number of cores corresponds to larger hollow space (i.e. smaller equivalent thickness). The calculation approach for appropriate  $Ratio_{cr}$  and equivalent thickness for different design conditions has been presented by Chen et al. [20].

The storage capacity of a unit is directly related to its cross section area. Normally, the geometry of the cross section of a standard wall or slab unit is optimized for structural requirement. Hence, the cross section area of a unit cannot be reduced without compromising the unit's structural strength. But it can be enlarged through topping, plastering, using a stronger unit with larger panel depth/width, or all of them. Furthermore, new energy efficient structural units can be developed.

#### 2.3.1. Precast hollow-core concrete slabs

The cross sections of hollow core slabs are slightly different from each manufacturer to another. Cross sections with circular hollow cores are studied here since they have the maximum net cross section area for a given  $Ratio_{cr}$ , and hence more thermal storage mass. Table 1 shows the cross section configurations of different standard hollow core slabs and their variations. The equivalent thicknesses (i.e. cross section areas) of standard units are enlarged by reducing the  $Ratio_{cr}$  from their standard values to 1.0, with and without reducing the number of cores. Note that the core diameter will affect the friction between the air and the core surface, and consequently the fan power. Furthermore, 50 mm (2 in.) of topping is often used in practice.

#### 2.3.2. Hollow-core masonry walls

A concrete masonry block (Fig. 5) has a standard actual length of 390 mm (15 5/8 in.), and a width of 190 mm (7 5/8 in.). In practice, a mortar joint of 10 mm is added between blocks (hence resulting in block patterns of 200 mmx400 mm, i.e. 8 in.x16 in.), and 10–20 mm of plastering is usually applied to the surface of a masonry wall. Minimum allowable web and face shell thicknesses and the net cross section area are defined by structural strength requirement. Table 2 shows the cross section configurations of different standard concrete masonry blocks and their variations. Concrete masonry walls are often used as non-structural components (i.e. partitions) due to their high fire safety rating and acoustic insulation characteristics.

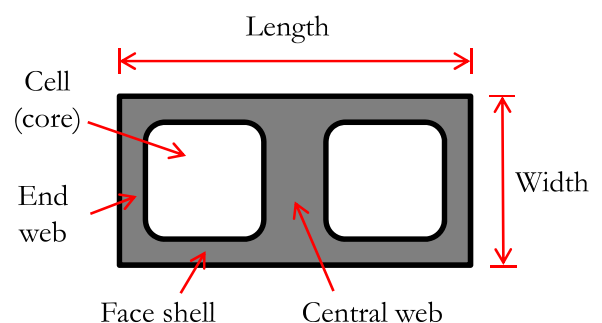


Fig. 5. A typical hollow-core concrete masonry block.

**Table 2**  
Thermal properties related dimensions of standard concrete masonry blocks [24,25] and their variations.

| Nominal unit width<br>m (in.) | Equivalent wall thickness<br>m (in.) | Ratio <sub>cr</sub> | Note                     |
|-------------------------------|--------------------------------------|---------------------|--------------------------|
| 0.152 (6)                     | 0.070 (2.7)                          | 2.5                 | Two normal cells         |
|                               | 0.106 (4.2)                          | 1.7                 | Two smaller square cells |
|                               | 0.106 (4.2)                          | 1.2                 | One normal cell grouted  |
| 0.203 (8)                     | 0.091 (3.6)                          | 2.8                 | Two normal cells         |
|                               | 0.140 (5.5)                          | 2.0                 | Two smaller square cells |
|                               | 0.140 (5.5)                          | 1.4                 | One normal cell grouted  |
| 0.254 (10)                    | 0.111 (4.4)                          | 3.3                 | Two normal cells         |
|                               | 0.177 (7.0)                          | 2.3                 | Two smaller square cells |
|                               | 0.177 (7.0)                          | 1.6                 | One normal cell grouted  |
| 0.305 (12)                    | 0.127 (5.0)                          | 3.7                 | Two normal cells         |
|                               | 0.211 (8.3)                          | 2.6                 | Two smaller square cells |
|                               | 0.211 (8.3)                          | 1.9                 | One normal cell grouted  |

Note:  
1. The values in the hatched area are for minimum allowable thickness for face shell and webs.  
2. In calculating the net cross section, 0.025 m (3/8 in.) thickness of web is added to the equivalent web thickness per meter length.  
3. Ratio<sub>cr</sub> is based on one side of the wall.  
4. Two smaller square cells: Fig. 7(b).

Fig. 6 proposes a connection configuration between parallel hollow cores (air channels). Webs of masonry blocks near the upper or lower ends of the wall are partially removed to create openings for connecting adjacent channels. Turning vanes smooth

airflow turning and hence reduce friction. Precast connecting blocks with web openings and turning vanes can be used to facilitate construction. Air channels should avoid going through reinforcement and grouted cells and hence weakening walls'

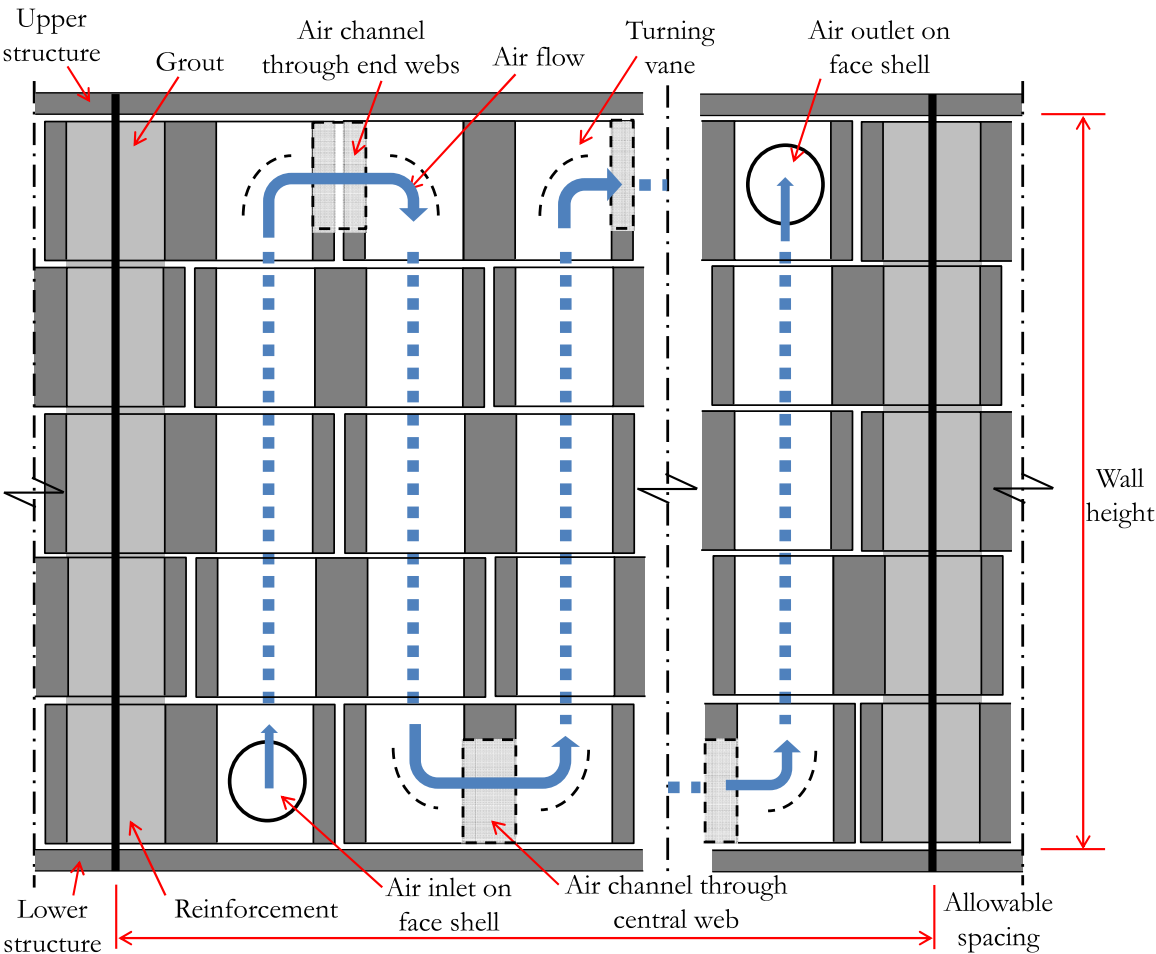


**Fig. 6.** Schematic of creating connection between hollow cores (air channels).

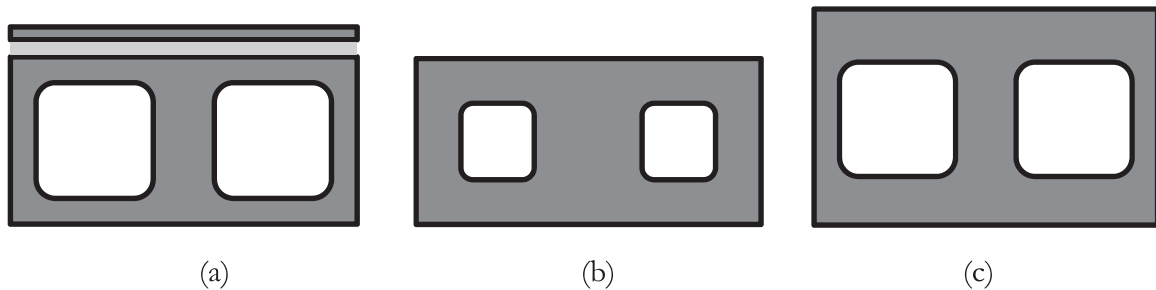


**Fig. 7.** Potential approaches for increasing storage capacity: (a) adding thicker plastering or additional thermal storage panels; (b) reduce void space; (c) increase face shell thickness.

structural strength. For non-load bearing masonry walls, neither grout nor reinforcement is needed; hence, air channels can be connected with more flexibility.

When a thermal storage capacity (e.g. net cross section area) larger than standard values is needed, three potential approaches can be adopted (Fig. 7). Thermal storage panels or thick plastering can be added (Fig. 7(a)). Void area can be reduced (Fig. 7(b)) if a smaller core diameter does not result in significant friction loss for airflow. Also, the face shell thickness can be increased (new types of blocks) with void area unchanged (Fig. 7(c)).

### 3. Results and discussion

Thermal performance simulations are conducted on a simple room equipped with different BITES systems. A typical space heating scenario is chosen to compare the ventilated BITES slabs with airflow to zone (Fig. 4) and a normal solid concrete floor. Then, a high-demanding space cooling scenario is used to compare a ventilated BITES slab with airflow to zone and a hydronic BITES floor (i.e. no airflow to zone BITES). The simulated thermal performance and their comparison are presented in this section.

A 10 m (length) × 3.6 m (width) × 3 m (height) room is used. The equator-oriented façade (10 m × 3 m) of the room has an 8 m<sup>2</sup> triple-glazed window area, and it is the only exterior wall. See Appendix for other physical parameters of the room. The room is set to have no heat exchange through interior partitions and ceiling. The equivalent (excluding the hollow core space) thickness of the slab is 0.3 m. A PID (proportional–integral–derivative) controller with the room air temperature as input is used to regulate the heating/cooling supply of the AHU. The output capacity of the AHU is unlimited for the sake of exploratory study. The air inside the room is assumed perfectly mixed.

Explicit finite difference models are created for the room and the slabs with a time step of 60 s. Studies have showed that one-dimensional thermal models can approximate the thermal behavior of BITES systems under conditions of practical interest [26–29]. The charging system (e.g. air channels or water pipes) can be replaced with an imaginary thickness-less heat “source layer” [30]. The transformed cross section has the same area as the original. Fig. 8 shows the transformed cross section of the active BITES floor adopted in the room. Heat transfer is one dimensional normal to the room-side surface. Chen et al. [30,31] have presented relevant modeling techniques that were verified with full-scale experiment. Their approach is adopted here. Other detailed simulation information was described by Chen et al. [32].

#### 3.1. Comparisons between proposed configurations and solid BITES

A five-day winter period with intermittent high solar radiation is chosen for simulation. The performance of ventilated BITES slabs

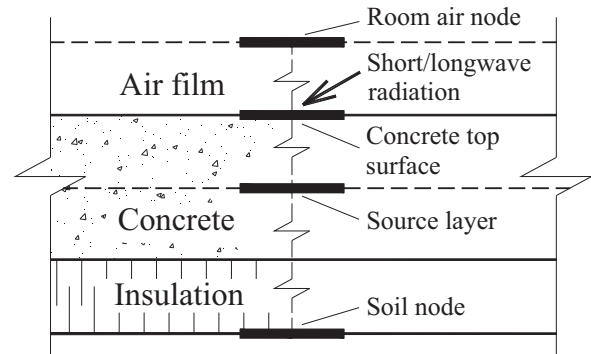


**Fig. 8.** Thermal network of an active BITES floor with its cross section transformed.

with airflow to zone (Fig. 4) and a normal solid concrete floor are evaluated. Fig. 9 shows the boundary conditions of the last three days of this simulation period. The simulated performance (Fig. 10) of the room in the period of day 4 and 5 (i.e. between hour 72 and 120) is used for comparison. Room temperature is set to be 23 °C with a throttling range of 2 °C.

The thermal performance of the room with a solid slab is shown in Fig. 10(a). The performance of configurations “room then BITES” and “local circulation” is almost identical and hence only one is shown in Fig. 10(b). From Fig. 10(a) and (b), it can be seen that near the end of the sunny period (hour 92) the slab core temperature of the “room then BITES” or “local circulation” configuration was about 1 °C higher than that of the configuration with solid slab. This temperature difference indicates a significantly higher amount of excess heat (about 5 kW h or 0.14 kW h/m<sup>2</sup>) was transferred from the room air to the ventilated BITES. Space cooling during the sunny period and space heating in

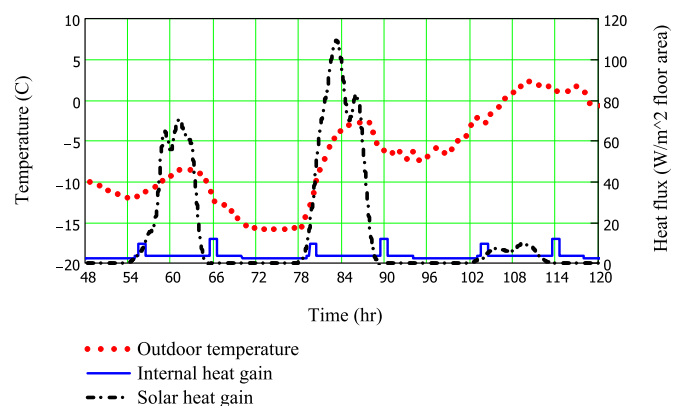


**Fig. 9.** Weather profiles of the space heating period.

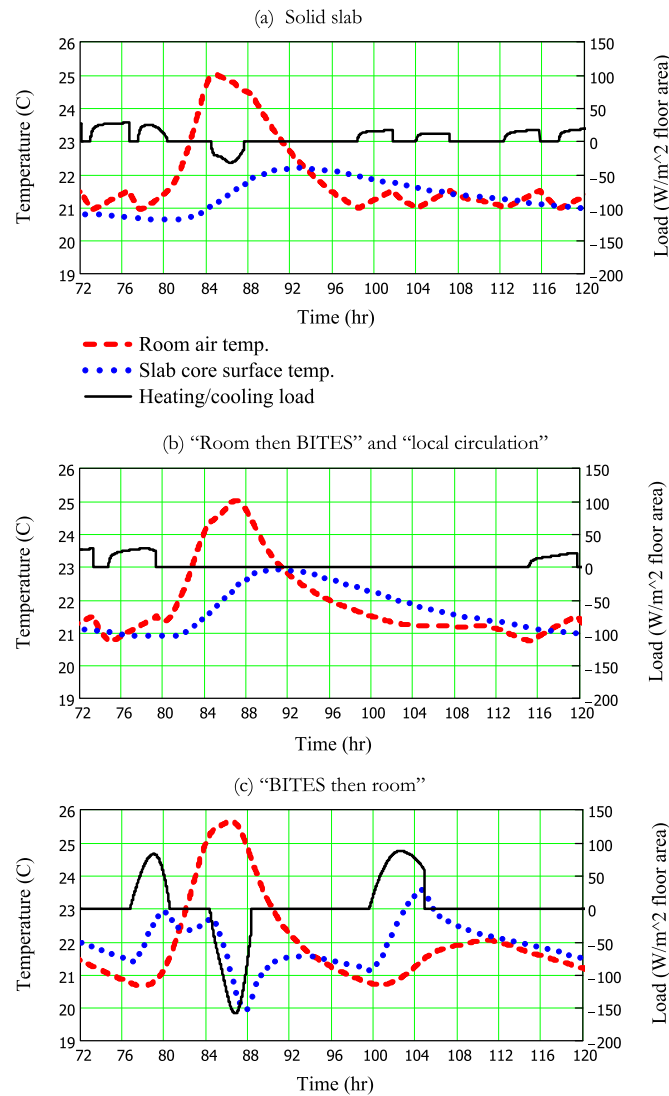


Fig. 10. Simulated performance of the room with different BITES systems.

the following cold night period are avoided. "BITES then room" configuration showed a different behavior (Fig. 10(c)). This behavior is mainly due to the high heat gain and loss of the room together with its heating/cooling sequence – the space conditioning air from the AHU will be attenuated after passing the ventilated BITES. Between hour 77 and 81, the slab was heated up in order to warm up the room air. Later on between hour 84 and 88, the slab was cooled down to offset the high solar heat gain. Space heating and cooling energy was wasted in counteracting each other. To make full use of the passive solar heat gain, one feasible solution is to increase the thermal coupling between the slab and the rest of the room by increasing the circulation flowrate. Another possible solution is predictive control. For example, between hour 72 and 77, the slab can be heated up slightly (about 1 °C). The slab will be cool enough to store all the excess solar heat gain in the coming sunny period, similar to that in Fig. 10(b). Then space heating and cooling would be avoided for the following hours. A predictive control methodology has been proposed by Chen et al. [20].

The simulations also show that the performance is sensitive to the heating/cooling load, thermal coupling level (e.g. circulation flowrate), the variable used as input for the PID controller (room air temperature in this case), and its setpoint and throttling range values.

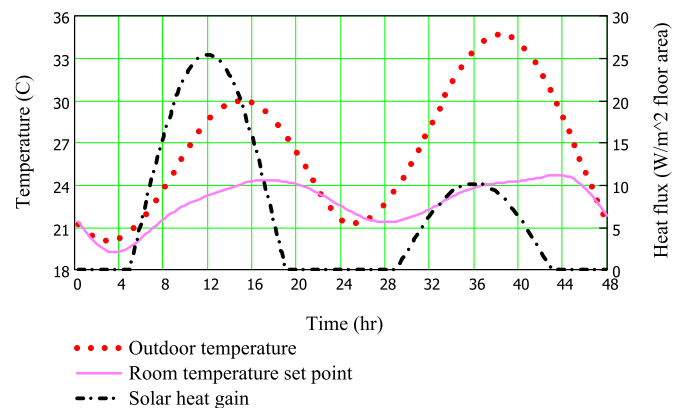


Fig. 11. Weather profiles of the space cooling period.

### 3.2. Comparison against "no airflow to zone" systems

Primary space conditioning can be supplied through active BITES, with or without airflow to zone. For example, the "BITES then room" configuration shown in Fig. 4(b) is the one with airflow to zone, and

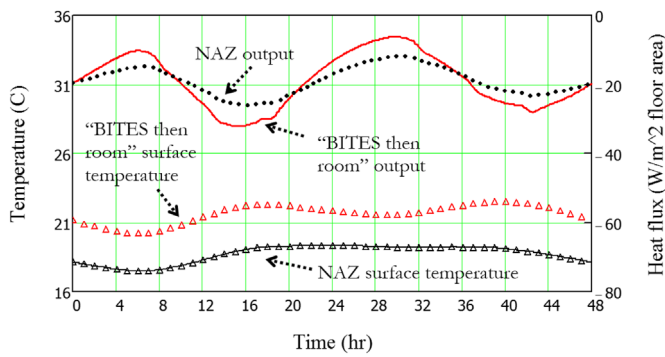


**Fig. 12.** Comparison of simulated thermal performance of two configurations: “BITES then room” and no-airflow-to-zone (NAZ).

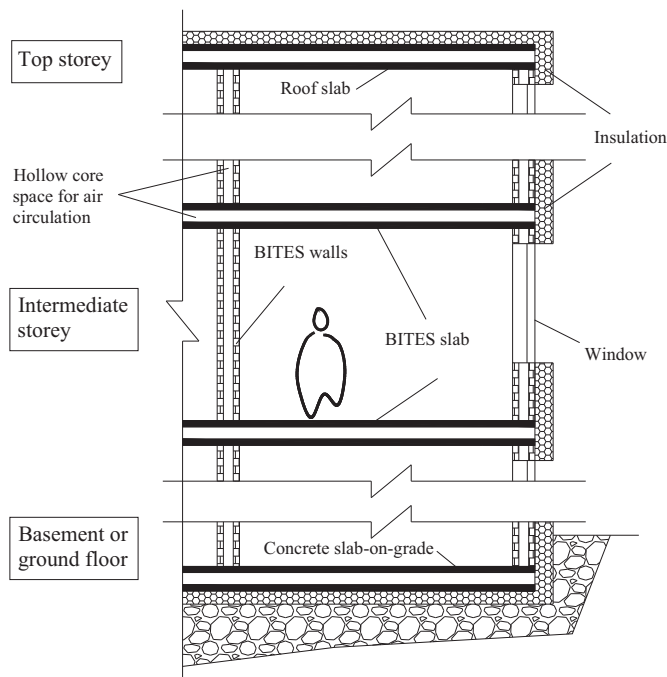


**Fig. 13.** Schematic of possible locations of hollow-core concrete slabs and masonry walls.

hydronic floor heating/cooling systems have no airflow to zone. In either of these two cases, the room side surface of BITES behaves like large radiant space conditioning panels. Its heating and cooling capacities are about  $30\text{--}40\text{ W/m}^2$  [33–35]. For “no airflow to zone” configurations, when space conditioning load is high, the surface temperature of “no airflow to zone” system needs to be uncomfortably low for space cooling or high for space heating, especially for the scenarios of radiant floor cooling or ceiling heating. The convective heat transfer coefficients (CHTC) in these scenarios are extremely low due to heat flow being against buoyancy, and hence large temperature potential is needed for compensation. Condensation may result from using radiant space cooling in warm and humid climatic conditions [8]. On the other hand, “BITES then room” configuration combines forced-air and radiant space conditioning systems. Additional thermal output is provided by the advective heat transfer from the airflow flowing to zone. Hence substantially higher thermal output can be provided without drafts and uncomfortably cold floor or hot ceiling surfaces. This improvement is part of the benefit of strong thermal coupling.

A summer period with high space cooling demand is chosen for simulation. Fig. 11 shows the steady-periodic boundary conditions and room temperature setpoint profile. The internal heat gain is

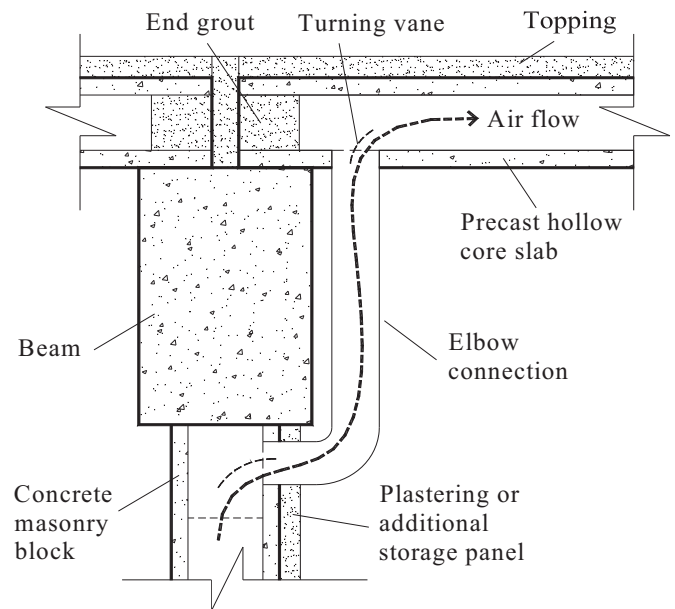


**Fig. 14.** Schematic of an air channel connection between a hollow core slab and a masonry block wall.

the same as in Fig. 9. The peak cooling load is about  $35\text{ W/m}^2$ . Fig. 12 compares the simulated cooling performance of a “BITES then room” ventilated BITES floor and a “no airflow to zone” system (a hydronic BITES floor system in this case). As seen, the floor surface of the “BITES then room” system is within thermal comfort range for satisfying the room air temperature setpoint, while the hydronic floor cooling (i.e. “no airflow to zone” configuration) results in an uncomfortably cold floor surface. This comparison suggests that “BITES then room” configuration is preferable for high space conditioning load conditions. Furthermore, because of its additional advective thermal output, “BITES then room” configuration has faster response to sudden demand changes and reduces impact from coverings, as compared to “no airflow to zone” configuration.

### 3.3. Design considerations

The hollow cores of standard construction units can be used as air channels with minor alterations. The alterations from conventional construction methods would mainly include connecting the hollow cores inside the units and creating holes on room side surfaces for air inlets and outlets.

For flexural strength of reinforced concrete slabs, since concrete is not essential in providing tensile strength, holes on the tension side of the slabs will not significantly affect its flexural strength. In some cases, holes are opened on the compression side. In these cases, the flexural strength may be affected, depending on the capacity of the remaining cross section and the size of the opening. Note that brittle failure (compression side failure) is not permitted in concrete structure design [11]. For slabs that are pin-supported at both ends, the maximum bending moment occurs near the mid-span. For non-structural masonry walls, they are not subjected to primary stresses; hence they have minimum reinforcements at wide spacing just for providing structural integrity.

In connecting the air channels within the walls and slabs, holes will be opened on the inner webs that are between the air channels and normal to the room-side surface. By doing this, the shear strength of the structural components will be weakened. For slabs, the largest shear load exists near their supports. Instead of one

hole, two smaller holes along the air channel can be used. Hence the reduction to the shear capacity of the original cross-section will be decreased.

Hollow-core masonry walls and concrete slabs can be used as ventilated BITES in most parts of the buildings (Fig. 13). They can be structural or nonstructural components. If a masonry wall and a concrete slab in one room are both used for active BITES, their air channels can be connected. Bends or angles can be used to facilitate the connection (Fig. 14). Ideally, the connection should go around the supporting beams to avoid complicating the structure design and construction.

#### 4. Conclusions

This paper explains the benefits of using hollow-core masonry walls and precast concrete slabs for ventilated Building-Integrated Thermal Energy Storage (BITES), with focus on the “with airflow to zone” configurations:

- This approach can integrate the functions of structure, thermal storage, space conditioning and ventilation into one building fabric component, and hence save overall cost and room space;
- It makes effective use of material both for thermal and building fabric/structural functions. Thermally and structurally less inactive materials are removed and replaced with hollow cores, which in turn are used as air channels for air circulation to enhance thermal charge and discharge effectiveness;
- Ventilating BITES can provide a significant amount of effective mass for thermal energy storage and strong thermal coupling between the BITES and the rest of the room. Circulating air between the cores of the BITES and its zone enhances the heat exchange rate between them.

Three system configurations that enhance the thermal coupling between a BITES and its zone are presented and compared. Their strong thermal coupling with their zone significantly enhances the thermal performance of the zone, such as reduced space conditioning energy consumption and peak demand by storing excess thermal energy. The “local circulation” configuration is more flexible in operation but has higher construction costs. It and “room then BITES” configuration suit better natural ventilation and passive solar heating. The “BITES then room” configuration suits better mechanical space cooling and precooling by storing more coolness in the BITES than the other two configurations. However,

it has larger thermal inertia in regulating room air temperature. It and “room then BITES” configuration integrate space conditioning, ventilation, and thermal energy storage functions.

As compared to “no airflow to zone” configuration (e.g. hydronic floors) for space cooling, “BITES then room” configuration is preferable for high space conditioning load conditions – more comfortable surface temperature and low peak power demand. “BITES then room” configuration also has faster response to sudden demand changes and reduces impact from coverings.

Using standard hollow-core masonry block walls and precast concrete slabs as ventilated BITES can facilitate the integrated design process for BITES. It minimizes alterations in current construction practices, such as constructability and re-design for structural aspects. The thermal properties of standard wall and slab units and their variations are presented. Other design considerations are discussed for practical implementation.

#### 5. Future development

The energy performance of ventilated BITES systems (e.g. consumption of fan energy, heating and cooling energy) has not been presented in this study. In general, the energy performance heavily depends on the built environment (e.g. building usage and envelope types), and operation strategies (e.g. charging with renewable energy). This topic is highly recommended for future studies.

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#### Appendix

See Appendix [Table A1](#)

**Table A1**  
Key parameters of the room thermal model

| Parameters                                        | Values                                                                                       | Note                                                           |
|---------------------------------------------------|----------------------------------------------------------------------------------------------|----------------------------------------------------------------|
| BITES slab thickness                              | 0.3 m                                                                                        | Equivalent thickness of concrete                               |
| Thermal insulation under BITES slab               | 0.5 W/m <sup>2</sup> /K                                                                      |                                                                |
| Window                                            | 8 m <sup>2</sup> , 1.2 W/m <sup>2</sup> /K, SHGC of 0.5                                      | On the 10 mx3 m façade facing the equator                      |
| Ventilation and infiltration                      | 0.3 air changes per hour                                                                     |                                                                |
| Effective thermal storage capacitance of room air | 30 times room air capacitance                                                                | Including indoor objects such as furniture and partition walls |
| Thermo-physical properties of concrete            | 840 J/kg/K for specific heat; 2200 kg/m <sup>3</sup> for density; 1.7 W/m/K for conductivity | Constant                                                       |
| Thermo-physical properties of air                 | 1300 J/m <sup>3</sup> /K for volumetric heat capacity                                        | Constant                                                       |
| Soil node temperature                             | 10 °C                                                                                        | Constant                                                       |

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