

Modeling, design and thermal performance of a BIPV/T system thermally coupled with a ventilated concrete slab in a low energy solar house: Part 2, ventilated concrete slab

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Abstract

This paper is the second of two papers that describe the modeling and design of a building-integrated photovoltaic–thermal (BIPV/T) system thermally coupled with a ventilated concrete slab (VCS) adopted in a prefabricated, two-storey detached, low energy solar house and their performance assessment based on monitored data. The VCS concept is based on an integrated thermal–structural design with active storage of solar thermal energy while serving as a structural component – the basement floor slab ($\sim 33 \text{ m}^2$). This paper describes the numerical modeling, design, and thermal performance assessment of the VCS. The thermal performance of the VCS during the commissioning of the unoccupied house is presented. Analysis of the monitored data shows that the VCS can store 9–12 kWh of heat from the total thermal energy collected by the BIPV/T system, on a typical clear sunny day with an outdoor temperature of about 0°C . It can also accumulate thermal energy during a series of clear sunny days without overheating the slab surface or the living space. This research shows that coupling the VCS with the BIPV/T system is a viable method to enhance the utilization of collected solar thermal energy. A method is presented for creating a simplified three-dimensional, control volume finite difference, explicit thermal model of the VCS. The model is created and validated using monitored data. The modeling method is suitable for detailed parametric study of the thermal behavior of the VCS without excessive computational effort.

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Keywords: Solar thermal energy; Ventilated concrete slab; Thermal–structural design integration; Active thermal energy storage; Active solar heating; Thermo-active building systems (TABS)

1. Introduction

Integrating distributed thermal mass in a building has been shown to be efficient and effective in improving the thermal performance of buildings (Anderson, 1990; Balcomb, 1992). It can reduce the room temperature fluctuation and load, and also shift the peak load (Braun, 2003; Henze et al., 2005). Concrete is a common and effective building material used as thermal mass (ACI Committee 122, 2002).

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Concrete slab, in a distributed form, has the potential advantages of combining the functions of thermal energy storage (TES) and structural element (Howard and Fraker, 1990) without taking up living space. Bilgen and Richard (2002) conducted experimental and theoretical studies on a passive system consisting of a horizontal concrete slab and presented its detailed thermal behavior. Athienitis et al. conducted experiments and simulations to study the thermal behavior of passively charged concrete slabs (1994) and concrete slabs used in hydronic floor heating systems (1997, 2000) and they reported that the control strategy for active thermal charging must be planned in conjunction with the anticipated passive solar gains.

Nomenclature

c_{air}	specific heat capacity of air (J/kg/K)	U_c and $U_{c_required}$	convective conductance inside air channel per meter length of channel (W/K)
D_h	hydraulic diameter (m)	W_{chn}	width of the air channel (m)
k_{air}	thermal conductivity of air (W/m/K)	μ_{air}	dynamic viscosity of air (kg/s/m)
h_c	convective heat transfer coefficient inside air channel (W/m ² /K)	v_{air}	air velocity inside the air channel (m/s)
$h_{c,r}$	combined convective and radiative heat transfer coefficient (W/m ² /K)	ρ_{air}	density of air (kg/m ³)
$h_{c,vcs}$	calculated convective heat transfer coefficient inside air channel (W/m ² /K)	Acronyms	
H_{chn}	height of the air channel (m)	BIPV/T	building-integrated photovoltaic/thermal
Re	Reynolds number	CHTC	convective heat transfer coefficient
Pr	Prandtl number of air	CV	control volume
$u_{soil,in}$	thermal conductance of insulation under the concrete slab (W/m ² /K)	LMTD	log mean temperature difference
		TABS	thermo-active building systems
		TES	thermal energy storage
		VCS	ventilated concrete slab

A major shortcoming of passive storage and release of thermal energy (i.e. thermally coupled with air through a natural convection mechanism on the exposed surfaces only) is that the effectiveness of heat exchange is relatively low due to the fact that the surface area in direct contact with the air is restricted by its exposed surface area and the heat transfer coefficient by natural convection alone is relatively low (Shaw et al., 1994). The concept of actively charging building thermal storage by means of thermo-active building systems (TABS) has been introduced in the industry and applied. In the studies of hydronic TABS (Henze et al., 2008; Lehmann et al., 2007; Olesen et al., 2006), concrete slabs are actively pre-conditioned and conditioned by hydronic piping embedded in the slab and the cooling or heating rate can be controlled so as to achieve the desired slab average temperature in an efficient manner. Several studies have been conducted on using TABS to assist space heating. In the simulation study conducted by Henze et al. (2008), a hydronic TABS is adopted to assist the conventional variable air volume system for space heating and cooling in a low energy office building. Fraisse et al. (2007) investigated the energy performance of photovoltaic/thermal (PV/T) collectors with a closed loop liquid heat recovery thermally coupled with a hydronic TABS in a space heating system with focus on the PV/T thermal behavior. Zhai et al. (2009) investigated a hydronic TABS powered by solar thermal collectors using experimental data and simulations. Fraisse et al. (2006) studied, through simulations of different configurations, the energy performance of an interior ventilated wall thermally coupled with solar air collectors in a timber frame house.

A ventilated concrete slab (VCS) is a type of forced-air TABS in which the concrete slabs exchanges thermal energy with the air passing through its internal hollow voids (Winwood et al., 1997; Braham, 2000). The stored thermal energy can be released to the living space passively by natural convection and radiation through the slabs

exposed surfaces, or actively by mechanical ventilation through its internal hollow voids to extract heat from the slab (Fort, 2000). Forced airflow through the internal hollow voids of thermal mass enhances the convective heat transfer coefficient (CHTC) (Ren and Wright, 1998) and utilizes a larger heat transfer area compared to outer surfaces by natural convection alone. Consequently, the TES effectiveness is considerably increased – the heat exchange rate between the thermal mass and the heat source is significantly increased, more thermal mass can become active, and more thermal energy can be stored or released. Mechanically facilitated heat transfer within the thermal mass also helps in improving the control of TES (e.g. temperature and heat transfer rate) (Shaw et al., 1994).

On the utilization of VCS, the present survey of the literature revealed that most studies focused mainly on reducing and shifting the cooling load of buildings. Furthermore, design methodology, parametric analysis of the sizing of the slab, detailed thermal behavior (e.g. the temperature distribution in the slab), and data from on-site application are rare, especially in a combisystem with solar thermal air collectors. There is a need to investigate VCS as a means of supplementing passive storage in solar houses in order to facilitate efforts aiming at design for net-zero annual energy consumption in cold climate regions with cold but sunny winters. A detailed study on the application of a VCS thermally coupled with a building-integrated photovoltaic/thermal (BIPV/T) system (BIPV/T-VCS) to utilize solar thermal energy to reduce space heating energy demand, is presented in this paper, including the method for modeling, system design, and assessment of the on-site thermal performance.

Implementing active solar heating with active thermal storage is one of the techniques employed in ÉcoTerra house to approach net-zero annual energy consumption. The VCS was employed for the first time in direct connection with a BIPV/T system (Fig. 1) in a new demonstration

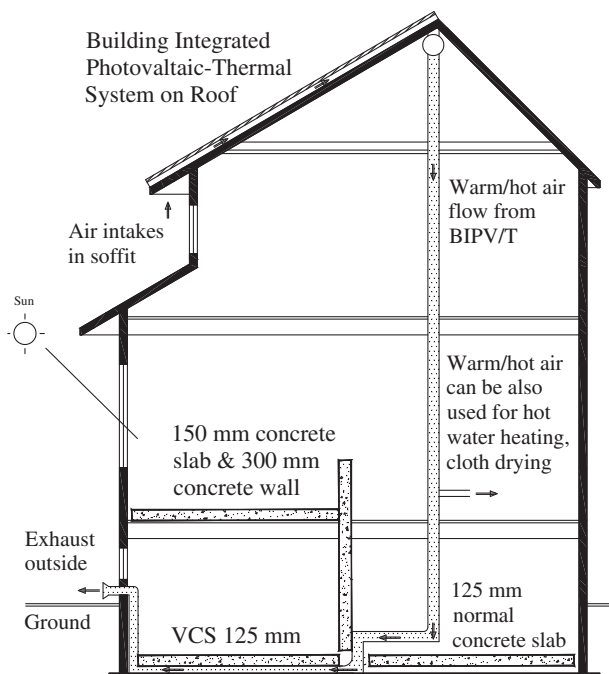


Fig. 1. Schematic showing passive storage mass in ground floor and VCS linked with BIPV/T system.

solar house in Canada (see the companion paper part 1 for detailed information of the BIPV/T system and the house). The construction of the house was completed in November 2007 and was then tested and commissioned/monitored over a period of about 18 months before being unoccupied.

The VCS is located in the basement. Besides its structural function as the basement slab, the VCS also serves as actively charged thermal mass to store solar thermal energy and then passively releases it to assist space heating. The VCS is charged with solar-heated outdoor air in an open loop configuration. Different configurations are possible, such as a closed loop system where the air is circulated back to the roof, but in this particular case an open loop system was selected for simplicity, to avoid the risk of air quality and moisture problems, and also to provide a capability for use of the BIPV/T air for three other purposes – clothes drying, domestic hot water heating through an air-to-water heat exchanger and free night cooling during the cooling season as discussed in the companion paper part 1. The VCS is based on commonly available construction technologies and can thus be easily implemented in North American homes as the common practice is to have a basement slab.

2. Design of ventilated concrete slab

The main design requirements for the VCS adopted in ÉcoTerra were the following:

- I Efficient storage of thermal energy collected by the BIPV/T system. The number of air channels and their total cross sectional area need to suit the air flow rate

of the BIPV/T system in order to optimize the flow rate in each air channel to have a desired CHTC and reduce friction loss. The layout of the air channels needs to evenly distribute the air flow and the thermal energy.

- II Avoid overheating on the top surface. The comfortable temperature range for concrete slab surface (with no cover) is between 26 and 28.5 °C for people with bare feet (ASHRAE, 2005); and 19–29 °C for people wearing lightweight indoor shoes in office environment (ASHRAE, 2004). The latter temperature range is applied as a constraint in this research project.
- III Optimal thickness of the thermal mass. Suitable amount of concrete is needed to absorb maximum heat without surface overheating or releasing heat passively in an appropriate rate. Too much concrete increases cost and structural load.
- IV Serve as a structural component. The structural considerations, such as cracks due to shear and flexural forces, as well as differential settlement need to be considered.

A new type of VCS design suitable for basements is created to satisfy the above mentioned design requirements (Fig. 2) – it is a ribbed concrete slab with voids that act as air channels. The stored thermal energy is released to the living space passively from the top surface of the slab. The released heat from the VCS will slowly be distributed through the forced-air HVAC system to the rest of the house. The house has a forced air system, with the fan recirculating air through the house at low flow rate (200 L/s) when heating is not required, thus helping to redistribute the solar gains. Bottom heat loss to soil underneath is minimized through use of adequate insulation.

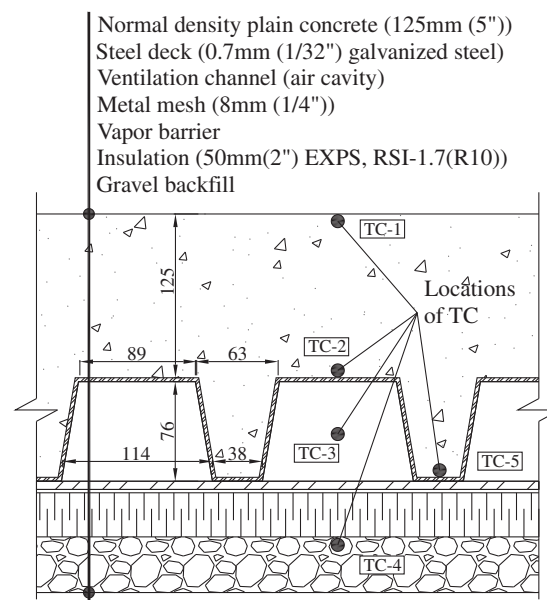


Fig. 2. Transverse cross section of VCS (monitoring points for temperatures also shown).

Placing the VCS on grade in the basement has two advantages. First advantage is that the construction of the air distribution system is simple: the manifolds and the steel decks are placed directly on grade (with rigid insulation underneath). No structural support is needed. This implies easy construction and low cost. Another advantage is that the VCS can store more thermal energy efficiently as the basement slab temperature before charging is lower than that of the other floors. This is because the basement is colder than other living spaces due to temperature stratification and the lower setpoint, as well as the lower temperature of the soil under the slab (about 9 °C). Generally, with a target temperature of 19 °C in the basement, the floor slab will be approximately at 18 °C. BIPV/T air at 21 °C or higher will be useful for heat storage, but as the temperature of the slab rises, so is the required setpoint for the incoming BIPV/T air. Because the air channels and the manifolds are surrounded by the concrete poured on top and the water barrier and soil underneath, the VCS is air tight.

Normal density concrete was poured on the corrugated steel decks. The channels in the steel decks become the air channels. In order to promote turbulence and thus a higher CHTC inside the channels, a layer of metal mesh was placed under the steel deck. The metal mesh also distributes the structural load from the flutes of the steel deck to the rigid insulation form – extruded polystyrene underneath. The compressive strength of the insulation ranges from 25 to 140 psi (NRC-IRC, 2008) (from 170 to 960 kPa) at 5% deflection. The calculated compression due to the combined load is about 20.5 kPa (assuming 125-mm thick concrete), which is much smaller than its compressive capacity.

The design of the VCS is interrelated with the design of the house and the BIPV/T roof. The sizing of the steel deck (e.g. length, cross section geometry, and number of air channels) and the concrete slab (e.g. the amount of concrete and its thermophysical properties) are related to the thermal capacitance and the heating load of the house, the thermal energy output of the BIPV/T roof (e.g. air temperature and flow rate), the geometry of the basement, the CHTC inside the VCS channels, the prevention of top surface overheating of the VCS, and the structural design considerations.

2.1. Preliminary design

At the preliminary design stage, the geometry of the cross section of the air channel and its length, and the thickness of the slab (i.e. the amount of concrete) are the three main parameters to be decided. The geometry of the cross section significantly affects the heat transfer rate between the steel deck and the air as follows:

- The total cross sectional area of all air channels determines the required air velocity v_{air} .
- The cross section geometry (i.e. height and width) determines the hydraulic diameter D_h .
- The Reynolds number Re is based on the v_{air} and D_h . It determines the CHTC inside the channel h_c .

- The cross section perimeter and the h_c are the main parameters that determine the conductance U_c (W/K) between the flowing air and the concrete per unit meter channel length.

If the slab is long enough, the slab can recover the maximum heat possible from the warm air, and the temperature of the outlet air will be almost the same as the temperature of the concrete near the outlet. However, longer air channel will result in higher friction loss. The thickness of the slab affects the amount of thermal energy that can be stored, and the rate of storage/release, and also the temperature of the slab top surface (which is limited due to comfort constraints).

With the estimated inlet flow rate (i.e. the typical flow rate of the BIPV/T system), the required CHTC for maximum heat recovery, $U_{c_required}$, can be calculated from Eq. (1). ΔT_{LMTD} is the log mean temperature difference (LMTD) between the slab and the warm air. If maximum heat from the air is recovered by the slab, the outlet air temperature will be very close to the slab temperature.

$$U_{c_required} = \frac{\dot{m}_{air} \cdot c_{p,air}}{No_{ch} \cdot L_{ch} \cdot \Delta T_{LMTD}} \quad (1)$$

where

$$\Delta T_{LMTD} = \frac{\Delta T_{out} - \Delta T_{in}}{\ln(\Delta T_{out}/\Delta T_{in})}$$

At the preliminary stage, the h_c and the U_c were estimated for various cross sections of steel decks available in the market, using the following equations. The optimal combination of the U_c , the number of channels No_{ch} , the length L_{ch} of the air channel, and the thickness of the slab are selected based on the thermal performance obtained by numerical simulations.

$$Re = \frac{\rho_{air} \cdot v_{air} \cdot D_h}{\mu_{air}} \quad (2)$$

Based on Colburn's Analogy (ASHRAE, 2005, 19) the heat transfer coefficient can be estimated as follows:

$$Nu = \frac{f}{8} \cdot Re \cdot Pr_{air}^{\frac{1}{3}} \quad (3)$$

$$h_c = Nu \cdot \frac{k_{air}}{D_h} \quad (4)$$

$$U_c = (2 \cdot H_{chn} + W_{chn}) \cdot h_c \quad (5)$$

The thermodynamic properties of air are taken at 20 °C. The calculation of the Darcy friction factor (f) for turbulent flows uses an interpolation formula Eq. (6) by Colebrook (White, 2003) as follows, which represents the data in the Moody chart:

$$\frac{1}{\sqrt{f}} = -2 \cdot \log \left(\frac{\varepsilon/D_h}{3.7} + \frac{2.51}{Re \cdot \sqrt{f}} \right) \quad (6)$$

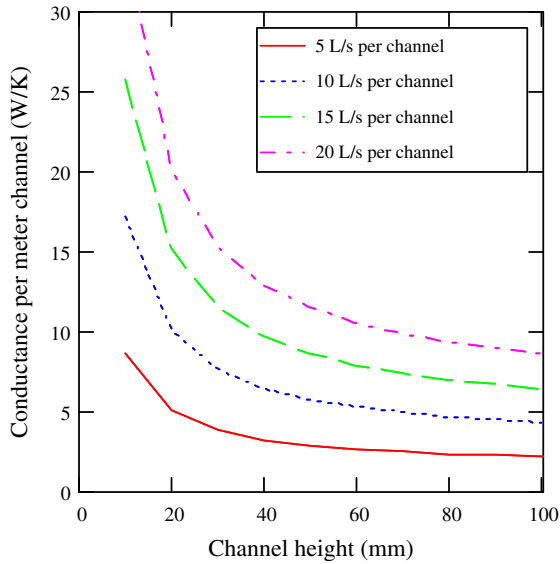


Fig. 3. Conductance U_c for different configurations of channel height H_{chn} and flowrate.

The metal mesh is very rough, therefore 5 mm is used for average roughness ε . Calculations show that friction factor is not very sensitive to cross section geometry. It ranges from 0.087 to 0.073 for channel width of 100 mm (the common width of steel deck channels) and different heights. By using 0.08 as the value of friction factor (i.e. Eq. (6) is not used), and combining Eqs. (2)–(5), we obtain:

$$U_c = C \cdot \text{FlowRate}_{chn} \left(\frac{2}{W_{chn}} + \frac{1}{H_{chn}} \right) \quad (7)$$

where $C = \frac{\rho_{air} \cdot k_{air} \cdot Pr^{1/3}}{100 \cdot \mu_{air}}$ and FlowRate_{chn} is the flow rate per channel.

Fig. 3 shows the estimated U_c at different channel flow rates and channel heights when the channel width is set as 100 mm. Smaller cross section area results in higher air

velocity, and consequently, higher U_c ; however, it also means higher pressure drop.

The center-to-center distance between channels in available steel sections is 152 mm (i.e. channel width W_{chn} of 100 mm). The floor plan of the basement (Fig. 4) allows the channels to be orientated in east–west direction (20 channels 9 m long) or north–south direction (60 channels 3 m long). This means that the products of No_{ch} and L_{ch} are the same for both orientations, as well as the total contact area between the slab and the air. However, the air velocity in 9 m long channels will be three times that of the 3 m long channels and the U_c values will be quite different. The estimated operating flow rate of the BIPV/T system ranges from 150 to 250 L/s. The $U_{c_required}$ for 250 L/s flow rate is about 6.8 W/K for both orientations, assuming that the initial slab temperature is at 18 °C and that the inlet air temperature (air from BIPV/T system) is at 40 °C. After reviewing steel decks available in the market, the cross section shown in Fig. 2 was selected. From Fig. 3 it can be seen that for 76-mm high channel, 15 L/s of air flow (velocity of about 1.8 m/s) in each 9-m long channel results in a U_c of about 7.5 W/K, and a 3-m long channel results in a U_c of about 2.5 W/K with 5 L/s (about 0.6 m/s) in each channel. Orienting the air channels in north–south direction does not satisfy $U_{c_required}$. Nevertheless, further analysis is carried out to compare these two orientations and to determine the slab thickness using a numerical model.

A three-dimensional, control volume finite difference numerical model was created for the selected cross section. Benefiting from its symmetric shape, simulations were performed for half channel cross section. The discretization of the half channel is shown in Fig. 5. The slightly trapezoidal cross section of the channel is approximated as rectangular. The grid size is 15 mm in the X and Y directions, and 60 mm in the Z direction. The inlet air was set at 40 °C for 4 h, the initial temperature of the slab at 18 °C, the ground soil and

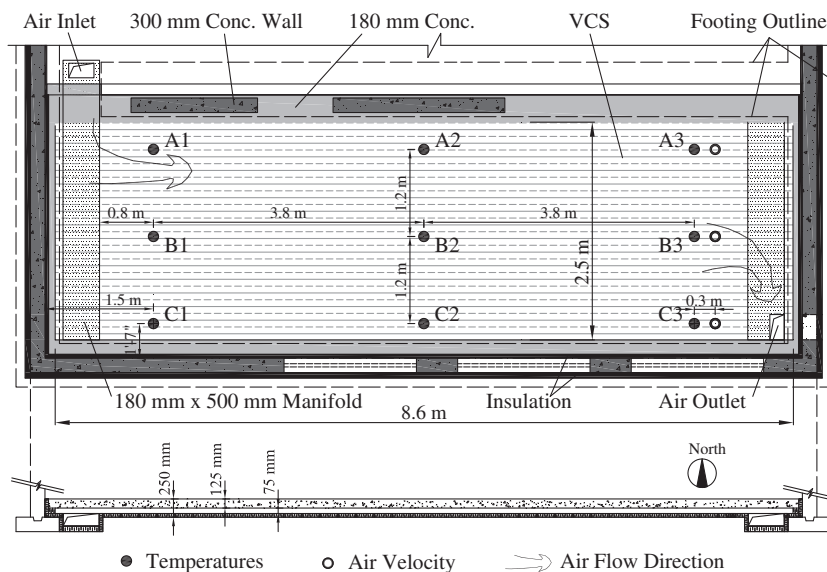


Fig. 4. Plan and longitudinal cross section of VCS (temperature monitoring points also depicted, e.g. A1).

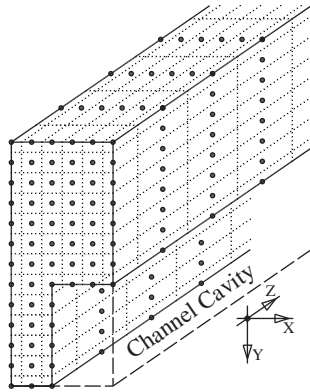


Fig. 5. Regular discretization for half channel (symmetrical about the middle YZ vertical plane).

the room temperatures were 12 and 19 °C, respectively. The combined (radiative plus convective) heat transfer coefficient between slab surface and room air was set at 9 W/m²/K (ASHRAE, 2005), constant. The insulation between the soil and steel deck is RSI 2. The physical properties of concrete were assumed to be as follows: specific heat is 920 J/kg/K, density is 2300 kg/m³, thermal conductivity is 1.9 W/m/K. Using Eq. (3) with Darcy friction factor of 0.08 and upwind scheme (Patankar, 1980) for convective heat transfer modeling within channel air flow, parametric analysis was conducted and Table 1 summarizes major results.

As can be seen from Table 1, for the 3-m long channel with air at velocity of 0.5 m/s (i.e. about 4 L/s flow rate in one channel), increasing the slab thickness from 6 cm to 15 cm does not significantly increase the amount of thermal energy stored. The outlet air temperature is more than 7 °C higher than the minimum slab temperature. When the air channels are placed east–west, heat stored by one 9-m long channel (0.866–0.885 kWh) is more than four times that by one 3-m channel (0.212–0.218 kWh). This means that east–west configuration recovers about 33% more heat from the air – the number of 3-m long channels is three times that of the 9-m long channel. This is mainly due to the higher U_c of the 9-m channels. For the option of using 9-m channels, the 6-cm thick concrete slab seems sufficient for optimal utilization of heat from hot air; however, the

maximum surface temperature is 30.3 °C, which exceeds the limit of 29 °C for thermal comfort purposes. For a 10-cm thick concrete slab, the maximum temperature drops to 28.6 °C, and the heat stored is slightly more. When concrete has a lower conductivity, 1.2 W/m/K, the upper surface temperature is lower. The amount of energy recovered from hot air is slightly less than that of concrete with conductivity of 1.9 W/m/K, but the slab thickness can be reduced to 6 cm without top surface exceeding 29 °C. The results of simulations also indicate that the pressure drop increases rapidly when the air velocity in the channels is raised from 0.5 to 1.5 m/s. For a given total flow rate, the pressure drop of the 9-m channel is higher than that of the 3-m channel. However, the absolute magnitude is not high. The pressure drop caused by the manifold will be more significant as shown later by the measured data. Further, considering the cost of the manifolds installation at both ends of the slab, east–west orientation is better than north–south orientation since the two manifolds will be only one third the size.

The final VCS configuration is shown in Fig. 4. There are a total of 19 channels in the slab. The total area of the cross section of the 19 air channels is 0.14 m². The air flow rate for each channel is about 8–13 L/s for the total flow rate ranging from 150 to 250 L/s from the BIPV/T system, and the corresponding air velocity ranges from 1 to 1.6 m/s. The design slab thickness is 100 mm; however, after construction, the measured actual thickness was about 125 mm. The volume of the concrete of the VCS is about 5 m³. The slab can store about 3 kWh of thermal energy for every degree Celsius increase of its average temperature. The air inlet (northwest corner) and outlet (southeast corner) (Fig. 4) of the VCS is located at the two diagonally opposite corners. This reverse-return layout ensures a balanced system with nearly equal airflows in each channel.

3. Thermal performance of VCS

3.1. Monitoring setup

“T” type (copper–constantan) thermocouples with accuracy of ± 0.3 °C were installed to measure temperatures at

Table 1
Thermal performance (simulated) of VCS for different configurations (at preliminary design stage).

Simulation settings					Results at the end of 4-h period (per channel)					
Concrete conductivity (W/m/K)	Slab thickness (m)	Slab length (m)	Air velocity (m/s)	CHTC (W/m ² /K)	Leaving air temperature (°C)	Stored energy (kWh)	Slab surface temperature (°C)			Pressure drop (Pa)
							Max.	Ave.	Min.	
1.9	0.06	3	0.5	7.1	29.5	0.212	25.5	23.8	22	0.4
	0.1	3	0.5	7.1	29.2	0.217	23	21.8	20.5	0.4
	0.15	3	0.5	7.1	29	0.218	21.2	20.3	19.5	0.4
	0.1	3	1	13	32	0.35	25.3	23.8	22.2	1.5
	0.06	9	1.5	20	26.6	0.866	30.3	25.2	21.9	10
	0.1	9	1.5	20	25.7	0.885	27	23.6	20.2	10
1.2	0.06	9	1.5	20	27.2	0.839	28.8	24.5	21.7	10
	0.1	9	1.5	20	26.5	0.855	24.9	21.8	20	10

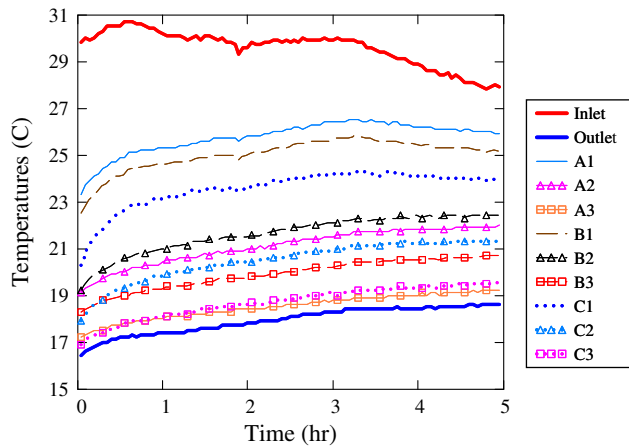


Fig. 6. Air temperature profiles in VCS during a charging experiment with heated air.

different locations. The total flow rates and corresponding pressure drops were measured manually. In the nine locations shown in Fig. 4, the temperatures of the top layer, the middle layer of the slab, the passing air, and the soil just under the insulation are measured by thermocouples “TC-1”, “TC-2”, “TC-3” and “TC-4” respectively, as indicated in Fig. 2. At locations “A2”, “B2”, and “C2”, the temperatures of the bottom layer of the slab are also monitored by “TC-5”. Inlet and outlet air temperatures are measured right before and after the slab inlet and outlet, accordingly. The temperatures are measured every 3 min.

The pressure drops were measured between the inlet and outlet manifolds using a hand-held digital manometer. The measured pressure drops were 0.01, 0.03, and 0.07 kPa at 100, 150 and 200 L/s total flow rates, respectively. These measurements show that the pressure drops are relatively low. For the 200 L/s flow rate, the fan power consumption is about 400 W. The power is used to draw the air through the BIPV/T roof, the duct connecting the BIPV/T roof and the VCS, and then through the VCS. The channel air veloc-

ities measured at three locations (see Fig. 4) are very close to each other. The maximum difference is less than 0.1 m/s at 200 L/s total flow rate. This indicates that the air flow from the inlet is almost evenly distributed into the 19 channels. The reverse-return layout strategy is applied successfully. Based on this observation, in the upcoming thermal modeling, the air flow was assumed to be evenly distributed.

3.2. Slab heating

Transmitted solar radiation through south-facing basement windows can reach the top surface of the VCS. In order to assess the performance of the VCS for active thermal energy storage excluding the influence of direct passive solar gain, one test was conducted during an overcast day. During the 5-h testing period, the transmitted solar radiation was below 50 W/m^2 . The inlet air was heated artificially, and the flow rate was maintained at about 150 L/s (1 m/s air velocity in the air channel). Fig. 6 shows the temperature profiles of the air at nine different locations (Fig. 4) as it was passing through the VCS. This graph indicates that, as expected, the heat transfer is high in the inlet manifold due to the high turbulence. The further the air channel is away from the inlet, the lower the temperature of the entering air. The large air temperature difference between the inlet and the “A1” location indicates that significant heat transfer happened near the inlet. It can be proved (Fig. 7) that this large amount of heat is recovered by the slab.

Fig. 7 shows the temperature distributions at different layers of the VCS during the site test. The plotted values are interpolated and extrapolated based on the values of the nine measurement points of each layer (see Figs. 2 and 4 for sensors’ locations). Even though the air flow is evenly distributed in the air channels, the temperature distribution across the slab is not. A considerable portion of heat is stored near the inlet manifold. The soil temperature distribution indicates that there was little heat loss from the air to the

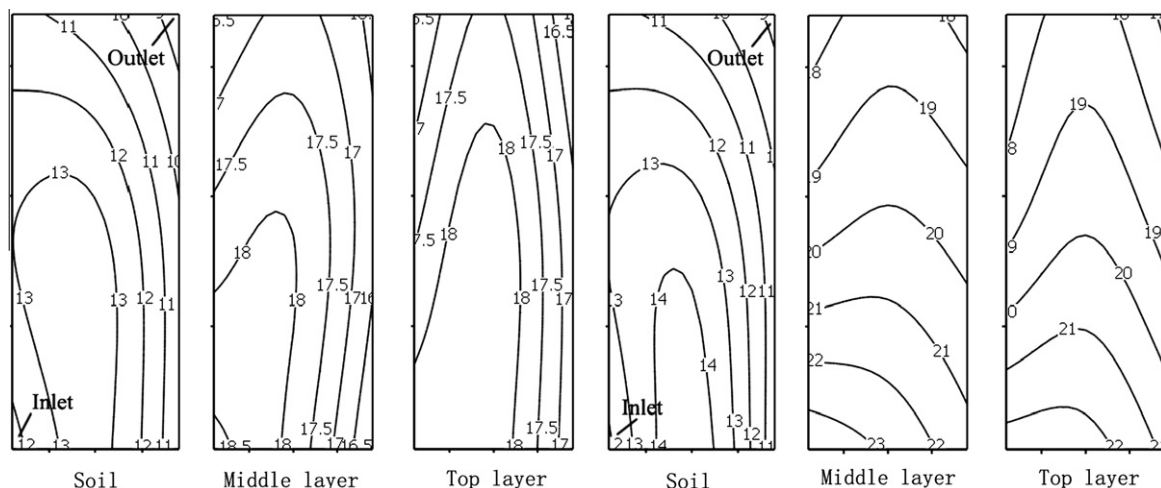


Fig. 7. Measured and interpolated temperature distributions in VCS during heating experiment (left block: beginning of test; right block: after 5 h, at end of test. The orientation of the slab in the plots is rotated 90° counter-clockwise).

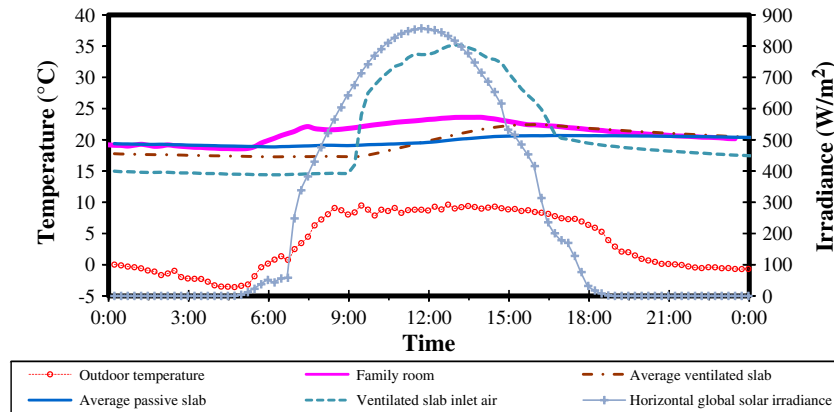


Fig. 8. Temperature profiles on a sunny day with passive (direct gains) and active VCS solar heating, April 15th, 2008.

ground. As can be observed from Figs. 6 and 7, the temperature difference between the outlet air and the center layer of the slab near the outlet is less than 1 °C. This indicates that most of the heat is stored in the slab. Heat exchange effectiveness is high. The monitored data also shows that the longitudinal temperature gradient is about 4 °C for 10 m. The temperature difference between the top surface and the center layer of the slab is less than 0.5 °C. This is because the inlet air temperature and flow rate were not high. Stored thermal energy has enough time to be redistributed inside the slab. This observation also reveals that dense grid is not needed in a finite difference thermal model.

Fig. 8 shows the monitored thermal performance of the VCS and the house on a sunny day with mild outdoor temperature (April 15th, 2008). The solar thermal energy input kept the temperature of the living space within a comfortable range. About 14 kWh thermal energy was stored in the VCS after blowing warm BIPV/T air at 200 L/s for 6.5 h. This excludes the heat released from the slab to the living space during the storage process, which was about 2 kWh. The heating load of that day was about 30 kWh. Fig. 9 shows the thermal response of the VCS over a 5-day sunny period in March, 2009. It shows that from the second day onwards, the house needed negligible auxiliary heating. A 4–5 °C increase in the average slab temperature during the charging period of each day represents about 12–15 kWh heat storage. This demonstrates that VCS can store a significant amount of thermal energy from BIPV/T system without overheating the living space. The VCS, together with passive thermal mass may thus contribute to significant reductions in energy consumption for heating.

Figs. 8 and 9 reveal one important factor in solar house design using active building-integrated thermal mass – the need to maximize the utilization of solar thermal gains without space overheating. During the daytime, when the house is passive solar-heated, the living space (family room in this case) is already warmed up. If the active thermal mass releases heat too fast to the living space, the temperature of the living space could exceed the thermal comfort upper

limit. This happens more likely in the shoulder seasons (e.g. fall or spring) when little heating may be required and only a portion of the solar gains are needed. Control of the house and choice of appropriate setpoints may enhance thermal storage; for example, lowering heating setpoint at nighttime before a predicted sunny day allows thermal mass to absorb more thermal energy and release heat at a lower rate over a longer time. In the case considered here, the nighttime heating setpoint is set back at 18 °C (see Fig. 8).

The potential overheating problem becomes more critical over a period of consecutive sunny days (Fig. 9). The daily heat storage in the slab is higher than the heat released from the slab to the living space. The average temperature of slab kept increasing over the 5 days indicating accumulation of heat from day to day. Higher slab temperature means higher heat injection rate from the slab to the living space. How to effectively store more thermal energy without overheating problems is an important performance aspect to be considered in sizing the mass in conjunction with the control strategy design.

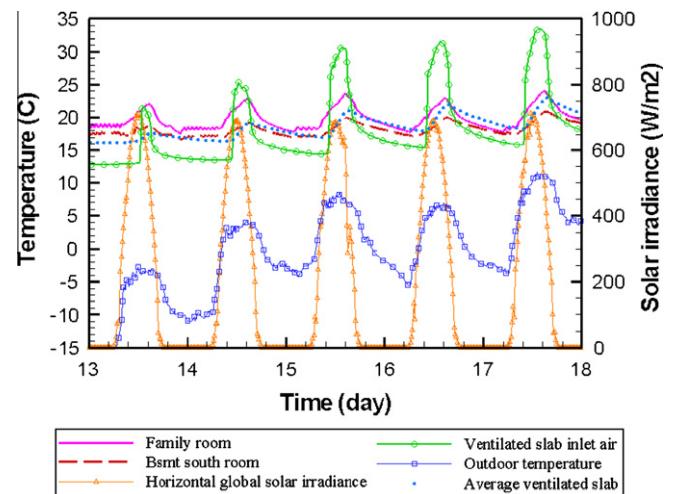


Fig. 9. Measured temperature profiles over five sunny days with operation of VCS (when inlet condition is met) during March, 2009 (the room thermostat setpoint is 18 °C at night).

4. Interior CHTC calculation

The control volume method (Fig. 10) is used in the calculation of the CHTC between the steel deck surface and the air inside the air channels of the VCS, $h_{c,vcs}$. Radiative heat transfer between the surfaces of the channel is small compared to convective heat transfer between the air and the surfaces. The control volume (CV) energy balance equation is as follows:

$$\Delta q_{slab} = \Delta q_{air} - \Delta q_{soil}$$

where

$$\Delta q_{slab} = \Delta T_{LMTD,slab} \cdot Area_{slab} \cdot h_{c,vcs}$$

So, we have:

$$h_{c,vcs} = (\Delta q_{air} - \Delta q_{soil}) / \Delta T_{LMTD,slab} \cdot Area_{slab} \quad (8)$$

where

$$\Delta q_{air} = (T_{air,out} - T_{air,in}) \cdot (\rho_{air} \cdot c_{air} \cdot Q_{air})$$

$$\Delta q_{soil} = \Delta T_{LMTD,soil} \cdot Area_{soil} \cdot u_{soil,in}$$

There are a total of six CV's. Each CV is defined by two adjacent temperature-measuring points. For example, from location "A1" to "A2" is CV "A1–2". The measured temperatures of air, slab and soil at inlets and outlets, respectively, were input into Eq. (7) to calculate the $h_{c,vcs}$ of each CV. The CHTC between the air and the bottom surface (metal mesh) was neglected because its thermal conductance value is relatively small (about 10 W/m²/K) compared to that of the rigid insulation $u_{soil,in}$ (about 0.5 W/m²/K) under the metal mesh.

A site test was conducted to obtain the required data for the calculation of $h_{c,vcs}$. During the test, different air flow rates were applied. Each flow rate was held constant for 45 min. The $h_{c,vcs}$ values in the 6 CV's were calculated from the measured data. Fig. 11 shows the calculation results. Except for CV's "A1–2" and "A2–3", the calculated $h_{c,vcs}$ for each of the CV's is similar to each other. As the flow rate decreased, the variations of $h_{c,vcs}$ between different channels became larger. This is possibly due to the fact that when there is smaller dynamic pressure in the air, less air is distributed to the channel "C" than that to channel "B".

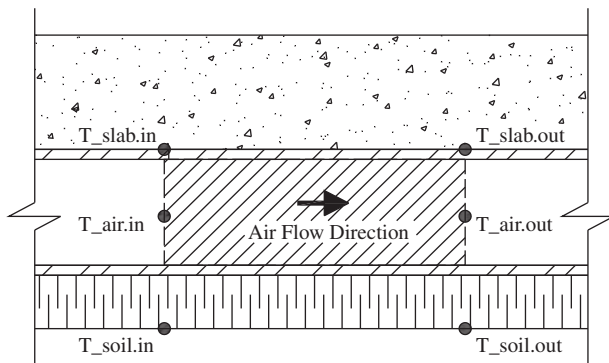


Fig. 10. Schematic of the control volume in VCS.

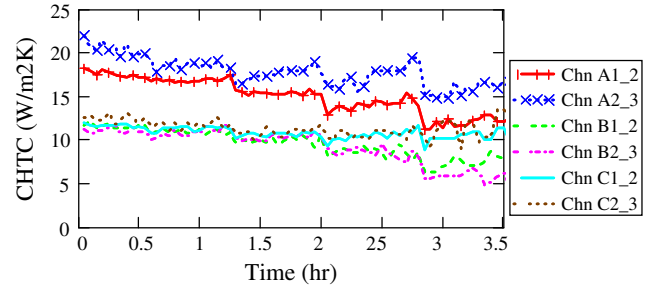


Fig. 11. Calculated $h_{c,vcs}$ for each slab section.

The main reason for the difference in values obtained in CV's "A1–2" and "A2–3" is that there are actually 20 air channels in the VCS; however, the channel north of channel "A" shares the air flow with channel "A". This means that the air from one of the manifold outlets flows into two channels. Inputting higher than actual air mass flow rate in the calculation model caused the higher $h_{c,vcs}$ value than the actual value (i.e. the $h_{c,vcs}$ of other CV's). The actual causes for these deviations mentioned above need further investigation. Fig. 11 also shows that the calculated $h_{c,vcs}$ for one CV at one flow rate (e.g. from hour 2 to hour 2.8) is increasing as time passes. The possible reason for this increase is due to the change of the actual flow rate, which is caused by the temperature-dependent change of the buoyancy effect (ASHRAE, 2005) in the duct connecting the BIPV/T roof and the VCS.

Fig. 12 shows the experimental average $h_{c,vcs}$ as a function of air velocity in the channel. The $h_{c,vcs}$ value plotted is the average of the $h_{c,vcs}$ values of the four CV's "B1–2", "B2–3", "C1–2", and "C2–3". In Fig. 12, Colburn's analogy and Dittus-Boelter equation (Rohsenow et al., 1998) are also plotted for comparison. Note that Dittus-Boelter correlation is for smooth ducts and not suited to the present configuration, so it is expected to be lower and is only utilized to indicate a minimum expected bound on the heat transfer. Surface roughness of 0.8 mm, instead of 5 mm in the preliminary design stage, was used to calculate the friction factor f in Colburn's analogy. Reasonable values for $h_{c,vcs}$ are observed. The experimental $h_{c,vcs}$ is approximated by a linear correlation (8), which is a function of the air velocity. The corresponding Reynolds numbers for 0.7 and 1.5 m/s air velocities inside the channel are about 3850 and 8250 respectively. The following correlation is recommended for design purposes as a fit to the curve in Fig. 12:

$$h_{c,vcs} = 3.94 \cdot v_{air} + 5.45 \quad (9)$$

5. Modeling and simulation of the VCS

A simplified three-dimensional, explicit control volume finite difference thermal model was developed for the VCS. The physical properties of concrete are assumed as follows: specific heat is 900 J/kg/K; density is 2300 kg/m³; conductivity is 1.9 W/m/K. Small variations of the physical properties do not affect the slab's thermal behavior to a sig-

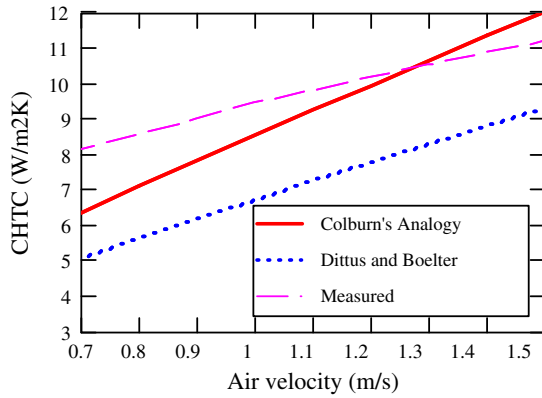


Fig. 12. Calculated average $h_{c,ves}$ vs. air velocity.

nificant extent (Bilgen and Richard, 2002). This statement is also validated by the preliminary design simulations (Table 1). Eq. (10) is the explicit finite difference equation for the concrete nodes. The last term of Eq. (10) is the combined convective and radiative heat transfer for exterior nodes of the VCS. For internal nodes, the last term equals to zero. For the CV of the air inside the channel, upwind scheme method (Patankar, 1980) is applied, as shown in Eq. (11).

$$\frac{(T_{x,y,z}^{t+\Delta t} - T_{x,y,z}^t) \cdot C_{x,y,z}}{\Delta t} = \sum_i (\Delta T_{x,y,z}^i \cdot U_{x,y,z}^i) + (T_{x,y,z}^{c,r} - T_{x,y,z}^t) \cdot A_{x,y,z} \cdot h_{x,y,z}^{c,r} \quad (10)$$

where $\Delta T_{x,y,z}^i$ is the temperature difference between current node at x, y, z and the adjacent node in direction i , $U_{x,y,z}^i$ is the conductance (W/K) between current node at x, y, z and the adjacent node in direction i , $T_{x,y,z}^{c,r}$ is the effective temperature for combined convective and radiative heat transfer (e.g. solar-air temperature), $h_{x,y,z}^{c,r}$ is the combined convective and radiative heat transfer coefficient.

$$T_{air}^p = \frac{\dot{m}c_{p,air} \cdot T_{air}^{p-1} + \sum_i (T_{surface}^i \cdot U_c^i)}{\dot{m}c_{p,air} + \sum_i U_c^i} \quad (11)$$

where T_{air}^{p-1} is the temperature of the air in the previous CV, U_c^i is the conductance (W/K) between current air node and the surface in contact at location i .

At the preliminary design stage of the VCS, in order to facilitate the modeling, the cross section of the slab channel was transformed and a regular-grid discretization scheme was employed (Fig. 5) in the modeling. The 3D modeling using a regular-grid discretization scheme requires a large computational effort. Performing transient simulations for the entire slab over a long period (e.g. for several days) is not practical.

Fig. 13 shows a contour plot of the typical pattern of temperature distribution on the cross section of the simulated half channel. Based on the pattern of the temperature distribution on the cross section, the discretization was modified (Fig. 14). The thickness of the CV is 2.4 mm for

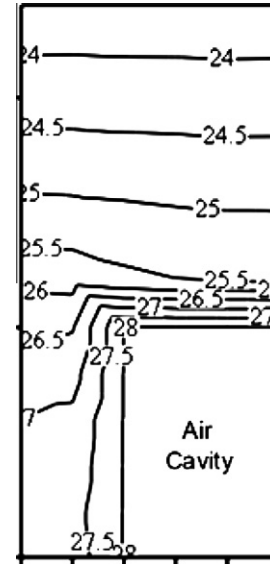


Fig. 13. Simulated typical pattern of temperature distribution of the cross section using regular discretization.

the top node “Y-1”. The corresponding Biot (Kreith and Bohn, 2001) number is 0.015, assuming the surface combined convective and radiative heat transfer coefficient $h_{c,r}$ is $10 \text{ W/m}^2/\text{K}$ and that there is no solar gain. If solar gain is present, the Biot number will increase. For the bottom node “Y-9”, the thickness is 2.7 mm. It is 1/16 of the bottom width of the flute (the strut of the steel deck). By using $h_{c,r}$ of $15 \text{ W/m}^2/\text{K}$, the calculated Biot number is about 0.02. Denser grids for the top layer and the bottom layer enhance the accuracy of the simulation of the heat transfer at the boundaries. From exterior layer to interior layer, the thickness of the layer increases with a scale factor of 2. The thickness of the top and bottom grids and the scale factor result in the 9-layer discretization scheme. The allowable maximum time step for explicit solving method is about 12 s for satisfying $Fo < 0.5$ (Kreith and Bohn, 2001). A 10-s time step was used in the simulation. The calculation of effective conductance between nodes with irregular shapes uses area-weighted distances. For the radiative heat transfer inside the air channels, it is assumed that the concrete nodes only exchange heat with the insulation surrounding the same air CV. This assumption is based on two factors: First, the length of the air CV stream-wise is 150 mm in this discretization scheme. This is two times the height of the air CV (i.e. the height of the air channel). Second, the temperature difference between two adjacent concrete nodes or two adjacent insulation nodes is negligibly small.

Validation of the thermal model was performed by comparing the measured and interpolated temperature from site tests with those from simulations using the measured boundary conditions (i.e. the flow rate, the temperatures of the room air, the ground soil, and the inlet air) as inputs. Fig. 15 shows one of the comparisons between the measured and simulated temperature distributions of the

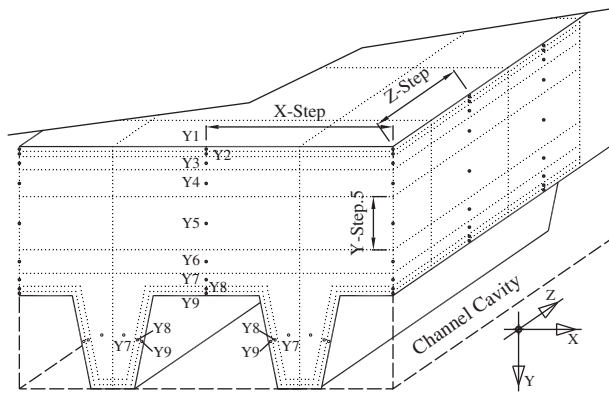


Fig. 14. Schematic of the 9-layer 3D discretization of the VCS.

VCS. The values shown are for the end of the site test. During the site test, warm air at temperatures ranging from 30 to 40 °C from the BIPV/T system was drawn through the ventilated slab at 200 L/s (1.3 m/s in the air channels) for about 4 h. The top end and the bottom end of the plots of the simulated data show the effect of the manifold. It can be seen that the simulation results match well with the measured data, especially when considering the pattern of the temperature distribution. The deviations are mainly due to the following factors:

- The actual boundary conditions of the VCS are complex. The soil temperatures were only measured at nine locations. The soil temperature is lower near the edge of the slab as shown in Fig. 7. The north side of the VCS is directly in contact with the concrete footing and the concrete wall. There was also transmitted solar irradiance absorbed by the room surface of the VCS. These factors cannot be completely represented in the simulation.
- The exact amount of the concrete mass is unknown. The slab was designed to be 10 cm thick; however, some parts of the slab were about 12 cm thick.

- The heat transfer in the inlet and outlet manifolds cannot be simulated precisely.
- The errors induced by the temperature measurement. The type of thermocouple used has an accuracy of ± 0.3 °C.

6. Conclusion

This paper presents an in-depth study of a ventilated concrete slab (VCS) used in a near net-zero energy solar house (described in the companion paper Part 1). The VCS serves as active thermal mass to store heat collected by a roof BIPV/T system in an open loop configuration with air as the heat transfer fluid. The heat release from the VCS is passive. A method for numerical simulation, design, and assessment of the thermal performance of the VCS is also presented. The construction of the VCS is based on commonly available construction technologies. It can be readily implemented in basements of new Canadian homes without much additional cost as the current practice is to have a basement foundation slab and a forced air system is often used.

The sizing of the VCS in this paper was based on the thermal output of the BIPV/T system on a typical sunny winter day – solar-heated air of about 250 L/s at 40 °C for roughly 4 h. The living space temperature in the basement where the VCS is located was set at 19 °C in the simulations. The sizing criteria are based on maximizing the storage of thermal energy and no floor surface overheating so as to meet comfort requirements. Analysis of the monitored data obtained during the commissioning of the house shows that the VCS can efficiently store much of the heat collected by the BIPV/T system. The VCS can store 9–12 kWh of thermal energy on a typical clear sunny day with 30–35 °C inlet air at 200 L/s flowing through the system for roughly 6 h. Its thermal coupling with the BIPV/T system significantly improves the overall efficiency of utilization of collected solar energy. One important observation is that

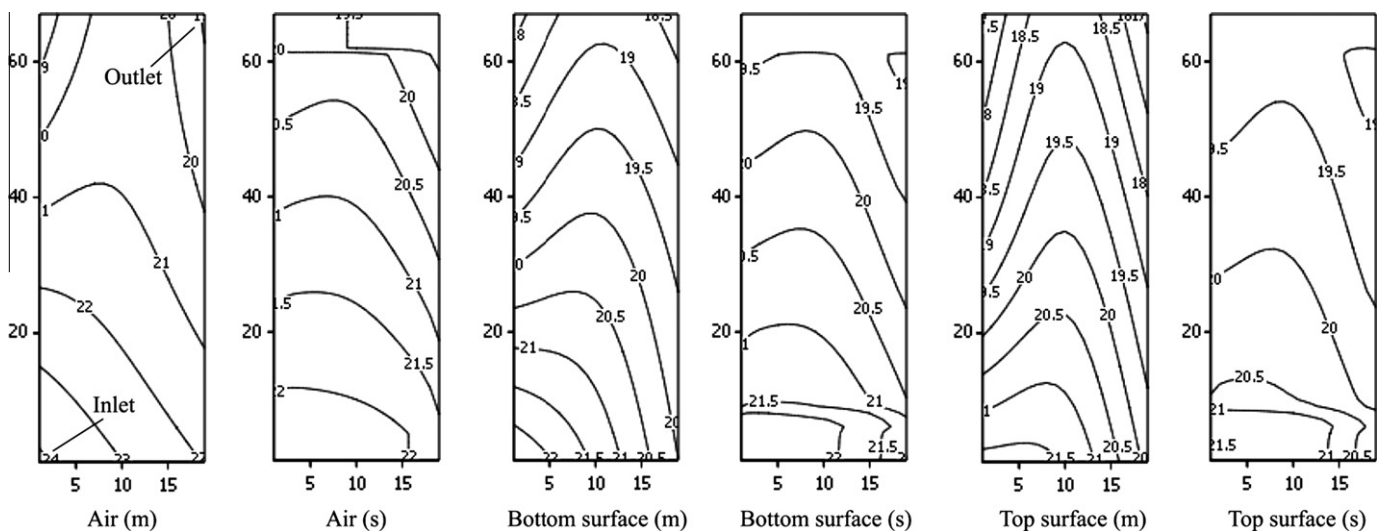


Fig. 15. Measured (m) and simulated (s) temperature distributions of VCS (The orientation of the slab in the plots is rotated 90° counterclockwise. Each unit of X or Y axis is the grid size (i.e. 150 mm)).

active thermal mass should not only be designed for neither 1 day heat storage nor be isolated from the passive direct gain design and the room temperature control strategy. The design should also consider the accumulation effect of heat injection from consecutive sunny days. The VCS design presented in this paper can be used to facilitate storage of thermal energy over a series of clear sunny days without overheating the living space.

A simplified three-dimensional, control volume, explicit finite difference thermal model was developed to simulate the thermal performance of the constructed VCS. The modeling approach can be applied to other types of VCS. The numerical model of the VCS evolved from a standard regular 3D discretization having a large number of control volumes to a simplified discretization – a 9-layer model. This simplification is based on the simulations and the monitored data. Using the simplified model, the computational effort required for simulation is greatly reduced while the accuracy is still acceptable. The developed model is showed to be appropriate for design purposes and for study of control strategies.

The design of the VCS is strongly interrelated with the thermal characteristic of the house (e.g. the passive solar design, the thermal response), and the thermal input from the solar air collectors (BIPV/T system in this case). General guidelines and methodologies for the integrated design and control of active and passive solar thermal energy collecting and storing systems, and the optimization of system design for different weather patterns will be developed in future study.

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