A HETEROGENEOUS SYSTEM SIMULATION OF A DOUBLE-SKIN FAÇADE

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ABSTRACT

This paper shows a new DSF modeling approach so-called a co-simulation of the heterogeneous systems. In this approach, the calibrated DSF MATLAB model developed by [Park 2003] and the EnergyPlus building model are integrated in the BCVTB environment. As a result, more reliable simulation results can be obtained. Finally, the paper shows the difference between two approaches: (1) DSF simulation with EnergyPlus only and (2) the heterogeneous simulation approach using the in-house DSF model augmented with the whole building simulation model.

INTRODUCTION

A number of simulation tools have been used to examine the energy performance of Double skin façade (DSF) systems. However, many researchers remain uncertain about the actual performance and simulation results obtained for DSFs (Pappas and Zhai, 2008). Wong et al. (2005) and Chan et al. (2009) reported that significant cooling energy savings can be achieved with DSFs due to reductions in transmitted solar radiation. Such reduction is possible due to the two layers of glazing in DSFs. In contrast, Gertis (1999) claimed that existing simulation tools are insufficient to model DSFs with an acceptable level of accuracy and that, in reality, DSF cavity air temperature is often increased to an undesirably high level when compared to the outdoor air temperature in the summer. Such a scenario causes an increase the cooling load. Gratia and Hendre (2004) also pointed out that DSF itself does not save energy, but rather increases the cooling energy.

Several whole building simulation tools (e.g., EnergyPlus, ESP-r, TRNSYS, TAS, IDA ICE, VA114, BSim) are used for energy performance assessment of DSFs. However, because these tools were developed for conventional building envelopes (with shadings) (Loutzenhiser et al., 2007), there is an accountability issue as to whether such tools can accurately describe the transient heat and mass transfer phenomena that occur in the complex three-dimensional (3-D) geometry of DSFs. According to Kalayanova et al. (2009), the different calculation algorithms of each tool can lead to different performance predictions and simulation errors for DSFs. Since there is a lack of consensus regarding the reliability or prediction accuracy of simulation tools for DSFs, further study is necessary to more fully address this issue.

A report on the empirical validation of building simulation tools for DSFs conducted by the International Energy Agency (IEA), Annex 43, Task 34 was released in 2009. The main objective of the study was to empirically validate and assess the suitability of current building energy analysis tools for predicting the energy use, heat transfer, ventilation flow rates, solar protection effects, and cavity air temperatures of DSFs. After comparing simulation results with experimental data, it was found that the current models are not sufficient and may need further improvements. In addition, Kim and Park (2010) noted that one of the full dynamic simulation tools, EnergyPlus, cannot accurately describe the behavior of DSFs. Major errors between the simulation results and actual measurements may be caused by uncertainty in the measurement and simulation input parameters, assumptions and simplifications of reality during the modeling process, and the limitations of the tool in question. Hence, it is necessary to pay careful attention when assessing the performance of DSFs.

To overcome the above disadvantages of general simulation tools, several in-house simulation models (MATLAB language) were developed in previous studies (Stec et al., 2003; Park, 2003; Yoon et al., 2011; Zanghirella et al., 2011). These in-house models were calibrated and, when compared to whole building simulation programs, proved to be reasonably accurate in describing DSFs. One of the major drawbacks of this approach is that it has difficulty handling building and system simulation models. In contrast, whole building simulation programs such as EnergyPlus can properly handle simulations of any whole building and its subsystems, but are ill-suited for particular domain simulations, such as for DSFs. Hence, a new DSF modeling approach, called co-simulation of heterogeneous systems, is examined in this work. In this approach, a modified MATLAB DSF model developed by Park (2003) and Yoon et al. (2011), as well as an EnergyPlus building model are integrated into the

Building Controls Virtual Test Bed (BCVTB) environment.

As a middleware program, the BCVTB synchronizes data exchange between the input/output of MATLAB and EnergyPlus during run-time. In this way, more reliable simulation results can be expected. Finally, the difference between the following two approaches is demonstrated via two simulations: (1) a DSF simulation with EnergyPlus and (2) a heterogeneous simulation approach using an in-house DSF model augmented with the whole building simulation model.

COUPLING APPROACHES

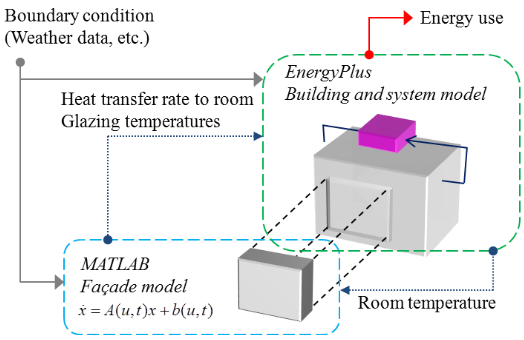
Coupling approaches can be divided into the following two categories

- *Internal coupling approaches*: The aim of these approaches is to encapsulate the source code of each simulation component model. This task can be achieved by converting models available in other tools into their own subroutines (Wang and Beausoleil-Morrison, 2009). In previous studies, the internal coupling approach was employed for the coupling between ESP-r and TRNSYS, Airnet and EnergyPlus, COMIS and TRNSYS, and EnergyPlus and MIT-CFD.

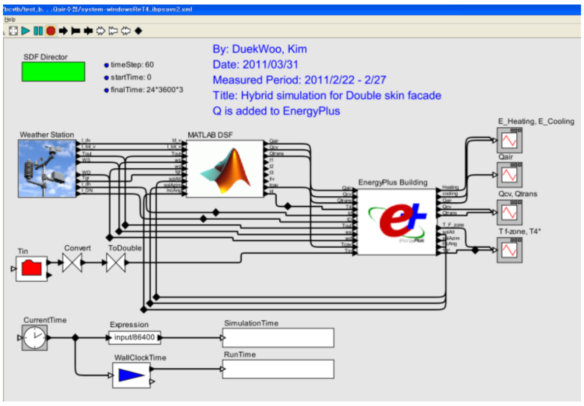
- *External coupling approaches (co-simulation)*: The goal of these approaches is to link simulations and exchange coupled data across them during the run-time. The simulations operate as separate and executable programs. The run-time coupling allows for an integrated simulation to be performed with different programs in consideration of the dynamic interactions between building subsystems. This approach is especially useful when the combined simulations are powerful in different domains. Since each individual domain has been developed independently, a user can take advantage of the latest developments (Djunaedy et al. 2003).

The BCVTB, which was developed in the Ptolemy II environment, uses an external coupling approach. As a middleware program, the BCVTB synchronizes data exchange between the input/output of MATLAB and EnergyPlus during run-time. One of the benefits of the BCVTB is that it makes optimal use of different domain-specific programs, such as Modelica (system modeling), EnergyPlus (building and subsystems modeling), MATLAB/Simulink (controller design), and Radiance (lighting and daylight design) simultaneously. It adopts loose coupling or ping-pong coupling approach, which is numerically robust enough and easier to implement (for a more detailed description about BCVTB, the reader is referred to Wetter, 2010). Due to the capability of the BCVTB, it is highly suitable for integrating the MATLAB façade model into the EnergyPlus building model.

Before execution of the coupling simulation, each variable that will be passed between the simulators must be defined. The key output variables from the MATLAB DSF model are selected (1) direct and diffuse solar radiation transmitted to the room, (2) convective heat gain/loss, (3) ventilation/infiltration heat gain/loss, and (4) surface temperature of interior glazing. During the runtime, these exported variables are passed to EnergyPlus using the *ExternalInterfaces object*. Likewise, the EnergyPlus variable, room temperature (*Tin*), is selected as key output variable. This exported variable is passed to MATLAB during the runtime. Figure 1 shows co-simulation overview in this study.



(a) Schematic view



(b) Graph Editor screen shot

Figure 1 Co-simulation overview.

In this paper, the DSF model developed by EnergyPlus is called "*EP-only*" (monolithic model), while the integrated model (MATLAB DSF model with EnergyPlus room model) is called "*BCVTB*" (co-simulation model).

EXPERIMENTAL SETUP

An experimental test facility was constructed to compare the performances of EP-only and BCVTB (Figure 2). The facility faces true south and the window system consists of low-E double glazing, normal double glazing, an automatic rotating Venetian blind, and electrically controlled ventilation inlet/outlet dampers at the top and bottom. Measuring instruments include pyranometers (LI-COR Inc), thermocouples for glazing and zone temperatures (OMEGA Inc.), a hot-sphere anemometer for measurement of the cavity airflow velocity (Testo

Inc.), and an ultrasonic anemometer for determining wind velocity and direction outside the unit (Gill Inc.). Data were collected with National Instruments Inc. data acquisition (DAQ) hardware for three days (00:00 a.m. 02/22/2011 to 23:59 p.m. 02/24/2011, for 72 hours, with a sampling time of 1 minute; the number of recorded data points was 4,320; winter condition), with the Venetian blind slats kept in the horizontal position. The room air temperature in the test facility was maintained at 20 ±2 °C and the ventilation modes were changed arbitrarily, as shown in Figure 3.

(a) View from outside *(b) View from inside*

Figure 2. The test facility installed at Sungkyunkwan University, Korea.

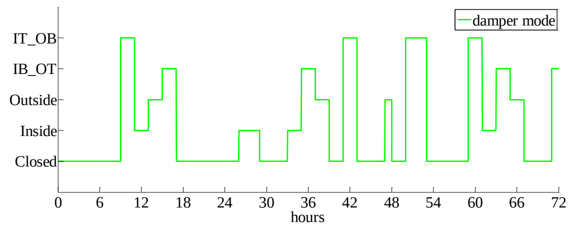


Figure 3 Operation of ventilation modes.

DSF SIMULATION MODELS

Both *EP-only* and *BCVTB* model are briefly described in the following sections. For more detailed information on EP-only and BCVTB, the reader is referred to Kim et al. (2010), Park (2003).

EP-only (EnergyPlus model)

As shown in Figure 4, the cavity and room of the DSF were modeled as three stacked zones to simulate airflow driven by buoyancy and wind pressure. The DSF simulation model has three vertical cavity nodes and three vertical room nodes with fictitious horizontal openings. Based on the airflow network method, this simulation model can mimic airflow through the dampers and fictitious horizontal openings.

The DSF is operated in five ventilation modes by controlling the four ventilation dampers located at the top and bottom of the exterior and interior façade (Figure 5). "Inside" means that the top and bottom dampers facing the room are open (inside circulation), while in the "Outside" configuration, the top and bottom dampers facing the room are closed (outside circulation). "IB-OT" means that the inside-bottom damper and outside-top damper are open, while "IT-OB" means that the inside top and outside bottom dampers are open. The "IB-OT" and "IT-OB" configurations allow for diagonal airflow either from inside to outside or outside to inside, respectively. "Closed" represents cases where the four dampers are closed.

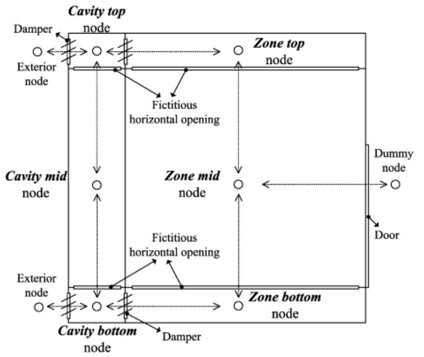


Figure 4 The modeled cavity and room divided into three stacked zones (section view).

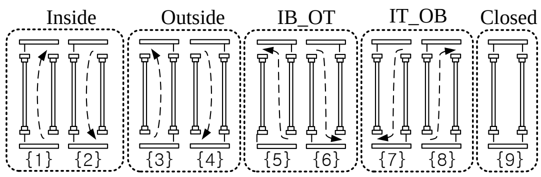


Figure 5 Five ventilation modes and nine airflow regimes (blind slats not drawn for clarity).

The properties of the installed glazing were obtained from the manufacturer's product specifications. For the Venetian blinds, the reflectance and emissivity of the blind slats (black) were assumed to be 0.1 and 0.97, respectively, according to the literature (Incropera et al. 2008). The leakage area is one of the major unknown parameters in building performance simulations. Hence, in this study, a blower test was performed to obtain effective leakage areas for each ventilation mode (inside, outside, closed mode). The entered leakage area of the room (including walls, floor, ceiling, and door) is 0.0128m^2, while that of the inside (or outside) top and bottom dampers is 0.0163m^2 (0.0139m^2). According to the ASHRAE (2009), the power consumption of the computer ranges from 48 W to 77 W. Thus, 75 W was selected as internal heat gain from a data acquisition computer in this study. Although the power consumption of the flat panel monitor ranges from about 20 W to 90 W (depending on the size), it can be negligible if the monitor is in idle mode. In fact, the monitor was kept in idle mode over most of the experimental time period.

BCVTB (MATLAB facade model with EnergyPlus room model)

In order to describe the dynamics of double-skin systems that are solvable with reasonable effort, a space-averaged lumped physical model with eight state variables was developed (Figure 6). The state variables represent the space-averaged temperatures in the horizontal and vertical directions of each glazing of the exterior double pane, the larger cavity air, the blind slats, the interior double pane, and the cavity air within the double pane glass. While this approach does not render explicit information regarding the vertical and horizontal temperature gradients, it is assumed to be sufficient to represent the overall thermal characteristics of any double-skin system.

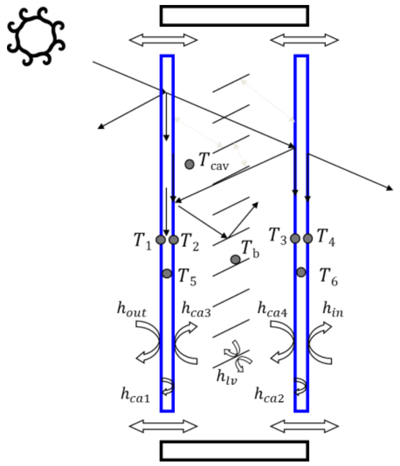


Figure 6 Simplified system in 2D (with state variables T, and convective transfer coefficients h).

While mathematically formulating the direct, diffuse, and reflected solar radiation and long wave radiation between surfaces, the theoretical model suggested by Rheault and Bilgen (1989) was used without extensive modification. Based on the assumption of a fictitious cavity bounded by adjacent blind slats and interior and exterior glazing, the direct and diffuse solar radiation, as well as its reflection, are calculated. In the modeling of the convective heat transfer, the seven unknown convective heat transfer coefficients (h_{out}, h_{ca1}, h_{ca3}, h_{ca4}, h_{lv}, h_{ca2}, h_{in}) (Figure 6) must be estimated because the literature values of these coefficients, as reported by Clarke (2001), Incropera et al. (2008), and ASHRAE (2009), were empirically driven for general cases and thus, vary significantly according to system configuration, location, surroundings, the nature of the surface, micro-climatic environment, and other variables. In the cavity, different vertical and horizontal heat flow patterns occur with changing temperatures and varying positions of the curved blind slats and bottom and top openings. Unfortunately, there are very limited data available on these behaviors. Thus, the above coefficients have been identified with a suitable parameter estimation technique based on extensive data points obtained from previous experiments (Yoon et al. 2011).

Similar to *EP-only*, the MATLAB DSF model can simulate airflows that occur in the cavity (Figure 5). The natural circulation loop can also be subdivided into two types according to the characteristics of the airflow. One type is an inside circulation (Figure 5, {1}-{2}) driven by thermal buoyancy, while the other type is an outside circulation (Figure 5, {3}-{4}) driven by thermal buoyancy and wind pressure. The former mainly causes upward flows, while the latter may cause either upward or downward flows depending on the wind pressure and direction. In addition to buoyancy and wind, the modeling of the diagonal airflows (Figure 5, {5}-{8}) includes more driving force in the form of a stack pressure difference caused by a pressurized/de-pressurized interior space. In the same way as the parameter estimation for unknown convective heat transfer coefficients, some parameters which are related to cavity airflow through the top/bottom dampers (e.g. form loss factor, flow coefficient, and flow exponent) were also estimated to compensate for lumped modeling simplifications (Yoon et al 2011). And a simple infiltration model (Sherman and Grimsrud, 1980) was recently added to mimic infiltration at the top/bottom dampers.

The treatments of the variables passed from MATLAB to EnergyPlus are shown in Figure 7. The key outputs of MATLAB are *Qtrans* (direct and diffuse solar radiation transmitted to the room), *Qcv* (convective heat gain/loss), *Qair* (ventilation/infiltration heat gain/loss), and *T4* (surface temperature of interior glazing). The *Qcv* and *Qair* outputs act as instantaneous loads on the EnergyPlus room (a negative sign means heat loss in the room, a positive sign denotes a heat gain).

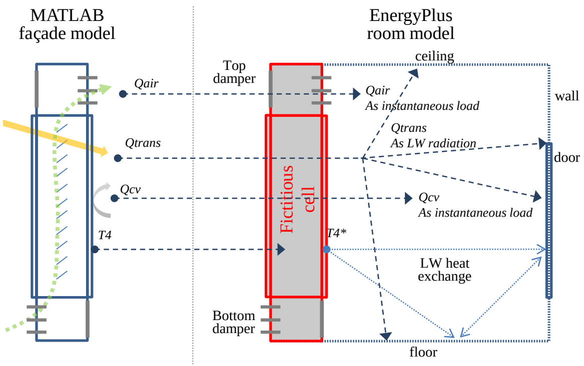


Figure 7 MATLAB facade model and EnergyPlus room model.

The "Fictitious cell" in Figure 7 is designed to account for long-wave radiation between the interior glazing surface (*T4**) and the room surfaces. However, when accounting for long-wave heat exchange, a problem arises due to the characteristics of the external coupling approach. For example, it is impossible to overwrite the glazing surface temperature in MATLAB on that of EnergyPlus because it is a state variable. In addition, convective heat transfer between the interior glazing surface temperature and room temperature is considered to be twice that in the EnergyPlus room model because EnergyPlus received *Qcv* from MATLAB, and also calculated it using its own procedure. Hence, the following alternative methods were employed:

- Consideration of long-wave heat transfer: The exported inside surface glazing temperature (*T4*) from MATLAB acts as a set-point temperature

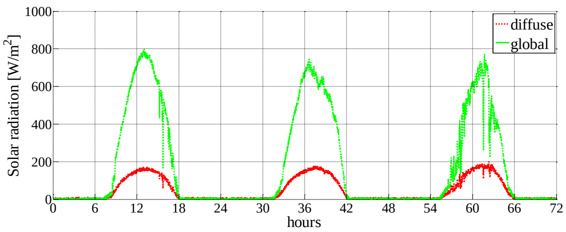
(*T4**) of the fictitious cell (Figure 7) in EnergyPlus. While this does not yield an exact solution to the problem, it will yield reasonable results that are better than those obtained when long-wave heat transfer is not considered.

- Consideration of transmitted solar radiation to the room side: The transmitted solar radiation (*Qtrans* in Figure 7) does not act as an instantaneous load but rather as a time-lagged load, i.e., it is absorbed into the structures (e.g., wall, floor, ceiling, etc.) and released as heat later. In this study, *Qtrans* is considered as long-wave radiation and is diffused around all of the surfaces of the room (Figure 7).
- Consideration of duplicated convective heat transfer: The EnergyPlus room model receives *Qcv* from MATLAB as an instantaneous load. EnergyPlus also calculates the convective heat transfer between *T4** and room temperature. Hence, a very small value of the heat transfer coefficient (0.1 W/m^{2}K) was allocated on facing the room surface in order to overcome the problem.

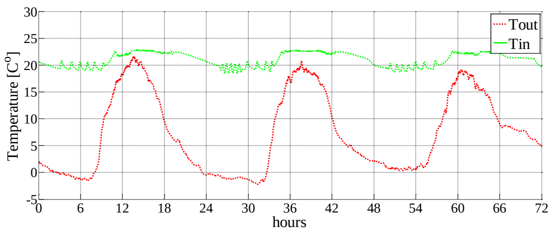
These three difficulties must be overcome, and further refinement of the model is necessary.

SIMULATION RESULTS

The measured solar radiation and indoor and outdoor air temperatures during the experiment (clear sky condition) are shown in Figure 8.



(a) Solar radiation on south vertical wall



(b) Outdoor and indoor air temperatures

Figure 8 Weather data collected during the experiment (02/22/2011–02/24/2011).

The transmitted solar radiation (direct and diffuse) to the room obtained with *EP-only* and *BCVTB* is presented in Figure 9. A slight discrepancy was found between the two models, although the permeability of both models is the same. This discrepancy is due to the use of different calculation procedures. In the case of the MATLAB model, specular inter-reflection of direct/diffuse radiation between slat surfaces is not considered. Instead, equivalent reflectance is employed (Park, 2003).

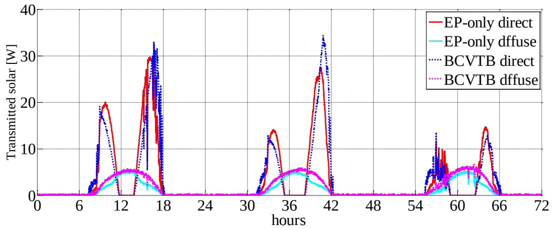


Figure 9 Comparison of Direct and diffuse transmitted solar radiation between EP-only and BCVTB

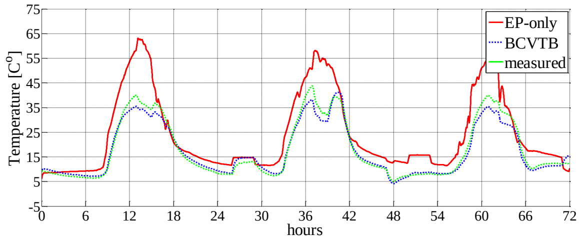
Temperature comparison

Compared to the measured values (denoted as "*measured*"), the *EP-only* simulation overestimated all glazing temperatures and the cavity temperature, while the *BCVTB* simulation results were acceptably close to the measured temperature profile (Figure 10). Especially for *EP-only*, significant simulation errors were found in the prediction of the inner glazing temperature of the exterior double pane (*T2*), the cavity air temperature (*Tcav*), and the outer glazing temperature of the interior double pane (*T3*), all of which are adjacent to the cavity. Among these temperatures, *T2* is the most significantly overestimated value. The calculation of h_{ca3} (Figure 4), originally intended to simulate conventional interior shading devices such as interior Venetian blinds, may not be suitable for DSF shading since in used algorithm in EP-model (DOE 2010), the effect of the cavity airflow on the convective heat transfer phenomena is not reflected. Thus h_{ca3}, h_{ca4}, and h_{lv} are calculated as small values, and leads to wrong prediction in state variables in the cavity (detailed information for h_{ca3}, h_{ca4}, and h_{lv} is omitted on account of space considerations but can be found in ISO15099 [2003]). In contrast, the *BCVTB* results are in good agreement with the measured values because the model includes an airflow velocity term in the heat transfer coefficients expression (it was also calibrated by parameter estimation [Yoon et al. 2011]).

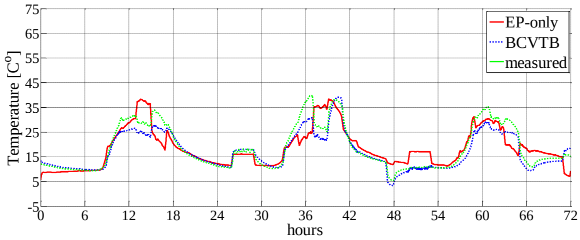
Cavity airflow comparison

The airflow regimes (AFR, Figure 5) of *EP-only* and *BCVTB*, as well as the measured cavity air velocities are shown in Figure 11(a). The velocity profiles of the simulations and the experimental data do not coincide. The overall averages of the prediction errors in the cavity airflow velocity are approximately 3.36-14.01 cm/s (*EP-only*) and 1.80-7.57 cm/s (*BCVTB*). When compared to the measured data (*measured*), *EP-only* underestimates the air velocity from 13 to 14 hours, 37 to 38 hours, and 65 to 67 hours (AFR {3}, Figure 7). This indicates that there is insufficient air circulation between the outside environment and the cavity. Thus, the temperature rises significantly (Figure 10(b)).

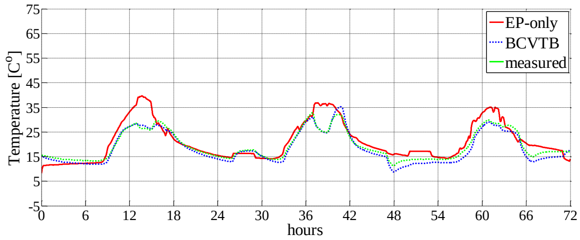
It should be noted that the actual airflow regimes can differ under the same damper mode (e.g., outward flow or inward flow). As shown in Figure 11(b)-(c), the estimated airflow regimes are different at 9, 50, and 58 hours. This decreases, increases, or has a static effect on the cavity temperature prediction according to the characteristics of airflow regimes such as AFR {7} (outward flow), AFR {8} (inward flow), and AFR {7}-{8} (fluctuation flow). For example, during the *EP-only* simulation, *Tcav* rises in the 50-53 hour period night time due to the prediction for AFR {7}, which warms cavity air using expelled room air (Figure 11(b)). On the other hand, for *BCVTB*, *Tcav* is somewhat balanced (Figure 10(c)) due to the fluctuated AFR {7}-{8}, which cools or warms *Tcav* using inhaled/exhaled outdoor/room air. We hypothesized that the overall simulation errors are not only caused by uncertain leakage areas, wind pressure coefficients, and discharge coefficients, but are also the result of an inaccurate airflow calculation algorithm. The effect of the uncertainty in simulation inputs relevant to the airflow in and around buildings is a potential explanation for inconsistencies between simulations and measurements (de Wit, 2001). This discrepancy may be overcome through use of the on-line parameter estimation technique (Yoon et al. 2011).



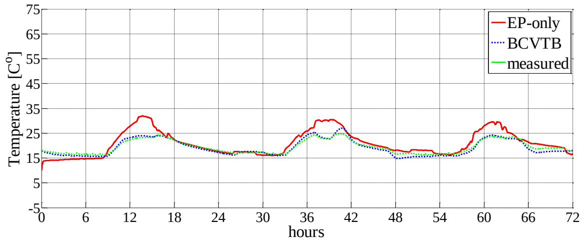
(a) Inner glazing temperature of the exterior double pane (T2)



(b) Cavity air temperature (Tcav)

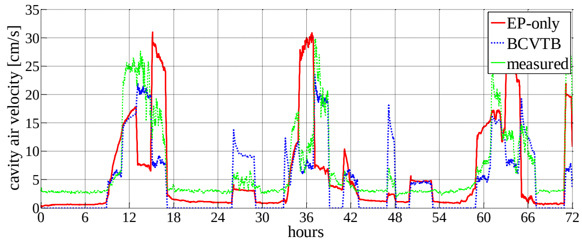


(c) Outer glazing temperature of the interior double pane (T3)

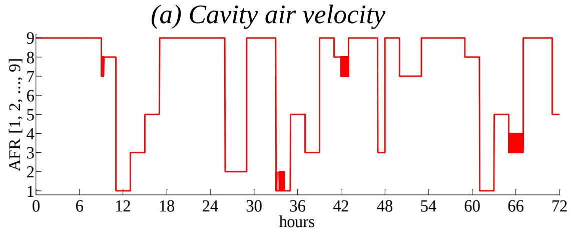


(d) Inner glazing temperature of the interior double pane (T4)

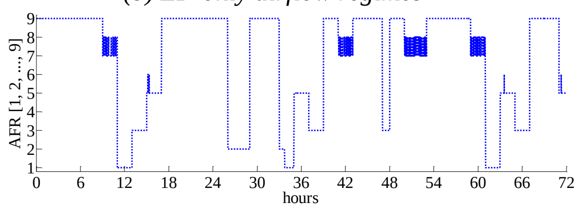
Figure 10 Comparisons of simulated and measured temperatures.



(a) Cavity air velocity



(b) EP-only airflow regimes



(c) BCVTB airflow regimes

Figure 11 (a) A comparison of the cavity air velocities between simulation and measurement, and illustration of the airflow regimes of (b) EP-only, (c) BCVTB.

Energy use comparison

The cooling and heating energy consumption of *EP-only* and *BCVTB* are presented in Figure 12. Both models yield results that are similar to measured values.

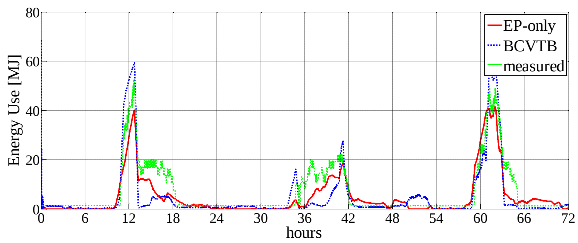
• *Cooling energy*

It was found that the predicted dynamic airflow regimes can have a significant effect on energy use. The ventilated/infiltrated heat gain is approximately up to 1000 W (Figure 13(a)), which is considerably greater than the transmitted solar energy (Figure 9(a)). For example, when *Tcav* is high (10-13 hours, daytime), the cooling energy is increased due to AFR {1} and {8} (Figure 12(a)), which make the warm cavity air inward. Other evidences are shown around 41, and 60 hours under AFR {8} and around 61 hours under AFR {1} (Figure 11).

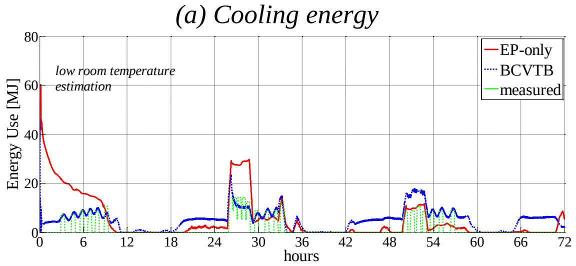
Meanwhile, for AFR {5} during the daytime (15 to 18, 35 to 37, 63 to 65 hours), the energy use of *EP-only* and *BCVTB* is relatively low when compared to *measured*. The reason for such a finding is that the air velocity and cavity air temperature predictions are not sufficiently accurate. For example, *Tcav* of *EP-only* is close to room air temperature under AFR {5} up to 23-25 °C due to the quickly exhausted room air (high velocity), while *Tcav* of *BCVTB* is close to 25-30 °C (low velocity) (Figure 11(c)). However, over the same time period, *measured Tcav* is 25-32 °C (relatively higher than that of *EP-only* and *BCVTB*) and thus, the *measured* cooling energy is greater (Figure 11(a)).

• *Heating energy*

Over the duration of the experiment, the heating energy consumption was relatively small and both *EP-only* and *BCVTB* showed a similar heating profile. It should be noted that the reason why *EP-only* predicts high heating energy at 0 hours is that the initial room temperature of the room is low (13.25 °C) after the warm-up period. From 26 to 30 hours (nighttime), the airflow regimes of *EP-only* and *BCVTB* are the same (AFR {2}, Figure 11(b)-(c)). The cold *Tcav* flows into the room via the interior opened bottom damper and thus, the heating energy is increased considerably (Figure 12(b)). Likewise, along with the cooling energy consumption, the heating energy use profile is significantly affected by the airflow mode. As shown in Figure 13(a), the ventilated/infiltrated heat loss is approximately -100 to -500 W. This is very large when compared with the convective heat loss of approximately -50 W (Figure 13(b)). It can be deduced that it is important to ensure the accuracy of the airflow model in order to simulate DSF performance properly and obtain better DSF simulation results.

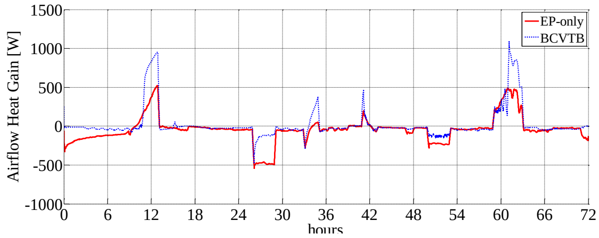


(a) Cooling energy

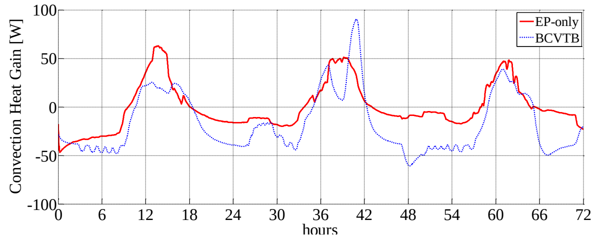


(b) Heating energy

Figure 12 Comparison of the heating and cooling energy consumption.



(a) Ventilation/infiltration heat gain (Qair)



(b) Convective heat gain from the inside glazing surface (Qcv)

Figure 13 Comparison of the room heat gain for EP-only and BCVTB (negative values denote heat loss).

CONCLUSION

The goal of this study was to use the heterogeneous system simulation approach to overcome the limitations of the simulation tool EnergyPlus. An in-house MATLAB façade model that was developed previously (Park, 2003; Yoon et al 2011) and the EnergyPlus room model were linked in the BCVTB environment. With the BCVTB environment, the heterogeneous simulators MATLAB and EnergyPlus can be easily connected with some modification of the configuration files. Ultimately, information about the augmented energy consumption was obtained and it was compared with that obtained from the *EP-only* (monolithic) model.

When compared with actual measurements, the EnergyPlus DSF model shows significant simulation errors in the prediction of the inner glazing temperature of the exterior double pane (*T2*), the cavity air temperature (*Tcav*), and the outer glazing temperature of the interior double pane (*T3*), all of which are adjacent to the cavity. Significant simulation errors arise with *T2* because the applied convective heat transfer coefficient correlation of EnergyPlus may not be suitable for a DSF, which has dynamic airflow patterns. On the other hand, the *BCVTB* (co-simulation) yields more accurate results because the model includes an airflow velocity term in the heat transfer coefficients expression.

The simulated cavity air velocity from both models does not precisely mimic actual physical phenomena. In addition, the results show that the prediction accuracy of the airflow regimes (outward, inward) is a crucial factor that influences cooling and heating energy use (*Qair* vs. *Qcv*).

Due to the rigidity of the EnergyPlus simulation tool, there are some problems that remain to be explored. Such issues include: (1) the treatment of long-wave heat transfer, (2) the treatment of transmitted solar radiation to the room side, and (3) the treatment of duplicated convective heat transfer. As noted by Trcka et al. (2009), more researches are needed to establish a general standardized framework and guidelines for the implementation of co-simulation.

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