Improving Accuracy with Minimal Computational Effort through Coupled Building Envelope and CFD Model

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Abstract

In this work, the performance of a whole building hygrothermal model is examined. The model is implemented by coupling the building envelope model Delphin to DesignBuilder CFD. The goal is to predict hygrothermal phenomenon in building envelopes as well as indoor thermal distribution in historic buildings. The thermal and moisture prediction capacity of the Delphin model is tested using Common Exercise 0, CE0 and Common Exercise 1, CE1, respectively. The test result obtained from CE0 confirmed the excellent thermal prediction capacity of the Delphin model. Similarly, the moisture analyzing capacity of the Delphin model accuracy is within 8% for case 0A of CE1 and 2% for case 0B of CE1. The coupled model predicts the hygrothermal conditions of a building envelope accurately and provides the indoor thermal distribution of a building with minimal computational effort. The model also provides better graphical visualization of the hygrothermal distribution of the building envelope.

1 Introduction

Accurate microclimate condition is highly desirable in historic buildings since many historic buildings such as castles, churches, museums, archives and historical libraries contains unique cultural heritages. Decay of historic buildings and artifacts, poor indoor environment quality as well as high energy demand caused by climate can be prevented by controlling the climatic environment. Keeping climatic conditions uniform is the prerequisites demanded by historic building restorers and museum technicians to diminish climate related decay (Bosshard 2005). Among several climate factors heat and moisture are the main actors which limit the useful life of historic buildings and historic collections besides affecting health and safety of inhabitants. To mitigate all these problems knowing the exact local phenomenon of heat and moisture in the building envelopes and inside the building is vital. Assessment by field or laboratory experiment is often too complex and very expensive. Numerical modeling/simulation becomes a cost effective and efficient alternative to investigate hygrothermal transport through building envelopes. Nowadays, heat and moisture transport phenomena through exterior building envelopes are well understood and many validated computer models have already been developed (Janssens, et al. 2008)(Künzel, et al. 2005).

Using validated whole building hygrothermal models, it is possible to assess indoor air quality, energy demand and the risk of decay of historic buildings. Nevertheless, most of the widely used whole hygrothermal models for heat and moisture transport in buildings consider indoor air as a well-mixed gas with uniform properties (Steeman, et al., 2005) (Wang and Wong 2009)(Zhai and Chen 2004). Such applications are not adequate for analysis of historic

buildings since knowledge of precise indoor heat and moisture profile is highly desired. However, there is no validated whole building hygrothermal model which can assess the hygrothermal conditions of building envelopes as well as provides the thermal distribution inside the building. Such a model can be developed by executing either of the two options. One option can be extending the capacity of CFD model to solve the hygrothermal interaction of the building envelopes. Nevertheless, this approach is very expensive computationally and would not become a practical design tools in the near future (Zhai and Chen 2003). Another option is to couple a building simulation model with CFD model. The CFD is used only for internal thermal distribution and the hygrothermal analysis of the building envelope is done using building simulation model. The CFD packages normally require a careful attention to setting up the correct geometry and boundary conditions. The coupling approach leads to a better accuracy because the number of employed assumptions is reduced compared to using the separate applications (Beausoleil-Morrison 2000)(Negrao 1995)(Zhai and Chen 2003)(Zhai, et al. 2002).

In this paper, the performance of a whole building hygrothermal which is implemented by coupling a building envelope simulation and CFD model is examined. The details are discussed below.

Building Envelope Simulation

Building envelope simulation accounts for the hygrothermal behavior of the building envelope and the microclimate near to the wall surfaces (Scheffler, et al. 2007). In the past two decades, numerical simulation has been rapidly increased and drawn growing attention as being an efficient technique to study hygrothermal performance of building envelopes. Several varieties of numerical simulation tools have been published. Most of the commonly used building simulation tools treat the moisture exchange with the envelope in a simplified way by assigning a certain moisture storage capacity to the interior of the building(Holm, et al. 2003) (Woloszyn and Rode 2008). This approach may be inadequate for conservation of historic buildings since knowledge of precise hygrothermal phenomenon in the building envelopes is often desired.

Within International Energy Agency, IEA Annex 41 a comprehensive review of 17 relevant building envelope simulation models was carried out (Janssens, et al. 2008).All the 17 models were classified based on the dimension of spatial discretization used since the prediction accuracy of numerical simulation tools which predict heat, air and moisture transport in building envelopes are highly dependent on the dimension of the spatial discretization used. The granularity of the model was classified as *Very fine-grained, Fine-grained, Intermediate-grained and Coarse-grained* models (Janssens, et al. 2008).

Among all the reviewed numerical simulation models, only Delphin has a finest granularity for building envelope than any other models and a coarse granularity for air discretization. This means, Delphin can be the best capable model to examine heat and mass transfer within the layers of the building envelope in a very precise way than air. Not only it's finest granularity of the model make it suitable for hygrothermal simulation of building envelope but also the large extent of integration of the hygrothermal interaction between the exterior and interior climates. Due to these facts Delphin model is selected for hygrothermal simulation after conducting a validation test.

Delphin Model

Delphin is a numerical simulation model for coupled heat, air, moisture and salt transport within a material (Bauklimatik Dresden 2011). The model allows building envelope performance analysis under transient climatic boundary conditions. It considers a material functions dependency on moisture and temperature. The model also include material database which includes historic and modern building materials.

Computational Fluid Dynamics, CFD

CFD is the most complicated airflow modeling method which simultaneously predicts airflow, heat transfer and contaminant transportation in and around buildings (Zhai 2006). Indeed, the application of CFD in built environment is very broad which can be used for natural ventilation design, prediction of smoke and fire in buildings, particulate dispersion in indoor environment, building element design, and even for space indoor environment analysis. Due to CFD's high competence it has gained popularity in built environment in the last few years after having been developed for over a quarter of a century(Chen and Zhai 2004) (Li, et al. 2009).

The capability of CFD to simulate distributions makes it possible to zoom in to local problems or to generate data that can be used in other models. Looking at the capability of traditional models to predict these distributions, lumped or zonal models cannot be used as they are by definition zero-dimensional. Consequently, the use of CFD tools is the logical choice to predict local effects (Steeman, et al. 2005). However, using CFD needs skillful users and a high speed computer since they are computationally intensive (Chen and Srebric 2000).

DesignBuilder CFD

DesignBuilder CFD has been especially designed to provide data on airflow and temperature distribution in and around buildings using the same methods as the general purpose pure CFD packages without the need for specialist knowledge (DesignBuilder 2011). The precision of CFD prediction is very sensitive to the assigned boundary conditions since boundary condition is the most important initial concept for CFD analyses. All dependent variable equations require meaningful values at the boundary of the calculation domain in order to generate meaningful values throughout the domain. The boundary conditions can be specified in different ways.

Unlike conventional CFD packages, defining the boundary condition using DesignBuilder CFD is not complex. It provides default wall and window boundary temperatures automatically but it is important to check that these defaults are appropriate ones and if it is not correct assigning of new boundary conditions is required. After completing the CFD calculation DesignBuilder CFD allows the user to quickly plot all the calculated data exactly in the desired way. The data are plotted on slices which are defined by the user. Slice can be defined at any position in all primary axes (X, Y and Z). Due to these facts DesignBuilder CFD was chosen to analyze the thermal distribution inside the building.

2 Methodology

As discuses in the introduction section, there is no a validated standalone whole building hygrothermal model which can predict the local phenomenon of heat and moisture in the building envelopes and inside the building. An alternative and better approach is to couple a building envelope simulation model with CFD model. This approach can reduces computing time since it does not solve the flow field during the transition from one time step to another. Coupling building simulation model and CFD also leads to a better accuracy because it minimize/avoid several assumptions employed in the separate applications (Beausoleil-Morrison 2000) (Negrao 1995)(Zhai and Chen 2003) (Zhai, et al. 2002).

Coupling of building envelope model or multi-zone building model is not a new application. There are several successful studies which show the advantage of coupling of multi-zone building simulation model to CFD (Beausoleil-Morrison 2000) (Negrao 1995) (Novoselac 2005). Building envelope simulation model and CFD programs provide complementary information about the whole building performance. The output gained from

building envelope simulation model can be used as an input for analyzing climate distribution in the zone/s in CFD.

One-time-step static coupling strategy was applied to integrate Delphin building envelope model to DesignBuilder CFD model. This strategy is generally a good choice for cases where building simulation and/or CFD are not very sensitive to the exchanged variables (Zhai, et al. 2002). One-time-step static coupling strategy exchanges data between the two models sequentially. It means that, the output data such as surface temperature from Delphin model transforms manually into DesignBuilder CFD program as an input (boundary condition) after the Delphin model has completed the simulation. The simulation flow of the coupled model is shown in Figure 1 as a flowchart.

Delphin building envelope simulation model analyze the hygrothermal performances of each wall, roof and floor sections. In order to analyze the hygrothermal performance of the envelope, it is a must to perform the following three main procedures. The first step is defining the exact geometry detail of the construction. The second major step is assigning the materials to the appropriate layer of the construction and discretizes them. There are a number

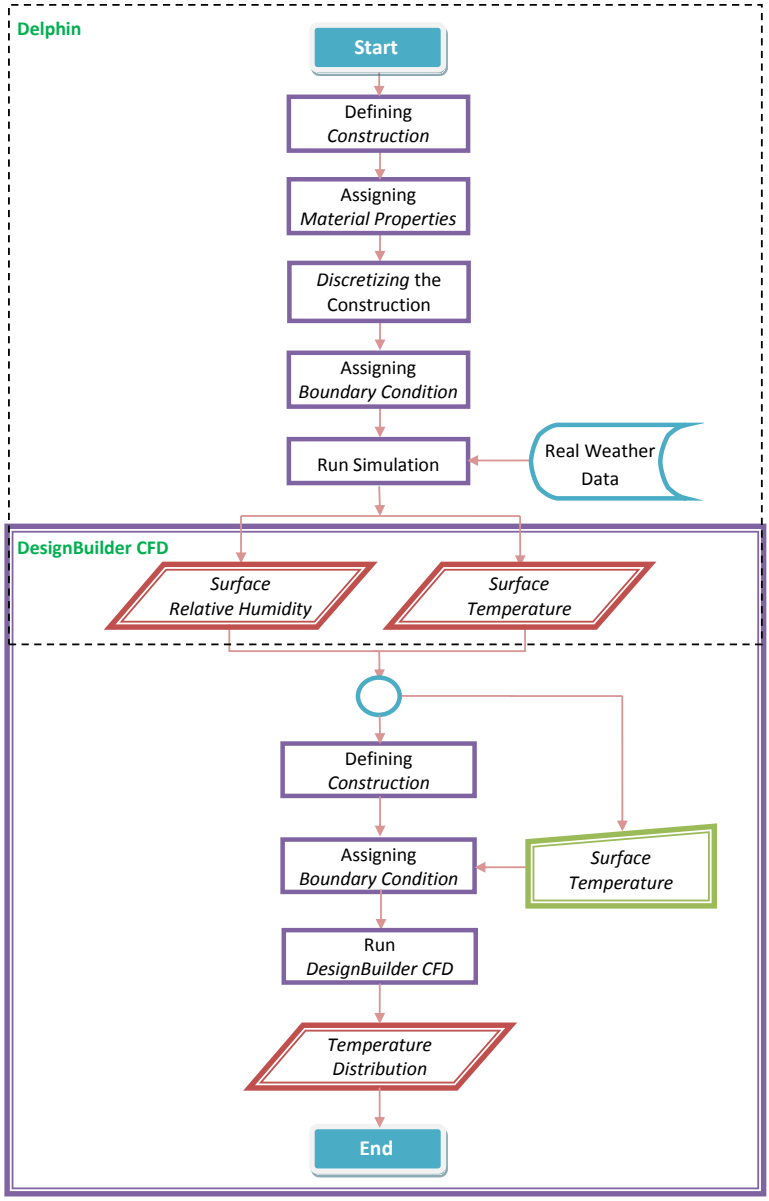

Figure 1: Flowchart of the coupled model for whole building simulation

of approved pre-defined materials in its database. It is also possible to define new materials and import it into the database. As the third step all boundary conditions need to be specified and assigned, so that the construction knows to which surface the boundary condition has been applied. It is also necessary to assign the initial condition of the construction. Then finally run simulation and get the hygrothermal behavior of the building envelope as well as the microclimate near to the wall surfaces such as: surface temperature and relative humidity. The microclimate data (surface temperatures) were used as the main input for DesignBuilder CFD model for analyzing the thermal distribution inside the building.

3 Validation Results

Before coupling Delphin model to DesignBuilder CFD, validation of Delphin model was carried out to assess its capacity to simulate complex processes. In this section, the validation procedure and its results are discussed in detail.

There are a number of Building Energy Simulation TEST (BESTEST)for validation of whole building simulation developed by International Energy Agency under IEA SHC Tasks 8,12 and 22, such as: IEA BESTEST (Judkoff and Neymark 1995), IEA HVAC BESTEST Volume 1 (Neymark and Judkoff 2002) and IEA HVAC BESTEST Volume 2 (Neymark and Judkoff 2004).

IEA BESTEST is a set of comparison tests in which, for specific input data, the program results of the program under test are compared to results of several well-tested and widely used building energy simulation programs such as: ESP, BLAST, DOE2, TRNSYS, S3PAS, TASE, CLIMA 2000, and SERIRES. Recently, IEA/ECBCS Annex 41 under Subtask 1 has developed tests known as Common Exercise 0 (CE0) and Common Exercise 1 (CE1) to validate the thermal and moisture prediction capacity of a model using BESTEST case building, respectively (Rode and Woloszyn 2007). For thermal building simulation validation test, IEA BESTEST can be used since CE0 is the same as IEA BESTEST which considers only four cases among several IEA BESTEST codes (Woloszyn 2008) (Rode and Woloszyn 2007). CE1 validation test is the expansion version of the IEA BESTEST by considering the moisture interactions between building envelopes and the indoor climate (Rode, et al. 2002) (Rode and Woloszyn 2007). The Delphin model was validated using Common Exercise 0, CE0 and Common Exercise 1, CE1.

Common Exercise 0, CE0

CE0 of IEA/ECBCS Annex 41 choose four cases from the original BESTEST procedure which are well appropriate for the whole-building approach, without focusing too much on some very specific issues, such as solar shading or transfers to the ground. The four cases are indicated by their BESTEST code, “600” for a building made of lightweight construction, “900” for a heavyweight building, and “FF” for buildings simulated under free-floating thermal conditions without heating or cooling systems (Woloszyn 2008). All CE0 cases are shown in Table 1. The general information about the building is stated as follows:

- Altitude: 1609m, latitude: 39.8^0 north, longitude: 104.9^0west;
- Ground temperature: 10°C;
- Weather data from city of Denver, Colorado;
- Radiative properties: Internal/ external opaque surfaces: emissivity = 0.9 and shortwave absorption = 0.6;
- Internal gains = 200W (100% sensible: 60% radiative, 40% convective; 0% latent);
- Ventilation 0.5 ach, altitude adjustment factor: 0.822 (if the program doesn’t perform the automatic altitude adjustment);

Table 1: Four cases of CE0

Case	Building structure	Heating and cooling
600 FF	Plasterboard, insulation, wood	None
600	Plasterboard, insulation, wood	Heating if T_{int}<20°C, Cooling if T_{int}>27°C
900 FF	Concrete, insulation, wood	None
900	Concrete, insulation, wood	Heating if T_{int}<20°C, Cooling if T_{int}>27°C

- Windows (double pane) : $U = 3.0\,W/m^2\,K$;
- Double pane shading coefficient (at normal incidence) : 0.916;
- Double pane solar heat gain coefficient (at normal incidence): 0.787.

The basic geometry of the BESTEST case building is a rectangular single zone without interior partitions. Figure 2 is the schematic presentation of the BESTEST building case. The geometric and materials specifications are purposely kept as simple as possible to minimize the opportunity for input errors on the part of the user. The building has two $6m^2$ windows facing south. The solar transmissions and gains through windows can significantly affect the overall thermal prediction. Many programs use different algorithms to calculate window transmittance. Nevertheless, Delphin model cannot calculate window transmittance, thus appropriate approximation was applied. The interior air volume of the building is$(6m * 8m * 2.7m = 129.6m^3)$. Most of the material properties used in the validation test was taken from (Judkoff and Neymark 1995). Using these data all the BESTEST cases were modeled and simulated for the whole period of one year using weather data of Denver, Colorado.

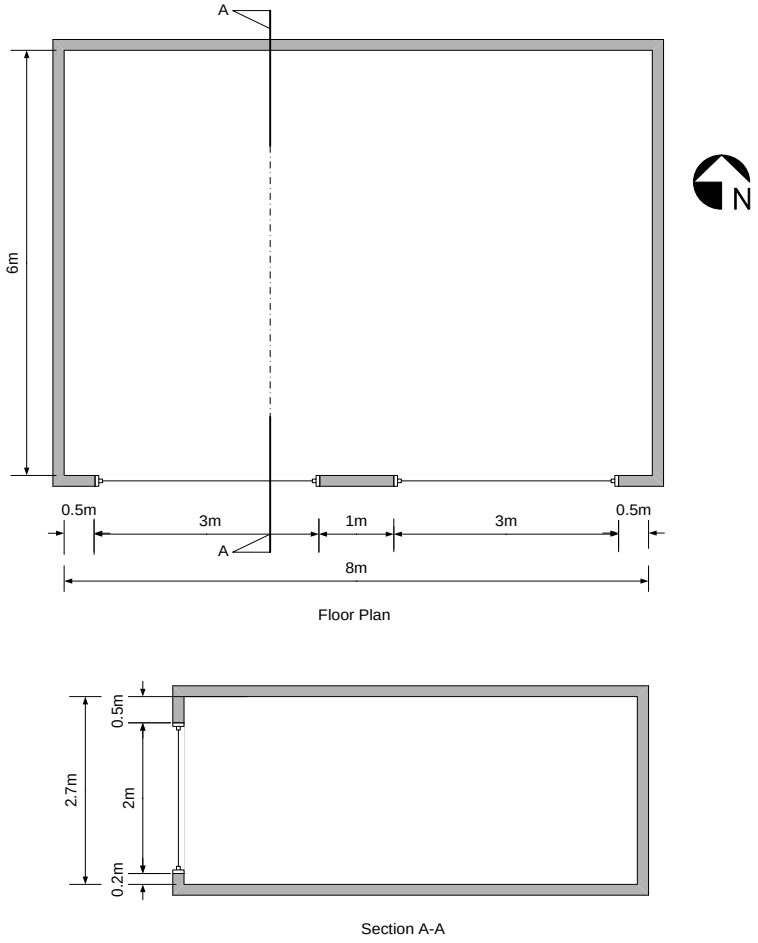

Figure 2: BESTEST base case building, adopted from (Judkoff and Neymark 1995)

The indoor temperature of the BESTEST case 600FF and 900FF was analyzed and the results are plotted in Figure 3 and 4, respectively. For each test case, the annual sensible heating and cooling load, peak cooling and heating loads were calculated by assuming as mixed air. Because, the heat flows and surface temperatures vary with time in buildings. The test results of Delphin model in BESTEST building are compared with the widely used programs and presented in Table 2. All the results of the Delphin model are within the range of the spread of results for all cases.

Common Exercise 1A, CE 1A

CE 1A is part of the Annex 41 which is used to verify the model from the hygric prediction capacity point of view (Rode, et al. 2008) (Rode and Woloszyn 2008). CE 1A applies simple conditions and uses properties which to some extent can be solved analytically. This exercise encompasses two cases; "Case 0A" and Case "0B". Compared to BESTEST cases the following changes were made for the case CE 1A:

- The altitude is 0 m;
- Constructions are made of monolithic aerated concrete with constant/linear properties;
- Tight membranes on the outside, and in case 0A also on the inside, prevent loss of vapor from the building by transport all the way through the walls;

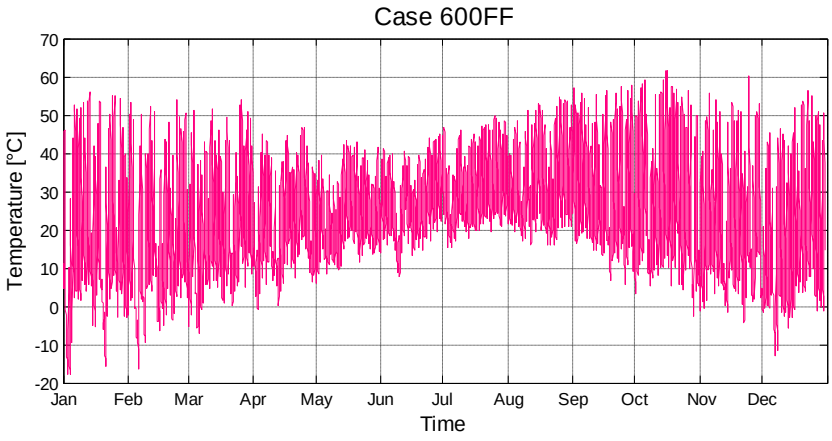

Figure 3: Indoor temperature in BESTEST case 600FF

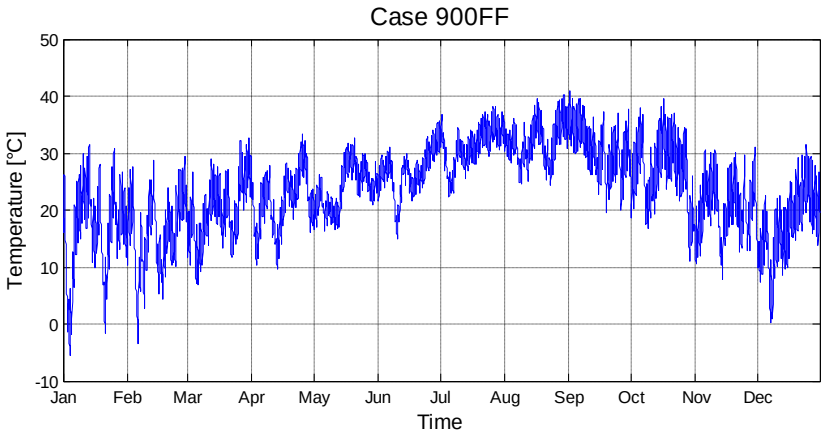

Figure 4: Indoor temperature in BESTEST case 900FF

Table 2: Result test comparison of Delphin with the standard test in BESTEST case

Case No.	Simulation of	IEA BESTEST		Delphin	Result
		Min	Max		
600FF	Mean indoor temperature [℃]	24.2	25.9	24.7	✓
600FF	Minimum indoor temperature [℃]	-18.8	-10.0	-18.7	✓
600FF	Maximum indoor temperature [℃]	64.9	69.8	64.8	✓
600	Annual sensible heating [MWh]	4.296	5.709	5.297	✓
600	Annual sensible cooling [MWh]	6.137	7.964	6.932	✓
600	Peak heating [kW]	3.437	4.357	3.921	✓
600	Peak sensible cooling [kW]	5.965	6.812	6.427	✓
900FF	Mean indoor temperature [℃]	24.6	25.9	24.9	✓
900FF	Minimum indoor temperature [℃]	-4.5	-1.6	-5.9	✓
900FF	Maximum indoor temperature [℃]	41.8	44.8	42.2	✓
900	Annual sensible heating [MWh]	1.170	2.041	2.011	✓
900	Annual sensible cooling [MWh]	2.132	3.415	2.427	✓
900	Peak heating [kW]	2.850	3.797	3.766	✓
900	Peak sensible cooling [kW]	2.888	3.567	3.482	✓

- The exposure is completely isothermal, i.e. the same outside temperature as inside the building. However, if solutions consider the latent heat of condensation/evaporation this may generate some (local) temperature changes;
- Outside and initial indoor conditions are: temperature is 20°C and relative humidity is 30%. These are also the initial conditions of materials in the constructions;
- The environment below the building is outside air (i.e. no ground);
- The geometry of the building is the same as shown in Figure 2 but without windows.

All cases consider an internal moisture gain of 500 g/h only from 9:00 - 17:00 every day. The air change rate is always 0.5 ach. The heating and the cooling control for all non-isothermal cases keeps the indoor temperature between 20°C and 27°C with an infinite capacity. The system is a 100% convective air system.

The relative humidity of case 0A and case 0B together were analyzed and plotted with the analytical results in Figure 5 and Figure 6, respectively. As it is clearly seen, the result obtained from the Delphin model is not fully matched with the analytical solution. The estimated errors are within 8% and 2% for case 0A and 0B, respectively. By considering some of the assumed parameters into consideration, the errors are very minor and it confirmed the excellent hygric prediction ability of the Delphin model.

4 Discussion

Delphin model is able to simulate well coupled HAM transport through the building envelope which is especially important for historic buildings. In order to analyze the temperature and moisture distribution in the building envelope, each building elements was simulated separately. The model cannot simulate all elements at once due to huge number of discretization elements.

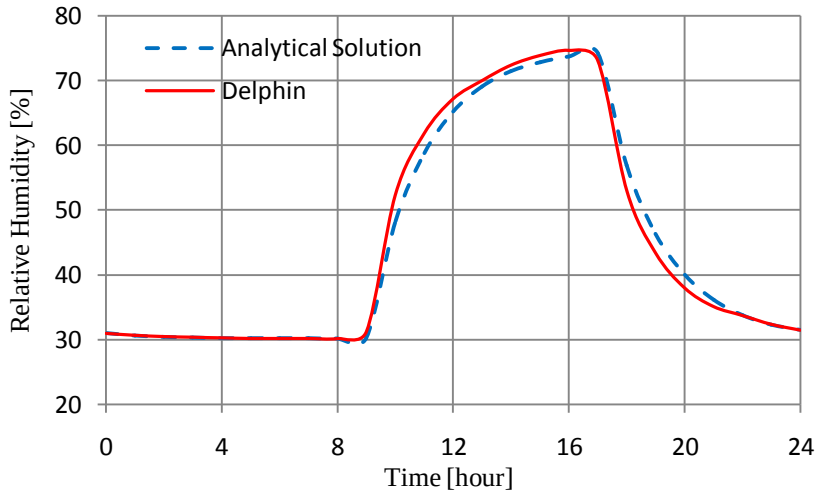

Figure 5: The numerical simulation result of CE1A, case 0A with analytical solution

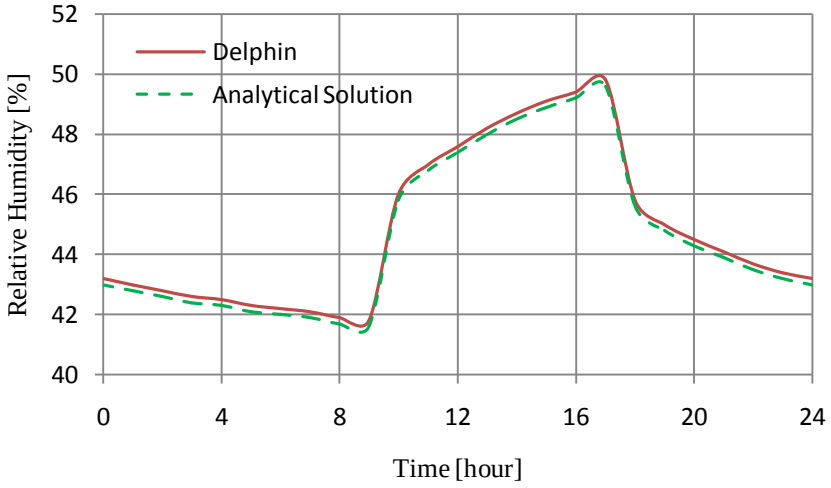

Figure 6: The numerical simulation result of CE1A, case 0B with analytical solution

The Delphin model can graphically present the hygrothermal distribution of the simulated building envelope. Once the hygrothermal simulation is executed, it is possible to see the local effects at desired time in the building envelope. The thermal distribution of Case 600 BESTEST building envelope is plotted in Figure 7 as an example. It shows the thermal distribution at 732 hour and the simulation has used climate data of Denver, Colorado. At this time the ambient climatic condition of Denver was: temperature 10.1℃ , diffusion radiation 88.89 $W/m^2$and direct radiation 0 W/m^2. The assumed ground temperature was 10℃ throughout the year. The simulation result shows the temperature in most of the floor area is 10℃ at 732 hr. The temperature across the wall is less than the actual ambient temperature. This is due to the effect of the cold temperature before 732 hr. It can be observed that the temperature at the corner where the wall meets the floor is colder than the other area. This graphical output helps the user to visualize the hygrothermal distribution on the specific parts of the building envelope in a better way and make it easier to figure out the possible location of the decay. The model also has the ability to capture the calculated values and display them quickly and easily in movie format.

As it is discussed above, knowledge of the local thermal condition inside historic building is extremely important for the assessment of the decay risk in cultural heritages caused by local microclimate. DesignerBuilder CFD was applied to assess the thermal distribution in the building. The surface temperature determined by Delphin model was

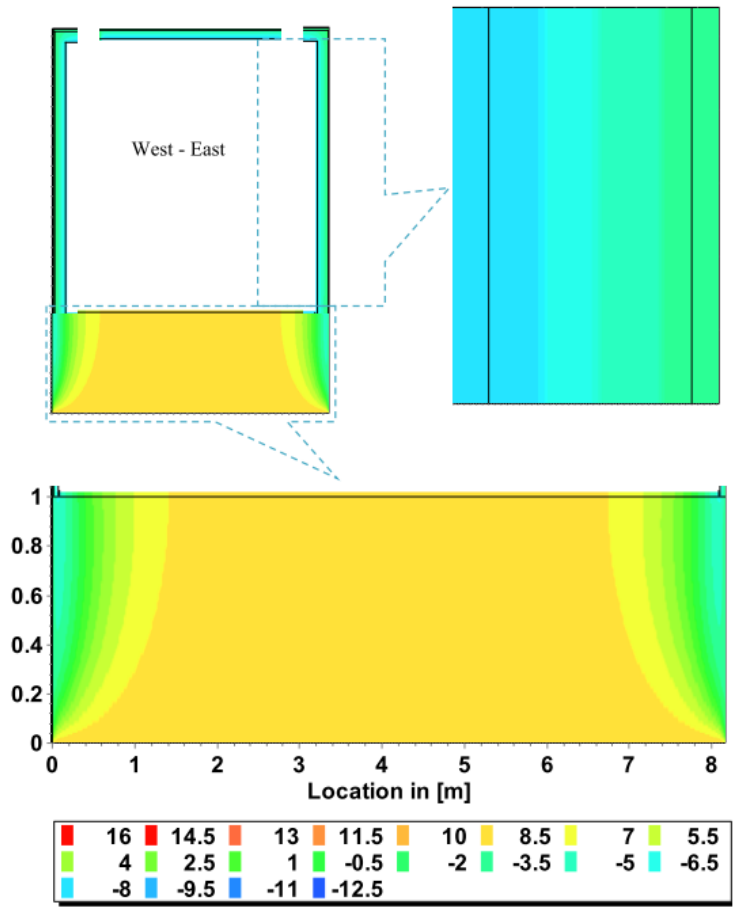

Figure 7: Thermal distributions at 732 hour in Case 600FF BESTEST building envelopes

assigned as a boundary condition for DesignBuilder CFD. Normally, boundary conditions can be specified in different ways. For instance, specifying the boundary conditions for external analyses is relatively straightforward. It just requires setting the building exposure, wind velocity and wind direction and all these are done using a single dialogue box. However internal analysis boundary conditions tend to be a bit more involved and can require the addition of zone surface boundaries such as supply diffusers, extract grilles, temperature and heat flux patches. Also it requires the incorporation of model assemblies representing occupants, radiators, fan-coil units, and etc. In this coupled model, only internal boundary conditions are required since CFD was used to analyze the thermal distribution inside the BESTEST building. Unlike many other CFD models, setting of the boundary conditions in DesignBuilder CFD did not demand more effort.

Figure 8 and 9 shows the thermal distribution inside Case 600FF building at horizontal and vertical middle area, respectively. In both cases the wall surface temperature 20 ℃ and window surface temperature 10 ℃ was assumed. As shown in both figures, the temperature distribution in the selected axis is well noticeable. The temperature around the windows and near to the corner area is lower and the temperature near to the wall surface is higher than the middle area. It is also possible to see the local effect more in detail by zooming in. Theoretically, it is necessary to run the DesignBuilder CFD for each time step, since the surface temperatures vary with time in buildings. However, it demands huge computational speed to complete within reasonable time. In addition, the correctness of the calculated thermal distribution is only verified using experimental investigation.

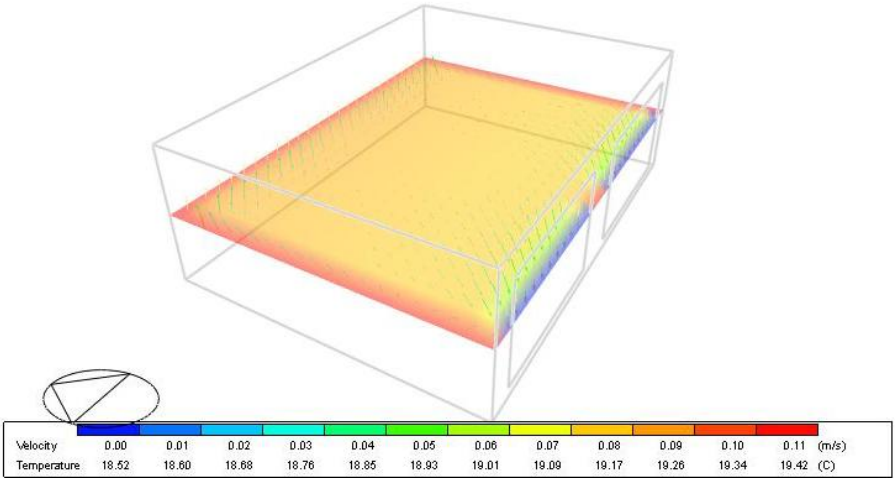

Figure 8: Indoor thermal distribution in Case 600FF BESTEST building (X-axis)

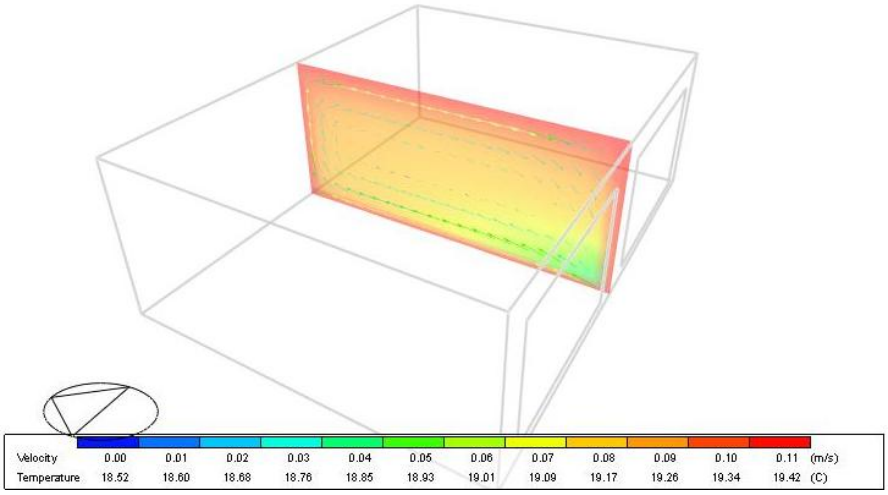

Figure 9: Indoor thermal distribution in Case 600FF BESTEST building (Y-axis)

5 Conclusions

Controlling microclimate condition is highly desirable in historic buildings in order to prolong their lifetime and to do so determining the exact local heat and moisture conditions in the building envelopes and inside the building is vital. A model that predicts hygrothermal interaction in the building envelope and thermal distribution inside a building is implemented by coupling building envelope simulation model, Delphin to CFD model DesignBuilder CFD. The model was tested by Common Exercise 0 (CE0) and Common Exercise 1 (CE1) which are part of the modified standard Building Energy Simulation TEST (BESTEST). The test result of CE0 showed that Delphin model was within the range of spread of results for all cases. Among the three test types of CE1, Common Exercise 1A (CE 1A) was applied. The result of this test showed that the error is within 8% and 2 % for case 0A and 0B of CE 1A, respectively. These reveal the outstanding hygric prediction capacity of the Delphin model. In addition, simulation of thermal distribution inside the building was carried out using the coupled model. Therefore, the implemented model predicts the hygrothermal conditions of a building envelope with better accuracy and provides the indoor thermal distribution of a building without requiring much computational effort. Furthermore, the coupled model provides better graphically representation of the hygrothermal distribution of the simulated building envelope.

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