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Published in:
Journal of Physics: Conference Series

DOI (link to publication from Publisher):
10.1088/1742-6596/2600/6/062003

Publication date:
2023

Document Version
Publisher's PDF, also known as Version of record

Citation for published version (APA):
Hu, Y., Larsen, O. K., Zhang, C., & Larsen, T. S. (2023). Energyplus model of double skin façade and diffuse ceiling ventilation. *Journal of Physics: Conference Series*, *2600*(6), 1-6. Article 062003. https://doi.org/10.1088/1742-6596/2600/6/062003

Journal of Physics: Conference
Series

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To cite this article: Y Hu *et al* 2023 *J. Phys.: Conf. Ser.* **2600** 062003

CISBAT 2023 IOP Publishing
Journal of Physics: Conference Series **2600** (2023) 062003 doi:10.1088/1742-6596/2600/6/062003

Energyplus model of double skin façade and diffuse ceiling ventilation

Y Hu[1], O K Larsen[1], C Zhang[1], T S Larsen[1]

[1] Department of Built Environment, Aalborg University, Thomas Manns Vej 23, Aalborg 9220, Denmark

Corresponding author's e-mail: hy@build.aau.dk

Abstract. This paper introduces an Energyplus model to combine the double skin façade and diffuse ceiling ventilation systems with weather-adjusted dynamic control for both heating and cooling purposes. The proposed Energyplus model is validated with measurement data for both the heating mode and cooling mode. The double skin façade, diffuse ceiling, and the room are modeled as different thermal zones in Energyplus. The ventilation between the adjacent zones is controlled by zone ventilation and zone mixing. The cooling mode of the double skin façade is modeled by wind and stack. An energy management system (EMS) controls the ventilation modes based on outdoor conditions and indoor air temperature. The geometry of the model is identical to the experiment room in the façade lab facing south, with the same internal load and ventilation mode. The model results are then compared to the experimental data, including both heating mode and cooling mode for 4 thermal zones: The DSF zone, the DSF top zone, the diffuse ceiling zone, and the room zone. For heating mode, the average discrepancy of all 4 thermal zones between the model results and experimental data is 13,75%, while for cooling mode, the average discrepancy is 13.78%. The model performance of the room zone is the highest, which has a discrepancy of 5.31% for the heating mode and 3.67% for the cooling mode compared to the experimental data.

Keywords: Double skin façade, Diffuse ceiling, Energyplus modelling, Experiment validation.

1. Introduction

Diffuse ceiling (DC) ventilation was found to have very low draft risk and low pressure drop compared to other ventilation inlets [1][2]. [3] proposed a DC ventilation combining thermally activated building systems for natural ventilation and found out that the system has a high cooling potential with very low draft risk and high energy saving potential. Compared to traditional mechanical ventilation, Diffuse ceiling (DC) ventilation has the advantage of a significantly low draft for high cooling demand buildings or ventilation in summer and transition seasons; it also has the advantage of low pressure drop for reduced fans and ducts [4] The double skin façade (DSF) has the advantages of decreasing the heating demand of the building in winter working as extra insolation of the room and heat source of the ventilation, and decreasing the solar heat gains in summer. The drawback of the DSF system as a stand-alone solution is the high draught risk. Thus, the combination of DSF and DC ventilation has the advantages of both systems for better indoor thermal comfort and lower energy demand. Such systems are also beneficial for the renovation project because of the lack of duct systems due to the low pressure loss compare to other building ventilation renovations.

Several studies have used the building energy simulation software Energyplus to model DSF by the approach of airflow network [5][6]. In the models, the DSF is split into three thermal zones that are vertically connected by internal openings to improve the mean radiant temperature characterization. In Mateus's model, the internal convection coefficient algorithm is used in the simulation (TARP). Chan et. al. considered only the buoyancy drive but not the wind drive in the simulation. A detailed thermal convection model, the MoWiTT model, based on measurements taken at the Mobile Window Thermal Test (MoWiTT) facility [7] was adopted in this computer model. There have not been studies about the experiment vilified modeling of the combined DC and DSF system. The combined system has been modeled in IDA-ICE by [8]. The model results show that the system has an energy saving of 11% compared to a traditional balanced mechanical ventilation solution.

This paper proposed the modeling of the system with zone ventilation and zone mixing for the dynamic control based on indoor and outdoor conditions in Energyplus. To validate the model, a full-scale experiment is carried out in the façade lab, including continuously running heating mode and cooling mode for two weeks. The comparison of the model results for both heating mode and cooling mode with measurement data shows good agreement.

2. Method

2.1. Measurement

The DC combining DSF system is installed in one of the rooms in the façade lab. The DSF is installed on the south external wall. The façade lab is on the top floor of the 5-story and is with no surrounding objects. The geometry of the installation room is shown in Figure 1. Four heat sources are placed symmetrically in the room to simulate internal heat gains. An exhaust fan is placed on the north wall to keep a constant airflow through the system. The Lindab Ultralink is used to measure the airflow through the exhaust fan, which has an uncertainly of ± 5%; 77 type K thermocouples are used to measure the temperature in the DSF, DC cavity, and room, which have an uncertainly of ± 0.09%. The local weather station 10 meters away from the façade lab provides the solar radiation, wind direction, wind speed, and outdoor dry-bulb temperature of the ambient. More details of the experiment can be found in [9].

Figure 2 shows the heating and cooling mode of the system been tested and modeled. In heating mode, which is shown in Figure 2(a), the ventilation airflow goes from the bottom of the DSF to the DC cavity and ventilates to the room; in the cooling mode, as shown in Figure 2(b), the ventilation airflow goes from the top of the DSF to the DC cavity and ventilate to the room, meanwhile, the lower part of the DSF is in self-cooling mode, which is ventilated by natural ventilation driven by wind and buoyancy force.

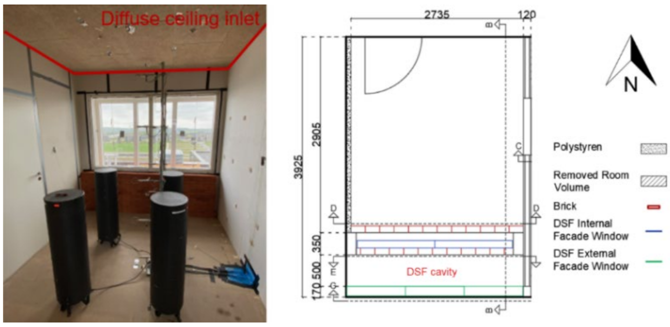


Figure 1. The geometry of the installation [9]

2.2. Energyplus models

A single office room with the same geometry as the façade lab is simulated in Energyplus. The U-value of the external wall is 0.30 W/m²K. All other walls, floor, and roof are set as adiabatic. The DC panel has a density of 359.13 kg/m³, thermal conductivity of 0.085 W/mK, and porosity of 65%. The DSF external window has a U value of 1.53 W/m²K and a g value of 0.73, and the internal window adjacent to the room has a U value of 1.6 W/m²K and a g value of 0.63. The internal load is set as the same as in the experiment.

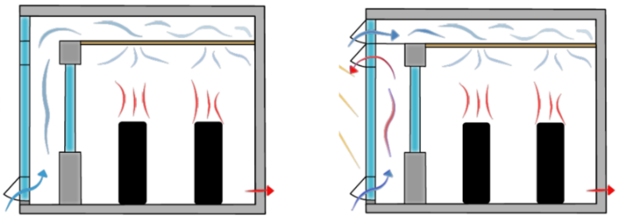


Figure 2. The ventilation mode. a. heating mode. b. cooling mode

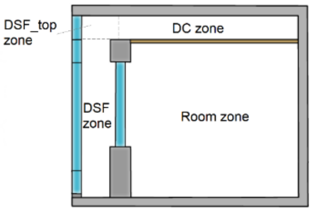


Figure 3. The thermal zones in the Energyplus model

The model is divided into 4 thermal zones: the DSF zone, the DSF top zone, the DC zone, and the room zone, as shown in Figure 3.

The zone ventilation object is used when the ventilation is directly from the outdoors to a thermal zone driven by a fan. The ventilation is specified as a design level that is modified by a schedule fraction, temperature difference, and wind speed[10] :

$$Q = \mathrm{V}_{design}\, F_{schedule}(A + B|(T_{\mathrm{zone}} - T_{\mathrm{odb}})| + C\, v + D\, v^2) \tag{1}$$

Where Q is the zone ventilation flowrate; V_{design} is the designed ventilation rate; $F_{schedule}$ is the schedule of the ventilation in function of time; T_{zone} is the zone air dry-bulb temperature (°C); T_{odb} is the local outdoor air dry-bulb temperature (°C); and v is the local wind speed (m/s).
In this model, the parameters are set as A=1, B=0, C=0, and D=0.

The zone mixing Object is used when the airflow goes between two zones. The zone mixing in Energyplus is a simple air exchange from one zone to another. Note that this statement only affects the energy balance of the "receiving" zone and will not produce any effect on the "source" zone. Mixing statements can be complementary and include multiple zones. [10]

Wind and stack ventilation calculates the airflow by wind speed effect and thermal stack effect of the self-cooling mode of the DSF during the cooling mode. The airflow by wind speed effect is calculated by Equation (2).

$$Q_w = C_w A f_{schedule} v \tag{2}$$

Where Q_w is the airflow rate driven by wind (m³/s); C_w is the opening effectiveness, which is auto-calculated by Energyplus; A is the opening area (m²), which is set as 0.15 m²; $f_{schedule}$ is the schedule of opening fraction, which is set as 1; and v is the local wind speed (m/s).

The opening effectiveness is calculated by the angle between the effective angle and real-time wind direction for each simulated time step, as shown in Equation (3).

$$C_w = 0.55 - \frac{|EffectiveAngle - WindDirection|}{180} \times 0.25 \tag{3}$$

The airflow rate driven by thermal stack effect Q_s is shown in Equation (4).

$$Q_s = C_s A f_{schedule} \sqrt{2g\Delta h(|T_i - T_o|/T_i)} \tag{4}$$

Where Δh is the height from the midpoint of the lower opening to the neutral pressure level (m); T_i is the zone air temperature (°C); T_o is the outdoor air temperature (°C); C_s is the discharge coefficient for opening, which is defined by Equation (5).

$$C_s = 0.4 + 0.0045|T_i - T_o| \tag{5}$$

The total airflow rate is calculated by Equation (6).

$$Q = \sqrt{Q_s^2 + Q_w^2} \tag{6}$$

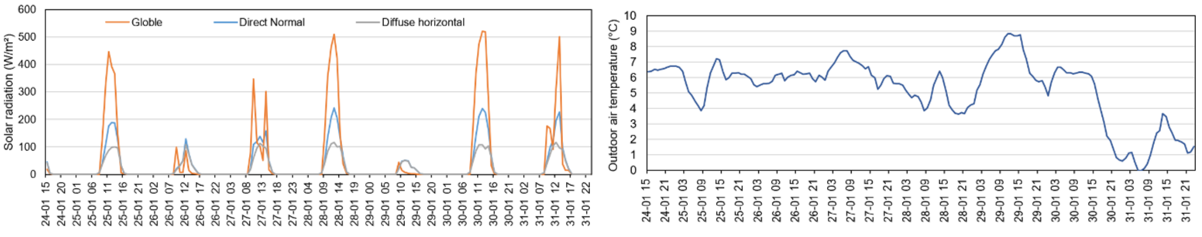
The fan used in zone ventilation is a constant fan with a fixed total pressure rise and efficiency. In this model the fan pressure rise is 1080 pa, and the fan total efficient is 0.6.

3. Results

3.1. Heating mode comparison

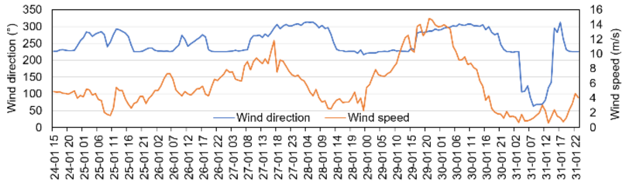
During the experiment, the heating mode was running continuously for 7 days, with 396 W internal loads 0-24 hours per day. The ventilation rate of the exhaust fan is 132 m³/h. The weather data during heating mode is shown in Figure 4. It includes two days of cloudy days and 5 days of sunny days. The weather data is then used as weather input for the Energyplus model. The Energyplus model has the same ventilation mode, ventilation rate, and internal loads as the experiment.

The comparison of the model results and experiment for the heating mode are shown in Figure 5. It shows good agreement between the model results and experiment, except for the beginning of the experiment for DC_cavity and room temperature, which is due to the reason that in the model it is hard to adjust the initial thermal conditions of the model at the beginning of the simulation to match the experiment. The standard errors of the model compared to the experiment for the DSF, DSF_top, DC_cavity and the room are 23.25%, 11.75%, 14.68%, and 5.31% respectively. The average error of the whole system is 13.75%.



a. Measured solar radiation.

b. Measured outdoor air temperature.



c. Measured wind direction and wind speed.

Figure 4. The weather data monitored by the local weather station for heating mode

3.2. Cooling mode comparison

The experiment of cooling mode was running continuously for 7 days, with 396 W internal loads. The ventilation rate of the exhaust fan is 132 m³/h. The weather data is then used as weather input for the Energyplus model, as shown in Figure 6.

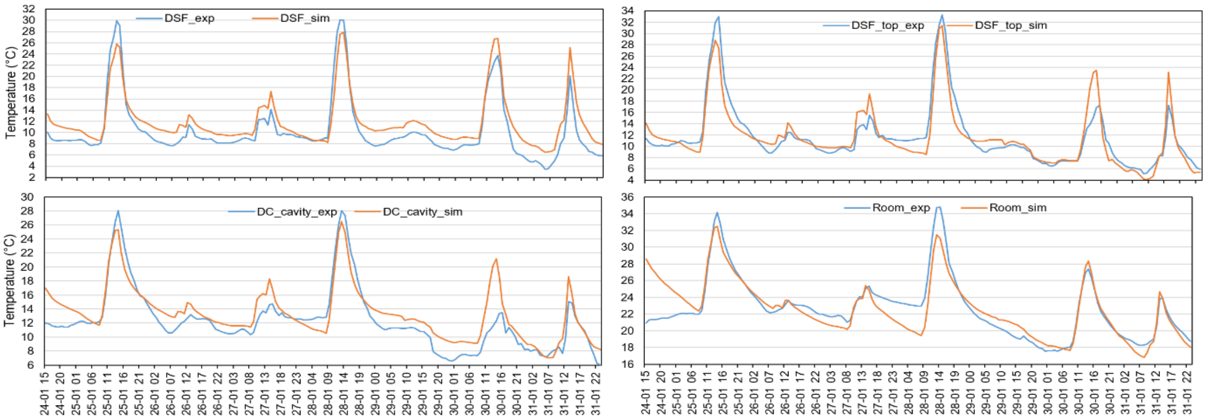
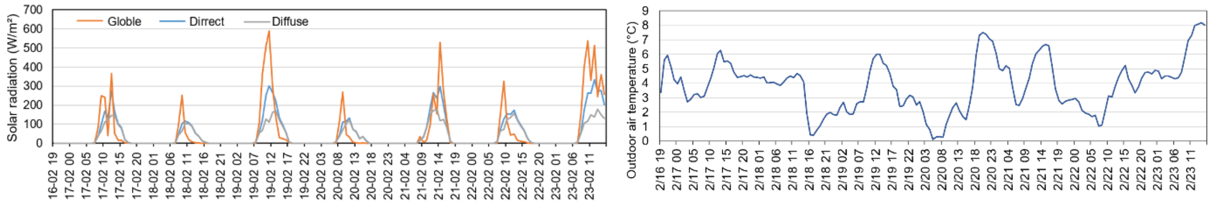
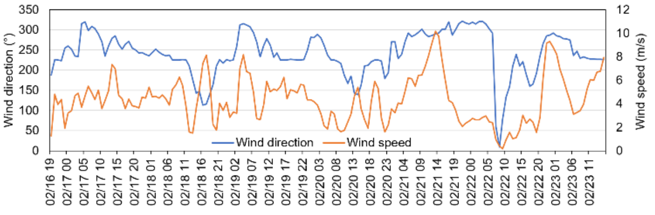


Figure 5. The model validation of the heating mode



a. Measured solar radiation. b. Measured outdoor air temperature.



c. Measured wind direction and wind speed.

Figure 6. The weather data monitored by local weather station for cooling mode

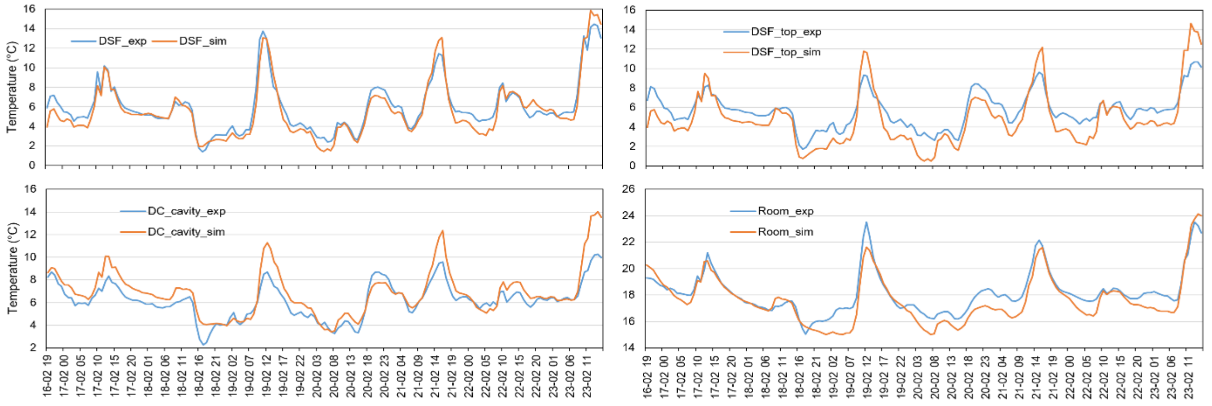


Figure 7. The model validation of the cooling mode

The comparison of the model results and experiment for the cooling mode are shown in Figure 7. It shows good agreement between the model results and the experiment. The standard errors of the model compared to the experiment for the DSF, DSF_top, DC_cavity and the room are 12.18%, 25.77%, 13.51%, and 3.66% respectively. The average error of the whole system is 13.78%.

4. Conclusions

This paper proposed the modeling of a novel ventilation system of double skin façade combined diffuse ceiling ventilation in Energyplus. The system is modeled with zone ventilation, zone mixing, wind and stack ventilation for heating and cooling mode. the model has a dynamic control based on indoor and outdoor conditions. To validate the model, a full-scale experiment is carried out in the façade lab, including continuously running heating mode and cooling mode for two weeks. The geometry of the model is identical to the experiment room, with the same internal load and ventilation mode. The weather data from a local weather station are set as boundary conditions for the model. The comparison of the model results with measurement data shows good agreement, including both heating mode and cooling mode for 4 thermal zones: The DSF zone, the DSF top zone, the diffuse ceiling zone, and the room zone. For heating mode, the average discrepancy of all 4 thermal zones between the model results and experimental data is 13,75%, while for cooling mode, the average discrepancy is 13.78%. The model performance of the room zone is the highest, which has a discrepancy of 5.31% for the heating mode and 3.67% for the cooling mode compared to the experimental data. With the validated model, future work includes sensitivity analysis for system optimization, including control setpoint, glazing, thermal mass, ventilation rate, etc. The impact of solar shading on the energy saving potential of this system needs yet to be studied.

Acknowledgment

This work has received funding from the EUDP Programme under grant agreement No. 64020-2140 (I-DIFFER).

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