INTEGRATING THERMO-FLUID COMPUTATIONAL MODELS INTO UNDERSTANDING SUSTAINABLE BUILDING DESIGN

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BACKGROUND AND CURRENT STATE OF THE ART

While contemporary architects desire the integration of natural ventilation flow and passive solar strategies into architectural design concepts, the evaluation of natural air movement and related energy performance are still difficult to predict due to the complexity of related physics.

The interaction of natural ventilation flow with thermal material properties remains a challenge. Air velocity and thermal capacity of materials are still difficult to be jointly simulated and turbulences in larger spaces cannot be clearly predicted. For example current energy evaluation tools like DOE's Energy Plus do not model thermal stratification of air. Therefore, further research into architectural design and fluid dynamics is needed. CFD is popularly applied in engineering computing but at the same time too complicated for architects. Although it cannot provide an accurate simulation of real situation, a reference for practical models is well appreciated.

METHODOLOGY

An in depth literature review was conducted to understand the current state of the art of natural ventilation CFD simulation, which revealed new research questions on the interaction of space, solar radiation, air movement and material properties. This project thus started by modeling whole building ventilation scenarios of wind and buoyancy driven natural flows with ANSYS FLUENT14.0 first on very basic cubic geometries based on representative studies found in the literature. Then we applied the knowledge gained to the case study house, which will later on enable us to verify the simulations with measurements on site.

BUOYANCY AND WIND DRIVEN AIR MOVEMENT WITH SOALR RADIATION

Natural ventilation is driven by two major external forces based on pressure differences: wind (Hydrostatic Pressure Differences) and stack effect (density pressure difference). Both macro and micro climates need to be considered. The overall results are determined by the interaction of these forces with resistances and obstacles within the flow path, which is directly given by the building and its openings, as well as the relationship of the building and its context. The condition of the urban or rural context, its roughness or smoothness will instantly relate to the velocity and direction and seasonal or even daily patterns of wind. Natural ventilation can only be implemented into the architectural design process if related to spatial composition of the flow path and the direction and intensity of the driving force.

The resistance to the flow in the path is determined by the building shape, form, height, orientation and internal spatial composition. The ventilation rate is then determined by the pressure difference acting across a ventilation path and the resistance of that path.

Air is 'lighter' and less dense when temperature increases, thus rising hot air potentially leads to temperature stratification. Pure air doesn't absorb solar radiation unless it contains water vapor.

MODELING OF RADIATION AND ENERGY TRANSFER IN AIR

In order to conduct CFD simulations of natural ventilation three important steps were followed.

First, basic models with different boundary (environment) conditions were established. Then different simulation results were compared and the physics laws interpreted with visualized diagrams. Finally, a real house model with more complicated geometry and operation options was simulated and the physics learnt from the basic models was used to summarize guidelines for understanding air flow in a complex space.

In previous studies[14-15], the simulation of natural ventilation has been successfully implemented through FLUENT. This paper is written as a summary of the continuous work: the simulation with solar radiation.

Simulation platform

According to previous studies modeling solar radiation with CFD tools is a computational intensive task. Therefore a dedicated server with Intel Xeon W3690 3.46 12MB CPU and 24GB memory was assigned to simulate all the models discussed in this paper. The most complicated model in this paper contains more than 2 million mesh elements and the server ensures that simulations run by ANSYS FLUENT 14.0 can be achieved in one day.

Basic Models for Simulation

In order to understand the effect of solar radiation on indoor air movement, two simple models with 7 different scenarios were designed.

The First Model

The first model used here is a 4m×4m×4m room with two 2m×1m windows on the south and north facades, as is shown in figure 1.a. This model is simulated at noon on both winter and summer solstice day with a typical Iowa weather condition for these seasons.

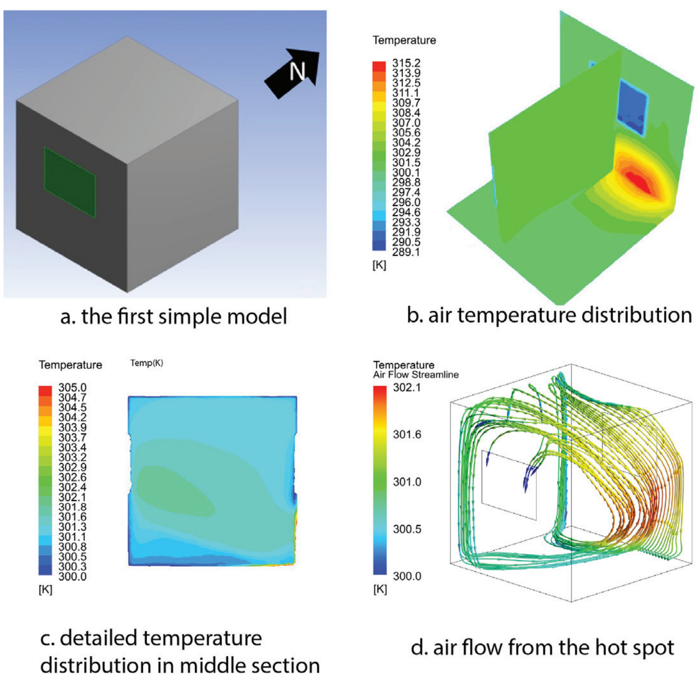


Figure 1.The first simple model with simulation results of temperature distribution and velocity field.

Based on this model there are 5 scenarios simulated with different solar irradiation and different material properties in order to study their affect on air movement.

The first scenario is on winter solstice, the overall heat transfer coefficient (U-values) are set to 1w/ m^2k for windows and 0.12w/ m^2k for wall, roof and floor; outside temperature is considered to be 270k; solar irradiation level is 748w/m^2 direct and 232w/m^2 diffuse; the Solar Heat Gain Coefficient (SHGC) of south window is 0.41 while the north window is 0.62.

Figure 1.b shows the interior air temperature distribution of scenario 1. The highest temperature in scenario 1 is 315K (42°C), which is found at the bottom of the north wall interior surface. That area on the wall is first heated by direct solar radiation and then heat is transferred to ambient air by convection. The lowest temperature of air is found at the area close to the windows at 289K (16°C). The reason is that the U-value of window is higher than that of the wall. Except for the air close to the boundary, the whole room's temperature is rather stable, which is around 301K~302K (28°C~29°C).

Part of the airflow is shown in figure 1.d, from which the air flow pattern can be recognized. Solar radiation drives air moving in this closed domain. As hot air rises, the direction is changed along the ceiling, then down to the floor and rise up again for another loop. Additionally turbulent loops in different directions are formed automatically in 3D space as a whole system.

Figure 1.c shows the detailed air temperature distribution in the middle section mentioned in Figure 1.b. It is not a typical buoyancy-driven airflow pattern with hot air above and cool air at bottom. Due to the existence of water vapor, air in the room can indeed absorb solar radiation. The absorbed solar radiation by air gradually decreases along the path away from the south window. Cool air on top is caused by air movement with flow pattern mentioned in Figure 1.d.

In scenario 2 to 4, the U-value of the envelope and solar radiation levels are changed respectively in order to compare the impact on closed domain in winter. The simulation results show similar patterns for temperature and velocity with Figure 1. Only the temperature range and air speed varies significantly as shown in Table 1.

Once all solar radiation is allowed to pass through a window like in scenario 2, air temperature will be around 329K~334K (56°C~61°C) which is too high to endure. So in the region with high radiation in winter, controlling the windows' SHGC is necessary.

Iowa is a region with long winters. Clouds and snow can block the solar radiation during many winter days. The thermal performance of the building envelope is thus important for cold climate zones like Iowa. Scenario 3 and 4 are designed with low U-value materials and regular U-value materials on a cloudy day in winter. The solar radiation is 327 W/ m^2 direct and 195 W/m^2 diffuse; SHGC is set to 0.41 for south window and 0.62 for north window; Scenario 3 has U-value of 1w/m^2k for windows, 0.12w/m^2k for walls; while Scenario 4 has U-value of 3w/m^2k for windows and 2w/m^2k for walls. The model in scenario 3 is developed with low U-value materials. The interior air temperature thus maintains an acceptable range of 287-292K (14°C~19°C) while outside is 270K (-3°C).

Scenario	Solar (W/m2) Direct/Diffuse	SHGC South/North	U-value(W/m2) Window/Wall	wall temp(K)	Air temp(K)	Highest air Speed(m/s)
1	748/232	0.41/0.62	1/0.12	289~315	300~ 305	3.08×10^{-1}
2	748/232	1/1	1/0.12	309~358	329~ 334	4.41×10^{-1}
3	327/195	0.41/0.62	1/0.12	282~297	287~292	2.25×10^{-1}
4	327/195	0.41/0.62	3/2	272~275	272~274	3.28×10^{-3}

Table 1, comparison of scenario 1 to 4

Considering the setting of solar irradiation and outside temperature this model represents a fairly common winter condition; many buildings may even have higher U values than the model, the interior temperature in the real world could be almost the same as outside.

Scenario 4 is designed without low U-value materials and high solar radiation, which is the worst situation in winter, the building envelope cannot retain energy to warm up air. The heat gained from solar radiation transfers to the outside quickly. The interior air temperature is merely 272-274K (-1°C~1°C), only 2~4 degrees higher than the outside. The low temperature impression causes occupants in low insulated homes to need heating in winter without realizing that the indoor environment could be comfortable enough without additional heating if higher insulation is employed as shown in scenario 1 to 3.

For buildings in cold continental climate regions such as Iowa, hot summers are an equally important issue that cannot be neglected although the heating season dominates. Scenario 5 is thus dedicated to simulating the model on summer solstice day at noon with clear sky. Except for setting outside temperature to 300K and adjusting solar angle to summer, all other parameters remain the same as scenario 1.

In this scenario, indoor air temperature results in a range of 315-318K (42°C~45°C). The hot spot caused by direct sun light is closer to the window and the area is smaller than in winter as the solar angle has changed. At the same time less interior air is exposed to solar radiation, which means both the interior surface and air absorb less solar radiation than in winter. This phenomenon indeed leads to smaller difference between indoor and outdoor temperature than during winter. However, the high outside temperature makes the convection not as effective as in winter; a lot of heat is kept inside the room. In order to decrease indoor air temperature and invite the cool fresh air from outside, natural cross ventilation should be considered as an additional passive strategy.

The Second Model

According to CIBSE[16], natural ventilation can be classified as:

- Cross ventilation;
- Single-sided ventilation;
- Stack ventilation;
- Mechanically assisted ventilation.

The second simple model is used to study cross ventilation with different compositions of window openings to allow for natural cross ventilation. It is based on the same 4m×4m×4m room but with three 2m×1m windows on south, east and north facades.

Since the air passing through the building is driven by the pressure difference around the building and air velocity is just a movement phenomenon, windows were considered as pressure inlets rather than velocity inlets in ANSYS FLUENT. The gauge pressure at openings could be predicted through large field computing. Chen (2003)[17] separately simulated the indoor and outdoor airflow with different mesh sizes to save computing time.

Based on the above analysis and simulation, wind velocity in the outdoor environment of 3m/s will cause a gauge pressure of 7pascal at the façade facing the wind.

In this model, the U-value of 0.12w/m^{2}k is set for walls, roof, floor and closed window; outside temperature is 300k; solar irradiation is 748w/m^2 direct and 232w/m^2 diffuse; the south window is set as pressure inlet with gauge pressure of 7pascal.

Scenario 6 and 7 are simulated with this model. In scenario 6 the south window and north window are open while the east window is closed. In scenario 7 the north window is closed and other windows are open.

Figure 2.a and 2.b show the vertical middle section and horizontal middle section of air velocity in scenario 6. The air flows in the room and spreads out like a balloon with small circles around the edges. As simulated in scenario 1, buoyancy effect drives up to 0.3m/s air speed in the room. Once the gauge pressure can bring in air movement at higher velocity than 0.3m/s the buoyancy effect is hard to observe. The 7pascal gauge pressure drives air at inlet opening with almost the same 2.5m/s velocity at every spot. According to momentum equation, although the air velocity at outlet varies to a small degree, the mean value should be the same as the inlet.

Air temperature distribution is tightly related to the velocity field. High air speed provides enough fresh outdoor air change rate, so the temperature of the central zone in the box is almost the same as the outside. The edge zone experiences lower air speed and air change rate by forming small circles, thus the temperature remains higher than outside by 1~5 degrees. The temperature difference is bigger at the corners close to the inlet opening than outlet opening.

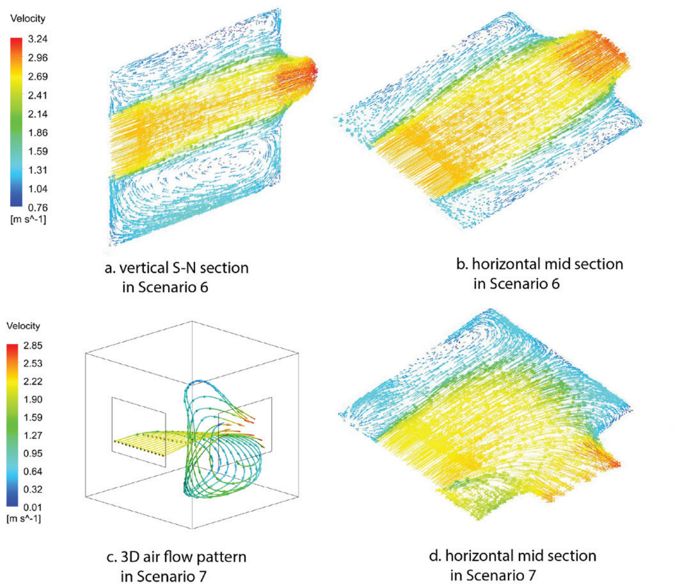


Figure 2 Simple box with natural ventilation in summer

Figure 2.c and 2.d show part of the 3D air flow path and horizontal middle section of air velocity in scenario 7. With the south window open as pressure inlet and east window open as pressure outlet, a main "L" shaped stream is formed. The "L" pattern does not only appear on a two dimensional plane but also in the three dimensional space. An obvious result of "L" turns is the divergence of air flow direction at the outlet as shown in figure 2.c. Compared to south-north opening, the interior air speed is lower both at inlet and outlet. Thus with the same opening size, the south-east opening composition has lower air change rate. Although the air temperature difference in the whole room is also 1~5 degrees higher than outside when the air movement reaches the steady status, the cooling speed will definitely be slower for the south-east case. And in a real world scenario, once obstacles like furniture and blinds block part of the air movement, the south-east opening has less potential to get effective natural ventilation.

The east-west opening has a similar pattern with south-north opening. But the one factor that matters is the wind direction and speed in a large field which determines the pressure difference around the building. Thus at this location wind comes from south in summer, the pressure difference between east and west façade is not as big as other openings, which makes the east-west opening not as effective as south-north openings.

SIMULATING SOLAR RADIATION IN THE INTERLOCK HOUSE

After simulating and analyzing those simple models, the following section analyzes CFD simulation of a whole one story house with ANSYS FLUENT 14.0.

The ISU Interlock House was built for the 2009 US DOE Solar Decathlon which challenged collegiate teams to design, build, and operate solar-powered houses that are cost-effective, energy-efficient, and attractive[18]. This single-story house has a 720sqft (approx. 67m^2) open floor plan with a sunspace facing south which is composed of removable glass walls and skylight as shown in Figure 3. The sunspace plays different roles in different seasons. It can be closed to collect solar radiation in winter and open to invite fresh air in summer. Even with all glass walls closed, there are 3 operable windows connecting the air in the sun space with air in the main space (living room, kitchen and bedroom). All the features make the Interlock House a perfect model to study the airflow with solar radiation.

Simulation of Interlock House in Winter

In ANSYS FLUENT14.0 the winter condition is simulated with the following settings: All exterior windows are closed; in the sunspace the two windows above and the one connecting to the bedroom at lower level are open. The U-value is 1W/m^{2}k for windows and 0.12 W/m^{2}k for walls, roof and floor. Outside the air temperature is 270K (-3°C) with 748w/m2 direct and 232w/m2 diffuse solar radiation. The SHGC is 0.41 for south and 0.62 for north.

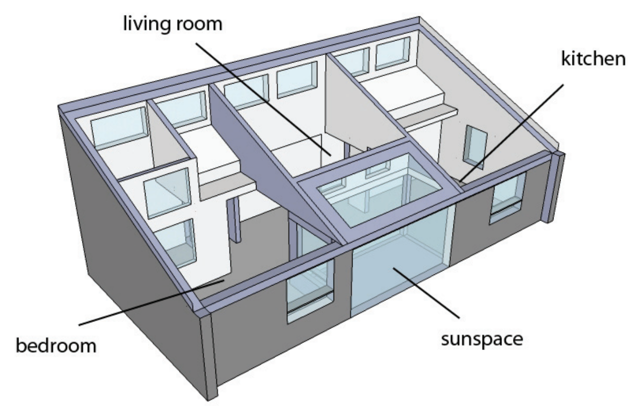


Figure 3 Interlock House with sun space closed in winter

In Figure 4.d, the roof; south, east and west walls are removed for better presentation. While the floor and second glass door are heated to 320K (47°C), the frame wall above the sunspace reaches up to 325K (52°C) because of the extra solar radiation from skylight. East kitchen and west bedroom are also heated by the solar radiation passing through the south facing windows on each side. However, the high point on the west side is 10 degrees lower than the east side, which proves again that low velocity airflow at corners helps to accumulate heat. There is also an area at the bottom of the north wall with higher temperature than ambient surface. The heat comes from the solar radiation through the two small operable windows above the sunspace.

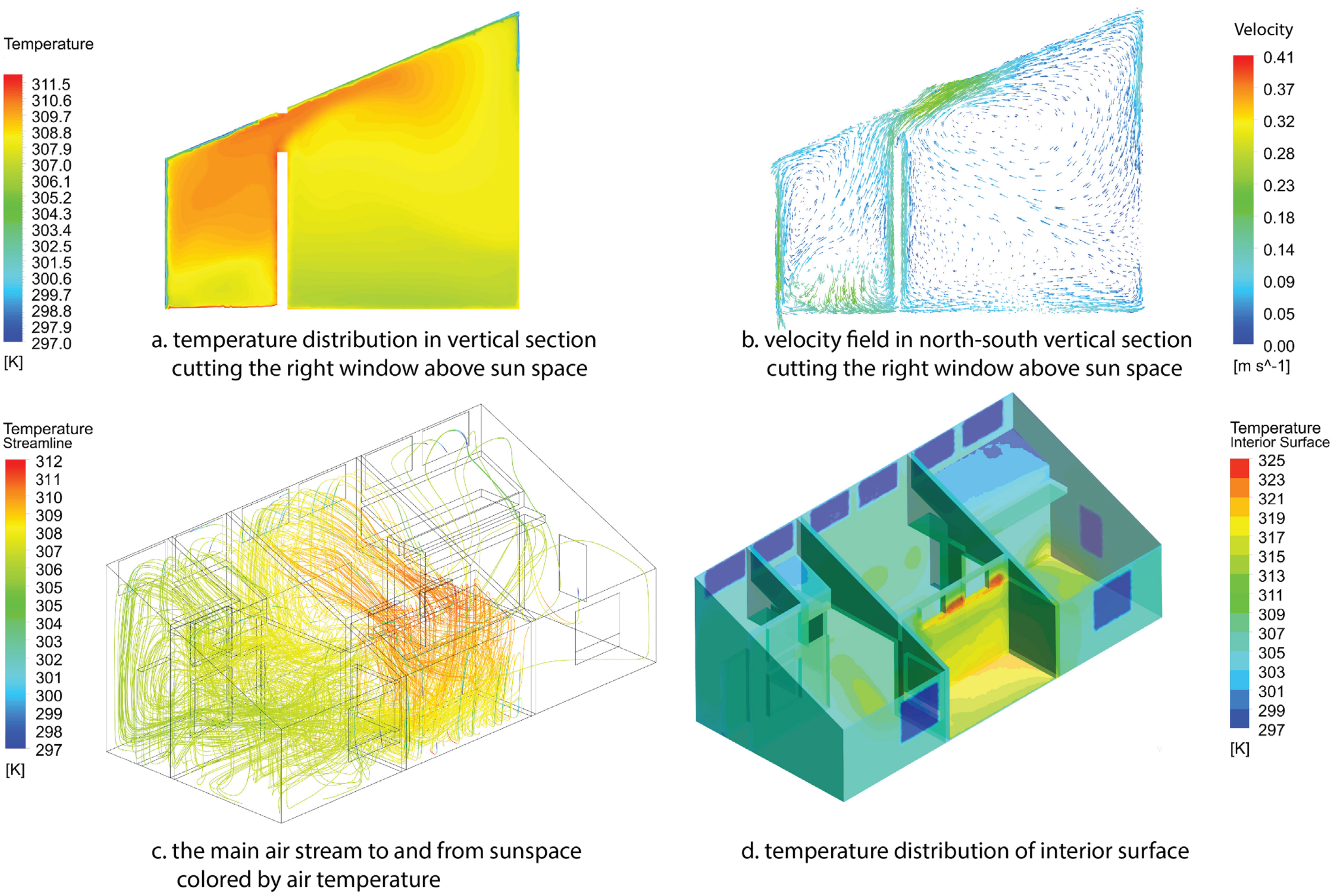
As shown in Figure 4.a, solar radiation heats the ground in the sunspace and the second glass door. The floor behind the second glass door is also heated but not as much as the floor in the sunspace. Most air can be warmed up to 307~310K (34°C~37°C) in the sunspace and 305~308K (32°C~35°C) in the living room.

In the sunspace hot air rises along the second glass door and flows into the main space at a speed of 0.2m/s as shown in 4.b. Considering the mass equation, as long as air is flowing out there should be air flowing in. In this case the lower opening, which is the operable window connecting sunspace to the bedroom, provides the inlet air to the sunspace at a speed of up to 0.4m/s. Organizing convective air loops is an important design strategy to minimize the temperature difference in a closed complex space. Otherwise the air would flow out and in through the same opening, which is no good for making full use of the hot air in the sun space. With the air loop connecting living room, bedroom and sunspace (see Figure 4.c), the temperature in these space ranges between 307~312K (34°C~39°C). Although the main air stream does not pass through the east kitchen, the air movement in the kitchen is also driven by the solar radiation and forms loops in a relatively isolated zone. Only the southeast corner has 1 degree cooler temperature than other area.

If not considering the air leakage in the envelope, the Interlock House could become too hot on a sunny day in winter, but as long as the user can open operable window to let in some cold air it's easy to lower down the indoor temperature.

Simulation of Interlock House in Summer

In summer the skylight is covered by photovoltaic panels, all operable windows and the south door are open so the sunspace cannot accumulate heat in a closed domain. The second glass door operates as the main south door. If both the south door and north door are open, the velocity pattern would be similar as shown in Figure 2.a and 2.b. Complex spaces provide more options for ventilation strategies. The option simulated here for the Interlock House is to open the south door as pressure inlet, close the second glass door and north door while the operable windows are open. This composition helps to keep the air speed slow on the lower level for human comfort while removing the heat accumulated close to ceil-



a. temperature distribution in vertical section cutting the right window above sun space

b. velocity field in north-south vertical section cutting the right window above sun space

c. the main air stream to and from sunspace colored by air temperature

d. temperature distribution of interior surface

Figure 4 Velocity field and temperature distribution in the Interlock House in winter ing quickly. A 7pascal gauge pressure at the south operable window was set for the indoor simulation.

As shown in Figure 5.c, at the inlet air speed reaches up to 3m/s while in Figure 5.a air flows close to floor at a speed around 0.4m/s. The low speed decreases the air change rate. But for this small house with air change rate 5.7m^3/s the cooling time is very short. Temperature is tightly couple with air speed, in steady status, with outside air temperature at 300K, most interior air are in the range of 300~301K (27°C~28°C) as shown in figure 5.b and 5.d. The south entry space and the "tunnel" along the ceiling get the closest temperature to outside while warmer air remains at lower level and corners because of slow air movement.

DISCUSSION OF RESULTS

With the visualizations from ANSYS FLUENT14.0, the physics behind indoor air movement is revealed and easy to understand. As simulated both with simple model and complex model, solar radiation is very powerful. Designers and users should be careful about making full use of the solar radiation in winter with the awareness that it could bring more heat than needed. Direct solar radiation transmitted through a window glass always gives a high temperature spot on a certain indoor surface and this surface serves as the "fireplace" for the whole house, which together with radiation absorbed by water vapor in the air, increases the interior temperature in winter. In the warming up process of hot air rising around the hot spot, air loops develop to spread the heat to other zones. To keep the whole space warm, both insulation and air loop matter greatly. As the idea of good insulation is widely accepted, more attention should be paid to the air loop. It is the air movement that spreads heat from one spot to the whole room/ house. Once the loop is blocked or air leakage infiltrates the heat to the outside, hot air cannot reach the relatively cold indoor zones as it should be and mechanical heating might be needed at a certain point.

Natural ventilation is driven directly by the pressure difference around building. Although usually the south-north opening will achieve cross ventilation, the opening composition should be evaluated for each local situation to achieve relative accurate predictions. As simulation needs to incorporate a large environment, the designers should be aware that the study of the landscape around buildings is crucial for natural ventilation. In a complex space the design of openings should offer options to enable the adjustment of air velocity for human com-

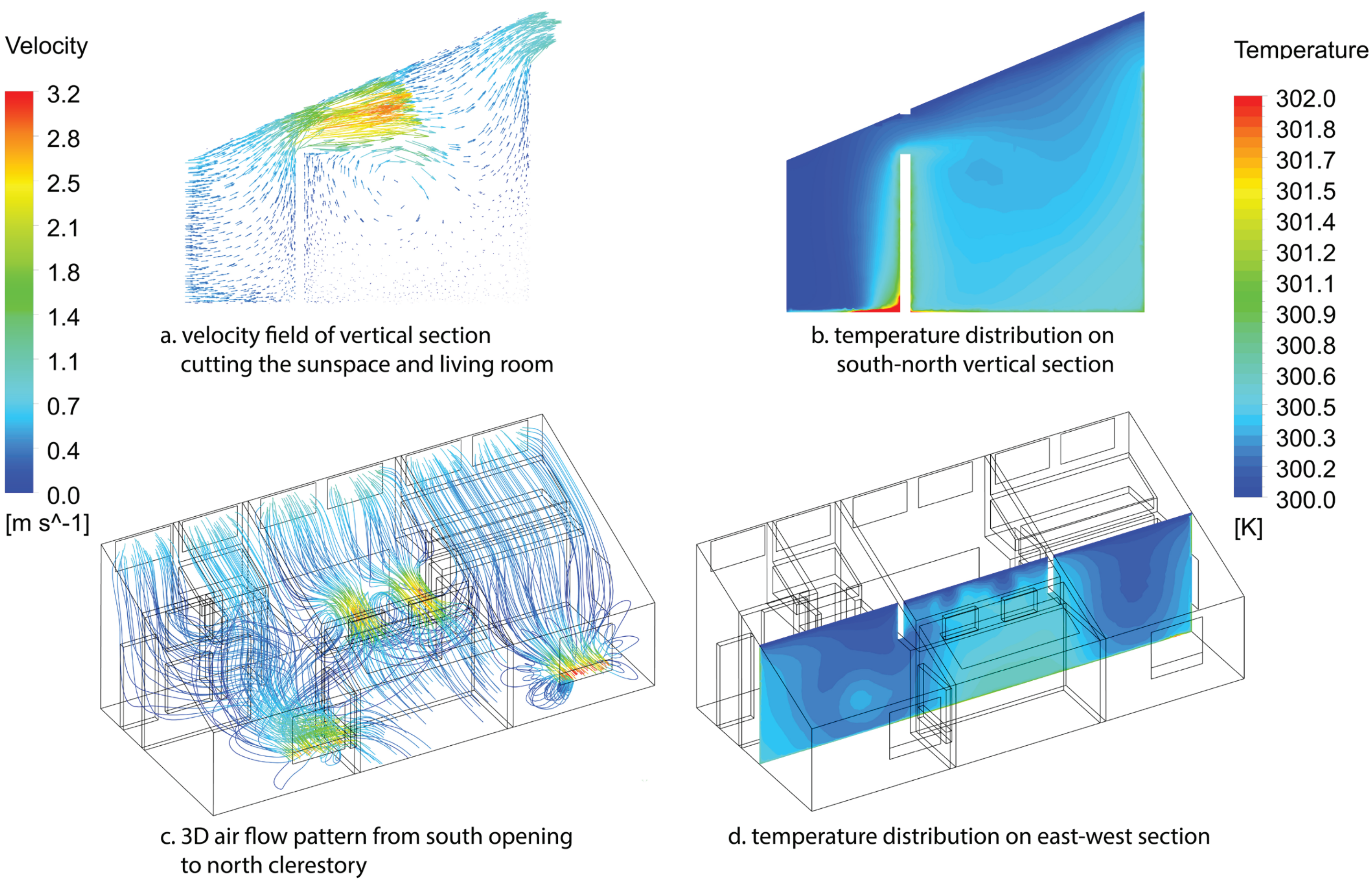


Figure 5 Velocity field and temperature distribution of Interlock House in summer

fort. The incorporation of human comfort will be brought into the natural ventilation evaluation with further work.

ACKNOWLEDGEMENTS

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