Improving Airflow Performance Models for Passive Solar and Natural Ventilation Design:

Comparing Simulation and Preliminary Measurements

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ABSTRACT: To achieve net-zero energy buildings, a complex relationship exists between orientation, spatial composition, building fabric, and thermal and climatic conditions. Airflow conditions are the result of balancing the above relationships and directly affect occupant comfort. The opportunity for architects is that airflow and related energy performance can be organized by spatial composition. Understanding the indoor airflow movement and related energy performance can promote the effectiveness of space planning. A solar house built in 2009 for the Solar Decathlon competition held by U.S. Department of Energy has now been re-established as a community field laboratory to study its overall energy performance. This paper focuses on studying the airflow movement in the solar house with Computational Fluid Dynamics (CFD). Furthermore, the passive heating and cooling effects are initially compared with onsite temperature measurements from an advanced data acquisition system installed at the house based on one year of data collection. Our final goal is to develop design guidelines based on numerical analysis and onsite measurements characterizing airflow patterns in complex residential spaces.
Keywords: Passive Solar Architecture, Airflow Simulation, Computational Fluid Dynamics, Natural Ventilation

INTRODUCTION

Sustainable buildings demand a holistic approach towards the design of space, envelope, environmental control systems; the construction materials and occupational behaviour. The goal of our research is to push whole building performance evaluation and simulation to higher levels. Therefore our team has started an interdisciplinary research endeavour coupling engineering expertise in computational fluid dynamics (CFD) with architectural design to build simulation expertise for designing natural ventilation strategies in buildings. We utilize an operating solar powered house as a laboratory for modelling and testing. The building explores an efficient balance of passive design and active energy harvesting strategies. Our research goal is to enhance the utilization of naturally occurring energy flows through space, within or around building materials to achieve thermal comfort, individual control and air quality, while eliminating fossil fuel consumption and negative environmental health impacts. We aim to achieve this goal by integrating computational fluid dynamics (CFD) simulation and visualization tools into the design process. In particular we investigate the relationship between spatial composition and natural air movement as free heating and cooling ventilation strategies by tightly coupling computational fluid dynamics modelling and architectural design. A successful implementation of this research will significantly reduce the need for active mechanical systems in buildings and provide a holistic performance assessment model, which will greatly enhance the acceptance of green technology.

An in depth literature review was conducted to understand the current state of the art of natural ventilation simulation identifying new research questions on the interaction of space, air movement and material properties. After modelling simple geometry space ventilation scenarios of wind and buoyancy driven natural flows with ANSYS FLUENT 14.0 based on representative studies [1]. We then applied the knowledge to the case study house, which enables us to compare the simulations with energy performance measurements that are available from an advanced data acquisition system in the house.

While contemporary architects desire the integration of natural ventilation flow and passive solar strategies into architectural design concepts, the 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.

METHOD OF ANALYSIS

Physical Model

The solar house selected as the research object is located in the mid-west America with extreme cold dry winter, and warm humid summer. Although it is currently running as the naturalist office by the occupants, this house can still prove the effectiveness of design and building material despite of its altered usage [2]. This approximately 70 m^2 house is composed of 5 zones: sun space, living room, kitchen, bedroom and bathroom. The mechanical room is not involved in the passive design strategy and therefore not considered a zone. The sun space is facing south and designed to be the solar heat collector in winter with 5cm thickness concrete slab in the floor. It is surrounded by glass walls and windows. The walls can be removed in summer. All the other four zones are here summarized as the main space.

As temperature is the basic character of air movement, the measurements used in this paper are from 11 thermocouples located in different zones and heights, with 6 HOBO U12 sensors in the sun space as shown in Fig. 1. All the sensors are protected with radiation shields so the temperature can represent ambient air.

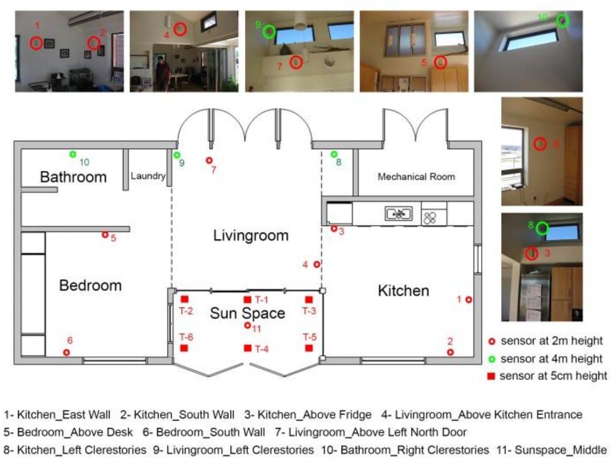

Figure 1: Temperature sensor location in the house

Numerical Model

Many environmental and energy performance design tools exist, but computational fluid dynamics simulations (CFD) appears as the most accurate to simulate the relationship between spatial continuity and physical environment by analyzing the fluid dynamics of air movement. ANSYS FLUENT 14.0 has been chosen as a relatively user friendly interface and accurate CFD tool to carry out the tasks. The usage of the simulation results is introduced in this section.

The most accurate CFD analysis could provide absolute numerical values [3] for the entire fluid field within a simulated scenario. It requires precise input values such as exact temperature and heat transfer coefficient distributions on boundary layers, which are difficult to collect and determine. The secondary level of accuracy, which a CFD analysis could achieve, would be to provide incremental quantitative values. This means, if input values are altered, the corresponding change of output in CFD analysis and real world are very close, if not the same. A holistic understanding of spatial composition, airflow and energy performance should lie between the first and second accuracy level described above. Higher level of accuracy could be achieved by spending more time on simulation and even some measurements to correlate the boundary setting. But for architects the effort on CFD simulation should never overwhelm the architectural design itself. So it is very important to trade off the simulation accuracy with design guideline.

With the intent to understand the physical process within a building environment, which could help preliminary design decisions, two transient CFD models are analysed in this paper [4]. The passive heating scenario is chosen from Mar.13 to Mar.14 2013. This scenario focuses on the effect of solar heating, building orientation and material, and space composition of this passive solar heated house with all windows closed. The summer case was modelled based on Sep.12 2012 data, which focuses on analysing the cooling effect with a specific opening strategy to invite natural ventilation. Both models are run with a minimum of 48-hour time, of which only the last 24-hour period is convergent and selected. The interior air together with walls and windows have all been considered and given physical properties. The k-ε turbulence equation with enhanced wall function and full buoyancy effect is selected for both models. The under-relaxation factors are tuned to ensure convergence at each time step.

RESULTS AND DISCUSSION

Results are analysed from four aspects: Building orientation, building material, spatial composition and opening strategy.

Building Orientation

Building orientation (the window locations and sizes), together with the solar angle decides where the solar ray projects on the interior surfaces. Some researches assume the same air temperature everywhere in one room. This leads architects to carry out schematic design without considering the possible temperature distribution. It could cause unnecessary heating/cooling loads for mechanical design in the next step and even some discomfort after built. By considering the uneven interior temperature distribution, the indoor environment and outdoor climate are more closely connected and the design strategies for building orientation can be improved.

In dry winter, solar radiation cannot directly warm up the interior air without water vapour to absorb the infrared solar ray. But it does not mean the solar heat gains are wasted. In a passive design condition, the temperature of indoor warm air mainly derives from the objects absorbing solar radiation. These objects could be floors, counter tops, walls, furniture and appliances. As shown in Fig. 2, with the sun movement the absorbers cannot receive the same angle of solar radiation all the time, making the projection on the interior surface differ with time. Thus the temperature distribution in the house cannot be uniform as assumed in many energy models.

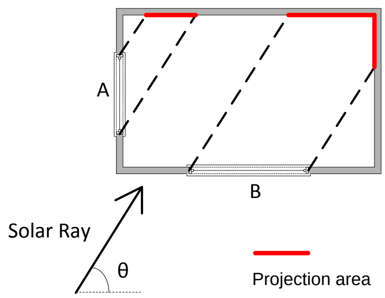

Figure 2: Solar ray angle and indoor projection

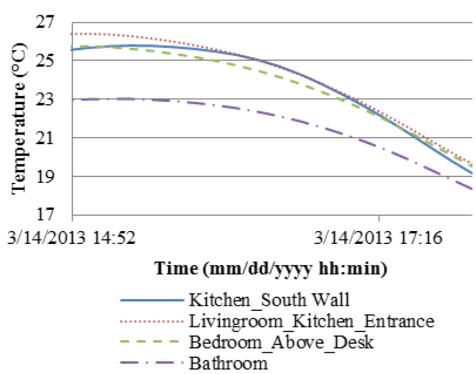

Figure 3a: Temperature at four locations in the house - CFD simulation

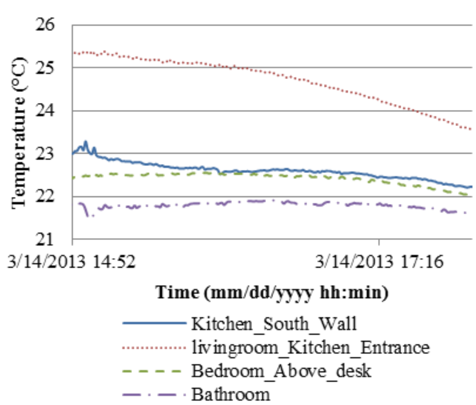

Figure 3b: Temperature at the same four locations in the house - onsite measurements

The Fig. 3a and Fig. 3b display the indoor air temperature difference in the house on a winter afternoon. The temperature difference at various locations can be observed in both CFD simulation and onsite measurements. Generally both CFD and onsite measurements deliver the same information: In the late afternoon, all of the four locations are cooling down. The highest spot is at the entrance from living room to kitchen. This location is closest to the sun space which stores the solar heat. The temperature readings in kitchen and bedroom vary slightly but remain close to each other. The coldest zone is the bathroom, because it cannot be reached by direct solar ray during the entire day. The temperature in the bathroom derives from the indoor convection of air.

The air temperature in the main space at 2m height varies about 2.5 degrees Celsius at 3:30pm on March 14. The temperature range in Fig. 4 is adjusted to better demonstrate the stratification, not presenting the full scale of temperature variation, especially for the sun space. The temperature difference in a 3D room could be bigger considering the multiple planes at different height. More sensors are needed to validate the temperature stratification at different heights.

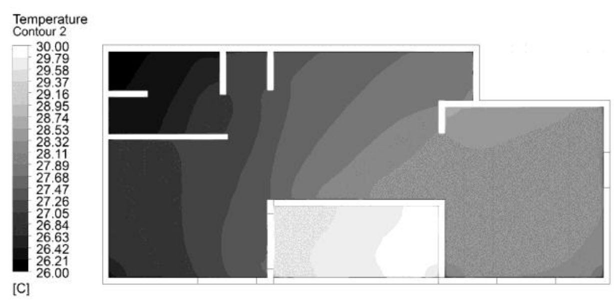

Figure 4: Temperature distributions at the 2m level height

Building Material

The boundary between solid object and fluid air is happening at a small scale but is indeed a very interesting engineering zone. Heat is conducted from the material surface to the air but quickly changes the air movement to convection and reduces the temperature difference as shown in Fig.5. This phenomenon is usually ignored in energy models so that prevailing understanding of spatial air distribution is that the highest temperature should be found just below the ceiling.

It has been widely accepted that for the indoor environment, hot air rises and air temperature should increase with height within an enclosed domain. However, when solar rays project at a lower level, e.g. on the floor, the air stratification is not exactly what was initially considered. The floor is heated up by solar radiation and the warm floor conducts the heat to the surrounding air, thus there is temperature stratification in both the floor and air. Then air at higher level receives lower temperature. This does not change the fact that hot air rises, but it adds another layer of complexity to consider: the buoyancy movement driven by earth gravity is not always as powerful as the convection driven by solar heat, and the thermal property of interior building material can affect the indoor thermal condition.

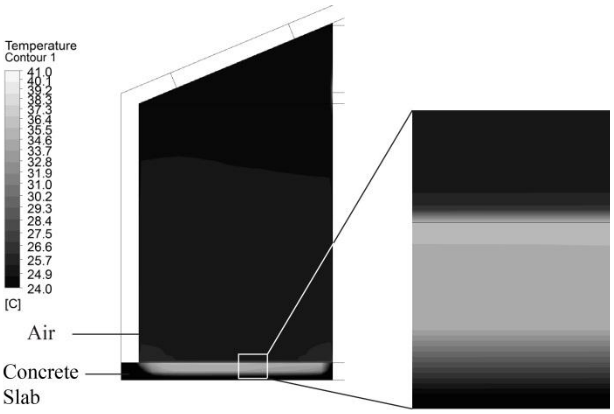

Figure 5: Heat transfer between air and floor - CFD simulation of the sun space section

In the sun space there are 6 sensors placed about 5cm above the floor and 1 sensor hanging in the middle of the air. Measurements from these sensors prove that higher location does not get higher temperature when there is strong solar radiation. Fig. 6 shows in the early afternoon T-5 continually capture higher temperature than the sensor in the middle of the sun space which is about 2m higher than T-5, as shown in Figure 1.

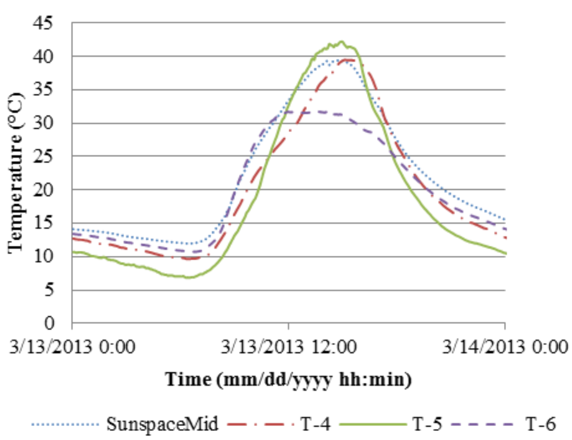

Figure 6: Temperature measurements in the sun space

The sun space floor contains a 5cm thick concrete slab as thermal mass. Amongst all the sensors on the floor only T-5 is above a 1.5 cm thick wood panel which has lower heat capacity. Comparing T-5 and other temperature sensors, it's obvious that T-5 rise up higher and reach the highest temperature earlier than T-4, although the T-4 location should get more solar heat in sun space than T-5. After sunset T-5 cools down quicker than any other sensors and keeps the lowest temperature all night. This phenomenon shows that the wood panel under T-5 warms up and cools down quicker than the concrete floor. Considering the measurement of HOBO sensors close to the sun space floor is representing the temperature change of the surface below each sensor, it proves the effectiveness of the added thermal mass. Furthermore, both the main space and sun space arrive at the lowest temperature around 17C at 7am on the second day while the lowest temperature outside happened at midnight (Fig. 7). With decreasing the thermal mass and insulation property, CFD predicted that neither the sun space nor the main space could maintain the lowest temperature at 17C during the 48-hour circle. This 7 hour time lag and minimum temperature is important for passive design. With the lowest temperature in the main space at 17 C degree the mechanical heating could be saved if it's acceptable to the occupant. On the other hand, if the house was occupied at night, the lowest temperature could be a little higher than 17 C in the morning. Human bodies and home activities like dinner cooking would also create heat sources.

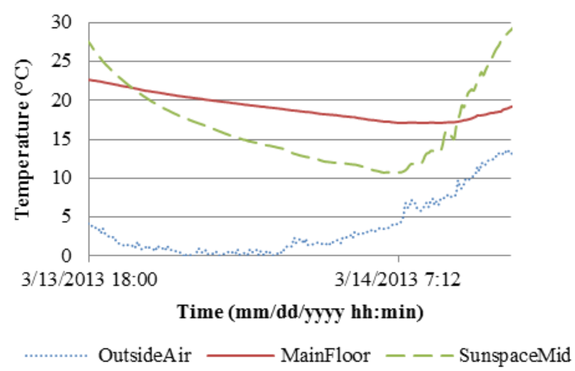

Figure 7: Indoor and outdoor temperature measurements

However, the thermal mass in the sun space is not sufficient to provide all thermal storage to the main space at night as desired. Fig. 7 shows the main space temperature is higher than the sun space, so the main space is losing heat to the sun space instead of gaining.

With a relative higher U-value it is understandable that the south glass doors loses heat to the outside quicker than the main space at night as shown in Table 1.

Table 1: U values of different building elements in the house

Building Elements	South Glass Door	Wall	Roof	Window	North Door
U value (W/m^2K)	2.1	0.12	0.1	1	0.14

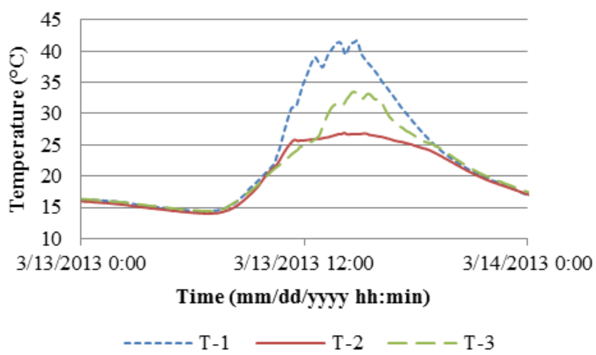

Figure 8a: Temperature difference in the sun space - onsite measurement

Figure 8b: Temperature difference in the sun space - CFD simulation

Without knowing the convective heat transfer coefficient between the concrete slab and air, it could be hypothesised that the concrete slab in the sun space keeps heat well so the heat released to the sun space air is not quick enough to make up the heat loss to the outside at night as seen in Fig. 7. This convective heat transfer coefficient is between the solid and fluid, which is different from the U-value of the floor. However, the hypothesis cannot be proven correct when sensor T-1 and T-3 in the sun space show quick reactions to the change in solar radiation. In Fig. 8a T-1 and T-3 show more fluctuations compared to the stable temperature of T-2. Because there is a wood shelf in front of T-2, before noon T-2 start staying in the shadow of the shelf and the temperature increase slowed down. T-1 is in the middle between T-2 and T-3, so the ground receives the solar radiation for the longest time, which makes temperature of T-1 climbing up to the highest level among these three. T-3 does not warm up as quickly as others until the afternoon for receiving no direct solar radiation in the morning. Once it exposed to the sunlight it shows similar fluctuations as T-1 because the front door frame shadow moves with the solar radiation. These observations show that the concrete slab lose its temperature in a short time without solar heating during day time instead of keeping the temperature for a while, so the assumption of low convective heat transfer coefficient between floor and air causing low air temperature in sun space at night does not stand.

In Fig. 8b, CFD shows the temperature stratification at 11:30am as T-2> T-1 > T-3 without considering the shelf shadow on T-2.

Spatial Composition

Fireplaces are usually found at the centre of old traditional buildings so that the heat could spread out to the indoor space as even as possible. In the Interlock House the sun space acts as a fireplace as well. In our case solar radiation passes through the south glass door and skylight into the sun space and turns it into the "fireplace". Then heat is conducted through the interior glass walls to the main space. Also three operable windows are designed to enhance the heat exchange between the sun space and the main space. On March 14 around noon, the occupant opened the three windows to connect the sun space and main space. As predicted in CFD (Fig. 9b) the warmer air, which gathered in the sun space flows into the living room through the two awning windows above sun space, and cooler air in the bedroom flows into sun space through the lower awning window on the west side of sun space. The closest sensor to the higher awning windows is the thermal couple above the kitchen entrance, so in the chart there is a sudden temperature rise around noon while T-2 and T-6, the two closest sensors to the awning window drop down suddenly in temperature.

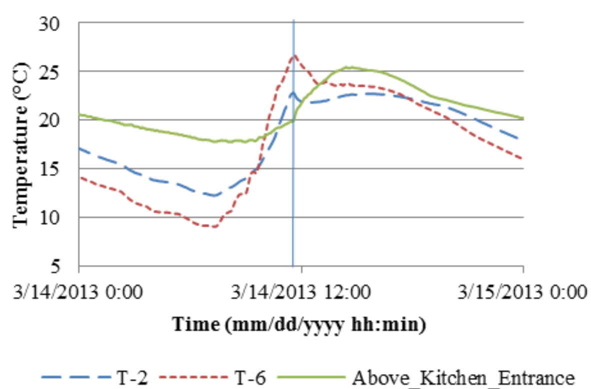

Figure 9a: Temperature rise and drop with sun space openings - onsite measurement

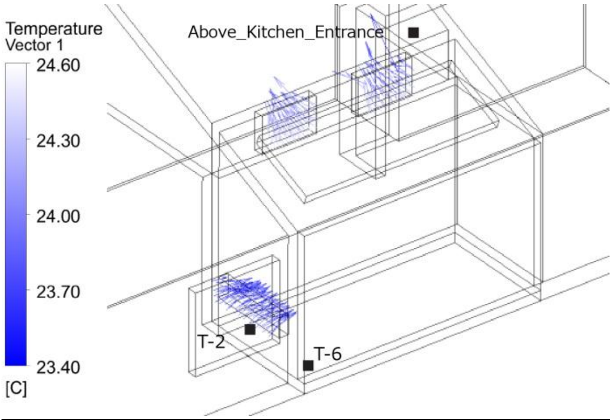

Figure 9b: Air flow pattern and temperature at sun space openings - CFD simulation

Opening Strategy for Natural Ventilation
Air change rate is always chosen as the most important parameter to evaluate ventilation effects. However, high air change rate does not ensure the air has been ventilated thoroughly everywhere in the house. According to the occupant log, the south door, inner glass wall and north door was open to invite natural ventilation around 7:30am on September 12, 2012. This operation has a high air change rate but still many parts of the house do not ventilate well. According to the CFD simulation the air change rate is about $13m^3/s$ for this opening scenario and the living room cools down within 30s. However, other zones do not cool down at the same rate. The temperature in bedroom and kitchen drops down slowly and in the bathroom no obvious temperature reduction can be observed in Fig. 10a.

The onsite measurements (Fig. 10b) show comparable cooling effect to the CFD results. The sensors at higher level in the bathroom and kitchen do not observe obvious temperature drop. While other sensors at lower level record the temperature drop, the air temperature close to the walls still remains about 2 degree higher than the wind entering the building for at least one hour. The difference between CFD simulation and the recorded measurements can be attributed to the process of opening the south door, inner glass wall and all the four north doors. This took a few minutes time, which is difficult and not cost-effective to simulate in CFD.

Both the CFD natural ventilation models and on-site measurements deliver an important message that solely chasing for high air change rate to get all the space natural ventilated may bring a result below expectation. And although natural ventilation cools down the air temperature quickly, it still needs longer time to remove the heat stored in the solid building material.

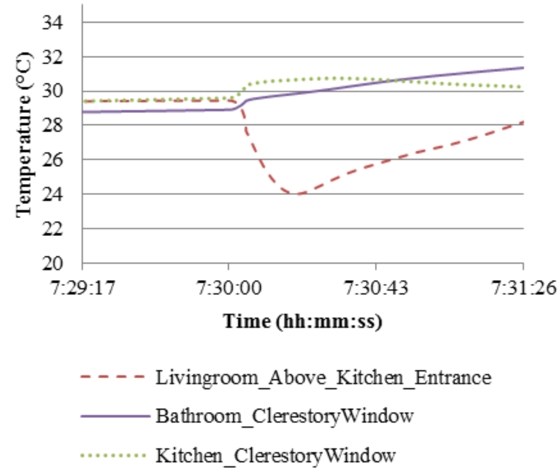

Figure 10a: Air temperature at different locations during natural ventilation - CFD simulation

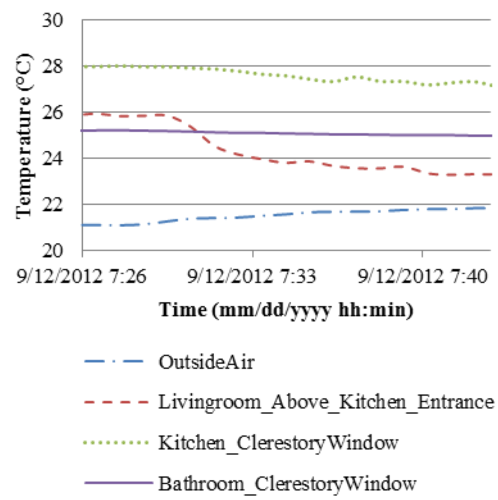

Figure 10b: Air temperature at different locations during natural ventilation - onsite measurements

CONCLUSION

In this paper, architectural design guidelines are being verified and identified by comparing CFD simulations and on site measurements. They are: 1. Temperature distribution in the house is not uniform and can be designed by building orientation. 2. When there is direct solar radiation projected in the house, the solar driven convection effect is greater than gravity driven buoyancy effect in a small space. 3. Wall and additional thermal mass play important roles in maintaining thermal comfort. 4. Spatial composition can be organized to enhance the passive heating. 5. Opening strategy should be considered to improve the efficiency of natural ventilation rather than solely relying on the air change rate. The guidelines above are important for architects when designing passive energy efficient buildings. And according to the study presented in this paper, they can all be simulated by CFD tool with acceptable accuracy as has been shown by comparing the CFD simulations with on site measurements.

Along with the design guidelines, the creditability of using ANSYS Fluent as a design tool to analyse the relationship of building orientation, building material, spatial composition and opening strategy with airflow and energy performance has been validated by comparing onsite measurements for two specific house operations with two transient CFD models. The analysis shows that ANSYS Fluent is accurate enough to provide incremental quantity values. It also has the potential to provide absolute quantity values if boundary conditions are properly adjusted. Obstacles in popularizing the use of CFD tools are the long computing time and the lack of user-friendly interfaces. However with the current computer technology development and inter-disciplinary collaboration these problems can soon be resolved.

At last we hope this preliminary study will provide concepts for new simulation approaches to passive solar and natural ventilation designs.

ACKNOWLEDGEMENTS

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