A METHOD FOR ESTIMATING COOLING ENERGY SAVINGS POTENTIAL FROM USING MIXED-MODE VENTILATION

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ABSTRACT

Mixed-mode ventilation is an effective way to reduce energy consumption as well as to improve thermal comfort. Presented here is an easy-to-implement method, which uses both energy simulation in EnergyPlus and airflow simulation in CFD to estimate cooling energy savings potential from using mixed-mode ventilation. The intention is to improve the accuracy of natural ventilation simulation by taking advantage of both algorithms. This paper focuses on one type of natural ventilation used in mixed-mode, wind-driven natural ventilation.

This paper first describes the workflow of this method. Then a case study is presented using a three-floor office building in an urban context. The result is compared with that of airflow network model in EnergyPlus. The accuracy level and advantages of this method are discussed.

INTRODUCTION

A design that enhances natural ventilation will not only reduce energy cost, but also improve thermal comfort and air quality. In some climates, it is not possible to rely exclusively on natural ventilation for cooling demand. Mixed-mode ventilation is suitable for such conditions in a wide range of climates and sites. Mixed-mode ventilation refers to a hybrid approach to space conditioning that uses a combination of natural ventilation and mechanical cooling (Brager et al., 2007). It is also called hybrid ventilation (Atkinson et al., 2009). Mixed-mode strategies allow buildings to be naturally ventilated during periods of the day or year when it is feasible, and uses mechanical cooling only when natural ventilation is not sufficient. A well designed and properly operated mixed-mode building can significantly reduce the energy use of mechanical cooling, and offer benefits to occupants including improved thermal comfort, health and productivity (Brager et al., 2007). A report states that mixed-mode ventilation is able to achieve 47-79% HVAC energy savings, 0.8-1.3% health cost savings and 3-18% productivity gain (CMU, 2004). Another study also reports more than 40% energy savings by using mixed-mode ventilation (Ezzeldin and Rees, 2013).

This paper aims to develop an easy-to-implement method for estimating cooling energy savings potential from using mixed-mode (hybrid) ventilation. This paper only discusses one category of mixed-mode operation strategy, change-over operation, where a building switches between mechanical cooling and natural ventilation (Brager et al., 2007). In terms of the type of natural ventilation used in mixed-mode, this paper concentrates on wind-driven natural ventilation. Buoyancy-driven natural ventilation is not simulated in this paper. Pressure difference is the main mechanism of wind driven ventilation, while buoyancy-driven ventilation occurs as a result of temperature differences between the interior and exterior. As the temperature difference between indoor and outdoor environment is small in cooling seasons, buoyancy-driven force usually has smaller influence on the ventilation rate, and wind-driven force often dominates, especially in the windy conditions (Asfour and Gadi, 2007; Khan et al., 2008; Haw et al., 2012; Shen et al., 2012).

In order to estimate cooling energy savings potential from using mix-mode ventilation, it is necessary to simulate both natural ventilation performance and energy consumption. EnergyPlus is a widely used energy simulation program with a built-in module for mixed-mode (hybrid) ventilation simulation. The module uses Airflow Network to simulate natural ventilation. Airflow Network is a multi-zone model. It consists of a set of nodes linked by airflow components. A zone is considered as a node, and openings such as doors and windows are considered as linkage components. Airflow Network solves air mass balance equations to calculate the pressure of each node and airflow rate of each linkage (DOE, 2014). Surrounding buildings are not included in the modelling process. As a result, wind-driven natural ventilation cannot be predicted accurately. This issue can be solved using CFD programs. CFD models are able to deal with complicated scenarios of airflow due to surroundings. In addition, the overall accuracy of predicting airflows of CFD models is usually higher than that of multi-zone models, as there are more simplifications and assumptions in multi-zone models (Wang and Chen, 2008). Shen et al. (2012) compared CFD model and multi-zone model with wind tunnel experiment. They have found that CFD model shows good performance of prediction of overall ventilation rate and airflow rate through openings, while large error may occur using the multi-zone method to estimate the ventilation rate in the case of large ridge openings. In short, CFD is a more reliable tool for evaluating ventilation performance. It has become more and more popular in various areas with the development of computer capacity and user-friendly CFD program interfaces (Chen, 2009; Tong et al., 2012; 2015). The CFD models are extensively applied to dealing with the challenges in natural ventilation design in recent years (Chen et al., 2007). CFD simulation could not directly predict thermal load and energy consumption, though. Ultimately, decision-makers would need to compare the energy consumption of different design strategies. Therefore, we need both EnergyPlus and CFD to develop a more accurate method for simulating mixed-mode ventilation strategies.

There are efforts in coupling CFD with multi-zone models (Tan and Glicksman, 2005), and CFD with energy simulation (Zhai et al. 2002, 2003, 2004, 2005) in order to improve predicting accuracy. Wang and Chen (2007) coupled a multi-zone network program with a CFD program. As a case study, cross ventilation in a four-zone building model is simulated using both CONTAM (a multi-zone network model) and their coupled program. The coupled simulation exchanges pressure between the multi-zone and CFD. As far as the flow rate of the openings in the investigated zone is concerned, the difference is around 60% between the solutions by CONTAM alone and by the coupled program. Wang and Wong (2008) developed a one-way static coupling strategy to couple CFD software FLUENT and building simulation software ESP-r. The building simulation generates information such as inside surface temperature for each wall and detailed boundary condition for the openings. The information is then passed to CFD simulation for indoor airflow and temperature simulation. Manz and Frank (2005) used CFD simulation results to generate coupling functions as the inputs to energy simulation in order to predict the thermal behaviour of a building with double-skin facades. Zhang et al. (2013) coupled EnergyPlus and FLUENT by exchanging airflow rates, air temperature and surface heat transfer coefficients at each time step. According to their case studies, the airflow rates during natural ventilation simulated by airflow network module and their coupling method are very different. As this method requires coupling at each time step, it might be difficult to run hourly simulations for an entire year.

The coupling methods in most of the studies described above effectively improve predicting accuracy. However, they also significantly increase the complexity of simulation. In some coupling methods, the simulation code needs to be modified. Although researchers seem rather willing to pay such price (Chen, 2009), it might not be feasible for designers and engineers to handle the complexity in their projects. To solve this problem, this research intends to develop an easy-to-implement method that uses both energy simulation and CFD algorithms to evaluate natural ventilation strategies. This method uses existing simulation programs and does not require code modification. CFD simulation and energy simulation can be performed independently and the simulation results can be coupled at the end of the process. This method does not require a large number of simulations and therefore it is computationally affordable. It is able to provide a fast but informative estimate of cooling energy savings potential. The outcomes are the number of natural ventilation hours and energy reduction from using mixed-mode strategies. The simulation results by using airflow network module in EnergyPlus and by using the new method are compared to show the difference in final results.

METHODOLOGY

The intention of this method is to replace the Airflow Network module in EnergyPlus with CFD simulations. In order to avoid code modification of simulation programs, this method externally and statically couples energy and CFD simulations. This means energy and CFD simulations perform independently and their simulation results are combined at the end of a simulation to derive cooling energy consumption of mixed-mode ventilation.

As this paper focuses on wind-driven natural ventilation, isothermal CFD calculations are performed to simulate airflows. Thermal buoyancy effects are not included in the modelling, as they are much smaller than wind-driven pressure when indoor and outdoor temperature difference is not large (Carrilho da Grac-a et al., 2002).

Figure 1 describes the methods for simulating energy consumption of mixed-mode strategies using wind-driven natural ventilation. In this case, CFD simulation is used to search for the temperature thresholds when natural ventilation alone is adequate for thermal comfort. Combined with other considerations, such as humidity constraints, whether natural ventilation is adequate for each hour could be determined. Energy simulation is used to calculate the energy consumption without natural ventilation strategies. Then subtract the energy consumption during natural ventilation hours from total energy consumption. The remaining amount is the energy consumption of mixed-mode ventilation. Compared with the cooling energy consumption of baseline case without natural ventilation or mixed-mode strategies, the cooling energy savings potential can be calculated.

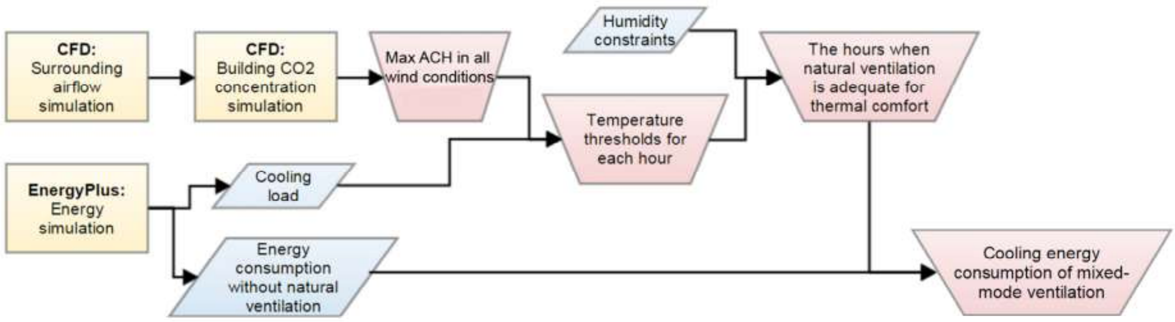


Figure 1 Method for simulating cooling energy consumption using mixed-mode ventilation

In wind-driven natural ventilation, isothermal CFD simulations are conducted to derive air change rate in different wind conditions. First, a neighbourhood-scale external airflow simulation is performed to derive micro-climate wind conditions. Using the micro-climate wind conditions as boundary conditions, indoor airflow pattern is simulated. Meanwhile, a continuous tracer source is added to each room in order to calculate the air change rate. According to Continuous-Injection, Long-Term Sampling (CILTS) Tracer-Gas Methods (Sherman et al., 2014), when it reaches steady state, the average air change rate can be calculated according to the following equation,

$$ACH = \frac{S}{C \cdot V} \tag{1}$$

where ACH is the average air change rate of the room, S is the source emission rate, V is the room volume and C is the steady state tracer concentration simulated by CFD. When simulating ACH, the windows are assumed to be fully open. Therefore, the ACH here is the maximum possible air change rate. The next step is to simulate cooling load in energy simulation programs. Combined with ACH from CFD programs, we are able to derive the temperature thresholds for natural ventilation. The highest possible temperature T_{out} for natural ventilation in each hour is calculated according to Equation (2),

$$C_p \cdot \rho \cdot ACH \cdot V \cdot (T_{out} - T_{in}) = Q \tag{2}$$

where, C_p is air specific heat, ρ is air density, ACH is room average air change rate in that hour simulated by CFD, V is room volume, T_{out} is the temperature threshold to be calculated, T_{in} is the indoor temperature set-point and Q is the zone sensible cooling load derived from energy simulation. Ventilation load of fresh air is not included in Q.

CASE STUDIES

This section presents one case study using the method described above. The final output is the cooling energy savings potential using mixed-mode ventilation strategies. Intermediate results including air change rate are compared with the results generated by Airflow Network, the built-in module of EnergyPlus for mixed-mode ventilation. The purpose of the comparison is to validate the necessity of using coupled CFD and energy simulations instead of completely relying on EnergyPlus when evaluating natural ventilation performance.

The building used for the case study is an existing three-floor building with a basement locating in Cambridge, Massachusetts. The total area of the building is 365 m^2. The building was a residential house but it is converted to an office building to accommodate 40 researchers. The internal load for lighting and equipment is estimated to be 22W/m^2. The building is timber-framed with U-values of 0.23 W/m^2·K for walls, 0.17 W/m^2·K for roof and 2.66 W/m^2·K for windows. The glazing solar heat gain coefficient is 0.7. Window air-conditioners are used for cooling. The indoor cooling set-point is 26.7°C. There is no mechanical fresh air supply. During mechanical cooling and heating, fresh air is simply introduced through infiltration. According to ASHRAE Standard 62.1 (ASHRAE, 2013b), 0.82 ACH will satisfy the ventilation requirement. Since the building envelopes are not well sealed, the infiltration rate is set to be 1 ACH in the simulation. As a simple example, it is assumed that the building is occupied all the time, and the internal load and cooling set-point stay the same 24/7. The software used for the case study is FlowDesigner (MI Research, Inc., 2014) and EnergyPlus (DOE, 2014). Figure 2 shows the floor plan of the second floor and a section of the building. The simulation results of the room on the southwest corner of the second floor are presented in details.

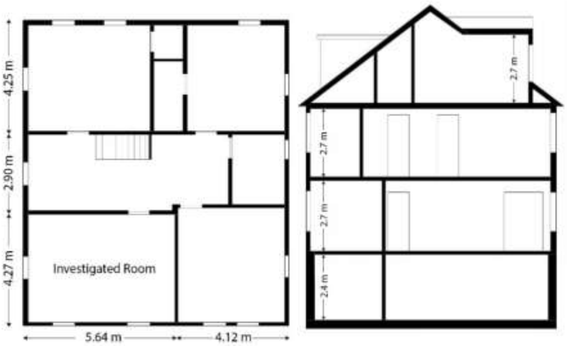


Figure 2 Floor plan and section of the case study

Simulation for wind-driven natural ventilation

As a first step, 3D models of surrounding buildings are exported from Google Earth and imported into FlowDesigner to perform neighbourhood-scale external airflow simulations. Then, simulation scenarios in terms of wind speed and wind direction need to be decided. Figure 3 shows the wind speed distribution when outdoor air temperature is between 15°C to 26.7°C, when it is possible to naturally ventilate the buildings in terms of outdoor temperature. In natural ventilation mode, outdoor temperature must be lower than the indoor set-point, which is 26.7°C in this study. Otherwise, it is impossible to maintain indoor temperature below the cooling set-point when there is heat gain from lights, plug-ins, occupants, and solar radiation. A lower limit of outdoor temperature is also set in this analysis. There are two reasons to set this lower limit. First, when it is cold outside, occupants are less likely to keep windows open (Rijal et al., 2007) as that might cause undesirable draft. Second, when outdoor temperature is low, there might not be any cooling load for external load dominant buildings. Even when there is cooling load, it can be easily offset by allowing a small amount of outdoor air coming in through windows. Since this scenario is not the interest of this study, this paper sets the lower limit for outdoor temperature as 15°C. According to Figure 3, the wind speed is below 9m/s during more than 95% of the hours that are possible for natural ventilation. Therefore, eight wind directions and five wind speeds (1m/s, 3m/s, 5m/s, 7m/s and 9m/s at the height of 10m) are selected as simulation scenarios. The wind profile for different height is taken into account in CFD simulation.

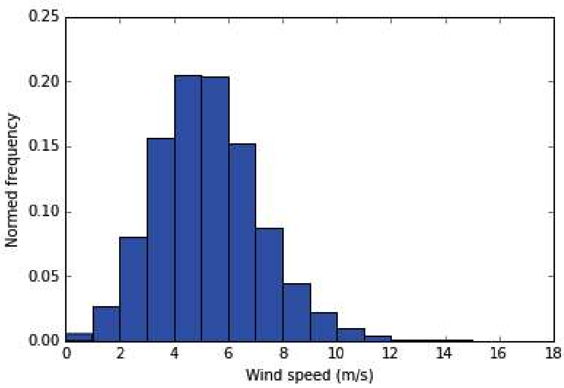


Figure 3 Normalized histogram of wind speed during hours that are possible for natural ventilation

Figure 4 shows a cropped view of the simulated external airflow distribution when the wind is coming from west at the speed of 9m/s. As shown in the Figure 4, the micro-climate wind speed is significantly reduced in an urban environment. The red rectangle highlighted the investigated house. The airflow conditions highlighted in the red rectangle are used as boundary conditions when simulating indoor airflow.

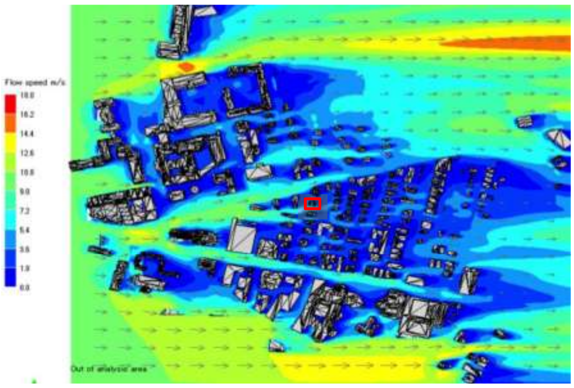
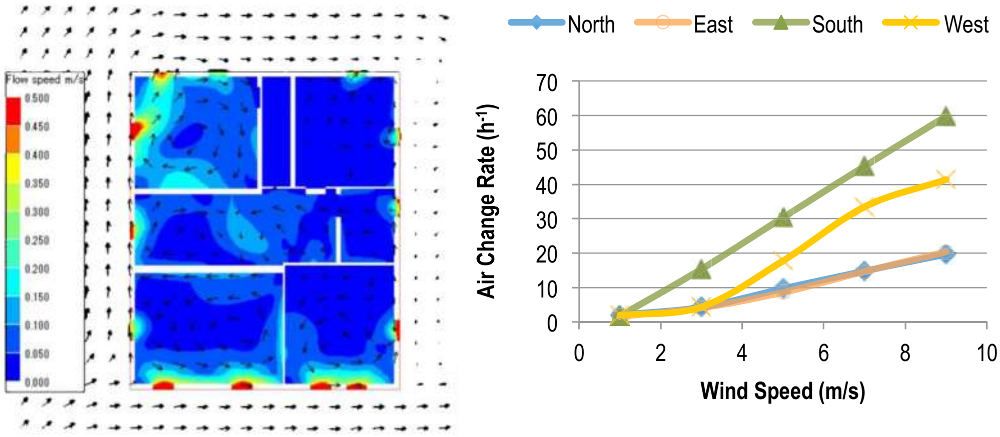


Figure 4 Neighbourhood-scale airflow simulation (blue –low velocity, green - medium velocity and orange – high velocity)

Air change rates of eight wind directions at wind speed of 1, 3, 5, 7 and 9m/s are simulated. Figure 5(a) shows indoor airflow simulation result for one wind condition. Figure 5(b) shows part of the air change rate results. Using interpolation, air change rate of different wind directions at the speed of 1 – 9 m/s can be derived. The air change rate of the investigated room when wind speed exceeds 9 m/s is considered to be the same as when the wind speed is 9 m/s, as a simplification. The air change rate of the investigated room reaches $42h^{-1}$ when the wind comes from west at the speed of 9m/s. In this condition, the indoor airflow speed is still well below 0.5m/s, as shown in Figure 5(a). Therefore, discomforting drafts will not be a concern in this case study (Cândido, et al., 2008, Evans, 1980).

The next step is to calculate the air change rate of each hour based on wind conditions in weather data and the simulated air change rates from CFD. Meanwhile, energy simulation outputs the cooling load of each hour. Then the outdoor temperature threshold of each hour can be calculated using Equation (2). If the actual outdoor temperature of that hour is lower than the temperature threshold and is higher than the lower limit, plus if the weather condition satisfies other constraints such as humidity, then natural ventilation is feasible for that hour. If there is cooling consumption in that hour, the cooling consumption is re-set to zero. In this way, the number of hours when natural ventilation alone is adequate for thermal comfort and the cooling energy consumption using mixed-mode strategies can be derived. In this case study, the humidity constraint is that outdoor dew point temperature must be below 18°C. Details regarding indoor temperature and humidity set-points are discussed in a later section.



(a) Indoor airflow (West wind, wind speed = 9m/s) (b) Air change rate of the investigated room

Figure 5 Airflow simulation results

As the energy savings potential is the concern, the cooling energy consumption needs to be compared with that of the baseline case. In this case study, the baseline case is simply defined as that the building is mechanically cooled and heated 24/7.

As shown in Table 1, the energy reduction using mixed-mode ventilation for the investigated room is 42%. Meanwhile, there are 3258 hours when outdoor temperature is above 15°C, which indicates how many hours the building might need cooling. Among these 3258 hours, there are 2363 hours in which outdoor air temperature is below the indoor temperature set-point and the humidity is acceptable, which indicates how many hours the weather is possible for natural ventilation. Define weather natural ventilation index as the number of hours in which outdoor temperature and humidity are possible for natural ventilation divided by the total cooling hours. A cool and dry climate will yield a high index. The weather natural ventilation index is 73% for Boston using TMY3 weather data in this study. This index can be easily derived from weather data without any simulation. It is recommended to check this index at the beginning to decide whether natural ventilation is applicable in a certain climate.

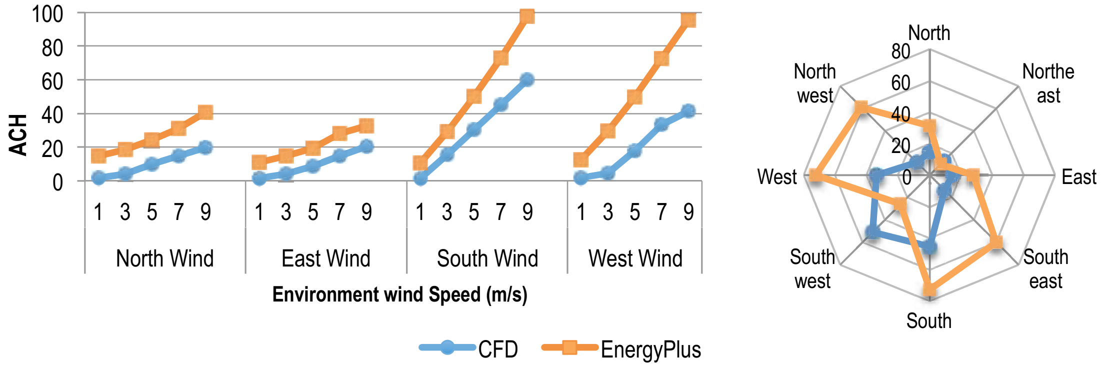
There are 1925 hours out of 2363 hours in which the outdoor air temperature is also lower than the temperature thresholds for natural ventilation derived from CFD and energy simulations. Define building natural ventilation index as the actual number of hours in which natural ventilation is adequate for thermal comfort of the investigated zone/building divided by the total number of hours in which outdoor temperature and humidity are possible for natural ventilation. This index considers building cooling load, envelope design and weather conditions. It suggests how much natural ventilation potential has been exploited for a certain zone/building. A high percentage indicates that there is not much room left to further improve the natural ventilation design. In this case study, for the investigated room, the building natural ventilation index is 81%, which means at most 19% more natural ventilation hours is theoretically possible to achieve.

Table 1 Natural ventilation hours and energy reduction

	Number of hours
T_{out}>15°C	3258
15°C < T_{out} <$T_{in,set}$, $T_{out,dew}$< 18°C	2363
15°C < T_{out} <$T_{out,threshold}$, $T_{out,dew}$< 18°C	1925
Weather natural ventilation index	73% (2363 / 3258 = 73%)
Building natural ventilation index	81% (1925 / 2363 = 81%)
Energy use reduction	42%

Comparison of EnergyPlus and FlowDesigner models

In EnergyPlus, Airflow Network could not fully take surrounding buildings into consideration. In EnergyPlus, the local wind speed at a certain height is extrapolated from the wind speed measured at a meteorological station using coefficients that depend on the roughness characteristics of the surrounding terrain (DOE, 2014). The actual surrounding buildings are not taken into account in the model. As shown in Figure 5(a), the airflow around the investigated building changes not only in speed but also in direction. Therefore, without considering the actual surrounding buildings, the accuracy of natural ventilation simulation is compromised.



(a) Air change rate of four wind directions and five wind speeds (b) Air change rate for eight wind directions at wind speed of 7m/s

Figure 6 Air change rate of the investigated room simulated by CFD (FlowDesigner) and EnergyPlus

In this comparison study, the air change rate of each room due to wind-driven airflow are simulated by the EnergyPlus Airflow Network module and CFD program FlowDesigner. In EnergyPlus, the terrain is set to be urban. The results of the investigated room in the case study are compared in Figure 6. As shown in Figure 6(a), for north, east, south and west wind directions, the air change rates simulated by EnergyPlus are significantly larger than those by CFD. In addition, as shown in Figure 6(b), their patterns are also different. According to EnergyPlus simulation, highest ventilation rate occurs at south and west wind directions, which are simply the window orientations. According to CFD simulations, highest ventilation rate occurs at southwest.

In terms of cooling consumption of mixed-mode ventilation, if humidity is not considered, our method outputs 230 kWh while EnergyPlus simulation outputs 185 kWh for the investigated room. The difference is noticeable. In summary, since EnergyPlus does not take detailed surrounding buildings into account, zone ventilation rate could not be predicted well. Combining the results of the CFD model with energy simulation could improve prediction accuracy.

Thermal comfort model for natural ventilation

In the case study above, we assume a fixed indoor temperature set-point, 26.7°C (80°F) according to ASHRAE Standard 55 (ASHRAE, 2013a). 26.7°C and 86% relative humidity is still within comfort zone when local air speed is 0.2m/s. If the local air speed reaches 0.3m/s, relative humidity could be as high as 100% at 26.7°C. Therefore, in natural ventilated buildings, the acceptable humidity range depends on local air speed. In this method, humidity requirement and latent load is not simulated in the same way as temperature requirement and sensible cooling load. Instead, a humidity constraint is set as an additional weather criterion. In this study, the humidity constraint is that outdoor dew point temperature must be lower than 18°C. With large ventilation rate, this condition will most likely ensure thermal comfort even when there is latent load. Designers and engineers can use a different humidity constraint for their projects if necessary.

Instead of a fixed set-point, the upper limit of indoor temperature during natural ventilation can be determined according to the adaptive model in ASHRAE 55 (ASHRAE, 2013a). This adaptive model established by de Dear and Brager (1998; 2002) has been widely used. The model uses mean monthly outdoor temperature to determine indoor temperature set-points. For each calendar month, there is one indoor temperature set-point. This study uses the 80% acceptable indoor temperature upper limit as indoor cooling set-point during natural ventilation, as shown in Figure 7. The adaptive thermal comfort only applies to natural ventilation. When the building uses mechanical cooling, the temperature set-point is still fixed at 26.7°C.

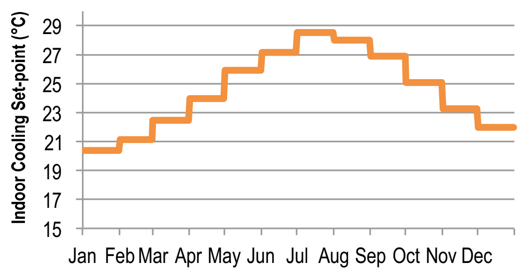


Figure 7 Indoor cooling set-point for natural ventilation based on adaptive thermal comfort model

In order to use the adaptive thermal comfort model in this method, only one more energy simulation is needed to estimate the cooling load with new indoor temperature set-points. There is no modification on the CFD side. In this case study, as the indoor cooling set-points for natural ventilation from June to September are higher than the fixed 26.7°C, cooling load in these months decreases. As a result, the number of natural ventilation hours increases and cooling energy consumption of mixed-mode ventilation is further reduced from June to

September, especially in July and August, as shown in Figure 8. In conclusion, more energy savings potential can be achieved by using the adaptive thermal comfort model.

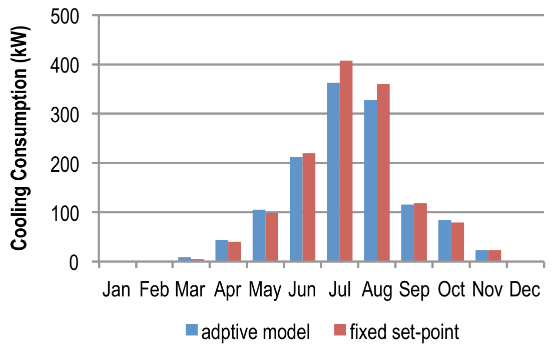


Figure 8 Cooling energy consumption of mixed-mode using adaptive thermal comfort model or fixed set-point

DISCUSSION

One assumption adopted in this research is that mechanical cooling can be switched to natural ventilation whenever it is adequate to maintain indoor thermal comfort based on the outside weather condition and indoor environment. In this way, the energy reduction is the maximum possible. In order to get a more realistic estimation, a schedule constraint can be easily added to this method to reflect different mixed-mode control strategies. A potential future research topic could be to find out an optimal mixed-mode control strategy to balance energy savings, thermal comfort as well as system operation and maintenance.

To develop methodology that involves CFD, computational cost is an important consideration. In this research, the idea of finding the thresholds instead of running 8760 hour-by-hour simulations is a key to achieve this goal. Moreover, as energy simulation and CFD airflow simulation can be "coupled" externally and only once, the complexity decreases significantly. Meanwhile, it is easy to incorporate different control strategies and thermal comfort models into this method. This paper focuses on one type of natural ventilation used in mixed-mode, wind-driven natural ventilation. If buoyancy effect needs to be concerned, this coupling method can be modified to take buoyancy-driven natural ventilation into account.

CONCLUSION

This paper describes an easy-to-implement method to estimate cooling energy savings potential from using mixed-mode ventilation in which wind-driven natural ventilation is considered. In this method, CFD simulation and energy simulation are performed separately and their results are combined to derive the number of natural ventilation hours and energy reduction. As a result, this method requires no code modification of simulation software and it is computationally affordable. One case study is discussed in details. Weather and building natural ventilation indexes are introduced to assist decision-making in natural ventilation design.

Simulation results of using EnergyPlus alone and using EnergyPlus combined with CFD are compared. For wind-driven natural ventilation, Airflow Network module in EnergyPlus tends to overestimate air change rate in this case study, as the complex surrounding buildings are not included in the modelling. As a result, using EnergyPlus alone is likely to overestimate the cooling energy savings potential from employing mixed-mode ventilation strategies. It should be noted that there are uncertainties in this comparative study. The method developed in this research assumes that CFD is more accurate than airflow network module, because CFD has more capacities in airflow simulation. One of the capacities is to include detailed surroundings in the simulation, which is important in wind-driven natural ventilation. As part of the further work, this method needs to be validated in order to generalize the conclusion.

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