2010

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Dong, Bing; Yu, Yuebin; and Hu, Yang, "Simulation-based Hybrid Ventilation System Design and Evaluation" (2010). *International High Performance Buildings Conference.* Paper 35.
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Simulation-based Hybrid Ventilation System Design and Evaluation

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ABSTRACT

Design and operation of an extended hybrid ventilation system are fully investigated in this study through an example building. Tools of genetic algorithm optimization, computer fluid dynamics and energy simulation are employed to assist the process. The objective is to maximize natural ventilation while maintain good indoor thermal and air quality. The dynamic operation of vents is based on wind directions, wind speed and outside dry bulb temperature. The overall results show that the hybrid ventilation strategy saves significant amount of energy comparing with traditional HVAC systems. Furthermore, the average natural ventilation time during occupied period from June to August is 69% of the total occupied hours. It was found, beside the good energy performance of the hybrid system, the thermal comfort can be ensured for more than 90% of the occupied time.

1. INTRODUCTION

With the increasing use of energy in buildings, designing and building energy efficient buildings become more and more important. The best way for buildings to save energy is to interact with surrounding environment as much as possible. Natural ventilation (NV) strategy has been widely implemented in buildings (Wang and Wong, 2007, Allard et al, 1998). Allard et al. (1998) presented detailed case studies and design guidelines for NV buildings. It also has been proven to provide thermal comfort under limited conditions (Wang and Wong, 2007). However, it is pointed by both Lomas et al. (2007) and ASHRAE Standard 62.1-2004 that there are some pre-requisites which should be met before implementing NV. An alternative way is to couple natural ventilation with air conditioning system, which is called the hybrid ventilation (HV) system. According to the cases studies by Heiselberg (2002), a reduction of 20%~30% in overall energy consumption and 50% in electricity have been achieved comparing to full air conditioned office buildings. Good comfort conditions have been also observed by giving the users accesses to control their own indoor climates. In addition, most of occupants appear to have a preference of using windows and clothing to modify conditions in mild mid-season weather. These case studies emphasize the importance of using hybrid ventilation strategies.

There are several simulation studies in the literature. Vuolle and Heinonen (2000) presented a simulation study using fan assisted passive stack balanced ventilation with heat recovery and demand control, which shows high heating energy use in heat recovery. Heinonen et al. (2002) described a similar simulation study of the performance of a hybrid ventilation system in a five-story office building in Finland. Four types of systems were compared for a building with an atrium. The results show that adequate ventilation is achievable with hybrid ventilation while reducing energy consumption of fan. Jeong and Haghighat (2002) presented a study on modeling a hybrid ventilated school building using the simulation tool ESP-r's coupled building thermal and airflow capability. Cron et al. (2003) reported a simulation study of a hybrid ventilation system for a classroom in 10 cities in France. The system includes fan-assisted natural ventilation with inlet vents controlled by room CO_2 concentration, operable windows, an exhaust stack, air-conditioning with night cooling strategies and heat recovery. SPARK program was used to conduct the simulations. The results show CO_2 based demand ventilation control provides better IAQ. The latest study was done by Emmerich (2006), who used CONTAMR software to model hybrid ventilation systems in a 5-sotry office building for cold, moderate and hot moths in five U.S. cities. The results show that hybrid system saved significant amounts of fan energy, reduced cooling loads or both in all climates but often resulted in higher heating loads.

The objective of this study is to design, simulate and evaluate a hybrid ventilation system for a 3-story, open plan, office building located in the centre of Glasgow with stack assisted cross ventilation, at the same time, demonstrate the concept of dynamic hybrid ventilation control strategy. The evaluation criteria for this design are indoor thermal comfort, ventilation and energy performance. The simulation tools chosen in this study are AirPak and EnergyPlus. The literature shows that there are few relevant studies using CFD and EnergyPlus Airflow Network.

2. PRE-MODELING ANALYSIS

2.1 Weather Data

The climate of Oban, Scotland was studied using data in EnergyPlus weather file (EPW) from the ASHRAE International Weather for Energy Calculations (IWEC) data for Oban, Scotland. The thermal comfort criteria for defining acceptable indoor thermal comfort conditions are referred from CIBSE standard. From Figure 1, the annual weather in Oban, Scotland is moderate. The outside air temperature ranges from -4 to 26 ^{0}C. From psychometric chart, while the relative humidity is high most of time in a year, the highest absolute humidity is not beyond 0.012 kg/kg. The comfort zone is calculated by Ecotect based on CIBSE standard. 0.012 kg/kg absolute humidity is within comfort range. Under Oban's weather condition, there is no need to dehumidify fresh air.

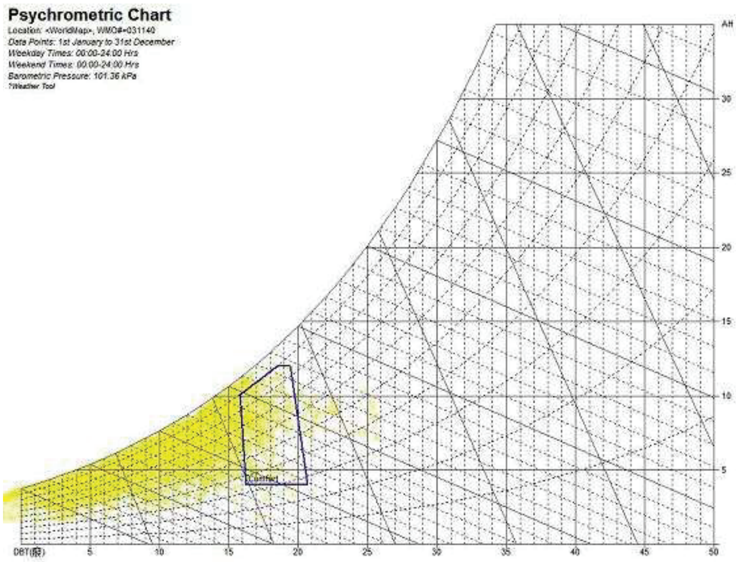


Figure 1 Temperature and moisture content in the Oban, Scotland

2.2 Building Geometry

A three story hypothetical building, named A, located in the center of Glasgow (Scotland) is adopted for this simulation and analysis. The building geometry is designed for hybrid ventilation purpose as shown in Figure 2.a. A one meter high plenum floor is constructed for building fresh air intake. Every side has two fresh air inlet vents with customer specified size. An 8 by 8 meter square light well in the middle of the building connects, as shown in Figure 2.b, to the center of the plenum floor ceiling and all the other 3 floors as a path for both light and air. Each floor is an open space layout surrounding the light well. The inter-surfaces between are toughened double layer glass, and light can travel into the spaces from the top floor to the bottom floor. Subfloor level openings connecting the light well and each floor are served in four orientations, so that fresh air coming from the plenum floor risen up by wind or buoyancy effect can go into zones for ventilation.

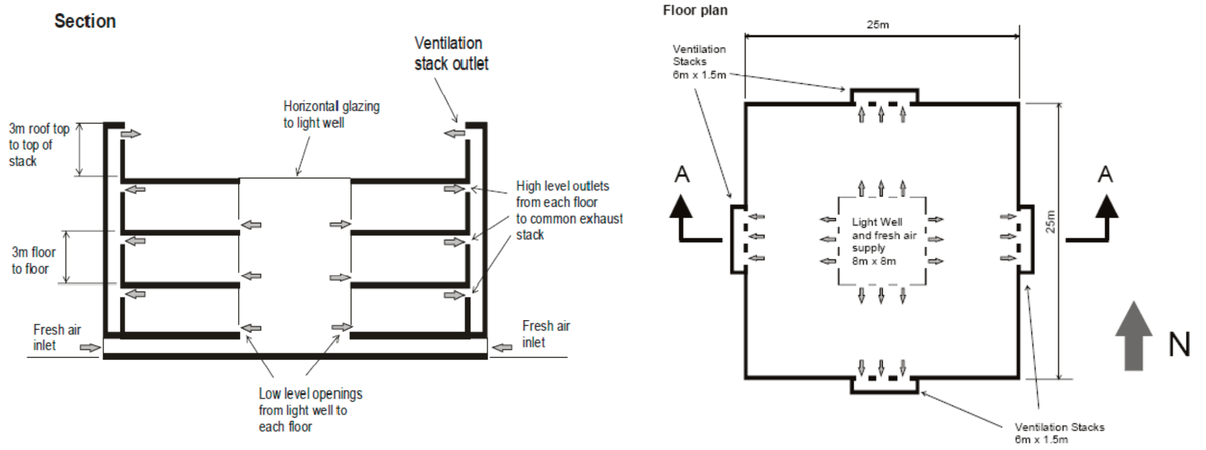
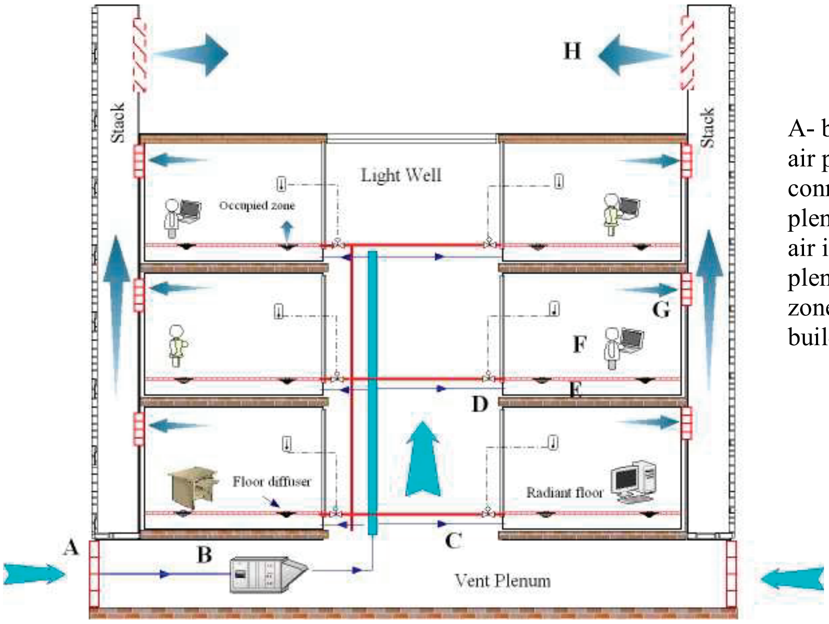


Figure 2 a) Section view of building A; b) A typical floor plan view of building A

Four stacks are constructed around the perimeter to strengthen natural ventilation of the building. Each stack is linked to the three floors of its orientation via construction openings at the top of interface walls. It is intended that the zone air coming in from the interior light well low opening crosses the whole zone before leaving through the common stack. An air outlet facing the opposite direction of the orientation is remained at the top of each stack. With ventilation plenum floor, light well, and stacks, the whole building has the ability of conducting cross ventilation for both thermal and air quality purposes. The challenge from the analysis of geometry is to the sizing of openings both in subfloor level and upper levels in order to provide adequate ventilation air.

2.3 HVAC System Design



A- building outside air inlet; B- air path in the vent plenum; C- connection jointing vent plenum and light well; D- zone air inlet opening; E- under floor plenum; F- occupied zone; G- zone air outlet opening; H- building exhaust air outlet

Figure 3 Schematic diagram for the integrated system

Based on the provided building layout, a hybrid ventilation system which mainly relies on outside air for cooling in summer and transitional season, and a hydraulic radiant floor heating system for heating in winter are to be installed in this building for advance energy performance and indoor air quality. Figure 3 illustrates the hybrid ventilation and floor heating system integrated in the building. A forced air mechanical ventilation system builds upon the layout of natural ventilation system, with outside air inlet placed in the plenum. Air duct paved in the light well connects to the inlet vents at the bottom of each zone inside wall for air distribution. By doing this, a parallel air path layout for natural and mechanical ventilation is configured so that a switch between them is easy and convenient once necessary. The air flow passes sequentially from A, B until H to the outside as noted in Figure 3. The system supply fan is chosen to have two speeds control, so that a high flow rate is used in summer for both ventilation and passive cooling, and a low one in winter for fresh air intake only. No return air is needed in this design as we mentioned in the previous section. An electric preheat coil is equipped after the supply fan to warm up the minimum fresh air in winter time, so that the air supplied through the under floor diffusers won't cause cold feeling. To ensure the air from each side of light well inlets evenly distributes in the space, each floor is divided into four zones and air is supplied into the space from suspended floor plenum. In total, 12 conditioned zones are involved in the building. For air distribution in each zone, slot diffusers are applied separately in parallel to the walls. Outside air coming from the light well air path or mechanical vent ducts is supplied into the space from the diffusers.

2.4 Hybrid Ventilation Control Strategy

A key to the success of the hybrid ventilation system is using an effective ventilation and temperature control strategy. Temperature control mode is adopted in this building for hybrid ventilation. All of the zone's operable windows and doors are opened if Tzone > Tout and Tzone > Tset and Venting Availability Schedule (see below) allows venting. Table 1 shows the setpoints for heating, cooling and ventilation.

Table 1: Hybrid ventilation control algorithms and setpoints

Item	Specifics
Heating set point	15 ^{0}C for unoccupied time, 22 ^{0}C for occupied time
Cooling set point	30 ^{0}C for unoccupied time, 24 ^{0}C for occupied time
Natural ventilation schedule	availability: when outside air temperature is between 15 ^{0}C and 22 ^{0}C

To avoid wind from only passing through the vents on the plenum floor, a dynamic and intelligent venting design is considered. The vent openings on four orientations of the building will be decided based on real-time wind speed so that proper cross ventilation through the whole building is accomplished. No two vents on the opposite orientations should open at the same time. For example, according to the local weather data, from May to August, the average and maximum outside air temperatures are higher than other months in the year. The corresponding dominant wind directions are found to be North, West, South and Northwest. As a substitution to the advance vent control if condition is constrained, the side of North and West can be open while the other two sides' vents close. So that a proper air pressure gradient in the horizontal and vertical dimensions can be obtained without complicated control and switching. Vents and dampers are installed on all the openings mentioned in the previous section. Therefore, the amount of air coming in and leaving out the building can be achieved by modulating the openness. The vent sizes are designed based on the air flow rate and velocity.

Based on the control strategy described above, the switch criteria between HVAC mechanical air loop and natural ventilation is when the natural ventilation is not sufficient to remove the internal loads, mechanical system will be turned on to condition the space.

3. Computer Modeling Process

3.1 CFD

CFD simulation is the thermal fluid simulation for steady state conditions. From the weather data study, the statistic annual daily average wind speed is around 4m/s. Under this condition, the natural ventilation flow rate is 38.4m^3/s, which meets the healthy requirement 2.4m^3/s for the building. The indoor air speed distribution and mean air age for the third floor are shown in Figure 4. The light well air supply opening area is first designed to be 9.6m^2, which is based on GenOpt program. However, the first floor cannot have a comfortable temperature distribution. Then the area of light well air supply opening area increases to 12 m^2. The reason to use bigger ventilation area in first floor is that the stack effect works perfect in second and third floors determined by CFD simulation, but the first floor inlet velocity is low. In order to have relatively same amount quantity of air flow rate, the opening area on the first floor should be bigger than the other two. Figure 5 shows the air distribution in the light well section view with adjusted openings.

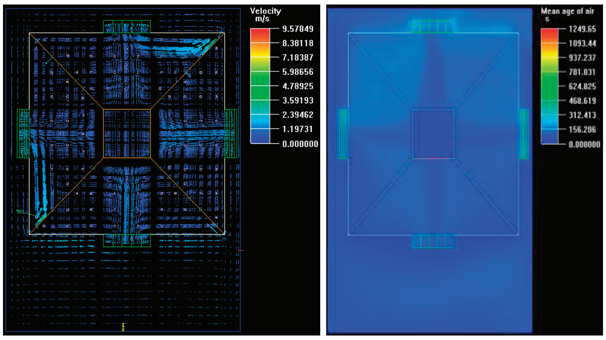


Figure 4 Third floor indoor air flow distribution and mean air age with outdoor wind speed at 4 m/s

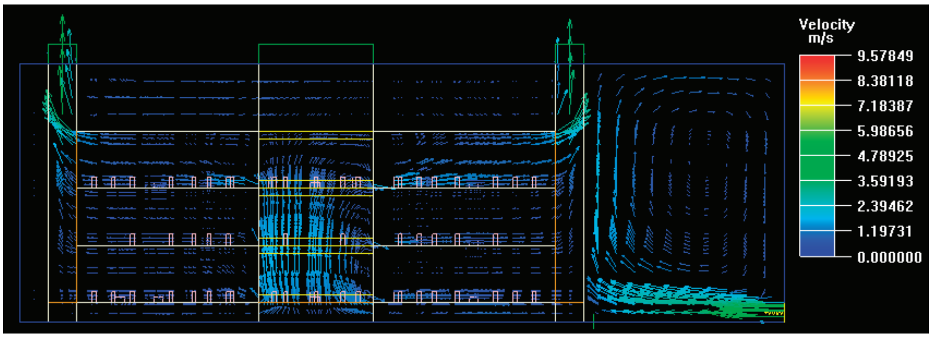


Figure 5 Air distribution in the light well section view

The air temperature distributions in second and third floor meet the requirement, the horizontal view of them are shown Figure 6 with the simulation condition: outdoor air temp 26^{0}C and wind speed 4m/s.

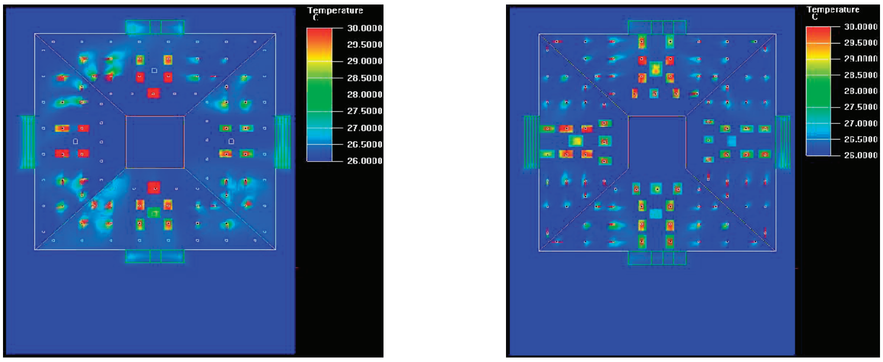


Figure 6 Air distribution in the light well section view: a) Second floor temperature distribution; b)third floor temperature distribution

3.2 EnergyPlus

3.2.1 Geometry Modeling

The building geometry was built in DesignBuilder software. Figure 7 presents an overview of building A. To ensure the air from each side of light well inlets evenly distributes in the space, occupied space on each floor is divided into four zones with air walls as shown in Figure 8. In total, 12 conditioned zones are involved in the building.

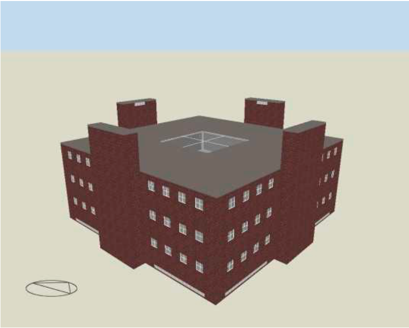


Figure 7 An overview of building A.

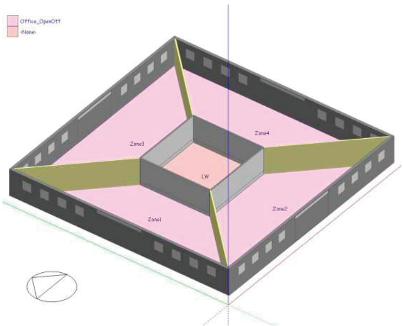


Figure 8 A typical floor plan

3.2.2 Airflow Modeling in EnergyPlus

The main process in conducting ventilation simulation in Energyplus is to specify and organize the air flow crossing zones in the group of air flow network. Related components and parameters include simulation control, individual zone, opening surface, duct work, system nodes and linkage. If only pure natural ventilation is desired, duct work, system nodes or linkage is not needed.

Five different openings types are first defined in airflow network for plenum floor vent, light well opening, zone inlet, zone outlet and stack outlet. Forty detailed surfaces with vents are associated with the corresponding thermal zones by entering in the class of surface. The openings, zones, ducts and ventilation equipments are integrated together after the final linkage of all the nodes is netted as shown in Figure 9.

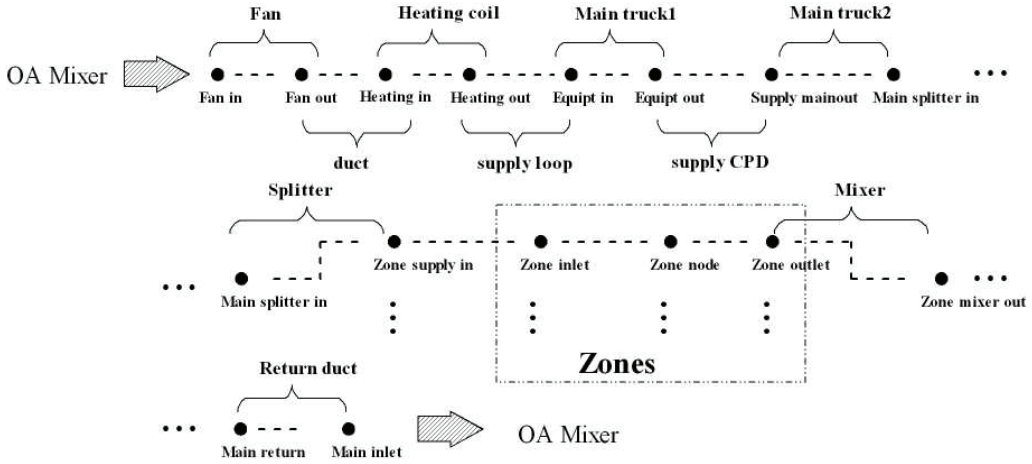
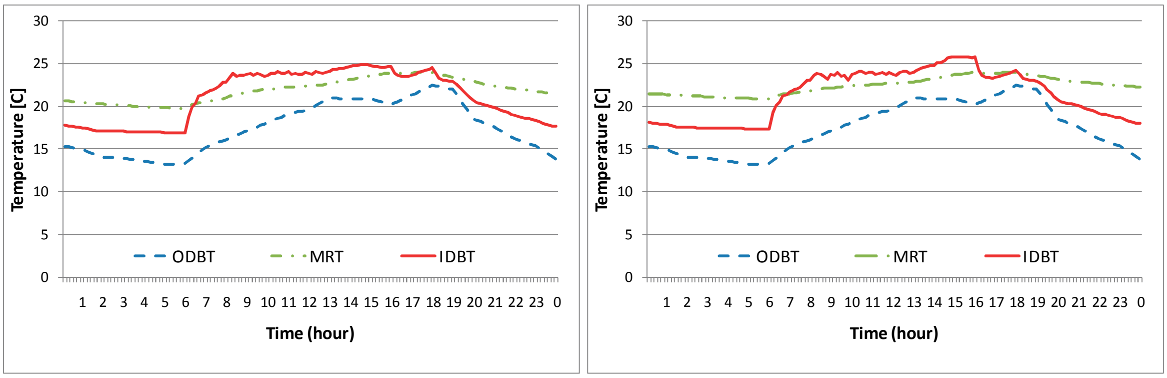


Figure 9 Airflow network linkage

4. Results and Discussion

4.1 Thermal Performance

All zones are investigated and found comfortable indoor air temperature throughout the year. Disadvantageous zones from level 1 (Zone_1_1) and level 3 (Zone_3_4) facing the west are presented here. Figure 10 shows similar temperature fluctuation of the two zones during summer time on July 21. Both indoor dry bulb temperatures remain in the comfort zone without any mechanical cooling. Zone_3_4 has a little time with temperature over 25 ^{0}C in the late afternoon because of the solar radiation on the west façade. Although achieving thermal comfort on design days is not an issue, it would be very useful to explore how many hours that indoor dry bulb temperature exceeds the resultant temperature during the most possible natural ventilation period. The period occurs from June to August according to the analysis of weather data. Table 2 presents the total hours that zone mean temperature exceeds dry resultant temperature (DRT) during occupied period. With the increasing of dry resultant temperature, the number of total hours decreases. Only 27 hours exceeds 28 ^{0}C DRT, which is much less than 1% of the occupied hours. This result demonstrates the concepts from pre-modeling analysis and assures the thermal comfort of this hybrid ventilation system. It also indicates that the guidance given in ASHRAE 62.1 should be revised to introduce more natural ventilation for low energy buildings. Finally, the total energy consumption from traditional VAV system is 158,369 kWh/year, while Hybrid Ventilation is 140,780 kWh/year, which saves around 12% of energy.



a) Zone Level 1_1 b) Zone Level 3_4

Figure 10. Predicted outdoor dry bulb temperature (ODBT), indoor dry bulb temperature (IDBT) and mean radiant temperature (MRT) on July 21. in a). Zone level 1_1 b) Zone level 3_4.

Table 2 Total hours that zone mean temperature exceeds resultant temperature during occupied period

DRT (^{0}C)	June	July	August	Total (Hrs)
25	209	129	82	420
26	126	67	51	244
27	62	32	26	120
28	17	10	0	27

4.2 Hybrid Ventilation Performance

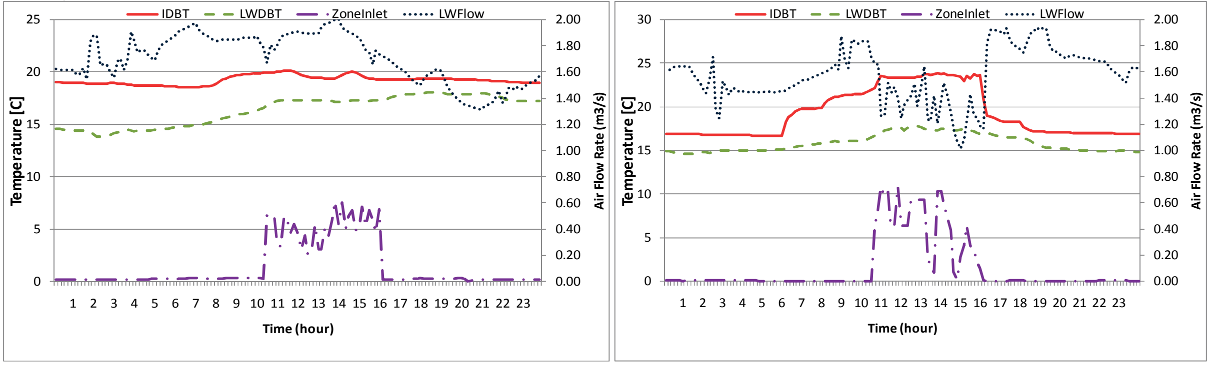


Figure 11 predicted airflow rate and dry bulb temperature in both light well and a) zone_ 1_1 on June 11 without mechanical ventilation; b) zone_ 3_4 on July 28 with night ventilation (ZoneInlet: Zone inlet air flow rate, LWFlow: Light well air flow rate)

CIBSE Guide B (2001) specifies the minimum fresh air requirement for office building is 8 L/s/person, which is 2.4m^3/s if there are 300 persons (assumed maximum number of people on level 3). Figure 11.a shows the predicted airflow and dry bulb temperature in both light well and zone_1_1 on June 11, which has mechanical ventilation off the whole day. The indoor temperature reaches the comfort level with little variations during the day. The light well air flow rate is higher than 1.5 m^3/s on average, while the zone inlet air flow rate is around 0.5 m3/s on average. This meets the ventilation requirements by CIBSE. On July 28, the mechanical ventilation in Zone_3_4 was off from 11:00am to 5:00pm because the outside condition is good and natural ventilation is on. As shown in Figure 11.b, the light well air flow rate dropped from 1.8 m^3/s to 1.2 m^3/s when the mechanical ventilation is off. This makes the air flow rate to the space as low as 0.54 m^3/s on average. It is within the requirements of CIBSE standards. The space temperature remains within the comfort range.

Table 3 describes a typical air flow features from light well to each zone. The floor level total air intake is assumed to be the sum of all four air inlets. They all satisfy the CIBSE requirements. The spaces with larger openings have larger airflow compared to other openings. With the same opening, larger internal heat gains have more flow rate because of a buoyancy driven flow regime.

Table 3 EnergyPlus results of airflow paths, free opening areas, heat gains, predicted air flow rates

Space	Inlet type	Outlet type	Free opening area		Maximum Heat gains		Predicted air flow rates	
			Actual (m^2)	% Floor area	W	W/m^2	m^3/s	Ach -1
Plenum	Ambient	Lightwell	9.6	1.5	-	-	-	-
1st floor	Lightwell	Stack	9.6	1.6	29,500	50.1	2.5	5.3
2nd floor	Lightwell	Stack	4.8	0.8	13,030	22.1	1.5	3.0
3rd floor	Lightwell	Stack	4.8	0.8	20,710	35.2	2.0	4.01

5. CONCLUSION

This paper presents discussions, analysis and results from a virtual building with proposed hybrid ventilation system and its control strategy. The weather data is explored to help pre-modeling analysis and the following computer simulations. CFD simulations are conducted to support decisions on openings sizes and acceptable inlet temperatures during different seasons. The performance of this virtual building is predicted using EnergyPlus and its latest airflow network modular, which couples airflow with building energy simulation. The results show that during the most possible natural ventilation season, only 31% of the occupied time needs mechanical ventilation, while maintaining the indoor thermal comfort at the same time. In addition, from the results of CFD simulation, the bottom floor is warmer than the top floor. The energy used by hybrid ventilation is also less than traditional full HVAC system. The different exceeding hours of dry resultant temperature indicate that the guidance given in ASHRAE 62.1 should be revised to encourage more natural ventilation for low energy buildings.

REFERENCES

Allard, F., Santamouris, M., Alvarez, S., 1998, European Commission. Directorate-General for Energy, ALTENER Programme. *Natural ventilation in buildings, a design handbook.* Earthscan.

ASHRAE. Ventilation for Acceptable Indoor Air Quality, American Society of Heating, Refrigeration and Air-conditioning Engineers, *Standard 62.1-2004*.

CIBSE Guide B: Heating, Ventilating, Air Conditioning and Refrigeration. *The Chartered Institution of Building Services Engineers*, 2001.

Cron, F., Inard, C., Belarbi, R., 2003, Numerical Analysis of Hybrid Ventilation Performance Depending on Climate Characteristics. *The International Journal of Ventilation,* Vol.1, no. 4: p.41-52.

Emmerich S.J., 2006, Simulated Performance of Natural and Hybrid Ventilation Systems in an Office Building, *HVAC&R Research, Vol. 12, no.4*: p.975-1004.

Heinonen, J., Vuolle, M., Heikkinen, J., Seppanen, O., 2002, Performance Simulations of Hybrid Ventilation Systems in a Five-Story Office Building. *ASHRAE Transactions*. Atlanta: Vol. 108: p. 1241-1251.

Heiselberg, P., 2002, Principles of Hybrid Ventilation. Aalborg University, Aalborg, Denmark. *Report to Annex 35*. 75p.

Jeong, Y., Haghighat, F., 2002, Modeling of a Hybrid Ventilated Building "Grong School". *Proceedings of Hybrid Ventilation 2002*. Concordia University

Lomas, K.J., Cook, M.J., Fiala, D., 2007, Low Energy Architecture for a Server US Climate: Design and Evaluation of a Hybrid Ventilation Strategy. *Energy and Buildings*, Vol. 29, 2007: p. 32-44.

Vuolle, M., Heinonen, J., 2000, Hybrid Ventilation Simulations in IDA Modular Simulation Environment. *Healthy Building 2000*. Espoo, Finland.

Wang, L.P., Wong N.H., 2007, Applying Natural Ventilation for Thermal Comfort in Residential Buildings in Singapore. *Architectural Science Review,* Vol. 50: p. 224-233.