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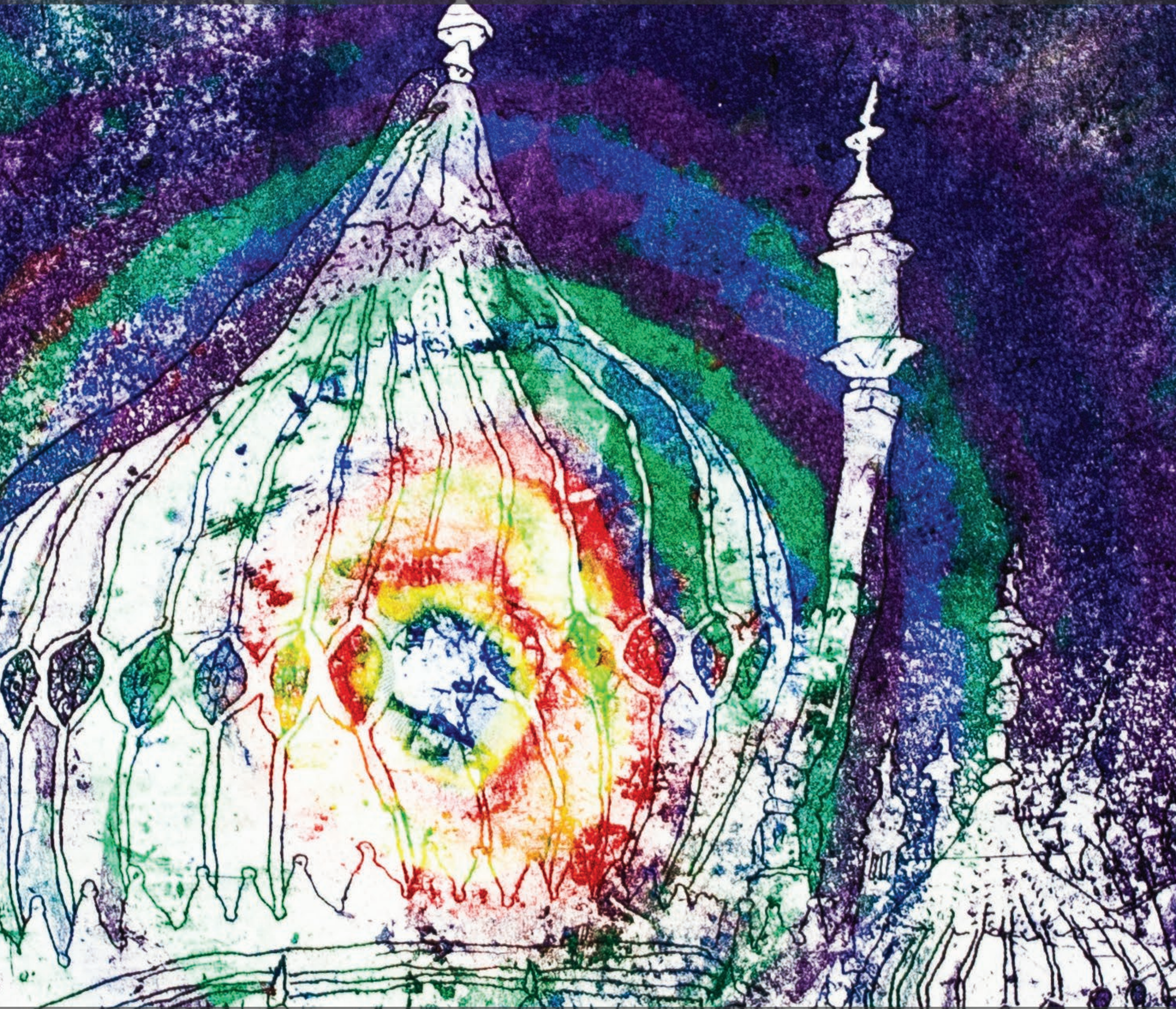

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# *The Influence of Skycourt as Part of Combined Ventilation Strategy in High-Rise Office Buildings*

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**Abstract**
Skycourts are recognised nowadays as essential transitional, movement and social interaction spaces in high-rise and mid-rise buildings. The paper reports on analytical research into the energy saving promising associated with the modification of air movement strategy in skycourt zones. Heating and cooling in office buildings use a high percentage of the overall energy consumption. Nevertheless, ventilation is addressed vastly according to cooling loads without considering its actual influence. The study aims to investigate the skycourt as a ventilated buffer space in high-rise office buildings and explore its impact on reducing energy demand for heating and cooling. Using a theoretical reference model of an office building, energy and CFD simulations are carried out over two modes; an air conditioning skycourt and a ventilated, unheated and uncooled skycourt. Results are compared with respect to energy reduction besides thermal comfort. Three spatial configurations of skycourt are investigated to define the optimal prototype of the skycourt in temperate climate exemplified by London. Overall, the simulation results highlight that the incorporation of skycourt as a ventilated buffer zone reduces the annual heating and cooling demand remarkably. Furthermore, the comparison between the skycourt prototypes shows a variation in the energy performance of the building and the thermal conditions inside the skycourt.

Keywords: Skycourt, Ventilation, Coupling Simulation, Thermal Comfort, Energy Efficiency

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## Introduction

A skycourt is defined as an integrated space in a high-rise building that offers a diversity of functions. This facilitates significant social, environmental and economic benefits, and improves the overall performance of the building. Skycourts help to create a sense of community in high-rise buildings where there is normally a lack of engagement between occupants. They perform as places for transitional, movement and social interaction. Furthermore, skycourts can enhance passive features and support heating and cooling strategies. Consequently, they can have a significant impact on reducing energy consumption and improving health, wellbeing and productivity. Also, they can provide climate responsive approaches to design, facilitate the holistic sustainable design and improve the performance of high-rise and mid-rise buildings (Pomeroy, 2014; Yeang, 1999).

The skycourt concept is initiated from re-adapting the traditional/vernacular elements in low-rise buildings, such as the courtyards and atriums (Figure 1). These spaces show significant potential in dealing with climate, culture and context. Therefore, skycourts in high-rise buildings could provide a contemporary alternative to courtyards or atria due to their potential to allow natural light to penetrate deeper into the interior of high-rise buildings and promote natural ventilation while avoiding unwanted solar gain. Other possible advantages of occupants' social networking and on more prestigious that build economic benefits. These have made skycourt to become a primary zone in these buildings.

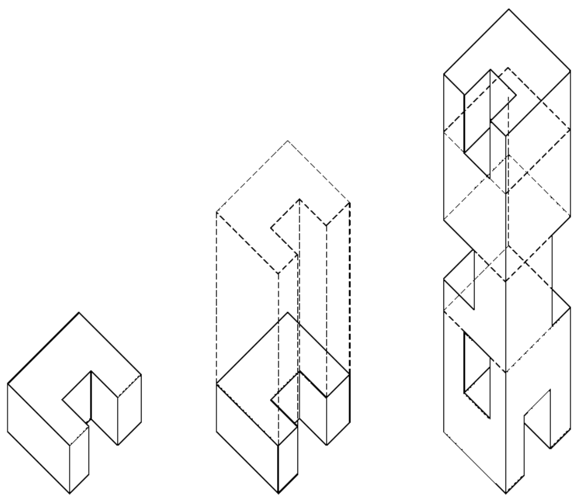

Figure 1: Transformation from courtyard at low-rise to skycourt at mid-rise and high-rise buildings.

A skycourt may be located within the high-rise building at the lower part (sky-entrance), the top of the building (sky-roof), or between the middle floors (sky-court). These void spaces are two or more floors height linked with the surrounding indoor and outdoor areas by open or enclosed walls. The spatial configuration or form geometry of skycourt can be classified into infill space, stepped terrace space, interstitial space, hollowed-out space, corner space, chimney and roof space (Pomeroy, 2014) (Figure 2). The hollowed-out prototype, the corner prototype and the sided prototype are the common spatial configurations in high-rise office buildings (Alnusairat, Hou, & Jones, 2017).

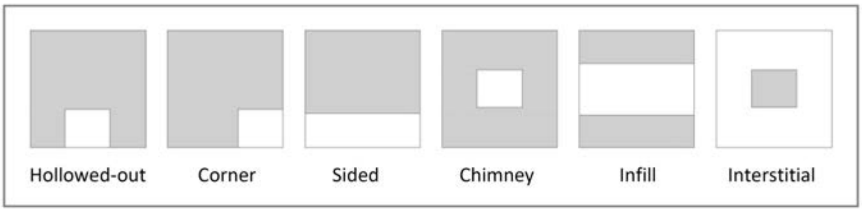


Figure 2: Spatial configurations of skycourt in high-rise buildings.

In UK, office and retail buildings' sector accounts for almost half the total of energy consumption, due to the extensive use of air conditioning systems (Pérez-Lombard, Ortiz, & Pout, 2008). Significantly, heating, cooling and ventilation in high-rise buildings consume nearly 40 percent of the total energy consumption (Al-Kodmany, 2015). Therefore, it is crucial to look for solutions to minimise the energy consumption and at the same time to enhance the quality of the built environment. Attention recently has focused on the effect of skycourt phenomena on the ventilation performance of high-rise buildings (Etheridge & Ford, 2008; Pomeroy, 2012; Taib, Abdullah, Ali, Fadzil, & Yeok, 2014). Skycourts could be integrated into the buildings and act as features for air supply, air exhaust and air circulation in the buildings and they are combined with other design elements to maximise the efficiency of airflow (Wood & Salib, 2013). However, studies addressing the impact of skucourt by its own on the total performance of the building are limited.

The paper aims to investigate the influence of skycourt as part of the ventilation strategy in office buildings. Ventilation is relatively the process of airflow to maintain a satisfactory environment within a building or an enclosed space, by controlling the temperature, humidity and providing good air quality (Moghaddam, Amindeldar, & Besharatizadeh, 2011). It can support cooling and improve heat exchange mechanism (CIBSE, 2001). This study suggests ventilation strategies to mediate the thermal conditions in skycourts based on the fresh air required for the adjacent offices. Convective heat transfer of air occures inside the volume of skycourt because of the variation in air temperature and height (Figure 3), and this air motion could induce significant thermal comfort cooling.

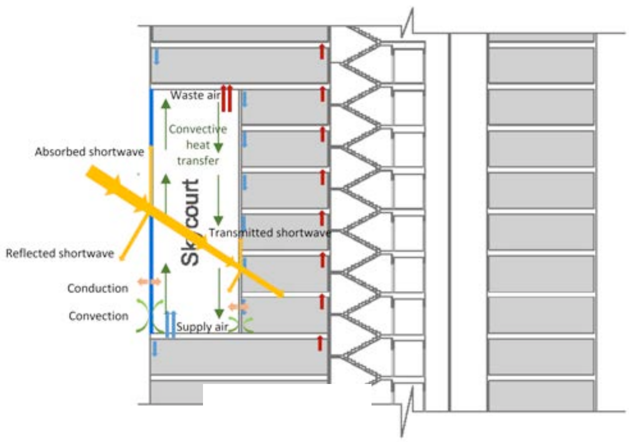


Figure 3: Heat transfer and airflow mechanisms in skycourt and adjacent offices.

In the study, three spatial configurations of skycourt are modelled using energy simulation and CFD. The models are examined under three proposed ventilation strategies: isolated ventilation, combined-exhaust ventilation and combined-supply ventilation. The strategies are evaluated regarding two criterions: the heating and cooling energy consumption for the building and the thermal conditions inside the skycourt. The following sections describe the process of the study.

## Methodology

The study uses a coupling simulation approach in which two models are integrated: Building Energy Simulation (BES) and Computational Fluid Dynamics (CFD). This method can produce equivalent information for the energy consumption and the indoor thermal conditions for buildings. Also, it can predict more accurate, detailed and quick results compared to separate simulations (Barbason & Reiter, 2014; Wang & Wong, 2008; Z. Zhai, Chen, Haves, & Klems, 2002; Z. J. Zhai & Chen, 2005). BES provides the thermal and energy analysis for the building on an hourly basis for the whole year. This includes mean (average) air temperature, heating, cooling, ventilation, solar gain, fabric and incidental loads. However, this type of simulation assumes the air is well-mixed. Therefore, it is unable to provide detailed predictions of the spaces' indoor air properties such as the distribution of air velocity and temperature. CFD can predict the full spatial distribution of air velocity, air temperature and air quality for both the natural and mechanical ventilation. However, it requires thermal and flows boundary conditions that are obtained from the BES.

In the study, the coupling approach uses the interior surface temperatures that are obtained from BES to set up the CFD model which, then predicts the air temperature and air velocity at the internal of the skycourt. This significance is essential for the assessment of thermal comfort (Figure 4).

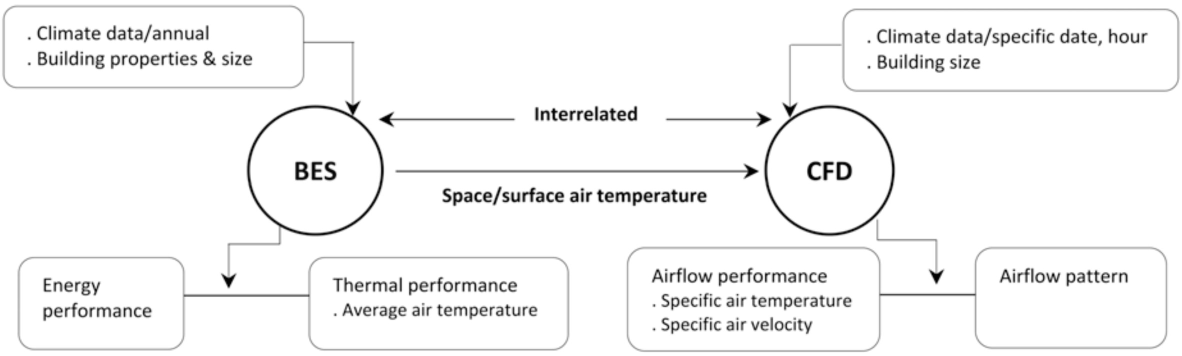


Figure 4: BES and CFD coupling models.

HTB2 and WinAir are coupled in this study. HTB2 software (version 10) is used to inform the thermal performance and energy efficiency, while WinAir (version 4) is adopted as a CFD simulation to inform the ventilation performance inside the skycourt. These two softwares were developed by the Welsh School of Architecture (WSA) at Cardiff University. HTB2 numerical model can predict the indoor thermal performance and estimate the energy demands for buildings during both design stage and occupancy period (Lewis & Alexander, 1990). It is recommended due to its high validity; it has undergone a series of extensive testing: the IEA Annex 1 (Oscar Faber and Partners, 1980), IEA Task 12 (Lomas, Eppel, Martin, & Bloomfield, 1994) and IEA BESTEST (Neymark, Judkoff, Alexander, Strachan, & Wijsman, 2011). Further, it has been validated under ASHREA standards (Alexander & Jenkins, 2015). Also, HTB2 has flexibility and ease of modification (Xing, Bagdanavicius, Lannon, Pirouti, & Bassett, 2012). WinAir can predict airflow patterns, indoor air velocities, indoor air temperature distribution and air flow rates in the skycourt. Thermal conditions for WinAir simulations are established from previously calculated values using the HTB2 including internal surfaces temperatures, heat gain and loss and constant air supply to modify the internal environment of the skycourt. Then, the resulted temperature from the CFD simulation was compared with the average skycourt temperature from the BES to find the predicted temperature difference. The temperature difference was small (approximately 1°C). That little difference is usually accepted for ventilation cases to continue the simulation for the next time step (Wang and Wong 2008). Therefore, one-step data exchange was adopted in the study.

## Coupling Simulation

A theoretical reference model was developed based on design guidelines for high-rise office buildings in London (British Council for Offices (BCO), 2014). To reduce the time required for each simulation run, the models were simplified to an eight-storey, since six-storeys is the most common height of skycourt in the research context. This study focuses on three representative configurations. These configurations function as buffer zones that intermediate between the inside air conditioning offices and the outside. This could be connected to the outdoors by one edge prototype (A) , two edges prototype (B) and three edges prototype (C) as illustrated in Figure 5.

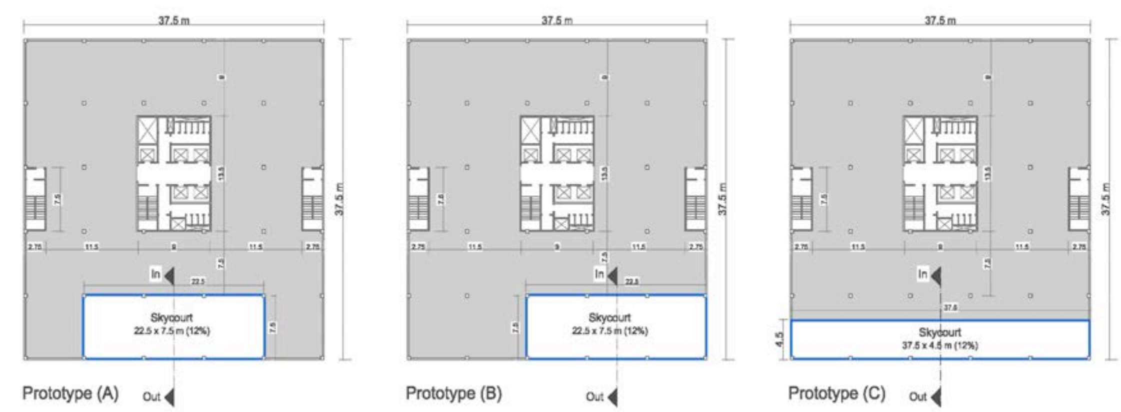


Figure 5: Spatial configurations of skycourt floor plans considered in the study: prototype (A), prototype (B) and prototype (C).

All energy simulation is carried out for one year period using the climate data of London. However, CFD simulation is carried out on three specific times, these are the following: the hottest external air temperature in summer (28.3 °C on 30th June at 14.00), the coldest external temperature in winter (-5.0 °C on 7th December at 9.00) and the typical temperature in mid-tseasons (13.2 °C on 19th April at 9.00) (Figure 6). The main criterions to assess the study's hypothesis are:

(1) the annual energy demand of heating and cooling (Kwh/$m^2$ .year) for the building and the annual energy reduction percentage.

(2) the occupants' thermal comfort: indoor air temperature (° C) and average air speed (m/s) at the occupied area of the skycourt (1.6m height above the floor level ).

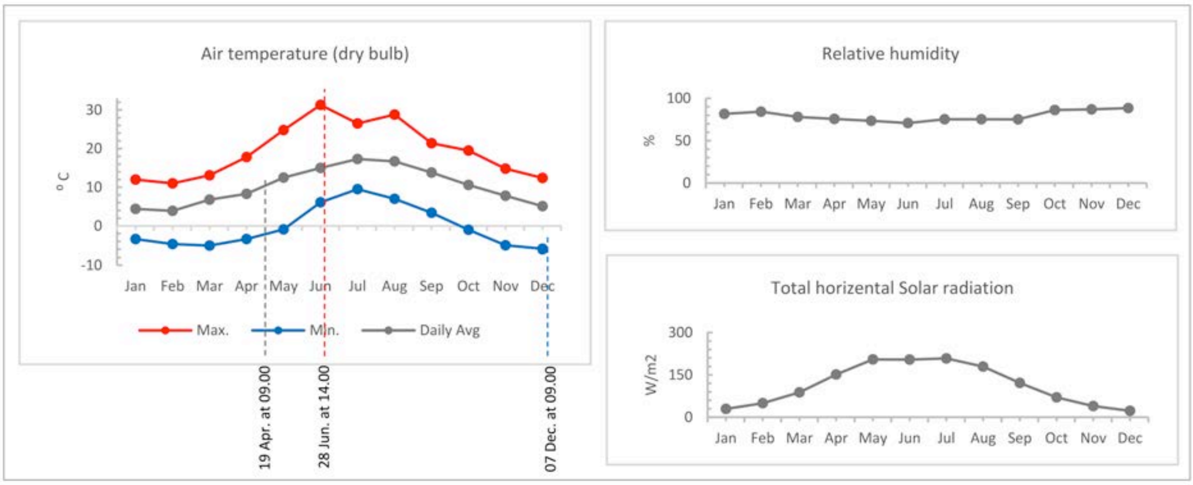


Figure 6. Weather data applied in the study.

All cases are simulated under same numerical settings and boundary conditions. South has assumed a standard orientation for the main facade. The minimum ventilation rate to maintain an accepted air-quality is determined based on the number of occupants, and taking into consideration the building envelope airtightness (infiltration) at the perimeter of the building. The heating set point is 18°C, and the cooling set point is 25°C. Single set point controls are used for cooling in the offices, while air handling unit controls heating. Table 1 illustrates the main numerical settings and assumptions for the simulation process.

Table 1: Summary of numerical settings of the study.

| | | | |
|---|---|---|---|
| **Workplace density:** | | **Ventilation setting:** | |
| NIA per workspace | 12 m² /person | Infiltration rate | 3.5 $m^3/(m^2.hr)$ at 50 Pa |
| | | Air supply rate | 10 L/s per person |
| **Internal heat gain*:** | | Heating set point | 18°C |
| People | 12 $w/m^2$ | Cooling set point | 25°C |
| Equipment | 15 $w/m^2$ | Operating time | 08:00-18:00 |
| Lighting | 12 $w/m^2$ | | |
| | | **Total simulation time:** | |
| **Fabric parameter U-value:** | | Energy building simulation | All over the year |
| Windows U-value | 1.53($W/m^2$.C) | CFD simulation | 3 peak hours (hottest, coldest, typical) |
| Window to Wall ratio | 70% | | |
| Wall U-value | 0.23($W/m^2$.C) | | |
| Floor U-value | 0.20($W/m^2$.C) | **Thermal comfort:** | |
| | | Air temperature-Winter | 20°C ± 2°C |
| | | Air temperature - summer | 24°C ± 2°C |

*Occupancy profile: the building occupied five days a week, based on the following schedule, for offices 09:00-13:00 occupied 100%, 13:00-14:00 occupied 70%, 14:00-18:00 occupied 100%. For Skycourt 09:00-18:00 occupied 100%

## Proposed Ventilation Strategies

Three ventilation strategies to mediate the thermal conditions of the skycourt are investigated, an isolated ventilation strategy and two combined ventilation strategies between the skycourt and the adjacent offices based on the required fresh air for the adjacent offices. Therefore, the skycourt in the combined strategies does not consume energy for heating either cooling. The follwing describes the prposed ventilation strategies:

I. The isolated ventilation strategy: both spaces, the skycourt and the adjacent offices of skycourt are mechanically ventilated, cooled and heated seperately as shown in Figure 7. These models are considered the base cases, as this ventilation strategy represents the common way to cool and heat skycourt in practice. The air change rate for each office floor is 3.1 ac/h and for the skycourt is 0.167 ac/h at 18 °C.

II. The combined-exhaust ventilation strategy that relies on the maximum airflow volume rate exhausted from the adjacent offices to the skycourt. The inlet air volume rate for the skycourt is 5.58$m^3$/s with air change rate 5.76 ac/h (Figure 8).

III. The combined-supply ventilation strategy. In this strategy, air flows in opposite direction: all supply air enters through skycourt zone then into the adjacent offices and all air exhausts through the offices' zone. The inlet air volume rate for the skycourt is 5.58$m^3$/s with air change rate 5.76 ac/h (Figure 9).

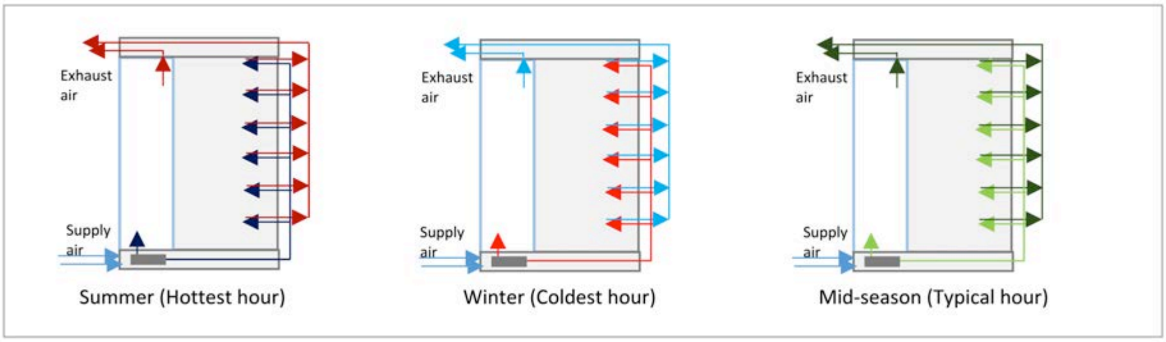


Figure 7: Ventilation strategy (I) in the base model: isolated mechanical ventilation.

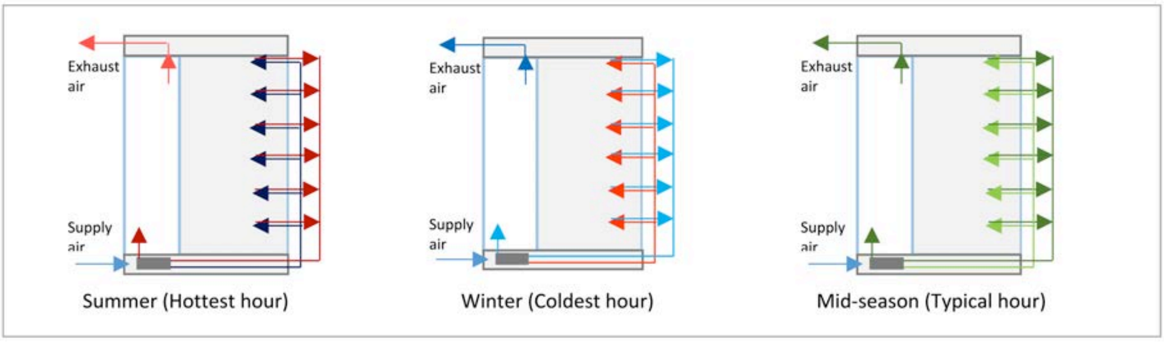


Figure 8: Ventilation strategy (II): combined-exhaust ventilation; skycourt is cooled, warmed and ventilated by the exhaust air from the office spaces.

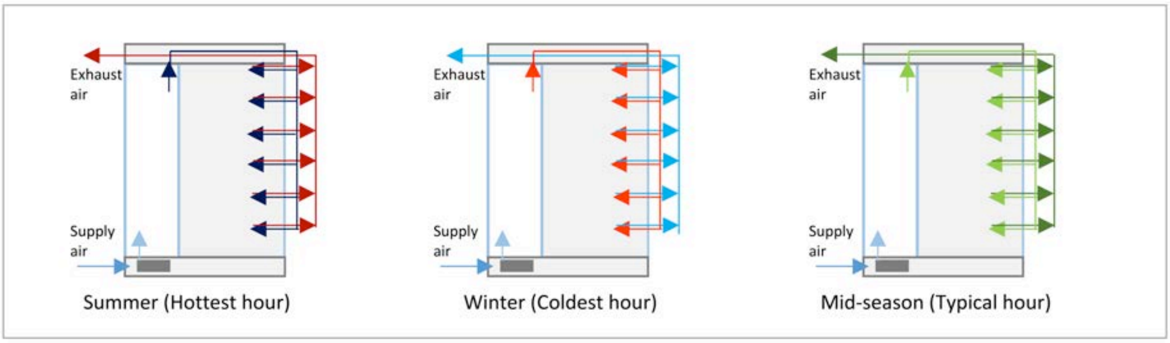


Figure 9: Ventilation strategy (III): combined-supply ventilation; skycourt is cooled, warmed and ventilated by the supplying air to the offices.

## Results and Discussion

The energy demand for heating and cooling of the building and the thermal comfort conditions at the occupancy level of the skycourt are taken as criteria of comparison. Thus to define the optimum ventilation strategy.

## Energy performance comparison

Figure 10 and Figure 11 illustrate the energy efficiency comparison for the different cases. It is apparent that the annual energy demand for heating and cooling of the (II) and (III) ventilation strategies is less than half of the demand in case of strategy (I). However, it is evident that there is a significant difference between the three prototypes in the case of ventilation strategy (I). While, strategies (II) and (III) have similar energy demand and this due to the assumption that skycourt is a ventilated, unheated and uncooled space and heating and cooling for the buildings depend on the office spaces only.

Skycourt (A) building consumes the least heating and cooling loads in case of strategy (I), while the building that integrates skycourt (C) uses the highest amount of cooling and heating loads. This is because skycourt (C) gets high solar gain from three external facades and this requires high-energy demand to cool the skycourt. The three prototypes (A), (B) and (C) accounted the following energy demand respectively, under ventilation strategy (I): 220 Kwh/m$^2$.yr, 245 Kwh/m$^2$.yr and 329 Kwh/m$^2$.yr. The energy demand when conducting ventilation strategy (II) recorded the following values: 91.9 Kwh/m$^2$.yr for prototype (A), 91.5 Kwh/m$^2$.yr for prototype (B) and 90.0 Kwh/m$^2$.yr for prototype (C). Results obtained from strategy (III) recorded the following: 110.0 Kwh/m$^2$.yr for prototype (A), 98.9 Kwh/m$^2$.yr for prototype (B) and 100.6 Kwh/m$^2$.yr for prototype (C).

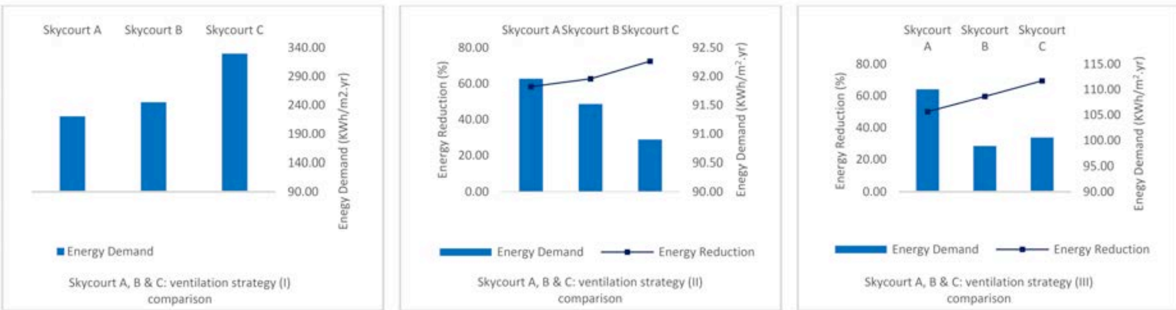


Figure 10 : Annual heating and cooling demand comparison for skycourts (A), (B) and (C): ventilation strategies (I), (II) and (III).

Comparing this data shows that the strategy (II) can reduce the annual total heating and cooling for skycourts (A), (B) and (C) by 58.3%, 62.7% and 72.4%, respectively. Whereas, strategy (III) obtain less energy reduction percentages. It accounts the following savings: 50.0% for skycourt (A), 59.7% for skycourt (B) and 69.5% for skycourt (C).

Taken together, the results indicate the effectiveness of strategy (II) -the combined exhaust ventilation strategy- to reduce the annual energy demand of heating and cooling for the building.

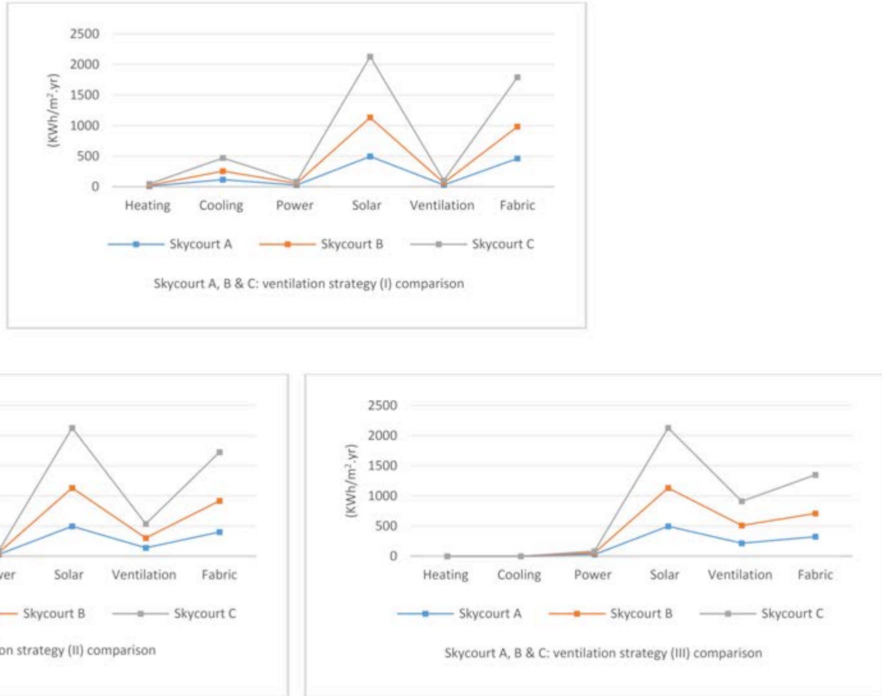


Figure 11: Annual heating, cooling, solar, fabric, ventilation and power loads comparison for skycourts (A), (B) and (C): ventilation strategies (I), (II) and (III).

**Thermal performance comparison**

Figures 12, 13 and 14 illustrate the CFD temperature and airspeed distributions inside the skycourt prototypes under the proposed ventilation strategies at three hours conditions, the highest, the coldest and the mid-degree of the external air temperature. Cross-section location is shown in Figure 5. The comfort criteria recommended by the British Council for Offices (BCO) guide (2014) is adapted to verify the thermal conditions at the occupancy level of the skycourt; air temperature ranges in summer 24°C ± 2°C, in winter 20°C ± 2°C and airspeed ranges between 0.1m/s and 0.2m/s (British Council for Offices (BCO), 2014). It is apparent that under ventilation strategy (I), the mean air temperature was very high and airspeed was very low and quite constant at the occupied area of the three skycourts in summer. In winter, airspeed was much higher and this air movement causes low temperature at the occupied level. The simulation records the following air temperature and airspeed at the occupied level for skycourt (A), (B) and (C) respectively: 33.8 °C and 0.031m/s, 34.7°C and 0.034m/s, 37.2°C and 0.039m/s in the hottest summer hour. Whereas results in the coldest winter hour were 11.6°C and 0.336m/s, 9.4°C and 0.35m/s , 8.8°C and 0.31m/s. Therefore, the results indicate the ineffectiveness of strategy (I) to produce thermal comfort conditions at the occupied area of the skycourt, as the supply air rate is considered small and might not be efficient due to the height of the skycourt.

Results for strategies (II) and (III) indicate better thermal conditions in the skycourts. The air temperature and airspeed were similar to the comfort conditions in the different seasons significantly under strategy (II). Strategy (III) records higher temperature in summer and lower temperature in winter.

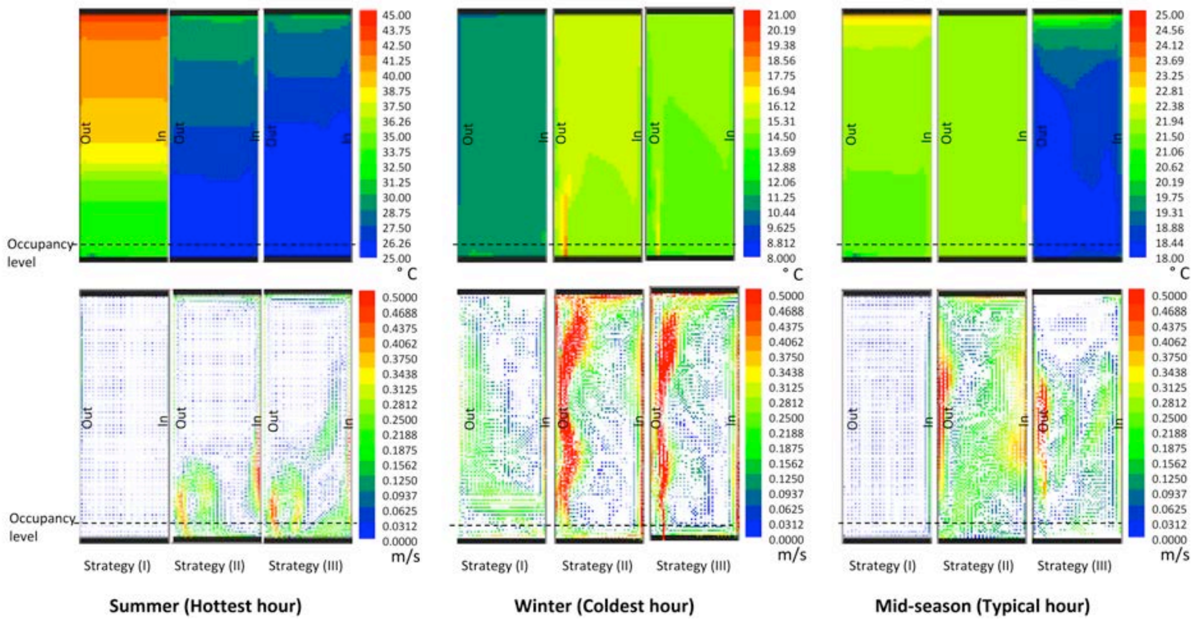


Figure 12. Thermal conditions in skycourt (A) comparison at the hottest hour in summer, the coldest hour in winter and typical hour in mid-season: ventilation strategies (I), (II) and (III).

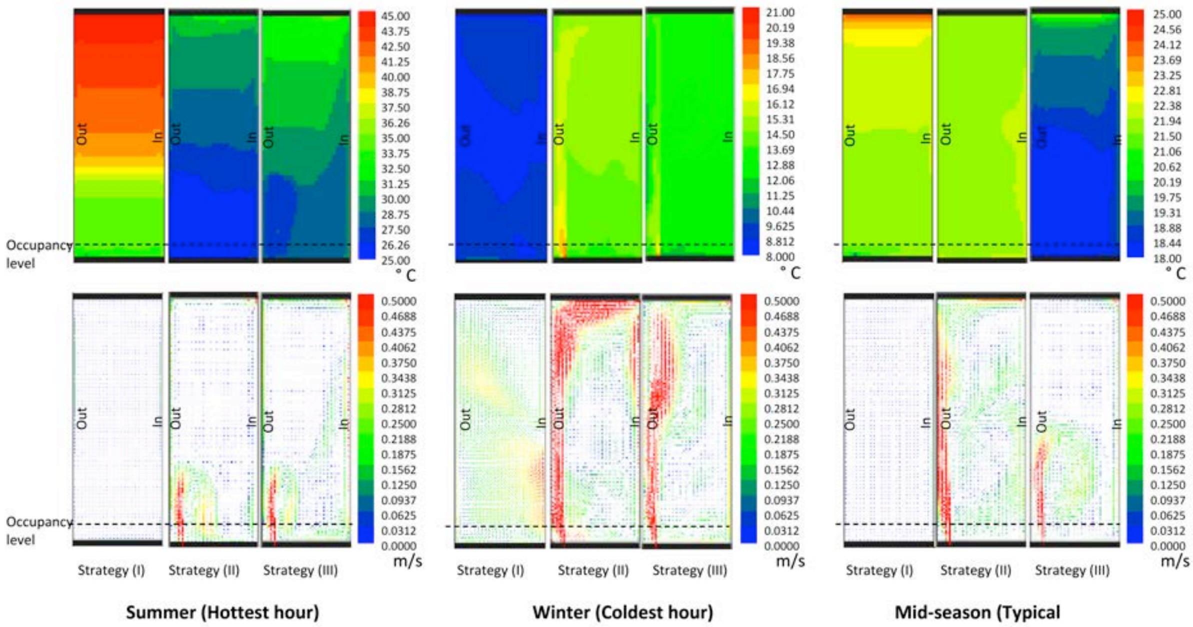


Figure 13. Thermal conditions in skycourt (B) comparison at the hottest hour in summer, the coldest hour in winter and typical hour in mid-season: ventilation strategies (I), (II) and (III).

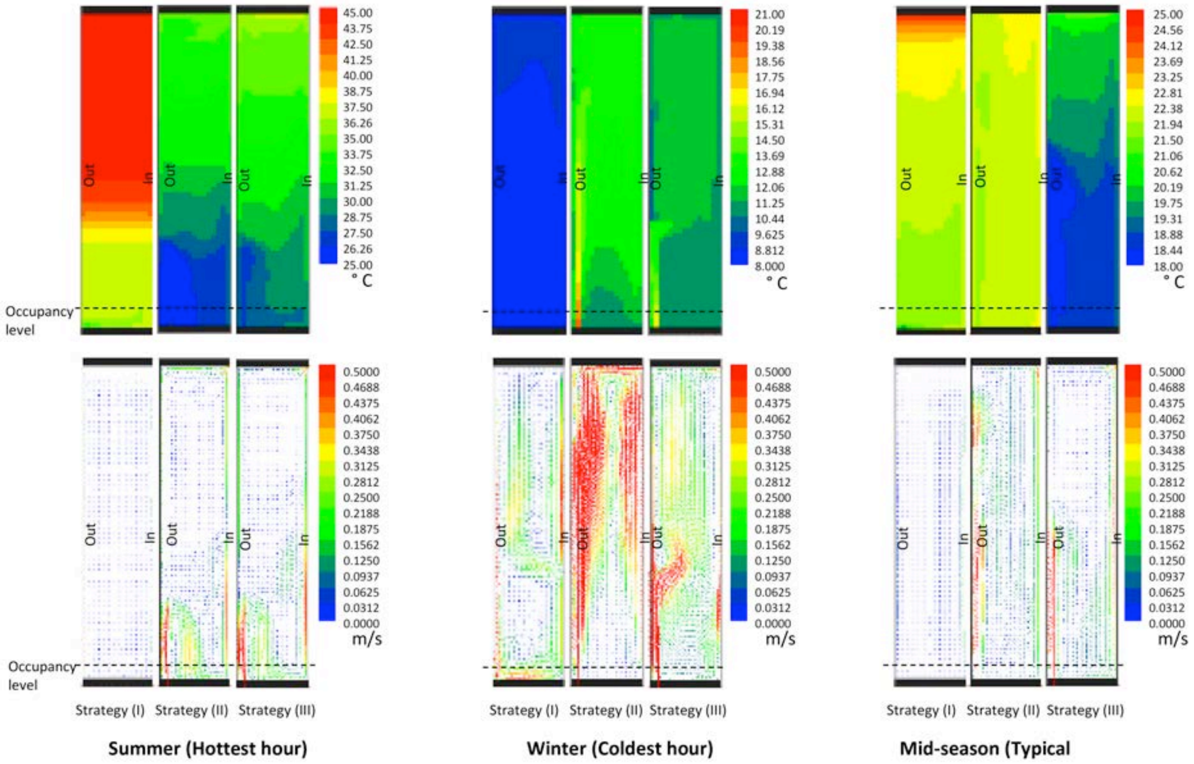


Figure 14. Thermal conditions in skycourt (C) comparison at the hottest hour in summer, the coldest hour in winter and typical hour in mid-season: ventilation strategies (I), (II) and (III).

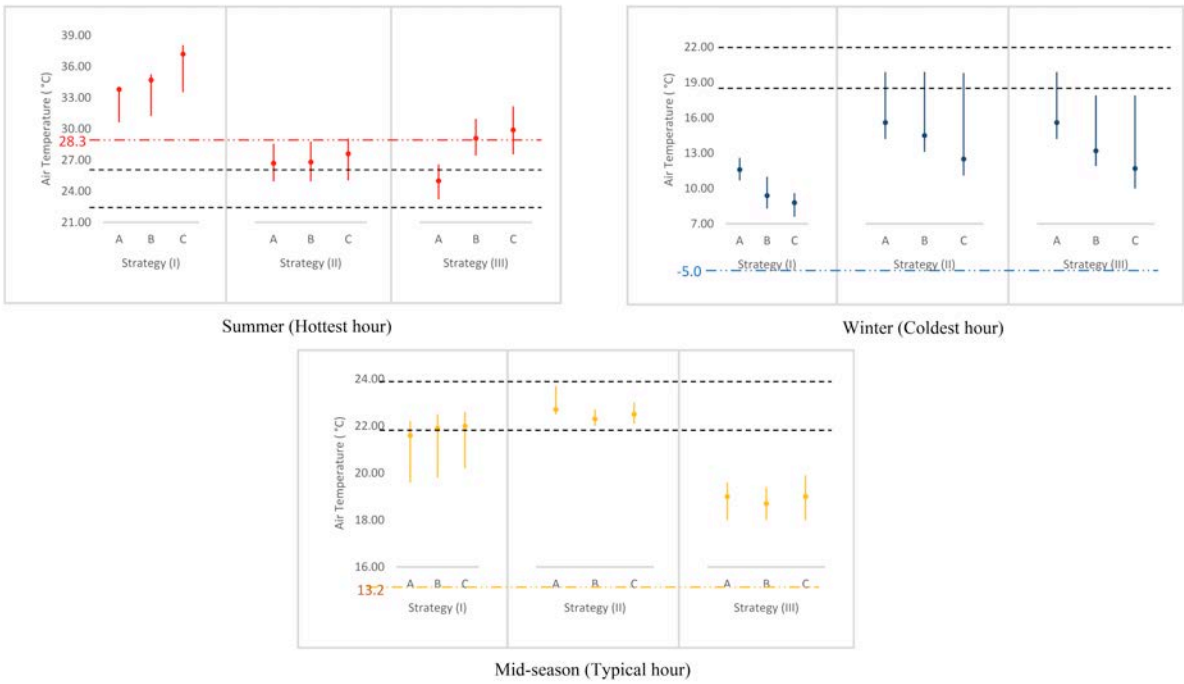


Figure 15. Air temperature comparison at occupancy level in skycourt (A), (B) and (C) (dotted-lines show comfort air temperature ranges, dots show mean air temperature): ventilation strategies (I), (II) and (III).

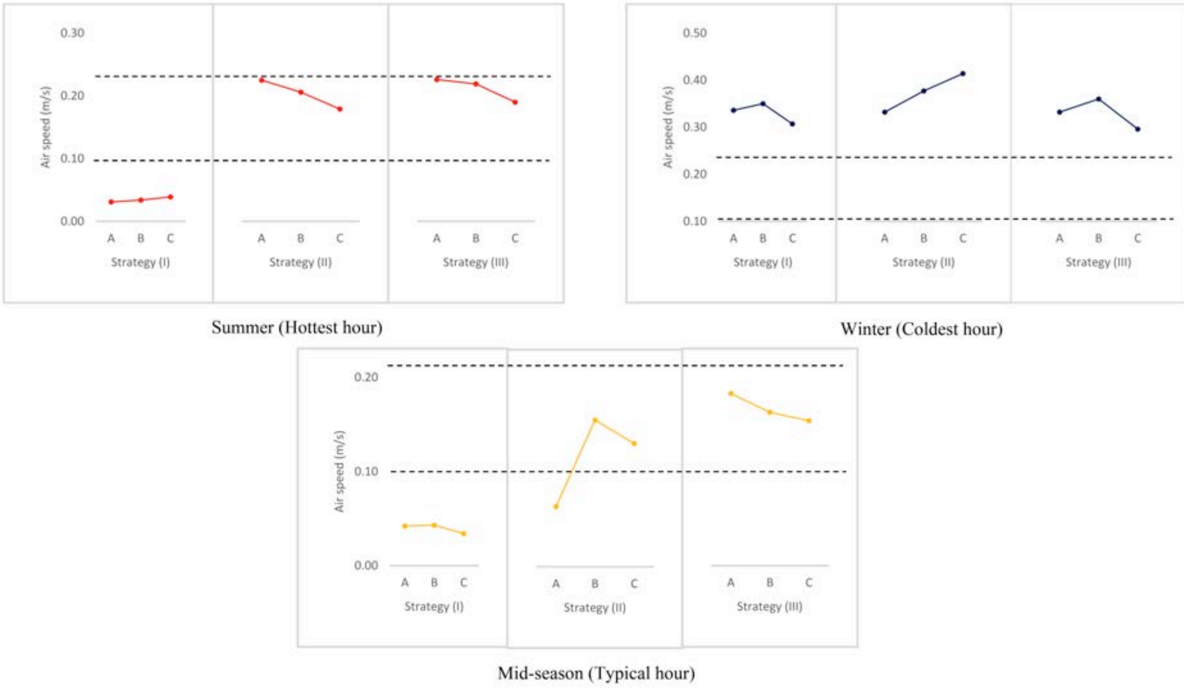


Figure 16. Airspeed comparison at occupancy level in skycourts (A), (B) and (C) (dotted-lines show comfort airspped ranges): ventilation strategies (I), (II) and (III).

Under strategy (II), the thermal conditions for skycourt (A) is about 26.4°C with 0.2m/s average airspeed in the summer hour. In the coldest hour, the air temperature ranges between 14.2°C and 20.0°C. However, airspeed is considered high and reaches up to 0.4m/s. For skycourt (B), the temperature records 26.8°C with 0.2m/s in the hottest hour and fgrom 13.1°C to 20.0°C with 0.38m/s in the coldest hour. In skycourt (C), the hottest hour records 27.6 °C with 0.18m/s and at the coldest hour, the temperature ranges between 11.1°C and 20.0°C with 0.414m/s.

However, when the results obtained from strategy (II) are comparable to those obtained from strategy (I) there is a reduction in air temperature of about 7°C to 9°C degrees in summer case and an increase in air temperature of about 4°C to 5°C degrees in winter. While, correlatining the thermal conditions between strategy (II) and strategy (III) shows that the previous method produces less air temperature range that is closer to thermal comfort levels in summer case. However, the winter comparison shows similar average air temperature in the different skycourt prototypes, yet, it is slightly lower in strategy (II).

The simulation at a normal hour in spring accounts the following results for the skycourt prototypes at the occupied area. Firstly, air temperature ranges between 20°C and 22.5°C with 0.04m/s average airspeed under strategy (I). Secondly, average air temperature under strategy (II) accounts around 22.3°C with 0.15m/s. Strategy (III) produces 19.0°C with 0.16m/s. The results, therefore, indicate the influence of strategy (II) in transitional seasons to provide thermal comfort conditions.

As can be seen from the analysis of data, strategy (II) - the combined exhaust ventilation strategy - indicates significant effectiveness to produce thermal comfort conditions at the occupied area of skycourt prototypes.

Air temperature and average air speed in the skycourts were related to the outdoor air temperature, solar gain, airflow volume rate and air inlet temperature. The thermal comparison between the skycourt prototypes shows that skycourt (A) - the hollowed-out - performs the optimal prototype under the proposed ventilation strategies. It is colder in summer and warmer in winter. This is due to less solar gain as it exposed to external conditions by one sided only, this is followed by skycourt (B), which is exposed to outside weather by two sides and finally, skycourt (C) with three outer sides.

## Conclusion

The paper has suggested that the skycourt, like a ventilated buffer zone in office buildings, has potential to produce significant heating and cooling savings and provides thermal comfort for occupants. Three ventilation modes have been investigated: the first considers the skycourt as an air conditioning space and the second and third consider it as a ventilated space that does not consume energy for heating nor cooling. The annual heating and cooling energy demand is employed to assess the energy performance of the cases. Whereas, the thermal performance is investigated at the occupied area of the skycourt. Three spatial prototypes of skycourt were examined.

The following conclusions can be drawn from the present study:

1) The different spatial prototypes of skycourt when perform as part of combined ventilation strategy in high-rise office buildings can achieve more than 50% heating and cooling reduction for the building. Furthermore, the results indicate the effectiveness of this strategy to produce thermal comfort conditions at the occupied area of the skycourt prototypes.

2) A combined ventilation strategy that depends on the maximum airflow volume rate exhausted from the adjacent offices to the skycourt has a significant effect on cooling the skycourt space and reducing the energy demand compared to the strategy that is based on the air flows with opposite direction.

3) The energy influence of the three skycourt prototypes under the combined-exhaust ventilation strategy shows a variation in the energy savings. Greater external façade areas requires greater cooling demand under the isolated ventilation strategy (air conditioning skycourt), therefore, greater energy reduction when applying the combine-exhaust ventilation strategy. However, less external facade areas provides better thermal performance. Therefore, the hollowed-out skycourt (A) is considered the optimal thermal comfort prototype under the proposed ventilation strategies in the different seasons.

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