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Energy Savings of a Hybrid Reversible Ventilation System in a Basement Parking Structure

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Keywords：fire safety engineering, CFD simulation, energy savings, basement parking structure, mechanical ventilation.

ABSTRACT

Urbanization stimulates many large developments. Utilizing the underground space for vehicle storage has become the de facto practice to overcome the high cost of super-high-rise buildings. Underground space requires an efficient mechanical ventilation system for its day-to-day operation as well as in the case of a fire emergency. These two ventilation requirements are often combined into one hybrid ventilation system. The conventional ventilation system in a basement parking structure involves the installation of a full extension of ductwork to prevent pockets of stale air. This paper introduces a semi-ducted reversible ventilation system. In this reversible concept, fans in the fire zone operate as exhaust. whereas fans at the opposing zone operate as supply. The performance of both ventilation systems was investigated in a rectangular basement parking structure. Results based on CFD simulations showed that the semi-ducted ventilation system outperformed the conventional ventilation system in the event of fire emergency. Site measurement showed that the CO level was kept at below 10 parts-per-million in the normal operating mode. The amount of ductwork in the semi-ducted system reduced by approximately 60%, and the fan static pressure reduced by 33%. Hence, an overall energy savings of 45.6% was achieved.

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INTRODUCTION

City urbanization encourages economy growth but, at the same time, it leads to other issues such as space limitation. The increase in human population and wealth promotes an increase in vehicle ownership (Mohamad, 2017). Building parking structures in underground spaces has become the de facto practice to overcome the high cost of super-high-rise buildings (Broere, 2016), As the aboveground space is more valuable for commercial purposes. In the last few decades, the quick economic growth of Kuala Lumpur has transformed the city from a quiet mining town into one of the fast-growing metropolis in South-East Asia. Many large mixed developments were designed and built to include basements as parking structures.

Because of its enclosed setting, an underground parking space is by nature more exposed to fire danger, and therefore, would require a different ventilation system compared to the aboveground space (Chow, 2006). Often, the ventilation systems for fire emergency and normal operating mode are combined into one hybrid system. As such, the design of a hybrid ventilation system in the basement parking space will have to meet the criteria for fire emergency as well as for a normal operating system. One of the requirements is the sufficient removal of heat and hazardous gases, such as carbon monoxide (CO) generated by vehicles. It is recommended in the ASHRAE Handbook that the ventilation rate at six air-change-per-hour (ACH) should be provided in a basement parking structure (ASHRAE, 2015). On the other hand, the dilution method of a minimum of ten ACH is required during a fire emergency, according to guidelines provided by some official design codes (Department of standards Malaysia, 2017; UBBL, 1984).

Lambert reported a fire incidence in a basement parking structure with no sprinklers underneath a residential building in New South Wales, Australia (Lambert, 1999). During the fire emergency, fire fighters faced difficulty in identifying and extinguishing the fire due to low and poor visibility. The intense heat generated by the inflamed vehicles caused severe structural damage, including concrete spalling and the dislodging of concrete slabs. In a different report, Burgi conducted a test with three vehicles were set on fire (Burgi, 1971). The test was carried out in an enclosed structure factory building with sprinklers protection system. He found that smoke is the main hazard in a vehicle parking building even in the presence of a functional sprinkler system. A similar test on fire sprinkler system was conducted by BHP, Australia (BHP, 1998). BHP indicated that sprinkler systems have reliability as high as 99.5 % for major stores and 98.5 % for specialty shops, when they are built in separate areas. In addition, Li suggested to provide a smoke control system to improve the safety of occupants and fire-fighters in the event of fire in enclosed parking structures (Li, 2004).

In addition to responding to a fire emergency, an efficient ventilation system is needed for day-to-day operation to ensure good air quality and thermal comfort in a basement parking structure. The major source of air pollution in a basement parking structure is the emission of vehicles, which includes carbon monoxide (CO), sulphur dioxide (SO_2), nitrogen oxide (NO), volatile organic compounds (VOCs) and fine particles (such as lead). Among these pollutants, CO is emitted at the highest level when vehicles are left idle or driven at low speed (Rogers 1984). It is expected when the CO level meets the safety requirement, other pollutants will fall within their respective safety levels. Therefore, the CO level is adopted as the main pollutant for the dilution requirement of vehicle exhaust. The acceptable maximum limit of CO level is 10 ppm (DOSH, 2010). The continuous operation of exhaust fans at six ACH requires higher energy consumption (Kong, 2019). Kong therefore proposed a variable-flow-reversible ventilation system for energy savings in a basement parking structure.

Conventional Ducted and Semi-Ducted Reversible Design

The building of a conventional ducted ventilation system often refers to the design code of smoke and heat control (BS 7346-7, 2013). In this design, the extraction points are extended at every possible spot in the parking space to minimize pockets of stale air. This ventilation system is normally unidirectional, where the exhaust and supply are predetermined at the design stage, as indicated in Fig. 1. Fans at northern side operate as exhaust, whereas fans at southern side are operated as supply. The ductwork is extended from fan shafts throughout the entire parking structure. The operation and control of this ventilation system is simple. However, this conventional ventilation systems is not efficient in clearing out large volume of smoke in the event of a fire emergency, leading to difficulties in evacuation and firefighting due to low visibility (Zhang, 2008).

In our reversible ventilation system design, fans are able to operate reversibly depending on the scenario. If a fan rotates in the clockwise direction is set as the supply mode, then, the anti-clockwise direction becomes the exhaust mode, and vice versa. This paper introduces the semi-ducted reversible ventilation system design, where the amount of ductwork is reduced. Investigations were carried out to determine the performance and energy savings of the system.

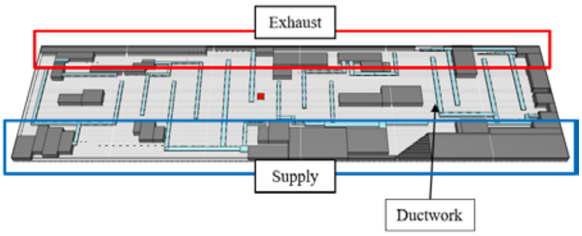

Fig. 1. Conventional ducted ventilation system. Exhaust at Northern side and supply at Southern side.

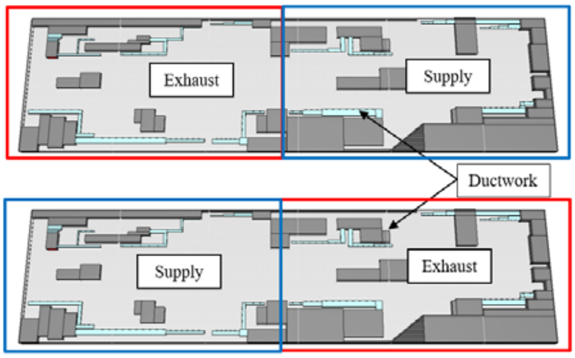

Fig. 2. Reversible semi-ducted ventilation system.

METHODOLOGY

The rectangular basement parking structure shown in Fig. 1 was used for the case study. It was divided into two zones as indicated in Fig. 2 as the left and the right. Each zone was installed with separate sets of ventilation fans, which are reversibly operational as either exhaust or supply. The change in the operation mode of these fans was determined and triggered by fire signal.

Comparing the amount of ductwork in Fig. 1 and Fig. 2, the ductwork of the reversible ventilation system was only installed at the northern and southern perimeter of the structure, which is equivalent to a reduction of approximately 60%. If a fire occurs in the left zone, fans in the left zone will operate as exhaust, whereas fans in the right zone will operate as supply, and vice versa. Although this ventilation system design could reduce significant amount of ductwork, it requires an advanced programmable control system.

An automatic sprinkler system was also installed. The sprinkler flow-switch zoning shown in Fig. 2. The size of the parking structure was approximately 300m long, 50m wide and 3m height. The net volume was approximately 36,000 m^3 after deducted some separated compartments. The ventilation flowrate during normal operating mode was set at 6 ACH (216,000 m^3/h), and during a fire emergency, it was designed to operate 12 ACH (432,000 m^3/h). For this simulation, the fire rated axial fan was selected. The forward flow direction was designed at 100% flow rate, whereas the reverse direction flow was set at 70% of total flow rate. The 100% forward flow was exhaust and 70% reverse flow was supply. This design was chosen to ensure that the space was maintained at negative pressure, and the 30% of make-up air could be drawn in via openings or leakages of the parking structure, in order to prevent smoke egress to other spaces.

Vehicle fire is considered as the greatest danger to the occupants in a basement parking structure (Weisenpacher, 2016). Weisenpacher had conducted a comparison between a full-scale experiment and CFD simulation results in Povazsky Chlmec. Some parameter studies related to certain selected material properties were carried out. He showed that in vehicles fire development, seat material properties are the most important.

In the event of a fire emergency, the fire zoning would be detected by the sprinkler flow-switch captured by the programmable addressable fire alarm system. The output fire signal was programmed to determine the operation of fans in either exhaust or supply mode. During the transition from normal operating mode to the fire emergency mode, a two-minute time delay was programmed to ensure that the fans came to a complete stop before re-operating in the reverse direction, according to the fire requirement. Activation of the sprinkler system automatically triggered the occupant warning system and the smoke management system.

Evaluation and Analysis

The performance of conventional and the semi-ducted ventilation system was investigated using computational fluid dynamics (CFD) (Chang, 2018), respectively. The fire and smoke spread model, Fire Dynamics Simulator (FDS) version 6 was used to model the fire scenarios (McGrattan, 2018). The NIST's field model FDS is a fire-driven fluid flow CFD model. This FDS software is suitable for thermally driven flow and low-speed with the emphasis on heat and smoke transport from fires. The simulation modelling results were presented by the 'Smokeview' program.

A CFD grid analysis was carried out and summarized in Fig. 3. It showed that the modelling results did not vary significantly beyond the mesh resolution for grid size of 0.25m and below. Therefore, the grid size of 0.25m was selected for the CFD analysis.

Fire growth rates were predicted according to the BHP car fire (Bennetts, 1988). For steady state modelling, the heat release rate of car fire was modified as shown in Fig. 4. When the fire grew to 4.5MW, the fire size remained at steady state. Therefore, the design peak fire size at 4.5MW was adopted.

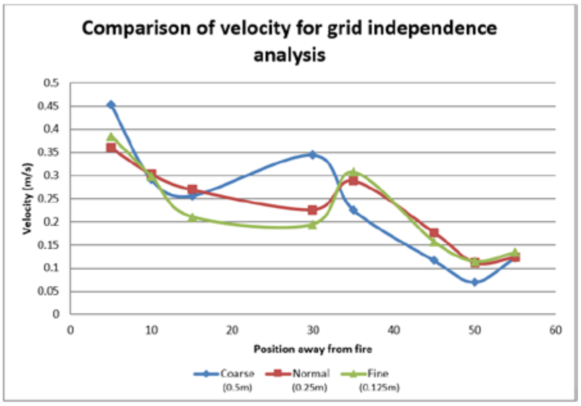

Fig. 3. Grid independent analysis.

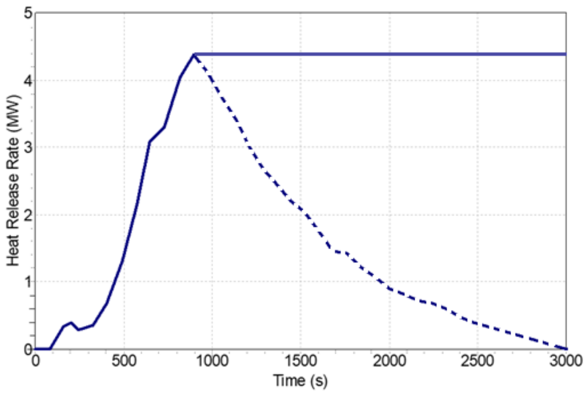

Fig. 4. Modified heat release rate of car fire.

The simulation results for both the ventilation systems were then evaluated against the tenability requirements according to NFPA 92 (Cote, 2011). The tenability criteria used for the assessment were visibility, air temperature and carbon monoxide concentration as listed below:

- Soot visibility > 10 m
- Air temperature < 60 °C
- CO concentration < 100 ppm

The tenability criteria were studied by Wang using performance-based approach (Wang, 2007). He carried out a full-scale experiment to assess the factors of available safe egress time (ASET). In general, the ASET in performance-based egress design complies with the smoke layer height descending to a certain distance above the floor. For this simulation results presentation, the slides were cut at 2.5m above floor.

For the conventional ducted design, three simulation scenarios were carried out as listed in Table 1, where the fire source is placed in left zone, right zone and middle of the parking space. The soot visibility, air temperature and CO concentration parameters were then presented.

For the semi-ducted reversible design, two simulation scenarios were carried out. The exhaust and supply operation are shown in Fig. 2. The soot visibility, air temperature and CO concentration parameters were presented. The simulation scenarios are tabulated in Table 1.

Table 1. Specific data for the tank vehicle.

Scenario	Description
1	Conventional ventilation system. Fire occurred at the left zone of the parking space. Exhaust at Northern side and supply at Southern side.
2	Conventional ventilation system. Fire occurred at the right zone of the parking space. Exhaust at Northern side and supply at Southern side.
3	Conventional ventilation system. Fire occurred in the middle of the parking space. Exhaust at Northern side and supply at Southern side.
4	Reversible ventilation system. Fire occurred in the middle of the parking space. Left zone was exhaust and right zone was supply.
5	Reversible ventilation system. Fire located at the middle of the parking space. Right zone was exhaust and left zone was supply.
6	Conventional unidirectional ducted ventilation system. Fire occurred in the middle of the parking space. Left zone was exhaust and right zone was supply.
7	Conventional unidirectional ducted ventilation system. Fire occurred at the right zone of the parking space. Left zone was exhaust and right zone was supply.

For the same amount of ventilation rate, the air-change swept across from the southern end to the northern end for the conventional system, whereas in the semi-ducted reversible design, the air was pushed and pulled in the longitudinal direction. The air velocity was relatively higher in the semi-ducted reversible design than the conventional system because the air passed through a smaller cross-sectional area. For the conventional unidirectional ducted system, another two scenarios were simulated based on longitudinal flow direction. The left zone is exhaust and the right zone is supply. Fire source was located in the middle and right zone respectively.

CO Measurement at Site

A site measurement of CO level was carried out under the normal operating mode during the peak hour at lunch time. The basement parking structure was fully occupied. Vehicles continued to enter and leave the premise. The estimated number of moving vehicles was approximately 5% of the total number of parking bays. This number was chosen based on the recommendation by ASHRAE (ASHRAE, 2015). Fans at northern side was set at the exhaust mode, and fans at the southern side supply fresh air into the space, as shown in Fig. 1. The ventilation rate was six ACH.

A hand-held CO meter of brand AZ Instrument, model 7701 was used to take field readings. The points surrounding the access lobbies were selected as shown in Fig. 5.

RESULTS AND DISCUSSION

The tenability assessment for both the conventional and the reversible ventilation designs was compared based on the simulation results. The results of soot visibility, air temperature and CO concentration at 2.5m above floor level were presented in Fig. 6, Fig. 7 and Fig 8, respectively. As indicated in Fig. 6, the worst-case condition occurred when the fire source was placed in the middle of the parking space, which was scenario 3.

Comparing scenario 3, 4 and 5, it was observed that the soot visibility and CO concentration distribution for the semi-ducted reversible ventilation system outperformed the conventional system. Due to the higher air velocity across the longitudinal direction that pushed and pulled the smoke to one end, the soot visibility near the seat of fire for the reversible ventilation system was better than the conventional ventilation system. In this case, the reversible ventilation system will provide an opportunity for the fire-fighters to identify the fire location and ease fire-fighting work. A full-scale test

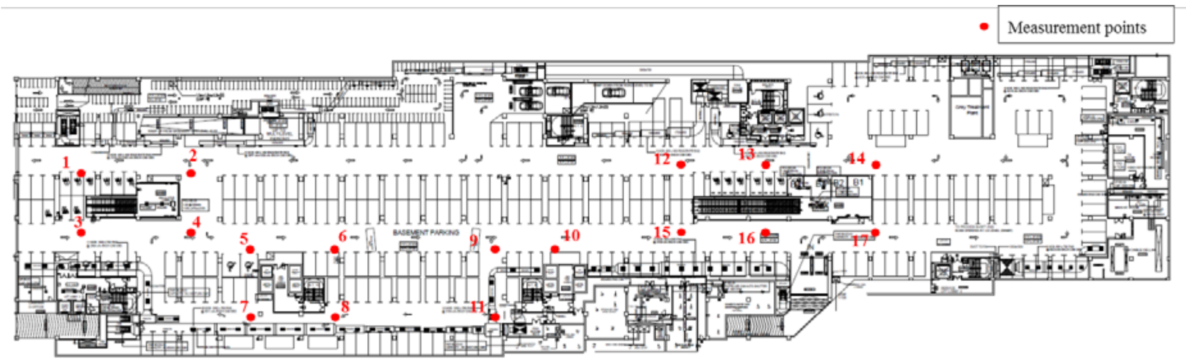

Fig. 5. CO measurement points.

was carried out by Lambert in a subway station using the push-pull concept. He found that the air flow at a critical velocity can affect the direction of the smoke or clear out the smoke after the fire to support the firefighting operations (Lambert, 2018). As clearly shown in Fig. 6, Fig. 7 and Fig. 8, respectively, the airflow generated in the longitudinal direction by the reversible ventilation system could achieve the critical velocity proposed/observed by Lambert.

For air temperature distribution, the area with hot air (above 60 ℃) was larger for the semi-ducted reversible scheme compared to the conventional design. This was mainly due to the higher air velocity flow in the fire zone. The mixing of larger amount of cool and hot air causes the hot layer to drop. However, the air temperature for both ventilation systems would eventually cool down by water sprouting from sprinklers.

For the conventional ducted ventilation system in longitudinal airflow direction shown in Fig. 9, the tenability condition when the fire occurred in the middle is good. However, the condition is not acceptable when fire occurred in the right zone, which was the supply zone. Therefore, for the conventional unidirectional ducted ventilation system, the preferred design option is exhaust at Northern side and supply at Southern side or vice versa. The smoke travel distance shall be as short as possible.

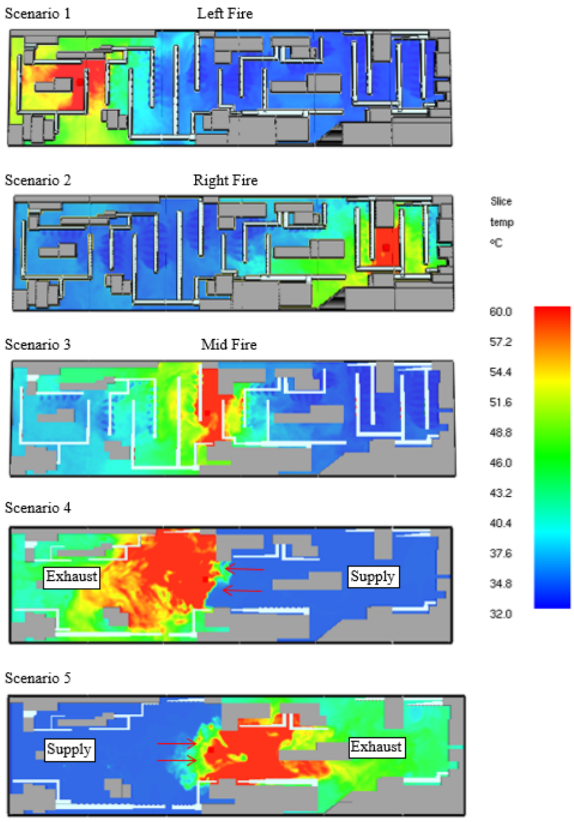

Fig. 7. Air temperature slides at 2.5m above floor level.

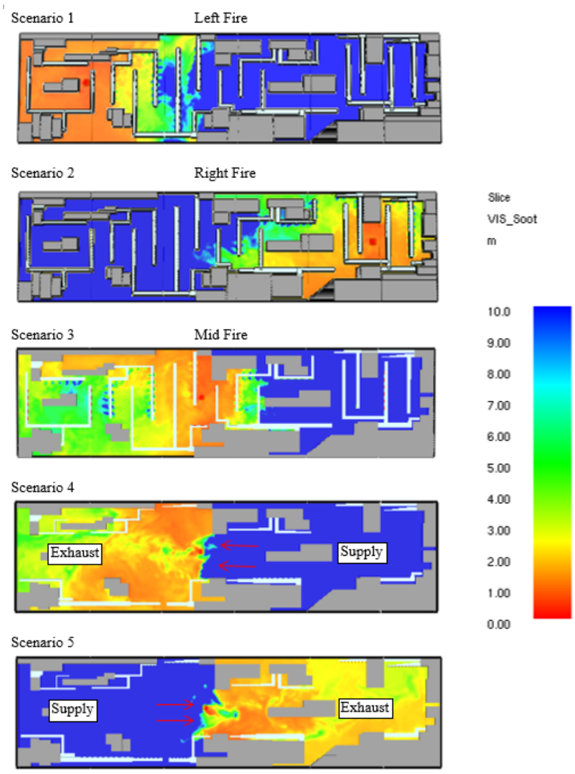

Fig. 6. Soot visibility slides at 2.5m above floor level.

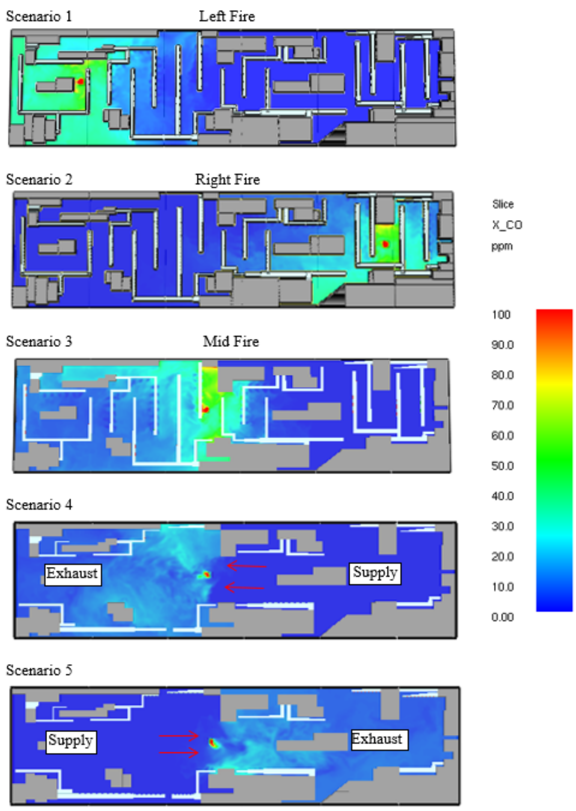

Fig. 8. CO concentration slides at 2.5m above floor level.

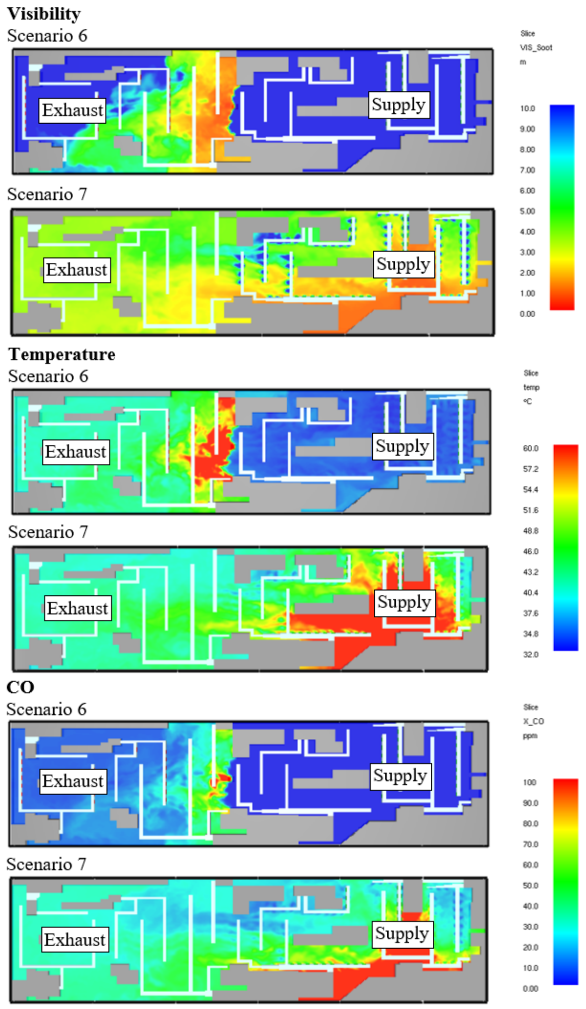

Fig. 9. Soot visibility, air temperature and CO concentration slides at 2.5m above floor level for the conventional unidirectional ventilation system in longitudinal direction.

CO Measurement at Site

CO emission of vehicles were measured as per Fig. 5. CO level of zero (0) ppm was recorded at all points. The semi-ducted ventilation system was capable of removing contaminated air effectively at the ventilation rate of six ACH even with a reduced amount of ductwork during peak hours.

Analysis of Energy Savings

The performance of both the conventional ducted and the semi-ducted reversible ventilation system were studied. Simulation results showed that in the event of a fire emergency, both systems were able to remove smoke effectively. In fact, the semi-ducted reversible ventilation system resulted in a greater visibility near the seat of fire from one side. This will greatly help the fire-fighting efforts.

For the semi-ducted ventilation system, there was a reduction of approximately 60 % in the amount of ductwork required. This reduction contributed to significant cost saving for the installation of the semi-ducted ventilation system. This hybrid ventilation system was also operational during the day-today business hour to remove contaminated air. Due to the lesser ductwork, the static pressure loss across the ducting network reduced. Under this circumstance, fans used less energy to push the same amount of air flowrate. During the daily routine operation, this commercial basement parking structure operated 15 hours a day from 8am to 11pm. The power of ventilation fans was 100 kW at the ventilation rate of six ACH. Hence, the daily energy consumption equated to 1,500 kWhr for 15-hour continuous operation.

From the Fan Affinity Law,

$$\frac{P_1}{P_2} = \left(\frac{H_1}{H_2}\right)^{3/2} \tag{1}$$

where P is the power, H is the fan static pressure. The fan static pressure reduced from 375 Pa (ducted) to the 250 Pa (semi-ducted) over the course of 15 hours. The reduction of power consumption was calculated as follows,

$$\begin{aligned} P_1 - P_2 &= \left(1 - \frac{P_2}{P_1}\right) P_1 = \left[1 - \left(\frac{H_2}{H_1}\right)^{3/2}\right] P_1 \\ &= \left[1 - \left(\frac{250}{375}\right)^{3/2}\right] 1500 = 683.5\ kWhr \end{aligned}$$

The power consumption reduced approximately 45.6 % during the normal operation. This semi-ducted reversible system required more advanced programming in controlling the fans based on fire zoning during fire emergency mode, which can be accomplished by the programmable addressable fire alarm system.

CONCLUSION

The hybrid ventilation system is designed to operate in the normal operating mode to remove contaminated air and in the event of fire emergency to remove hazardous smoke. The system requires approximately 60% less ductwork, which contributed to cost saving at the initiation of building construction. In the normal operating mode, the semi-ducted reversible ventilation system is able to keep the CO level below 10 ppm at the ventilation rate of six ACH. Because of the reduction of the fan static pressure, the overall energy saving is approximately 45.6%. In the event of a fire emergency, the semi-ducted reversible ventilation system uses the reversible zonal push-and-pull concept. The application of this concept allows the semi-ducted reversible ventilation system to achieve a better performance compared to the conventional ducted system. In essence, the semi-ducted reversible ventilation system is a superior system in parking structure of super-high-rise buildings.

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NOMENCLATURE

P the power

H the fan static pressure