EVALUATION OF TRACKWAY VENTILATION SYSTEM FOR THE NEW METRO LINE IN SINGAPORE

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ABSTRACT

Maintaining acceptable temperatures within the tunnels of underground metro systems is crucial particularly in countries with tropical climates like Singapore and the trackway ventilation system plays a vital role in achieving this. As the performance of the train air-conditioning (A/C) system is affected by the temperature in the tunnel, it is important to have a properly designed and effective trackway ventilation system to extract heat dissipated by the trains when they are dwelling at the stations.

Underground stations for the existing metro lines in Singapore are equipped with an Under-Platform Exhaust (UPE) system at each platform to extract the heat dissipated from the train air-conditioning system condensing units which are mounted at the train undercarriages. However, the UPE system may not be effective for extraction of the heat from the train a/c systems for the Cross-Island Line (CRL) because the A/C unit condensing units of the CRL trains are mounted on the roof of the train carriages.

In this paper, Computational Fluid Dynamics (CFD) is used to evaluate the effectiveness of the three types of trackway ventilation systems, namely the UPE, Over-Track Exhaust (OTE), and the combined OTE and Under-Platform Air Supply (UPAS) systems for adoption in the CRL underground stations. Results show that the combined OTE and UPAS system is the most effective in maintaining the lowest inlet air temperatures at the A/C units. It also has the least impact on the station A/C system during train dwelling at the stations.

Keywords: Tunnel Ventilation System (TVS), Over-Track Exhaust (OTE), Under-platform Air Supply (UPAS), Under-platform Exhaust (UPE)

1. INTRODUCTION

The underground metro network serves as a convenient mode of transportation for commuters, facilitating travel between places and helps alleviate traffic congestion, especially during peak hours. During peak periods when more trains are in operation, it is important to control the temperature within the tunnels to ensure the functionality of both train-borne equipment and equipment installed inside the tunnels. As trains traverse the tunnels, significant amounts of heat can be generated during acceleration and braking, and the operation of the air-conditioning (A/C) system. If the heat is not effectively removed by the tunnel ventilation system, it can result in elevated temperatures within the tunnel, potentially causing passenger discomfort if the performance of the A/C system is adversely affected. The trackway ventilation system, a component of the tunnel ventilation system (TVS) plays a vital role in helping to maintain acceptable temperatures within the tunnels. This is achieved by extracting significant amounts of heat dissipated from the train propulsion, braking and air-conditioning systems when dwelling at the station trackway.

Trains on the existing metro lines are equipped with the condensing units of the A/C system located underneath the train carriage. All underground stations are provided with platform screen doors (PSD) along the edge of the platforms, to isolate the platform from the tunnel, thereby maintain the station environment by minimizing exchange of air between the tunnel and station platform public area. The stations are equipped with an Under-Platform Exhaust (UPE) system, which comprises two or more UPE fans and a concrete duct with sliding plate dampers evenly distributed beneath each platform.

For the upcoming Cross-Island Line (CRL), the train A/C units are mounted on the roof of the train carriages instead of underneath. This change may result in the UPE system currently used in the existing lines being less effective for the CRL. Therefore, the objective of this study is to evaluate different variations of the trackway ventilation system and determine the most effective option for the CRL. The trackway ventilation systems studied were the Under-Platform Exhaust (UPE) system, Over-Track Exhaust (OTE) system and the combined Under-Platform Air Supply (UPAS) and Over-Track Exhaust (OTE) system.

2. LITERATURE REVIEW

Various studies have been conducted on the use of different types of trackway ventilation systems to aid in removal of the heat from the trains while at the stations. However, majority of the studies focused on the use of the OTE and/or UPE system, as underground metros worldwide typically employ a UPE and/or OTE trackway ventilation system, depending on the location of the equipment [1]. Alaa Hasan et. al. studied the effectiveness of the UPE system [2]. Wang & Li found that the heat removal efficiency of the OTE was positively correlated with the commuter density in the train, but the UPE had little effect on heat removal [3]. Liu et. al compared the effects of air distribution and thermal comfort in a subway station by applying three types of ventilation schemes [4].

The objective of this study is to evaluate different variations of the trackway ventilation system and determine the most effective option for the CRL. The evaluation focused on two main criteria: the average temperature at each condenser air intake, and the volume of air exchange at the PSD openings, using the commercial CFD software, ANSYS FLUENT. The design criteria of the TVS during normal and congested operations is to maintain the average temperature below 45°C at the air intake of the A/C condensers to ensure the functionality of the A/C units. If the temperature exceeds 45°C, the A/C units may start unloading, and subsequently result in uncomfortable conditions for the commuters inside the trains [3].

3. METHODOLOGY/APPROACH

3.1. Physical Model

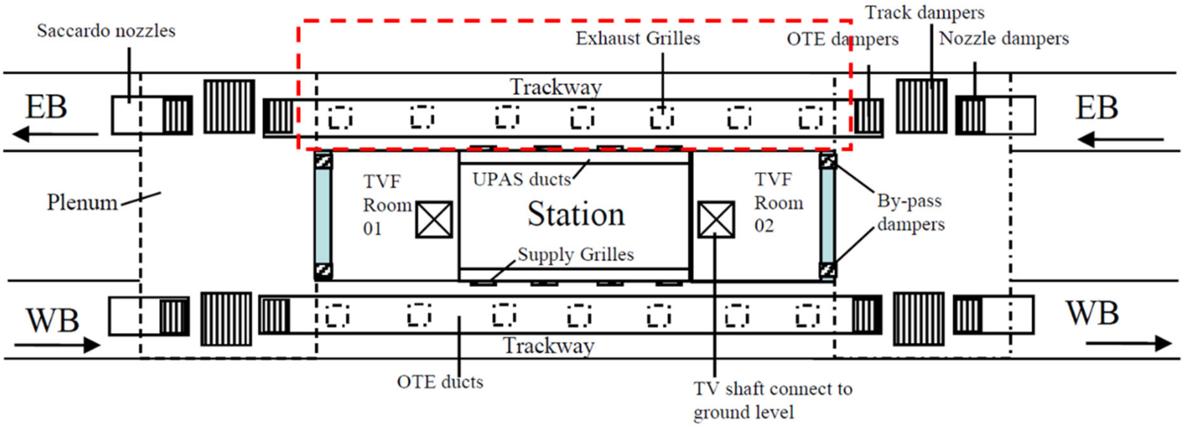


Figure 1: Typical TVS Arrangement in a CRL Station

Figure 1 shows the typical TVS arrangement in a CRL station. As the focus of this study is on the trackway ventilation system, the computational domain that was included in this study is depicted in red in Figure 1. The trackway ventilation system comprised of 32 numbers of 1.25m (L) x 1m (W) exhaust grilles along the OTE duct, located 0.5m away from the tunnel wall, and 64 numbers of 0.8m (L) x 0.5m (H) supply grilles along the UPAS duct below the platform. For the UPE system, the UPAS openings were replaced with UPE openings.

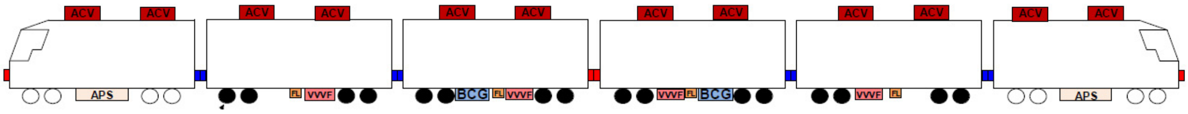


Figure 2: Heat Emitting Equipment on Train

Figure 2 shows the schematic of a six-car train, approximately 138.5m (L) x 3.2m (W) x 3.76m (H), together with the heat dissipating equipment. The equipment consisted of A/C units (ACV) located on the roof of the train carriages, and other equipment such as traction inverter (VVVF), filter inductor (FL), traction motor, auxiliary power supply system (APS), and battery charger (BCG) located on the underneath the train carriages. Heat dissipation from the abovementioned equipment can be found in Table 1 and the air flowrates for the A/C unit and the different trackway ventilation systems can be found in Table 2 respectively.

Table 1: Equipment Heat Dissipation

Equipment	Quantity per train	Heat Dissipation per train (kW)
ACV	12	162
VVVF	4	55.2
FL	4	128.8
Traction Motor	16	257.6
APS	2	39.8
BCG	2	3.6

Table 2: Flowrate of each Equipment

Equipment	Total Area (m^2)	Total Air Flowrate (m^3/s)
ACV	40	24
OTE	40	40
UPAS	25.6	40
UPE	25.6	40

4. NUMERICAL MODEL

4.1. Computational Domain and Boundary Conditions

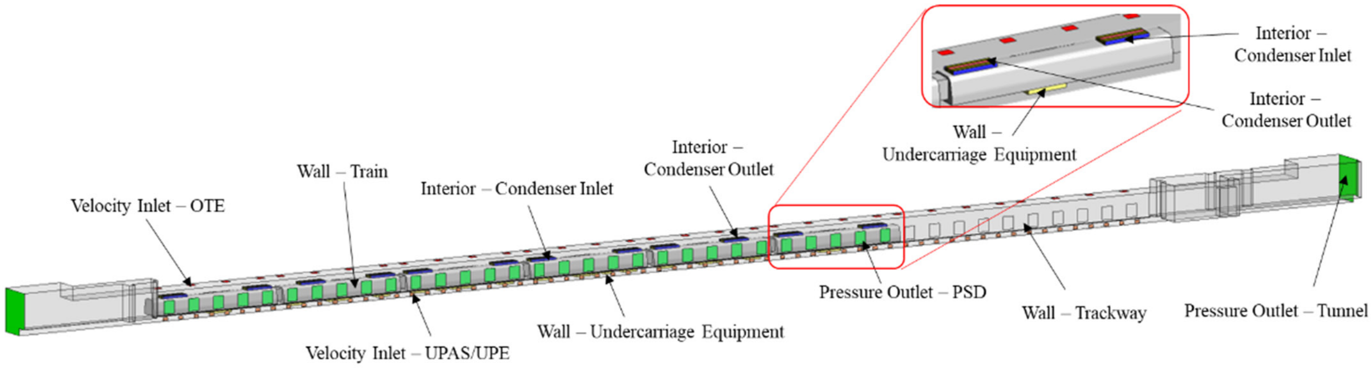


Figure 3: 3D view of Computational Domain

Although CRL stations are designed to cater for eight-car trains, six-car trains would be employed during the initial phase. Hence, PSD doors for the last two carriages at the station tail wall would remain closed. Figure 3 shows the computational domain of a typical station trackway with a six-car train located within the station trackway. Each train carriage has five numbers of doors, and they are aligned with the 30 numbers of PSDs indicated in light green. The OTE exhaust openings are indicated in red and the UPAS or UPE openings is reflected in orange. It should be noted that although the PSDs corresponding to the last two train carriages were closed, the supply and/or exhaust grilles for the OTE/UPAS would remain open and operate as intended. The A/C units have side air intakes depicted in blue, and top air discharge as shown in pink. On the underside of the train carriages, heat emitted from the equipment is shown in yellow.

Figure 3 also shows the boundary conditions that were used. The OTE, UPAS and UPE openings would be prescribed with *velocity inlet* as per Table 2. The end of the trackways indicated in dark green as well the PSD openings would be prescribed with the *pressure outlet* boundary condition. Backflow temperatures at the ends of the tunnel and PSDs were assumed to be 32°C and 25°C respectively. Heat emitted from equipment located along the undercarriages would be prescribed as *walls* with their respective heat fluxes. Finally, the A/C unit was modelled as fluid domains, prescribed with fixed values and energy sources to correspond with the fan and heat from the A/C unit.

The air flow was assumed to be independent of time, i.e., steady state and air was assumed to be non-viscous and density changes were accounted for by the incompressible ideal gas law.

4.2. Grid Independence Study

A grid independence test was performed by keeping the global mesh sizes constant while refinement to the local mesh sizes were half of the previous. Three sets of computational grids were produced as shown in Table 3. To ascertain grid independence, area-weighted average temperature and velocity at the 13th PSD openings were compared. Mesh types B and C produced similar results within 10% discrepancy. Hence, numerical analyses for this study would be performed with the use of mesh type B.

Table 3: Grid Independence Study

Mesh Type	A	B	C
Mesh Count	1,764,164	2,709,693	3,227,694
Temperature at 13th PSD (°C)	304.54	303.26	303.06
Error (%)	0.42	-	-0.07
Velocity at 13th PSD (m/s)	0.26	0.13	0.21
Error (%)	34.75	-	7.47

5. RESULTS AND DISCUSSIONS

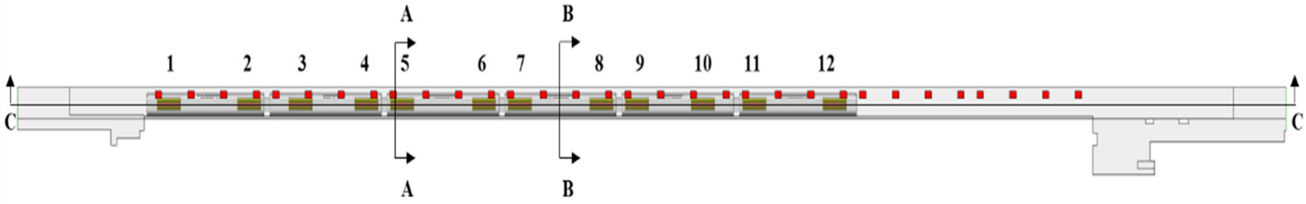


Figure 4: Cutting Plane Locations of Results (Plan View)

Results for the trackway ventilation systems are discussed in this section. Figure 4 shows the locations where results would be presented, and the numbers indicated correspond to the naming convention of the A/C units. Section A-A corresponds to a vertical section indicating the flow of air through the OTE and/or UPAS or the UPE, as well as the PSD openings. Section B-B cuts across a typical section of the PSD opening, away from the A/C units. Section C-C cuts across the exhaust openings of the A/C units.

5.1. Under-platform Exhaust (UPE)

Results for the UPE system is discussed in this section. The velocity vector at section A-A in Figure 5 indicates air was exhausted through the UPE openings, but some of the heat from the A/C unit was recirculated back into the air intake openings on the two sides. Figure 6 shows that in areas away from the A/C unit, the air flow might be relatively stagnant, as indicated by low air velocity of no more than 0.2m/s. In both illustrations, train A/C units drew most of air into the tunnel via the open PSDs.

Figure 7 and Figure 8 show the temperature contours along sections A-A and B-B respectively. Based on the results, it is evident that the A/C units drew air into the tunnel via the open PSD doors as the air temperatures near the PSD were between 25°C and 27°C. Although the UPE is effective in removing some of the heat from the undercarriage, the air temperatures within the tunnel are mostly at 45°C and above. Based on Figure 7, it seems that the air drawn into the tunnel by the train A/C units was wasted, as it was exhausted through the UPE openings, while cool air from the station platform area passed through the gap between the train and PSD. Figure 8 also shows that some of the heat could be trapped within the tunnel between the UPE openings due to limited air movement. Figure 9, which shows the temperature contour along section C-C, suggests that inadequate removal of heat within the tunnel led to the longitudinal propagation of heat, resulting in the temperature at the roof of the train carriages rising to 45°C and above, potentially causing A/C units to unload.

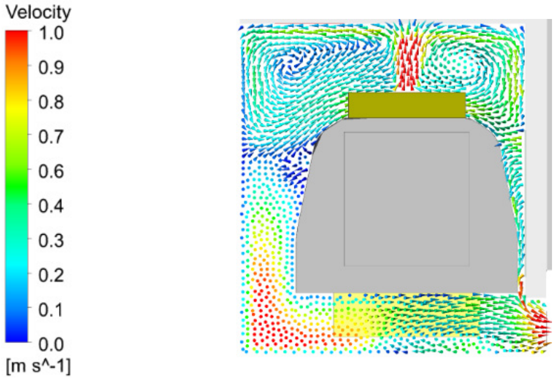


Figure 5: Velocity Vector of Air Distribution across Profile across Section A-A

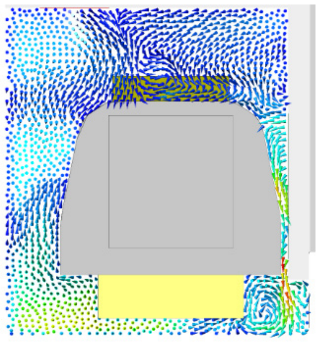


Figure 6: Velocity Vector of Air Distribution across Profile across Section B-B

Figure 7: Temperature Contour of Air Distribution across Profile across Section A-A

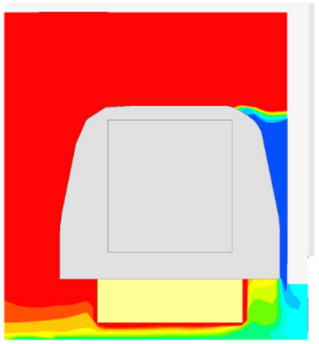
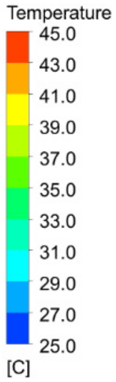


Figure 8: Temperature Contour of Air Distribution across Profile across Section B-B



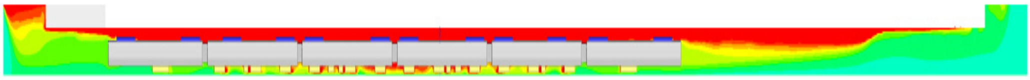
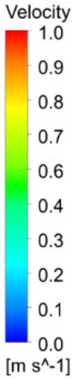


Figure 9: Section View of Temperature Contour across Section C-C

5.2. Over-track Exhaust (OTE)

This section discusses the results of the OTE system. Figure 10 and Figure 11 show the velocity vectors at Sections A-A and B-B respectively, while Figure 12 and Figure 13 show the corresponding temperature contour plots. Figure 10 shows that air from the A/C unit and undercarriage travels upwards and was then exhausted by the OTE. The OTE system shows higher air velocity in the tunnel as compared to the UPE system, as depicted in Figure 11. Like the UPE system, both Figure 10 and Figure 11 show that some air from the tunnel infiltrated into the station public area through the open PSD doors.

Figure 12 and Figure 13 show that the cool air drawn from the station public area assisted in maintaining the temperature within the tunnel to no more than 41°C at the top of the tunnel, except at localised areas near the exhaust openings. The results in Figure 14 demonstrated a similar trend, indicating that the tunnel temperatures can be maintained below 35°C.



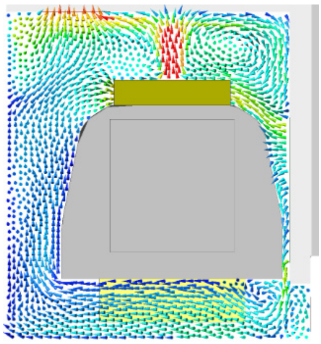


Figure 10: Velocity Vector of Air Distribution across Profile across Section A-A

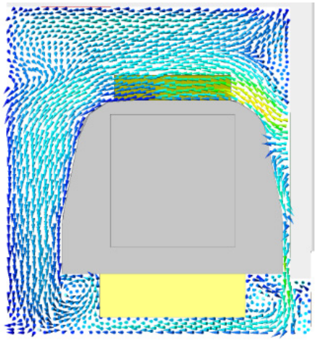
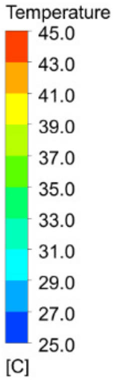


Figure 11: Velocity Vector of Air Distribution across Profile across Section B-B



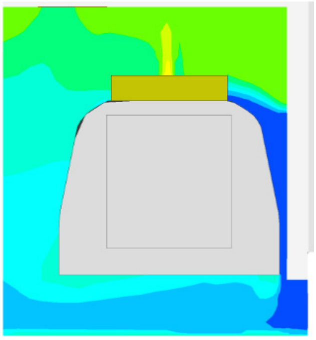


Figure 12: Temperature Contour of Air Distribution across Profile across Section A-A

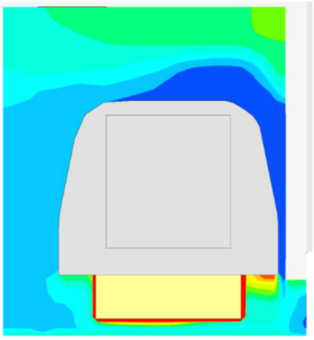


Figure 13: Temperature Contour of Air Distribution across Profile across Section B-B

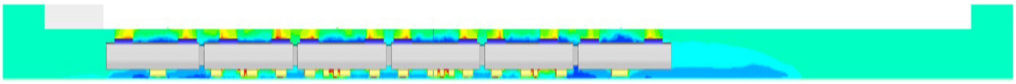


Figure 14: Section View of Temperature Contour across Section C-C

5.3. Combined Over-track Exhaust (OTE) and Under-Platform Air Supply (UPAS)

Airflow patterns for the combined OTE and UPAS system in sections A-A and B-B show that air from the UPAS openings pushes the heat from the undercarriage away from the PSD, before being exhausted through the OTE. Unlike the earlier two systems, a portion of the air from the A/C unit was drawn into the tunnel at low levels, while some of the warm air, ranging from 35°C to 37°C enters the station through the open PSD at high levels as shown by temperature contours in Figure 17 and Figure 18 respectively. However, it should be noted that some recirculation of heat from the discharge back to the intake of the A/C system is observed, particularly at the air intake near the PSD. This could be due to the OTE openings located off-centred, away from PSD. However, results in Figure 19, along section C-C, shows that although heat accumulation occurs at localised areas near the vicinity of the condensers, temperature throughout the tunnel is largely maintained below 35°C.

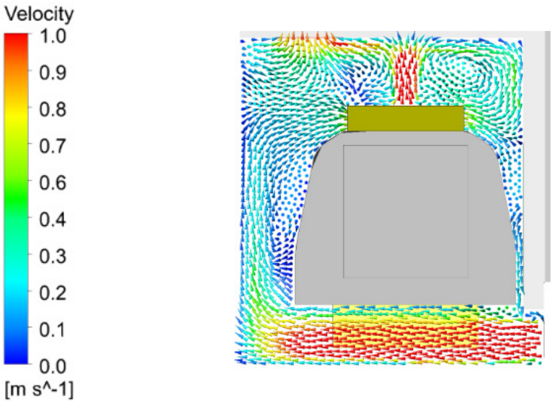


Figure 15: Velocity Vector of Air Distribution across Profile across Section A-A

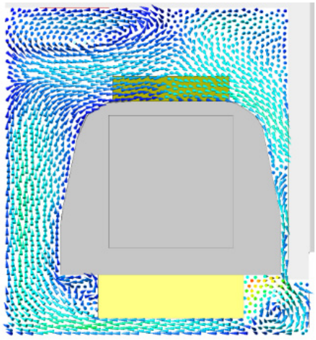


Figure 16: Velocity Vector of Air Distribution across Profile across Section B-B

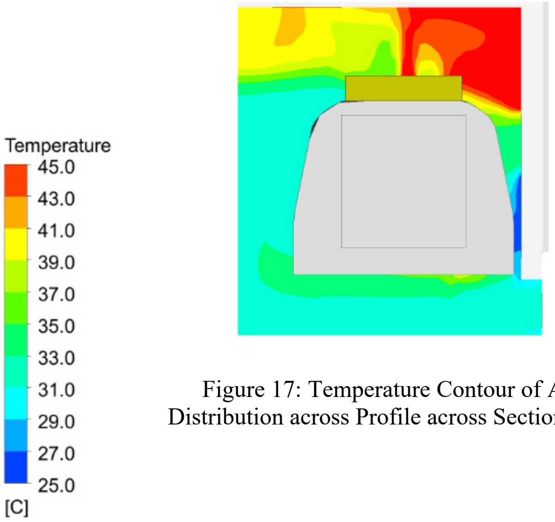


Figure 17: Temperature Contour of Air Distribution across Profile across Section A-A

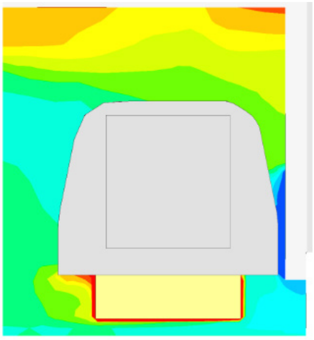


Figure 18: Temperature Contour of Air Distribution across Profile across Section B-B

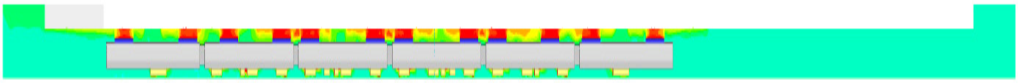


Figure 19: Section View of Temperature Contour across Section C-C

6. SUMMARY AND CONCLUSION

This section summarises the results presented in the earlier sections. Table 4 shows the average air inlet temperature at the respective train A/C unit condensers.

Table 4: Area-Weighted Average Inlet Temperature for Each Condenser

Condenser Location	**Temperature (°C)**		
	UPE	**OTE**	**OTE & UPAS**
1	59.20	32.90	37.49
2	65.34	31.85	38.24
3	68.31	32.71	39.44
4	68.96	33.92	40.47
5	69.08	32.99	40.18
6	69.32	31.84	40.45
7	69.28	31.52	40.15
8	68.76	32.85	40.56
9	68.18	31.35	40.22
10	67.04	31.60	40.56
11	64.27	29.99	38.72
12	58.66	31.07	37.99

For the current CRL train configuration with the A/C units located on the roof of the carriages, the conventional UPE system was not effective as it was unable to maintain the temperatures at the air inlet of the A/C unit condenser below the design criteria of maximum 45°C, thus potentially causing the A/C units to trip.

Both the OTE and the combined OTE and UPAS systems were able to maintain the temperatures at the air intake of the A/C unit condensers below 45°C. However, the temperatures at the condenser air intakes were generally lower for the OTE when compared to the combined OTE and UPAS system.

Table 5 shows the amount of air exchange through the PSD for the three systems. Positive and negative values indicate exfiltration of cool air from the station into the tunnel and infiltration of hot air from the tunnel into the station respectively. It is evident from Table 5 that both the UPE and OTE systems have significantly higher exfiltration of station cool air into the tunnel but smaller infiltration of tunnel hot air into the station as compared to the combined OTE and UPAD system. Conversely, the combined OTE and UPAS system resulted in a reduced pressure differential between the tunnel and station as compared to both the UPE system and the OTE system, thus reducing the overall air exchange through the open PSDs.

Table 5: Air Infiltration and Exfiltration at the Tunnel through Open PSDs

	Volume Flow Rate (m^3/s)		
	UPE	**OTE**	**OTE & UPAS**
Exfiltration	22.66	26.73	4.06
Infiltration	-3.50	-1.53	-4.99

In conclusion, the UPE system is not effective for the CRL as it cannot maintain the temperature in the tunnel within the design criteria of maximum 45°C and there was significant exfiltration of cool air from the station into the tunnel. Conversely, while the OTE system can maintain the lowest average temperature at the air intakes of the train A/C unit condensers, there would be significant exfiltration of station cool air into the tunnel through the open PSD. Although the combined OTE and UPAS system may result in higher air intake temperatures at the train A/C unit condensers as compared to the OTE system, the temperatures were well below the design criteria of maximum 45°C. Additionally, the OTE and UPAS system reduced the overall air exchange through the PSDs, which in turn led to impact to the A/C system of the station. Hence, in conclusion, the combined OTE and UPAS system would be the preferred trackway ventilation system for the CRL.

7. FURTHER STUDIES

This paper only studied the effects of the trackway ventilation systems during train dwelling at the stations. However, other factors could also be explored. This includes the use of 1D and 3D simulation tools to ascertain the infiltration and exfiltration rates due to the piston effects as trains ply between stations. The overall effect on the power consumption on the station A/C system due to infiltration of tunnel warm air and exfiltration station cool air could also be further evaluated.

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