ABSTRACT

Appropriate ventilation of underground rail transit (RT) systems has been a primary concern in the design of these systems. The ventilation concept of RT systems comprises two main issues, namely emergency ventilation and comfort ventilation. The emergency ventilation concept refers to the situation when one or more cars of the operational trains catch fire and the need for safe evacuation of the passengers arises. The emergency ventilation can be divided into two sub branches, which are tunnel emergency ventilation and station emergency ventilation, both of which has its own technical issues and operational measures. The comfort ventilation concept refers to the situation when the air quality within the stations is reduced due to presence of working mechanical, electrical equipments, train operation schedules and over-crowded stations. The passenger comfort can also be disturbed by excessive air movements induced by train operations, and thus the need for taking measures arises. This paper will expand the aforementioned concepts on ventilation of underground RT systems, design criteria and technical issues, amplifying their corresponding importance for safe and comfortable public transport giving specific examples from specific applications in Turkey.

Keywords: emergency ventilation, comfort ventilation, fire simulation, underground rail transit systems, piston effect

1. INTRODUCTION

Due to increase in fuel prices and traffic intensity, the need for mass transit systems increased considerably in big cities. Being among the most effective mass transit means in terms of passenger transport capacity, the underground rail transit systems are continuously built in cities whose populations are growing rapidly. From passengers' point of view, these systems should be fast, reliable, cheap and maybe above all, they should be safe and comfortable. The safety and comfort issues are closely related with ventilation strategies of these systems and these strategies play an important role in the planning and design process of the overall system. Ventilation for emergency requires selection of properly sized emergency ventilation fans and their equipment. Ventilation for comfort is important for passengers, who ought to be subjected to clean and comfortable air conditions, and it requires selection of appropriate ventilation fans and suitable ducting, as well as taking constructional measures to mitigate the adverse effects of air movements induced by train operations. These requirements must be determined and analyzed at the very first stage of planning and design phase of the overall system and the construction of the system must be started after these safety and comfort issues are warranted by technical investigations.
2. EMERGENCY VENTILATION

One of the most important safety measures of underground RT systems is the isolation of people from the danger zone when a part of the train catches fire. This is obtained by directing the generated smoke to a predetermined direction by ventilation equipment and evacuating the passengers in the opposite direction. The generated smoke is leaded to the predetermined direction by having sufficient amount of air velocity which is obtained by the emergency ventilation fans and equipments. In Turkey, these fans are usually located at the ends of the underground stations which have their own emergency ventilation rooms where these fans are seated. The initial design parameter of the emergency ventilation system is the determination of fan capacities which are capable of supplying sufficient amount of air into the fire location. Ventilation shafts and channels should be investigated to determine the fan total pressure rise requirements. The necessary amount of air that should be supplied into the fire zone and the features of emergency ventilation system are strongly affected by the fire load in the system. Thus, the fire load of the operational trains must be determined or gathered from technical specifications before the design and selection of the emergency ventilation fans and equipments. The underground RT systems in Turkey have different fire loads for emergency ventilation design because the trains are different for each city-specific application. The fire load of Underground Light Rail Systems in Istanbul and Bursa are specified as 15 MW\(^1\) and 12 MW\(^2\), where those of Ankara and İzmir are 9 MW\(^3\) and 12 MW\(^4\), respectively. The fire load of Istanbul Metro System is specified as 18 MW\(^5\) and that of Ankara is 15 MW\(^6\). Emergency ventilation can be divided into two sub branches, tunnel emergency ventilation and station emergency ventilation.

2.1. Tunnel Emergency Ventilation

The emergency situation in a tunnel initiates when a carriage of the train catches fire and train stays inoperable within the tunnel. At this situation, the passengers must be evacuated according to the requirements of a proper ventilation/evacuation scenario, which is capable of supplying fresh air above the critical air velocity over the fire zone, while evacuating the passengers to a safe zone free of smoke and excess temperatures. The critical air velocity is defined as the minimum air velocity that can drag the smoke to the downstream of the fire zone and prevent backlayering. Thus an escape route free of smoke and high temperatures for the evacuees is formed opposite to the ventilation direction. If the ventilation velocity is smaller than the critical velocity, then backlayering will occur and the escape route will be affected by the smoke and high temperatures.

In Turkey, the emergency ventilation of tunnels is usually accomplished by push-pull principle. This principle requires that the emergency ventilation fans located at one side of the fire location should work in “supply” mode while those on the other side of the fire location should work in “exhaust” mode (Figure 1). The number of stations whose emergency ventilation fans should be operated in an emergency case is dependent on several factors such as the location of fire, track alignment, tunnel geometry and it is determined via fire simulations.

One important aspect in the tunnel ventilation is the selection of ventilation direction in case of a fire incident. The ventilation direction must be selected such that minimum number of cars would be exposed to smoke and minimum number of passengers is affected by the smoke. Thus, according to the fire location on the train, the system operator must decide on the direction where minimum number of people is affected by smoke during the evacuation period. Because the fire location along the train is indefinite as a design parameter, the
emergency ventilation systems in Turkey are designed conservatively, such that the system can satisfy critical velocity requirement at both ventilation directions.

Figure 1: Push-Pull working principle of tunnel emergency ventilation fans.

In addition to satisfying critical velocity requirement as the lower limit, the ventilation velocity should not exceed the high limit of 11 m/s, as suggested by the SES Design Handbook, NFPA 130 and the Technical Specifications in action in Turkey, in order not to impede walking of evacuating passengers.

The fire simulations must show that the ventilation velocity is higher than the critical velocity in the fire region. The fire locations used in simulations should be selected after a detailed system investigation. Special attention must be paid to regions where tunnel gradient is severe and cross sectional area of the tunnel is high. For most of the underground RT systems in Turkey, numerous fire scenarios covering all the critical locations along the tunnels are simulated on a systematic basis. After these systematic simulations, flow capacities of the emergency ventilation fans which are capable of supplying the necessary flow rates into the underground tunnels are determined. Because the portals, through which emergency ventilation fans supply air into the underground system, are usually located at the ends of the stations, the fraction of airflow that goes to the holding tunnels is affected by the system resistance at the other side of the portal. In order to increase the fraction of air flow that goes to the holding tunnels, thus having the opportunity to select lower capacity fans, various measures may be taken. One common solution to this problem in Turkey is the application of fire doors in tube stations (Figure 2). The fire doors obstruct the air flow so that minimum amount of air “leaks” through the stairways and connecting tunnels; so a higher fraction of air is diverted to the tunnel on fire. Also, dampers are mounted to have the chance to ventilate the intended tunnel more effectively by closing the opening to the adjacent track (Figure 2).

Figure 2: Typical Tube Stations with Fire Doors and Dampers

Crossover regions, where cross sectional areas of the tunnels are large, are one of the most critical locations along the tunnels in terms of emergency ventilation. The ventilation air velocity in these regions gets smaller and the possibility of backlayering increases. Additional jet fans are frequently used in these regions. Jet fans impose extra momentum into the volume
and the ventilation air is supported to gain sufficient velocity in the region. However the
designer should be aware of the geometry of the crossover region and should work in
conjunction with the construction engineers for proper installation. Possible constructional
limitations on the installation of the jet fans will affect the selection and positioning of jet fans
in these regions. Common practice in Turkey is to have at least two rows of jet fans, each row
having the capability of sustaining the design air velocity individually, in case one row
becomes out of service during the fire incident.

Furthermore the presence of crossover regions between two neighboring stations strongly
affects the ventilation capacity of the holding tunnels. The blockage effect of the train in one
holding tunnel causes the airflow to follow the other low resistant route, i.e. adjacent tunnel.
This situation is thoroughly examined in the simulations and necessary precautions are taken
to supply the sufficient amount of air into the fire locations (Figure 3).

**Figure 3:** Typical precaution by jetfans in Crossover Regions

The temperature distribution along the evacuation route is another important design
parameter. NFPA 130<sup>th</sup> standard suggests that the temperature along the evacuation route
should not exceed 50°C. The simulations should be checked to satisfy these criteria and the
results should be presented to the authority.

How the emergency ventilation system is operated for particular fire scenarios are presented
via tables. These tables must give the information on the emergency ventilation fans to be
operated, their modes (supply or exhaust), jet fans and their operation directions, other
operational measures like fire door openings, evacuation direction etc. according to the each
critical fire location (Table 1). These tables are then integrated to SCADA systems which
automatically select the proper ventilation scenario for a particular fire location.

**Table 1:** A Typical Summary of Fire Scenarios

<table>
<thead>
<tr>
<th>SCENARIO</th>
<th>Station A fan A1-A2</th>
<th>Station A fan A3-A4</th>
<th>Station B fan B1-B2</th>
<th>Station B fan B3-B4</th>
<th>FIRE LOCATION (m)</th>
<th>FIRE LOCATION (TRACK)</th>
<th>Critical Velocity (m/s)</th>
<th>Ventilation Velocity (m/s)</th>
<th>Max. Temperature (C)</th>
<th>Evacuation Distance and duration (m/sn)</th>
<th>Evacuation Direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Supply</td>
<td>Supply</td>
<td>Exhaust</td>
<td>Exhaust</td>
<td>12485</td>
<td>Track-1</td>
<td>2.67</td>
<td>3.14</td>
<td>304</td>
<td>217/289</td>
<td>Station A</td>
<td></td>
</tr>
<tr>
<td>2 Supply</td>
<td>Supply</td>
<td>Exhaust</td>
<td>Exhaust</td>
<td>12475</td>
<td>Track-2</td>
<td>2.69</td>
<td>3.19</td>
<td>314</td>
<td>217/289</td>
<td>Station A</td>
<td></td>
</tr>
<tr>
<td>3 Exhaust</td>
<td>Exhaust</td>
<td>Supply</td>
<td>Supply</td>
<td>12485</td>
<td>Track-1</td>
<td>2.67</td>
<td>3.46</td>
<td>195</td>
<td>255/340</td>
<td>Station B</td>
<td></td>
</tr>
<tr>
<td>4 Exhaust</td>
<td>Exhaust</td>
<td>Supply</td>
<td>Supply</td>
<td>12475</td>
<td>Track-2</td>
<td>2.69</td>
<td>3.47</td>
<td>194</td>
<td>169/225</td>
<td>Station B</td>
<td></td>
</tr>
</tbody>
</table>
2.2. Station Emergency Ventilation

The emergency situation in a station can be considered as the incident when a carriage of the train catches fire but the train is still operable and brought to the nearest station. At this situation, the passengers must be evacuated according to the requirements of proper ventilation scenario which is obtained by detailed fire simulations. For fire simulations of large and complex constructions like the stations, advanced computational fluid dynamics (CFD) tools are used. The detailed three-dimensional CAD models of the stations are obtained and these models are solved with CFD tools to monitor smoke and temperature distribution in the station. The regions of high smoke density and temperature are determined and the evacuation routes are selected along with the ventilation scenario. In station fire simulations, ventilation is mainly obtained with tunnel emergency ventilation fans. However, in some applications, over track exhaust (OTE) fans that are resistant to high temperatures are complementarily used to facilitate the smoke extraction. The transient analyses which simulate the growth of heat release are performed; the smoke and temperature distributions in the stations are investigated at each instant of time. The conditions along the evacuation route at any instant of time are checked from safety point of view and it is ensured that smoke-free, low temperature conditions are satisfied. In the stations, 10 meters visibility range is set as the criteria for smoke-free conditions and 50°C maximum temperature in the evacuation route is set as the low temperature criteria. The criteria for evacuation period are set as 6 minutes for platform level and 10 minutes for the station. So the transient CFD analysis is expected to show that the evacuation route meets the aforementioned safety criteria during this evacuation period. Usually the reliability of transient analyses of each ventilation scenario is checked with steady-state analysis that simulates the conditions when full fire load is present at the initiation of fire and stays constant until the end of the evacuation period.

2.3. The Properties of Emergency Ventilation Fans

The emergency ventilation fans of underground RT systems have bi-directional (supply or exhaust) operation capability and should be selected as axial flow fans with 100% reversibility (no performance reduction when direction of rotation is reversed). Fans and all the related equipment that are subjected to smoke and high temperatures must be resistant to high temperatures. NFPA 1308 standard suggests that the emergency ventilation equipment must resist 250°C during at least one hour. However, the temperature limit is set as 400°C in Istanbul and Ankara RT systems, which is very conservative. A total pressure drop analysis of the ventilation system in which the fans are operating must thoroughly be done in order to select the most appropriate fan in supplying the required flow rate to the system. 15% of calculated total pressure rise is generally added as safety factor. The fans must be selected such that they will operate in regions away from their stall limit on their performance curve. Fan motors are required to achieve their full operating speeds within no more than 30 seconds.

3. COMFORT VENTILATION

Comfort ventilation for underground stations is essential as the continuous operation of trains and passengers cause the air quality within the station to decrease regarding cleanliness and comfortable temperature levels thus a need for supplying fresh air arises. This need is fulfilled by two mechanisms. The first mechanism is the piston effect of trains within the holding tunnels. The circulation due to piston effect feeds the station partly with outside atmospheric air via piston relief shafts and stairways and partly with the air inside the tunnels. The second mechanism is the mechanical ventilation with OTE fans. In some applications, the emergency
ventilation fans are operated at reduced speeds and used for routine ventilation with the help of convenient ducting. The effectiveness of the comfort ventilation is measured by the air exchange rate criteria set by ASHRAE standards.

The transient air movement within the stations due to piston effect must be investigated by simulations. The amount of fresh air entering into the station via piston relief shafts and stairways for a certain time period is determined and checked whether the air exchange rate criterion is satisfied. Air exchange rate of the underground stations’ platforms levels is defined as the ratio of total amount of fresh air entering to the platform level during one hour to the volume of the platform level. In ASHRAE standards, this criterion is specified to be within 8-12 range for closed atriums which have working electrical and mechanical equipment in it9. For underground stations, big part of the air exchange rate is covered by train piston effect. The amount of air entering to the station is calculated by simulations. The amount of air entering to the station during one hour is highly dependent on the train headway, so the headway information of the trains must be obtained from responsible authority and the simulations should take this parameter into account. Usual approach in Turkey is to simulate the critical conditions when passenger density is low and the train headway is high. A typical headway value for low passenger density hours is 600 seconds (6 trains/hour). The results of simulations are checked whether the criterion is satisfied. In situations when the criterion is not satisfied or in unusual situations like the presence of hot air currents or cease of piston effect due to train failures inside the tracks, OTE fans, Under Platform Exhaust (UPE) fans and the concourse level air conditioning systems are operated to back up the complementary part. The emergency ventilation fans running at reduced speeds with the help of frequency converters can be utilized for comfort ventilation if air treatment equipments are available.

Other concern of the piston effect is the platform air velocity limit that should be satisfied. The technical specifications require that the maximum air velocity due to train piston effect on the platforms and stairways should not exceed 5 m/s and 2.5 m/s, respectively. In order to maintain these velocity limits within the station, the piston relief shafts are designed to relieve the excessive air flow outside the underground system. The applications in Turkey have two major types of relief shafts. In the first type (Ankara RT Systems), the shaft portals are located at the side or ceiling of the tunnels and a separate shaft is directly venting the excessive air into atmosphere. In the second type (Istanbul RT Systems), unlike the direct venting of the first type, the piston air is passed through the fan rooms (around the fan unit) and then reaches the ventilation shaft (Figure 4). Because the design should consider that the air current should face minimum aerodynamic resistance, the first type of design is preferable.

![Figure 4: Schematic Representation of Vent shafts in Ankara and Istanbul RT systems](image)

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If the piston relief shafts are insufficient for piston air relief, additional precautions are taken. One major precaution is to increase the airflow resistance between the ends of the stations and relief shaft portals by building high flow resistant structures. This increased resistance causes the air current to pass through the vent shafts instead of passing through high flow resistant structure. This method is applied in most of the stations of Istanbul underground RT system (Figure 5). Another precaution to increase the amount of air stream passing through relief shafts is the abrupt area increase associated with a smooth directing of the stream by aerodynamic construction. This is applied in Ankara underground RT system (Figure 5).

![Diagram of ventilation setup in Istanbul and Ankara RT systems](image)

**Figure 5:** Measures for reducing piston effect in stations

Air velocity values should be checked by simulations. The air velocity in the stations due to piston effect is highly dependent on the train blockage ratio (train cross sectional area/tunnel area) and train speed profile within the tunnels, so this information of the trains must be obtained from responsible authority and the simulations should take these parameters into account. In Istanbul and Ankara RT systems; the train speed limits within the tunnel and station are 80 km/hour and 40 km/hour, respectively.

4. CONCLUSION

In this document, the technical issues and approaches regarding the ventilation design and simulation of underground RT systems are presented. Some variations among the applications in Turkey in terms of design approaches and criteria are adverted. In order to have safe and comfortable ventilation, the systems must be planned and designed properly prior to the construction so that structural precautions can be taken more easily and must be maintained and operated with well-defined procedures and methodologies.
5. REFERENCES

1. İstanbul Metropolitan Municipality İstanbul Light Rail System Project Construction and Electro-Mechanical System between Otogar and Bağcılar Station Technical Specifications

2. Bursa Metropolitan Municipality Bursaray Light Rail System Project Construction and Electro-Mechanical System Technical Specifications

3. Ankara Metropolitan Municipality Ankaray Light Rail System Project Construction and Electro-Mechanical System Technical Specifications

4. İzmir Metropolitan Municipality İzmir Light Rail System Project Construction and Electro-Mechanical System of III. Phase-Bornova and Center Connection Technical Specifications

5. İstanbul Metropolitan Municipality İstanbul Underground Transportation System Project Construction and Electro-Mechanical System of IV. Levent-Ayazaga Section Technical Specifications


