Carbon Monoxide Concentration, Visibility and Smoke Simulation Underground Railway Stations in Case of Emergency

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Introduction

This paper evaluates 3D simulation for Karaj Metro Line 2 with Fire Dynamic Simulator (FDS) software in order to validate the smoke management principles for those stations have low ceiling due to limitation of construction. The main design parameter is based on a combustion model of the polyurethane material and Heat release rate of 10 MW for train fire relying on Eddy dissipation model. The simulation time considered according to NFPA 130 standard require the platform of the underground stations to be evacuated in less than four minutes, and to evacuate to a point of safety area in less than six minutes. The simulation time is 10 minutes.

According to NFPA 130 maximum allowed dry-bulb temperature must not exceed 60°C, air carbon monoxide (CO) concentration should be 1150 ppm or less for the first 6 minutes of the exposure, visibility should be at least 10 meters in public area at both platforms and concourse level and smoke clearance height on platforms and concourse level should be minimum 2.5 meters. The boundary conditions of simulation included station entrances with outdoor ambient temperature, tunnel interfaces with open draught relief shafts and platform exhaust with 80 m3/s flow rate. When train or baggage fire takes place on the platform level system should be able to maintain a smoke-free condition and minimum air carbon monoxide content in the egress path including platform, concourse and evacuation stairs.

Acceptance criteria

NFPA 130 defines the tenability conditions that shall be fulfilled in all scenarios.

- Event of train fire or baggage fire on the platform level:

The system shall be able to maintain a smoke-free condition in the egress path including, platform, concourse and evacuation stairs, in the event of a train fire or Baggage fire on the platform level.

- Event of a baggage fire at the ticket hall level:

The dedicated smoke exhaust system for concourse level shall be able to maintain a smoke-free condition in the egress path for passengers already presents in the concourse level but also for passengers coming from Platform and escaping towards the station entrances.

These conditions shall be maintained during all the evacuation time of 6min (NFPA 130).

Factors that should be considered in maintaining a tenable environment for periods of short duration are described in NFPA 130. In all scenarios the allowed maximum air temperature, visibility and CO concentration criteria should be fulfilled:

- Maximum allowed dry-bulb temperature must not exceed 60°C,
- Visibility of 10 m in public area on both platform and concourse levels,
- CO concentration shall be less than 1150 ppm for the first 6 minutes of exposure
- Minimum smoke clearance height of 2.5m

The design criteria regarding visibility, pollution and temperature during emergency operation of the metro system are given in Table 1.

Table 1: Visibility, smoke and CO concentration criteria during emergency operation

Parameter	Tunnel	Platform	Stairs
visibility for height h < 2.5 m for the first 10 min or end of self-rescue phase after start of the fire	-	>10 m	-
visibility for height h < 1.5 m in the time period 10 min or end of self rescue phase < t < 30 min after start of the fire	-	>10 m	-
smoke concentration	no smoke upstream of fire	-	no smoke
Air Carbon Monoxide Content for the first 6 minutes of the exposure	-	≈1150 ppm	-
Air Carbon Monoxide Content for the first 15 minutes of the exposure	-	≈450 ppm	-
Tenable temperature for 10 minutes of the exposure without incapacitation	<60˚C	<60˚C	<60˚C

The height h of a smoke-free layer of air is defined as the distance above the platform level (see also Figure 1).

Figure 1: Definition of acceptable conditions in station: Non-smoke layer with visibility of more than 10 m higher than 2.5 m above platform

Fire modelling parameters

The modeling of the fire will be based on a combustion model of the polyurethane material and heat release rate (HRR) is based on Eddy dissipation model. Equation 1 defines the design fire for the train fire as used for the ventilation check during emergency mode. The design fire is specified based on the temporal evolution of the heat release rate. The following are the design fire sizes:

$Q = 27.78\ t^2$ (1)

Q: heat release rate [W]
t: time [s]

Figure 2 shows parabolic increase of the heat release rate (HRR) from 0 MW to 10 MW during 0 < t < 10 min;

After t = 10 min: constant HRR of 10 MW

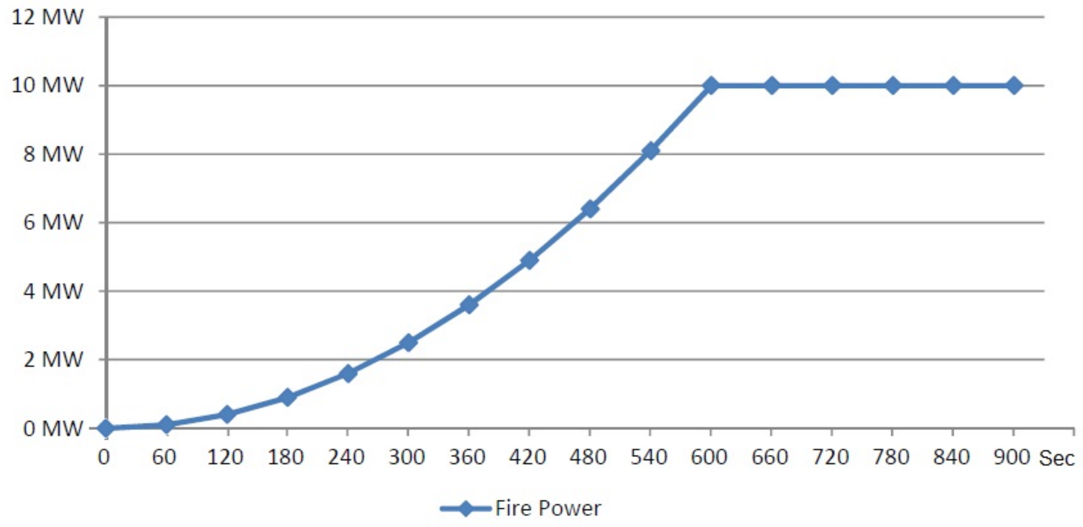

Figure 2: Heat release rate of the design fire (10 MW)

A maximum heat-release rate (HRR) of 10 MW was used in the numerical simulations. For the design fire a mixture fraction combustion model was used. The mixture fraction is a quantity representing the fuel and the products of combustion.

Given a volume containing a mixture of gas species, a mixture fraction can be defined that is the ratio of the mass of a subset of the species to the total mass present in the volume. In combustion, the mixture fraction is a conserved quantity traditionally defined as the (mass) fraction of the gas mixture that originates in the fuel stream. Thus, at a burner surface the mixture fraction is 1 and in fresh air it is 0. In a region where combustion has occurred this fraction will be comprised of any unburned fuel and that portion of the combustion products that came from the fuel. The mixture fraction is a function of space and time, commonly denoted Z(x; t). If it can be assumed that, upon mixing, the reaction of fuel and oxygen occurs rapidly and completely, the combustion process is referred to as “mixing-controlled.”

The definition of visibility through smoke can be made by using the following equation:

$$S = \frac{C}{K_M * \rho Y_S} \qquad (2)$$

where:

S	[m]	Visibility
C = 2.3	[-]	Visibility factor
K_M = 9250	m^2/Kg	Mass extinction coefficient
ρY_S	Kg/m^3	Density of smoke particulate within each volume element

It is assumed that a part of the train is burning. The fire is located inside the train and the smoke gases are free to flow out through the opened windows. In the model one opening for each side of the train is modelled. The location of the fire was chosen to be approximately in the middle of the train.

Simulation duration

The NFPA 130 standards require the platform to be evacuated in less than four minutes, and to evacuate to a point of safety in less than six minutes. The simulation time considered in the present study is equal to 10 min. This period includes the period from fire ignition to complete evacuation of passengers:

- t=0 s:

The train is stopped in the station,
A fire starts on the train.

- t=120 s:

The presence of fire is confirmed,
Evacuation of passengers from the incident train,
Alert sent to the control command center,
The ventilation system is activated.

- t=360s:
The platform area evacuated (4 minutes after the fire is confirmed).

- t=480s:
The station is evacuated (6 minutes after the fire is confirmed).

Ventilation System Hypothesis

In order to comply with the NFPA 130 requirement, several simulations have been performed in order to find the most adapted fire scenario by taking into account the constraint of the project.

From this iterative method, the following alternatives principle is proposed:

- **Train fire on platform level:** the principles are to:
  - Turn off the tunnel ventilation system and open the draught relief shafts
  - Put the Platform air supply system in reverse mode
- **Luggage fire on platform level:** same principle than above is proposed.
- **Luggage fire at concourse level:** it is proposed to use extraction at the level where fire lies.

The proposed ventilation principles have impact on the station architecture and civil work, particularly the extraction system on the platform and concourse level. The below chapter shows the most adapted fire scenario on platform level and the impact of the proposed system on stations:

Impact on the station

Platform arrangement

In order to have an efficient ventilation system on platform level, the best solution is to install the duct above the tracks and to implement the grilles along this duct. In comfort mode, it will very efficient because the fresh air will be forced to go over the platform where the people are standing. In case of fire, the smoke will fill the space between the arch and the duct and the grilles will extract directly in the smoke “tank”. In addition to this disposition, smoke curtains should be placed to the links towards the stairs. These smoke curtains should only allow a 2.3m free height for the passage of the people.

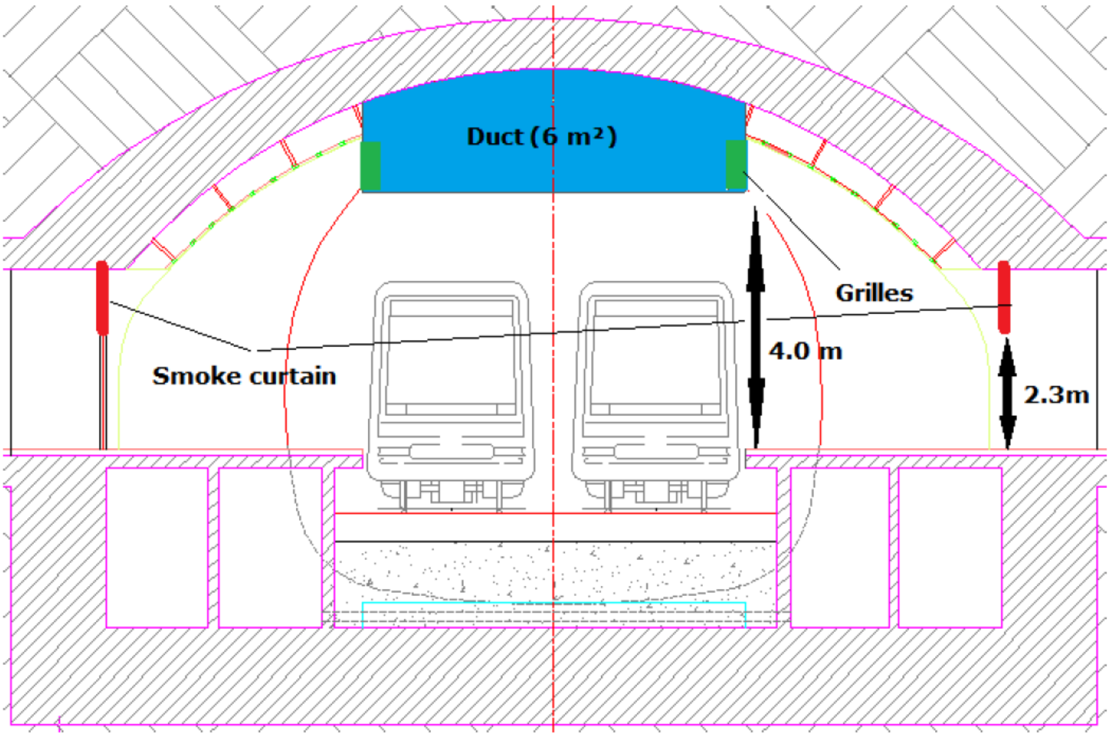

Figure 3: Schematic of smoke tank on platform level

Station air supply system

In order to have extraction system on the platform level, specific fans are generally provided. Considering the stations layouts, it seems that no extractions fan are located on the stations plans. Then, it is proposed to use the air washer fan in reverse mode.

The first impact is the fact that the fan shall be reversible. The second impact is the fact that a passage of smoke through the air washer system can damage this one. The best solution is to create a by-pass shaft to avoid the smoke travelling through the air-washer system. The creation of by-pass duct may have impact on the stations civil work. Then, the best solution consists of creating a horizontal by-pass duct to avoid passing through air washer. The size of this duct according to maximum air speed shall be around 8 m^2.

Concourse extraction

For the concourse level, no extraction is provided on the layout. In order to create an acceptable solution in case of fire, ventilation system must be create, otherwise the smoke exhaust is not possible and the concourse level will be totally smoky in case of luggage fire at the concourse.

The proposed solution is to provide an exhaust fan to be installed generally in the fourth ventilation room.

Simulations results in Station

The simulation presented below consider that an extraction system exist on the platform level (2 x 40 m3/s) and also at the concourse level (40 m3/s).

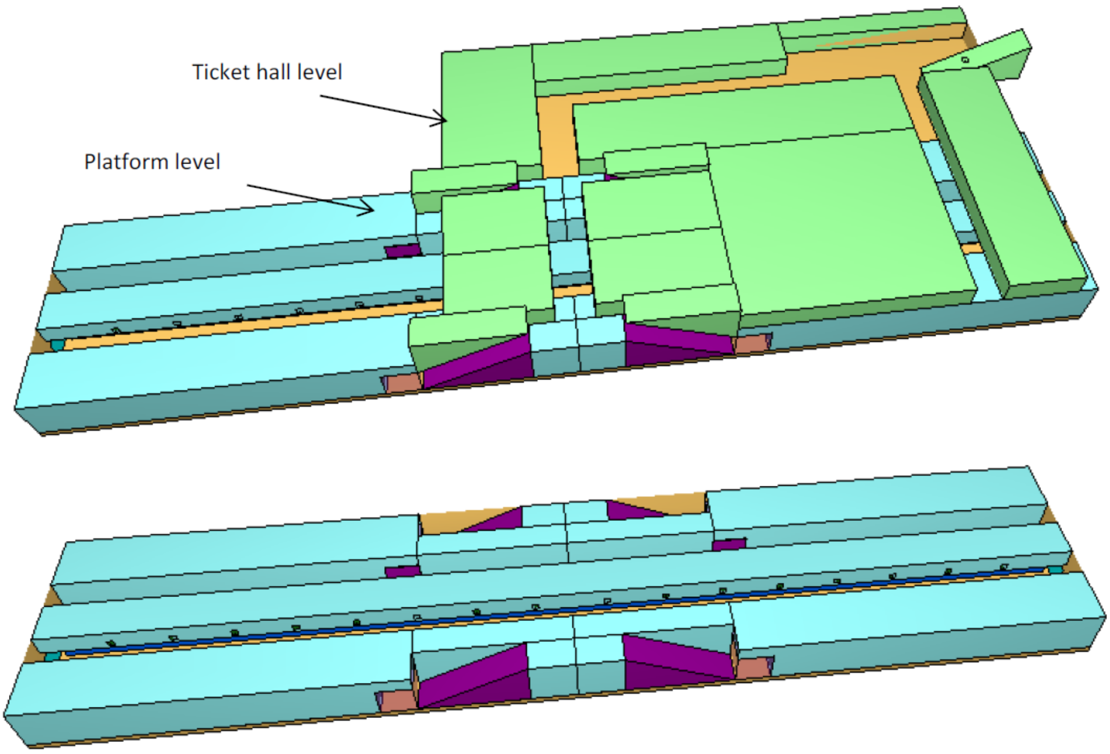

Figure 4: 3D model of station including platform and ticket hall

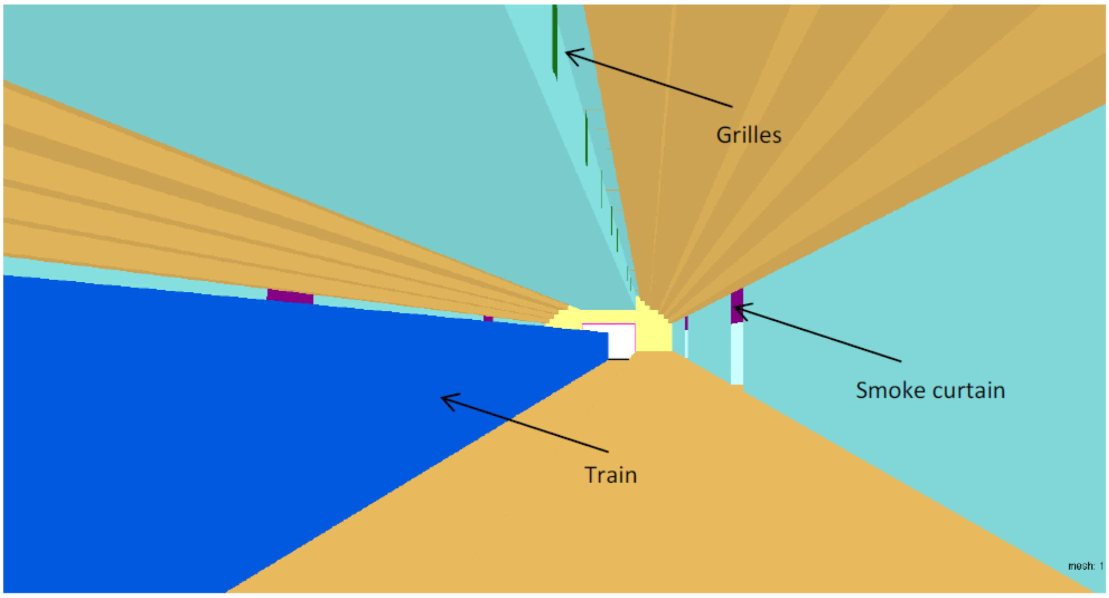

Figure 5: 3D model on platform of station

Train fire on platform level

The figure below shows the fire location on the side and on the roof of the train in the middle of the platform, which is the worst location as there is a risk of blocking the accesses to the concourse on this side.

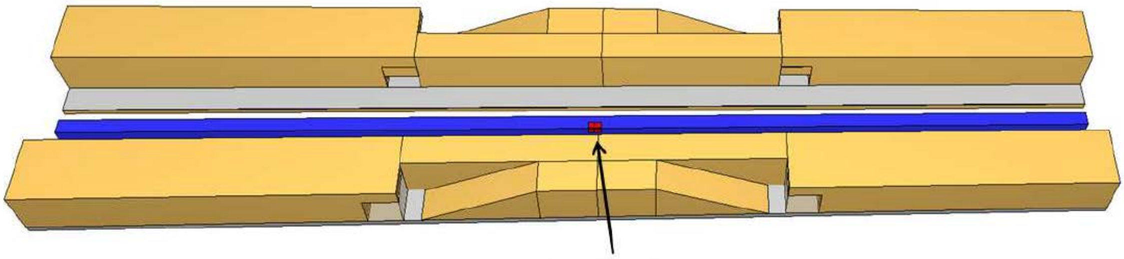

Figure 6: Fire location on platform

At t=120s, the platform exhaust fans of the station are activated. The tunnel ventilation is shut down and the draught relief shafts on both sides of the station are open to allow income of fresh air. Results of temperature, CO concentration and visibility indicate that the proposed smoke management system composed by the platform exhaust fans is capable of maintaining tenable conditions on the platform and at the ticket hall level that will allow a safe egress conditions. The figures below show that visibility, temperature and CO concentration monitored at a height of 2.5m remain acceptable during the evacuation period from the platform, with the hypothesis done.

The station is almost free of smoke at 2.5m above the platform enabling the majority of the passengers to use the stairs to the ticket hall the exits to the street. Even on the exhausting side of the station, we remark that stairs are still passable at the end of the platform evacuation at t=360s. The passages to the concourse are lower than the platform free height and they act like smoke curtains which helps maintaining the ticket hall completely free of smoke during the station evacuation time (480s).

- Smoke visualization at t=360s

Figure 7: Smoke visualization at t=360s

- Co concentration in kg/kg at t=360 s

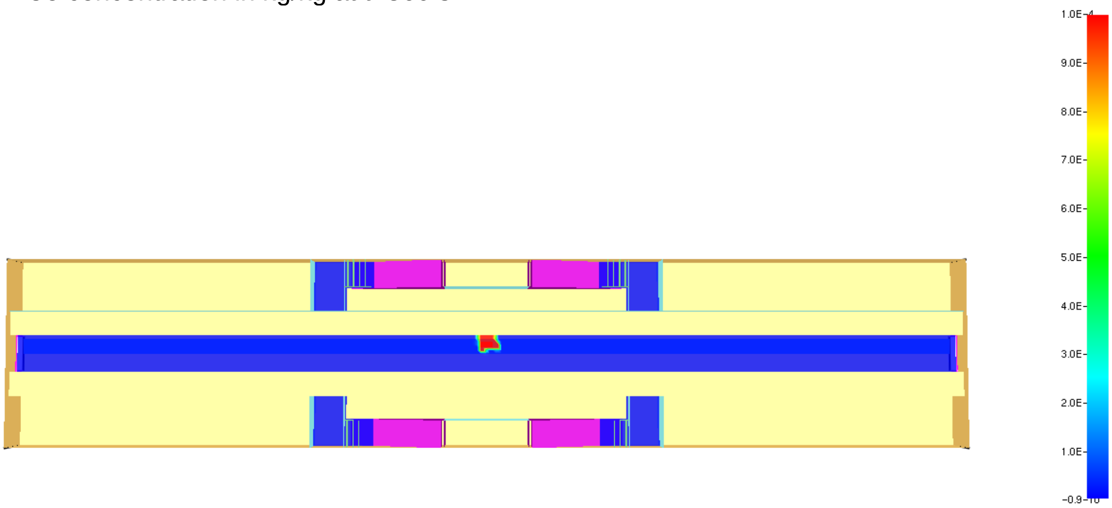

Figure 8: Train fire on platform: Co concentration at t=360s

The high CO concentration level is located just very close to the fire. On the rest of the platform, the level is way below the acceptance criteria.

- Temperature in °C

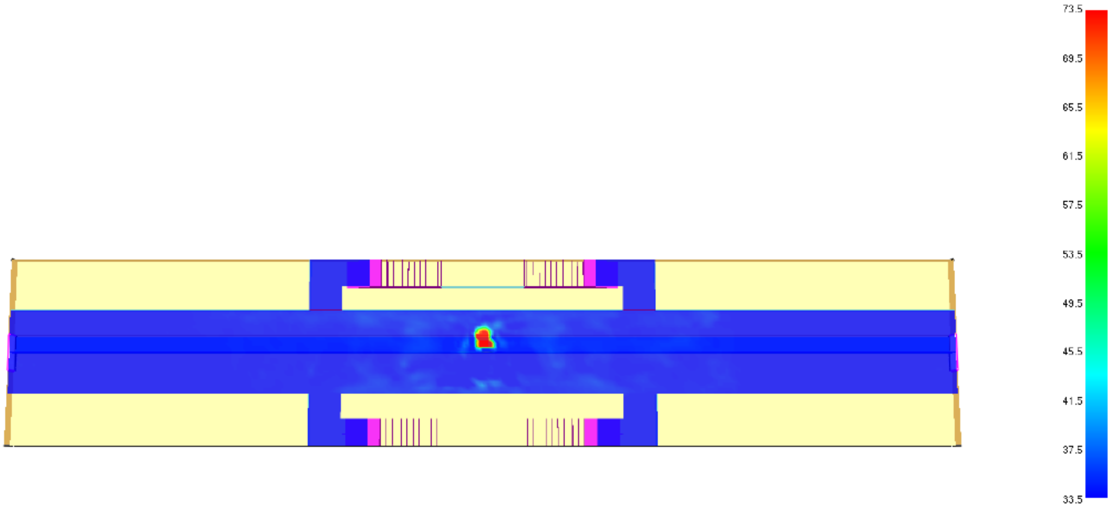

Figure 9: Train fire on platform: Temperature at t=360s

The stratification of the smoke layer due to the buoyancy effect makes the temperature below 2.5 m less than the acceptance criteria of 60°C even very close to the fire.

- Visibility in meter (m)

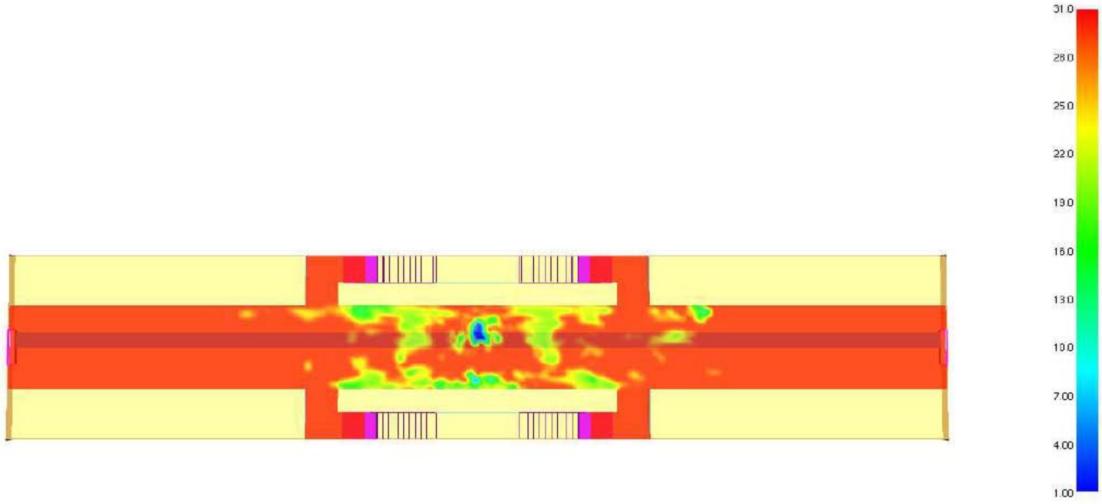

Figure 10: Train fire on platform: Visibility at t=360s

The results at 2.5m are very good. The smoke is kept at high level in the arch and is extracted by the system.

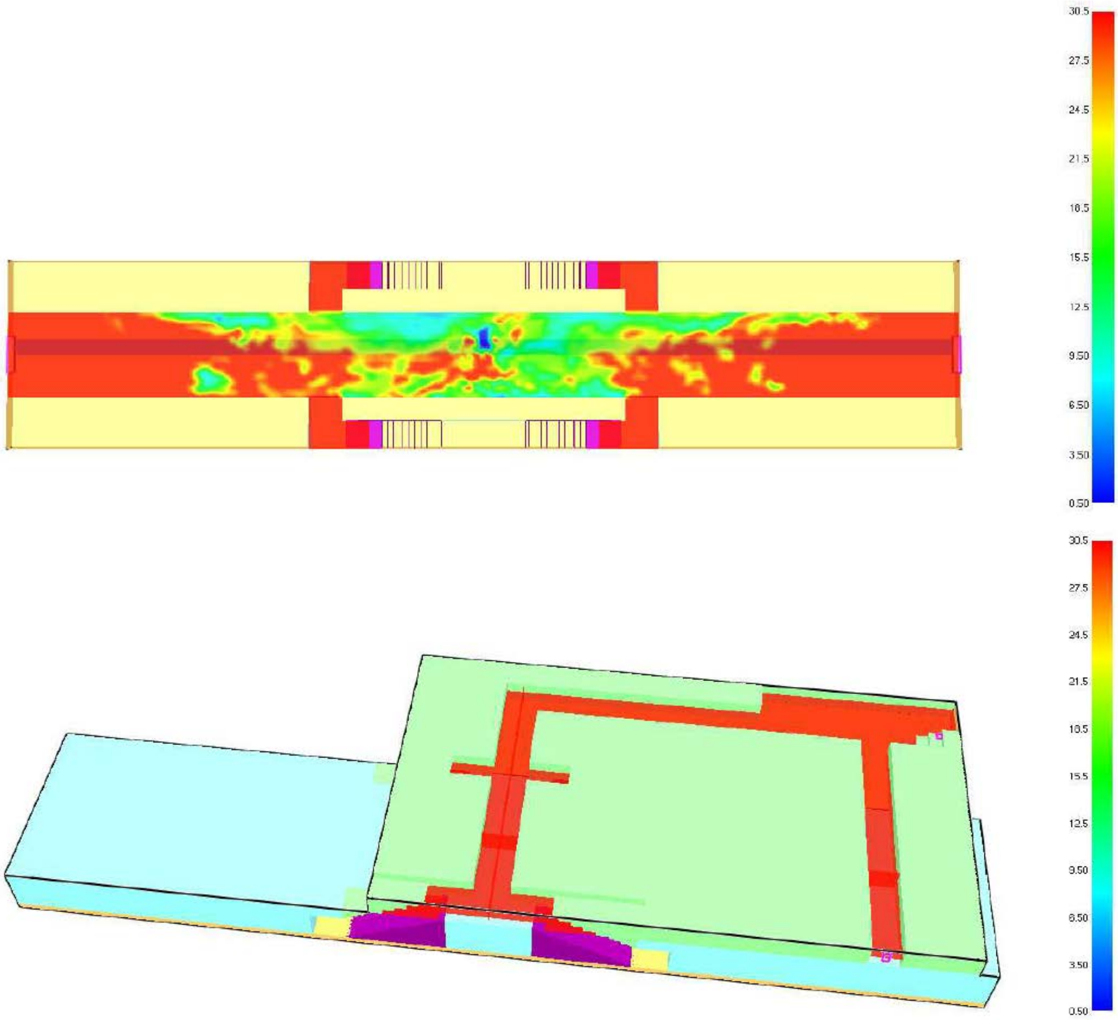

Figure 11: Train fire on platform: Visibility at ticket hall at t=480s

At the end of the station evacuation, the ticket hall is completely free of smoke and the conditions are normal.

Small fire on platform level

The figure below shows the fire location on the platform almost in the middle of the platform, which is the worst location as there is a risk of blocking the accesses to the ticket hall on this side.

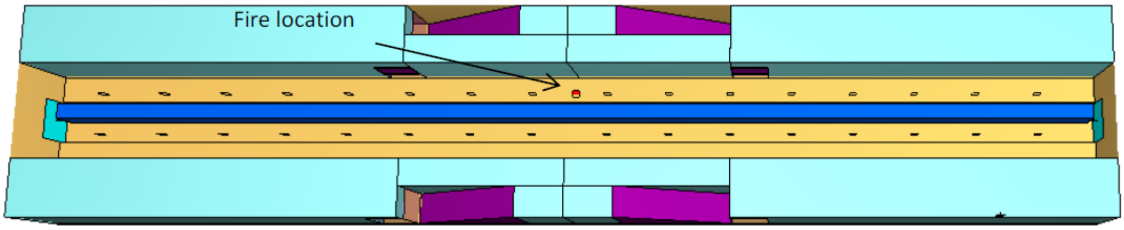

Figure 12: Fire location

Results of temperature, CO concentration and visibility indicate that the platform extraction rate is capable of maintaining tenable conditions on the platform and in the ticket hall public areas that will allow a safe egress conditions.

The smoke is stratified by the extraction of the platform exhaust fans. The visibility, temperature and CO concentration monitored at a height of 2.5m remain acceptable during the evacuation period from the platform, with the hypothesis done.

The passages to the concourse are lower than the platform free height and they act like smoke curtains which helps maintaining the ticket hall completely free of smoke during the station evacuation time (480s).

- CO concentration in kg/kg:

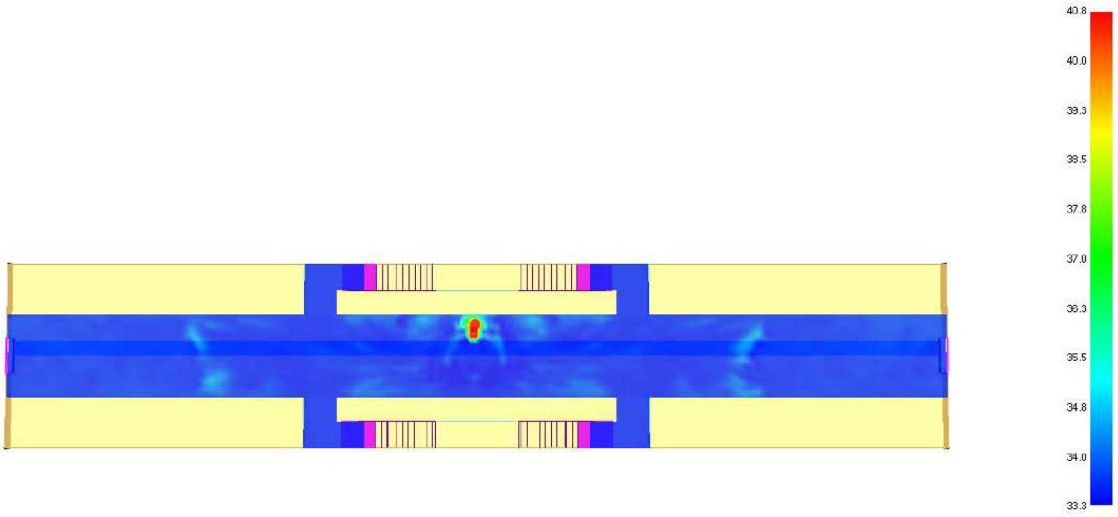

Figure 13: Small fire on platform: CO concentration at t=360 s

- Temperature in °C:

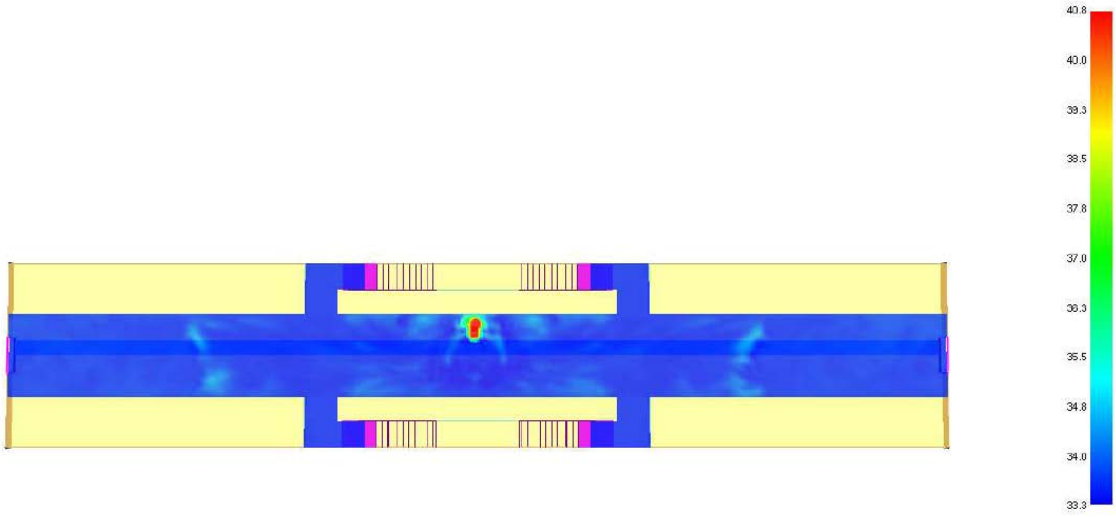

Figure 14: Small fire on platform: Temperature at t=360s

- Visibility in m:

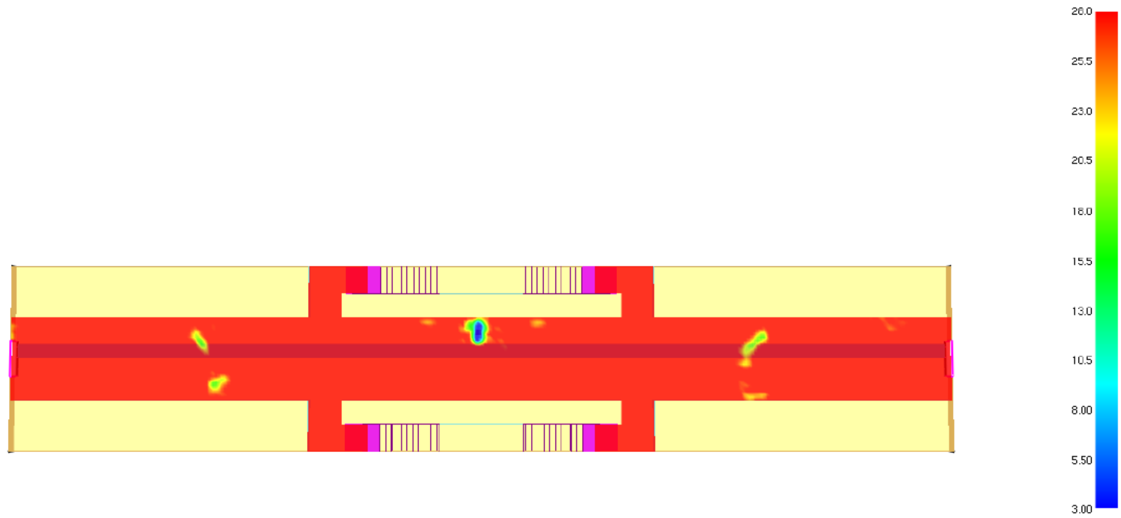

Figure 15: Small fire on platform: Visibility at t=360s

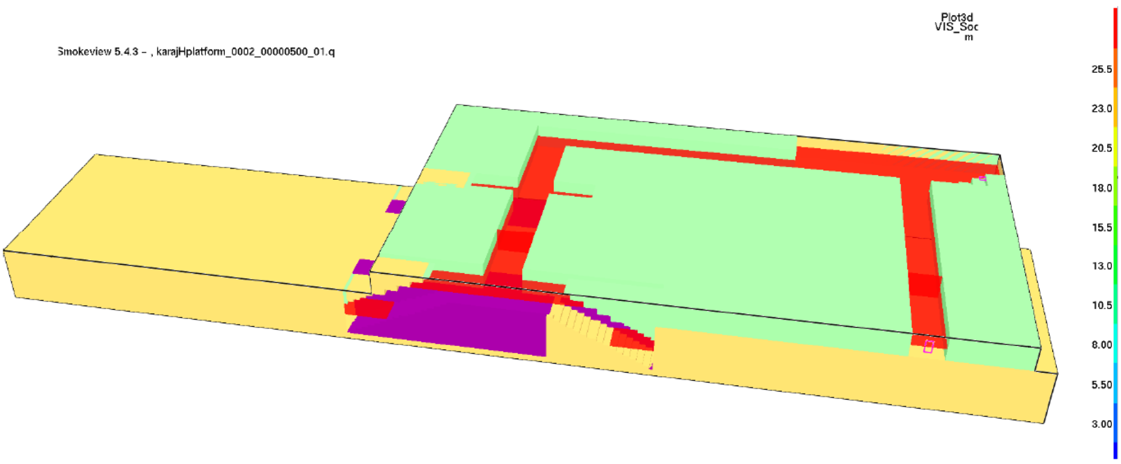

Figure 16: Small fire on platform: Visibility at ticket hall at t=480s

Small fire at ticket hall level

The figure below shows the fire location considered at the ticket hall level. It has been located between the two accesses from the platform which is the worst configuration.

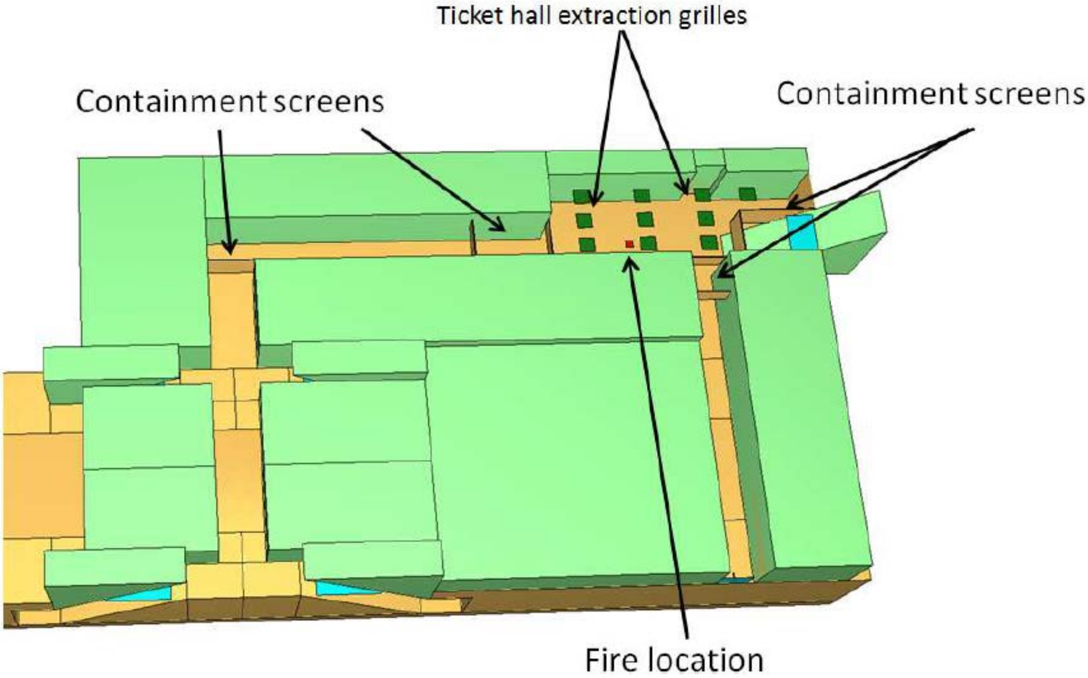

Figure 17: Small fire at ticket hall

The first simulations showed a lack of visibility and an escape of the smoke in the corridors. So some smoke curtains were added at the link between the ticket hall and the corridors in order to block the smoke in the ticket hall and improve the exhausting rate of smoke which will be closer to the exhausting grilles (the smoke curtains allow a height passage of 2.5 meters). More exhausting grilles (10) were used in order to homogenize the exhaust.

At t=120s, the ticket hall extraction system is activated.

Because of the small height (4 m) of the ticket hall the stratification effect is not as good as in usual station and it remains a little lack of visibility in the ticket hall. The path to the exit is still at a value of 10 meters visibility and the passengers can find their way out.

Results of temperature, CO concentration indicate that the ticket hall extraction system is capable of maintaining tenable conditions at the ticket hall that will allow a safe egress conditions.

The CO concentration is very low as the fire size is small. The smoke invades the level but thanks to the stratification and the extraction system, the visibility and temperature monitored at a height of 2.5m remain acceptable during the station evacuation time.

- CO concentration in kg/kg

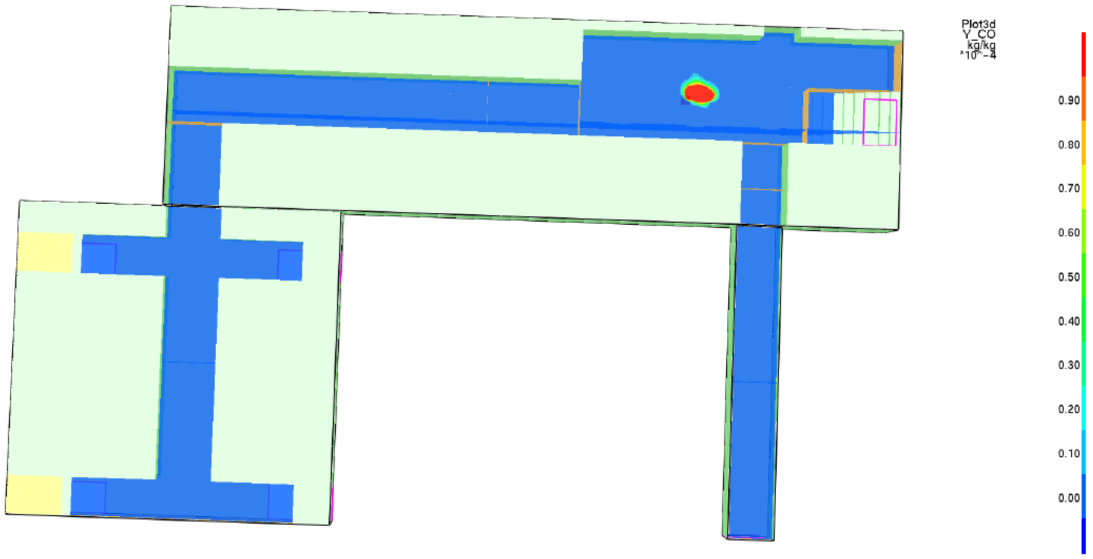

Figure 18: Small fire at ticket hall: CO concentration at t=480s

- Temperature in °C

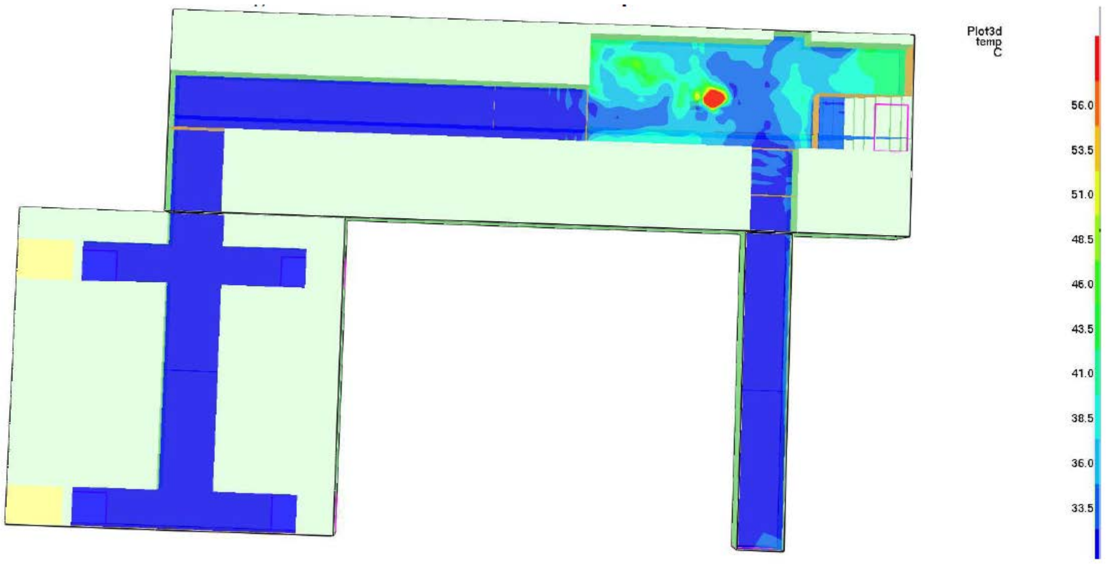

Figure 19: Small fire at ticket hall: Temperature at t=480s

• Visibility in m:

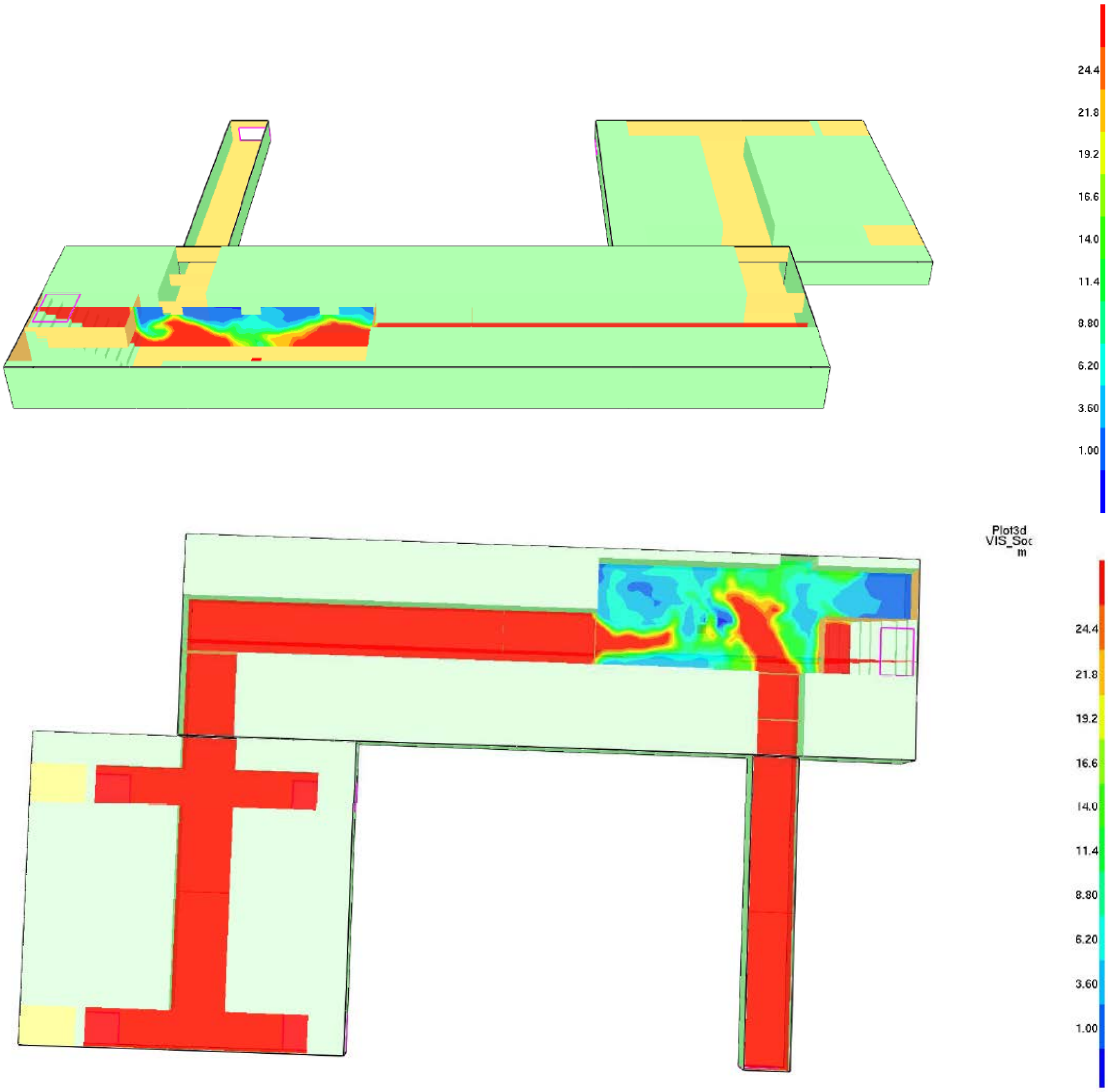

Figure 20: Small fire at ticket hall: Visibility at t=480s

Conclusion

The simulation results show that the fire location on the side and on the roof of the train in the middle of the platform, which is the worst location as there is a risk of blocking the accesses to the concourse. Results of temperature, CO concentration, smoke clearance height and visibility indicate that the proposed smoke management system composed by the platform exhaust fans is capable of maintaining tenable conditions on the platform, evacuation stairs, concourse and ticket hall level that will allow a safe egress conditions for passengers.

In stations without smoke evacuation system through using this method passengers are evacuated from the platform to the safe area without exposure air carbon monoxide (CO) and high temperature hazardous with visibility of over 10 meters.

It is proposed to use the air washer fan in exhaust mode and to use the supply air duct on the platform level as an exhaust duct. The arrangement proposed on the platform level gives very good results.

It is also advised to create a by-pass shaft at the air washer equipment level. In the case where the proposed solutions cannot be acceptable for the project (civil works restrictions, cost, delay...), smoke may pass through the air washer but specific measures shall be considered (fire rated equipment, possible replacement of the air washer after a fire…).

For the concourse level, it is proposed to have an extraction system either via a connection to the air washer fan (same principle as for platform but additional duct shall be provided on the concourse level), either via a dedicated fan (space for this fan shall be studied for each station). The solution depends on the location of the air washer fan and the possibility to provide connection

Under proposed assumptions, the 3D Fire Dynamics simulation conclusions are the following:

- The smoke management system insures tenable conditions for the 3 stations in case of a train fire and a small fire on platform.
- A solution without any ventilation does not insure tenable conditions.
- In case of fire in the ticket hall, the system management system is totally efficient in station Q because of the height of the ticket hall and the stratification of the smoke. In stations F and H the results are less good because of the small height (4 m) of the ticket halls and the visibility is in some little areas lower than 10 meters. Smoke curtains shall be added in order to improve the system. But there is still a path to the exits with a visibility of 8-10 meters.

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