DISCUSSIONS ON CRITICAL VELOCITY IN TUNNEL FIRES

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ABSTRACT

Critical ventilation velocity is the most crucial parameter in emergency operation in tunnel ventilation. It is the minimum longitudinal velocity to be provided in order for preventing reverse smoke movement in a fire event. Therefore, safe passenger evacuation depends on longitudinal air flow provided against buoyant smoke flow. This strategy, pushing air flow against smoke has been effective for decades. The critical Froude model is used to calculate required velocity in globally accepted standards and industry. Calculation of the critical velocity defined by several parameters namely; tunnel cross section area, fire size, incoming air temperature, tunnel height and also grade factor and Froude number factors. In latest NFPA 502 standard published in 2017 Froude number factor is changed as function of fire size which was a constant value in 2014.

This study targets to explore effectiveness of the classical calculation method considering different parameters which are not included in current method. Smoke behavior with different train-tunnel blockage ratios and different train overhead gaps are investigated with computational fluid dynamics method using Fire Dynamics Simulator (FDS). The main objective of this investigation is to assess current calculation methodology and explore effect of other parameters on smoke behavior.

Keywords: *Tunnel ventilation, critical velocity, fire*

INTRODUCTION

Critical velocity is defined as the minimum longitudinal velocity that should be presented against smoke flow to prevent back-layering in a tunnel fire. This value is critical for safe evacuation of passengers and defining required tunnel ventilation fan capacity, related auxiliary equipment and structural needs.

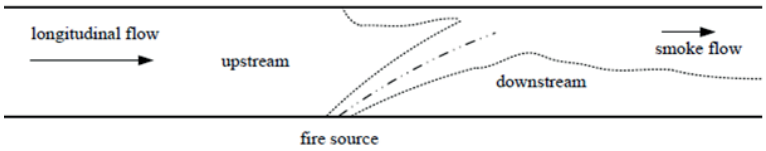


Figure 1. Critical velocity and smoke behavior [1]

According to Thomas' works [2,3] smoke movement can be stopped by providing an air flow upstream greater then buoyancy of hot smoke. He presented critical Froude number and K factor and defined critical Froude number as a function of air velocity, tunnel height, tunnel cross section area, air temperature. Kennedy [4], in 1996 introduced a conservative Froude number of 4.5 resulting a Froude number factor K_1. He also included a grade factor K_g to take tunnel slope in to account.

$$V_c = K_1 K_g \left(\frac{gHE_c}{\rho C_p A T_f}\right)^{1/3} \quad (1)$$

$$K_g = 1 + 0.0374(grade)^{0.8} \quad (2)$$

Later Li et al. [1] suggested that conservative Froude number proposed in Kennedy's work is not appropriate for all fire sizes as this study was based on 124 MW fire. They revealed that for relatively small fire sizes critical Froude number decreases resulting a higher Froude number factor K_1.

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In NFPA 502 Standard for Road Tunnels, Bridges, and Other Limited Access Highways-2017 edition, Li et al.'s methodology is addressed and increasing Froude number factor is introduced as in Table 1.

Table 1. Froude number factor in NFPA 502 [5]

Q(MW)	K_1
>100	0.606
90	0.62
70	0.64
50	0.68
30	0.74
<10	0.87

In this paper, critical velocity definition is investigated with a realistic tunnel-train configuration. The target is to reveal back-layering behavior and efficiency of phenomenon Li et al. [1] introduced. This parametric study focuses on overhead gap(OG) which is the distance between train top and tunnel ceiling and tunnel-train blockage ratio(BR). These parameters are changed in a number of 3D geometric model and CFD simulations are conducted in FDS software.

GEOMETRIC MODEL

A typical bored metro tunnel cross section is used as a base of geometric model. As FDS uses cartesian grid, tunnel geometry is converted to a rectangular model. Tunnel dimensions are 5.8m x 5.2m x 220m (HxWxL). The train placed 20 m away from the entry of the tunnel at left. Burning train car length is 22 m and cross section is changing according to blockage scenarios. The rest of the train is modeled as a single block for flow continuity.

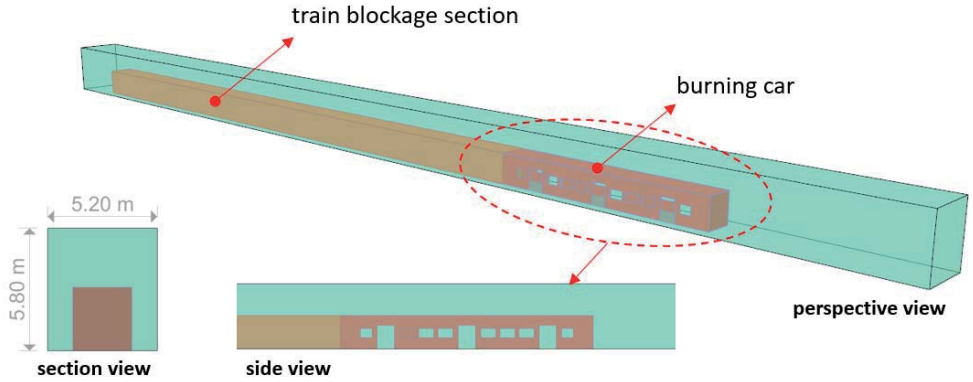


Figure 2. Tunnel and train geometry

SIMULATION PAREMETERS

Train-tunnel blockage is dominant parameter in this study as it affects free area in the tunnel for air flow requirements. A larger train cross section leads lower air velocity to achieve critical flow. A low blockage configuration, on the other hand, requires significantly more airflow to achieve the same ventilation.

Second parameter of this investigation is overhead gap(OG); by adjusting the train vertical position the gap between the train top and tunnel ceiling is adjusted. Several different overhead gaps have been investigated between 0.2m and 1.8m. It is expected that, the effect of OG should be very low that it would be negligible as it is not affecting a variable in discussed critical velocity calculation methodology. However, contrary to expectations results shows a dramatic difference in smoke behavior and back-layering distance. Results are discussed in following sections. Simulation matrix is presented in Figure 2 in order to explain the approach to simulation sets.

An additional mesh sensitivity case has also been included in the study to show the adequacy of the grid resolution.

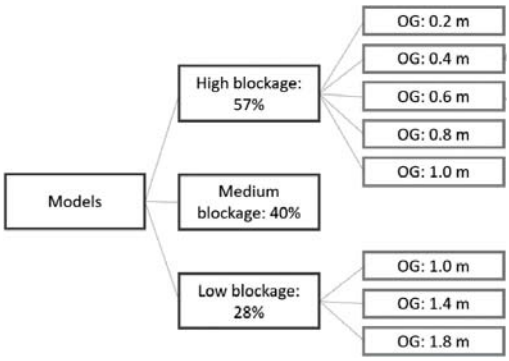


Figure 3. Simulation Matrix

SIMULATION CONDITIONS

The simulations include a single carriage fire. The fire starts at the rear end of the train and remains within the single carriage. The fire related parameters are kept constant for all the simulations, as given in Table 2. Fire is set to the full size from the start without growth. Similarly, the inlet boundaries are also applied without any ramping behavior. This simulates the steady conditions when the fire reaches to its peak value in the tunnel.

Table 2. Simulation conditions

Fire Settings		
Fire Size	8.8	MW
Convective Fraction	100 %	-
HRRPUA	1000	kW/m^2
Soot yield	0.1	kg/kg
Heat of Combustion	25300	kW/kg
Other Settings		
Tunnel velocity Inlet	critical velocity	m/s
Tunnel outlet	atmospheric outlet	-
Winter ambient temperature	-2.5	°C
Summer ambient temperature	28.3	°C
Grid size	0.2 x 0.2 x 0.2	m
Total simulation time	1000	sec.
Tunnel walls	concrete	-

The simulations are carried out in winter design conditions for London. The ambient temperature is taken as -2.5 °C. Winter conditions are selected since it causes a stronger buoyancy and leads to stronger back-layering. Nevertheless, a single summer case is also included in the study to compare the ventilation behavior. The summer design temperature is taken as 28.3 °C.

For all of the simulations, a constant grid size of 0.2x0.2x0.2 m (L x W x H) is utilized. This corresponds to a grid resolution between moderate and fine, based on the characteristic fire diameter as described in FDS user manual [6]. A mesh sensitivity analysis has also been performed for one of the sample cases, in which the grid has been refined further to 0.1x0.1x0.1 m to check the impact of the grid on the ventilation character.

RESULTS AND DISCUSSION

OVERHEAD GAP

OG is the vertical distance between tunnel ceiling and train top. Distance is varied between 0.2m and 1.8m. Simulations are conducted under -3% slope conditions with the ventilation in downgrade direction. While modifying the OG, train blockage is taken as constant; in other words, the train is moved upwards only to modify the gap. The results showing BD is given in Figure 4 for high blockage scenario. Back-layering decreases and disappears as the OG is increased,

this can be explained by the reforming of the flow around the train, as the gap below the train diminish the side and top gaps provide a more equal flow distribution leading to overcome the back-layering.

#	OG (m)	Longitudinal Section / Case: High Blockage	BD (m)	CV (m/s)
1	0.2		124 m	1.11
2	0.4		116 m	1.11
2-S	0.4		114 m	1.08
3	0.6		98 m	1.11
4	0.8		62 m	1.11
5	1.0		No BL	1.11

Figure 4. Back-layering distance: High Blockage – Variable OG

BLOCKAGE RATIO

Train blockage is modified by changing train height and width in three different case. In high blockage with 57% BR, train is 4.8m H x 3.6m W, in medium blockage case with 44% BR train is 4.2m H x 3.2m W and lastly in low blockage case train has a 3.0 m height and 2.8 m width with 28% BR. The simulations carried out for 1.0 m OG. Furthermore, the tunnel slope is taken as -3.0%.**Hata! Başvuru kaynağı bulunamadı.** 5 shows the ventilation performance behavior for different blockage cases. For medium blockage case, smoke back-layers until the end of the train and it remains at that level. In low level case back-layering is stronger and even exceeds the farther end of the train and proceeds up to the inlet boundary. This behavior indicates a very strong back-layering behavior.

#	Blockage	Longitudinal Section	BD (m)	CV (m/s)
1	High		No BL	1.11
2	Medium		BL	1.48
3	Low		BL	1.70

Figure 5. Back-layering distance: Different Blockages

GRID SENSITIVITY

A finer grid has also been tested to check the behavior of the fire for the same model. The aim of the grid sensitivity is to see if the back-layering behavior is affected by the grid resolution; i.e. whether the smoke back-layers or not. Grid adjustment is applied to the whole extent of the tunnel. The standard grid size of 0.2x0.2x0.2 m is adjusted for this particular case as 0.1x0.1x0.1 m, allowing further resolution inside the domain. The aim is to have more elements in the tunnel which can provide better resolution in the fire zone and better adjustment of airflow around the train. The case with high blockage and OG of 0.4 m is investigated for this purpose. The tunnel slope is taken as 3% for this case. The results show the back-layering behavior as presented in Figure 6. The finer grid shows a slightly shorter back-layering length, but the general characteristic of the flow remains the same.

#	Grid	Longitudinal Section / Case: High Blockage	BD (m)	CV (m/s)
1	Normal		116 m	1.11
2	Finer		110 m	1.11

Figure 6. Back-layering distance: High Blockage – Grid adjustment

CONCLUSION

During a metro train fire, smoke is pushed to appropriate direction in the tunnel to provide safe evacuation route for passengers. Critical ventilation velocity is the key parameter to stop smoke propagation to egress route. In this study, critical velocity calculation phenomenon and smoke back-layering distance are main focuses. Effect of BR and OG

gap on back-layering distance and smoke behavior is analyzed in 3D domain. Depending on the characteristics of the underground system and projects, these parameters may vary.
The parametric investigation shows that the flow behavior during ventilation changes significantly with blockage and overheard gap. Figure 5 shows the significant effect of BR on ventilation performance and smoke behavior. As the train cross section area reduces back-layering distance rises dramatically. The airflow passes beneath the train and reduces the airflow passing above the train. As a result, smoke back-layers more easily.

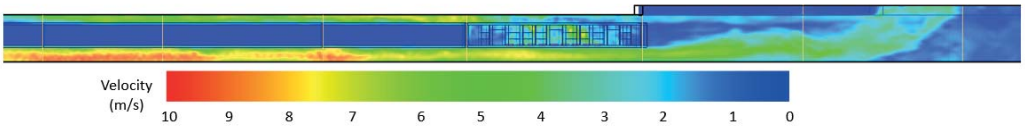


Figure 1. Centerline cut section showing the velocity contour - passes through the burning car – low blockage case

Overhead gap is another important parameter investigated in this study. Results are presented in Figure 4. As OG is increased back-layering distance reduces and ventilation performs better. In contrary, as this distance reduces the gap acts as a pathway for hot smoke, and it creeps backwards by the help of buoyancy. This is a dramatic result as ventilation requirement dictated in NFPA 502 standard is not changing with OG however it obviously affects smoke behavior. This is very critical and needs to be further investigated as passenger life may be under risk with rising back-layering distance.

NOMENCLATURE

$A = tunnel\ cross\ section\ (m^2)$
$c_p = specific\ heat\ of\ air$
$E_c = convective\ fire\ heat\ release\ rate\ (kW)$
$F_r = froude\ number$
$K_1 = froude\ number\ factor$
$K_g = grade\ factor$
$T_f = average\ temperature\ at\ fire\ site$
$V_c = critical\ velocity\ (^m/_s)$
$g = gravitational\ acceleration\ m/s^2$
$A = tunnel\ cross\ section\ (m^2)$

Greek symbols

$\rho = ambient\ density\ \left(^{kg}/_{m^3}\right)$

Subscripts
OG= overhead gap
BR= blockage ratio

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