EFFECT OF GEOMETRICAL PARAMETERS OF THE BURNING OBJECT AND VENTILATION VELOCITY ON THE MASS LOSS RATE IN TUNNEL FIRES

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Abstract

The 1/13 scaled model tunnel is constructed in order to investigate the blockage effect (the ratio of the model cross sectional area to the tunnel cross sectional area) on the mass loss rate inside the tunnel with different ventilation velocities. Scaling is done based on Froude number. In the experiments, wood sticks assembled in different geometrical configurations are burned with various longitudinal ventilation velocities inside the model tunnel. Mass of the burning models is measured to calculate the mass loss rate. A statistical model is developed by using Analysis of Variance (ANOVA) method. According to the statistical model, the variation in mass loss rate is composed of 81.0 % due to change in blockage ratio, 1.6% due to change in velocity, 13.1% due to change in thickness.

Introduction

Tunnels which have been used for mass transit since the 19th century are one of the primary means of transportation today. Tunnels possess fire safety tools consisting of detection, suppression and ventilation systems in order to use them safely. Although strict safety measures are implemented, fire incidents continue to occur inside the tunnels with generally catastrophic results. Fire can damage the tunnel and interrupt traffic for years. A detailed list of tunnel fires occurred in the history can be found at [1].

Longitudinal ventilation systems are used in order to sweep the smoke in case of a fire in the downstream direction which should permit safe evacuation of the passengers and safe intervention of fire fighters.. The proper ventilation/evacuation scenario should be capable of supplying fresh air above the critical air velocity over the fire zone defined as the minimum air velocity that can drag the smoke downstream of the fire zone and prevent back-layering. In this way, passengers can be transferred to a safe zone free of smoke and excess temperatures. Tunnel ventilation system is designed according to the design fire load. Proper ventilation for emergency requires the correct selection of the emergency ventilation fans and their equipments. It is crucial to predict the vehicle fire load for the design of emergency ventilation system.

Different types of tunnel fire studies have been performed in the literature. Various researchers investigated smoke control, critical velocity, vehicle fire load, temperature distribution along the tunnel and effect of ventilation on the burning rate in the tunnels. Full scale fire tests have been performed in order to investigate effectiveness of fire safety system in tunnels [1]. Kang investigated the effects of enclosure blockage ratio and aspect ratio on the critical velocity[2]. He suggested that tunnel hydraulic diameter of the annular area should be used for the calculation of the critical velocity in case of an enclosure fire within the tunnel. Lönnermark found a correlation between the energy content and the maximum heat release rate for passenger cars and heavy goods vehicles from data obtained for vehicle fire tests [3]. Ingason introduced simple mathematical expressions for the calculation of heat release rate in case of train compartment fire by performing experiments in a 1/10 scale model of a Swedish intercity passenger train compartment [4]. Heat release rate, time, energy and mass were scaled based on Froude number scaling. It is shown that the peak heat release rate was almost constant when all the windows were open at the time of ignition, independent of the interior surface materials used. Vauquelin and Wu investigated the influence of tunnel width on the critical velocity on a 1/20 scaled road tunnel [5]. It is emphasized that the critical velocity decreased as the tunnel width increased for aspect ratios greater than unity. On the other hand, for low values of the aspect ratio and for high enough fire heat release rates, the critical velocity significantly increased with tunnel width. Lee and Ryou presented their study on the effect of aspect ratio of the tunnel cross section on the critical velocity [6]. Based on Froude number scaling, the experiments were done in 1/20 scaled tunnels using ethanol as the fuel. It is confirmed that the critical velocity is dependent on the aspect ratio. It is found that as the aspect ratio of the tunnel with same hydraulic diameter increased, the critical velocity also increased. Carvel et al. investigated the influence of tunnel geometry and ventilation on the heat release rate of a fire [7]. It is shown that the heat release rate of fire in a tunnel is primarily influenced by the width of the tunnel. The heat release rate of tunnel fire also increased with forced ventilation velocity for car and wooden cribs fires and kerosene and heptane pool fires. Carvel et al. investigated the effect of forced longitudinal ventilation on the heat release rate for fires in the tunnels by using Bayesian methodology [8]. Data taken from cars, wood cribs and heavy goods vehicle fires are used and it is shown that forced ventilation has a great enhancing effect on the heat release rate of heavy goods vehicle fires, increasing the fire size up to 10 times. It is also shown that forced ventilation has little effect on the heat release rate of car fires.

There are very few studies in the literature on the tunnel vehicles (train, cars, trucks etc.) blockage effect and their geometrical configuration (i.e. length, width and height) on the mass loss rate, heat release rate and the critical velocity. In the present study, in order to investigate these effects, a 1/13 scaled model tunnel is constructed and based on Froude number scaling, wood materials with different geometrical configurations are burned in a controlled environment inside the model tunnel. The reasons for modelling vehicles with wood cribs are the following [9]. It is impossible to scale down the model vehicle due to a large variety of materials used in the vehicles. To simplify the tests, the variety of materials are represented by a single material, pine wood. Also it is hard to obtain the same configuration with different scale ratios due to the variety in geometrical configurations of vehicles. It is better to simplify the problem by conducting the tests with an easily constructed vehicle configuration. In many full scale tunnel tests, wood cribs are used and the total energy of the vehicles is simulated by an amount of wood of the same energy content in the tunnel [1].

The overall effect of the blockage ratio was previously studied by the authors [10]. However since it is possible to obtain the same blockage ratio from various geometrical parameter combinations, further experiments are performed and a statistical model is developed to investigate in detail the relative importance of various geometrical factors contributing to the blockage ratio. The mass loss rate measurements with different longitudinal ventilation velocities are also performed.

Experimental Setup and Scaling

A bored tunnel with a diameter of 520 cm and cross-sectional area of 20.75 m^2 is scaled down to a 1/13 scale. The scaled tunnel has a cross-sectional area of 0.128 m^2. An axial compressor is used to supply the air for longitudinal ventilation in the tunnel. The total length of the experimental setup is 650 cm without chimney connection. The model tunnel walls are covered with rock wool to isolate the system from extraneous effects. Figure 1 shows the experimental setup and the model tunnel dimensions.

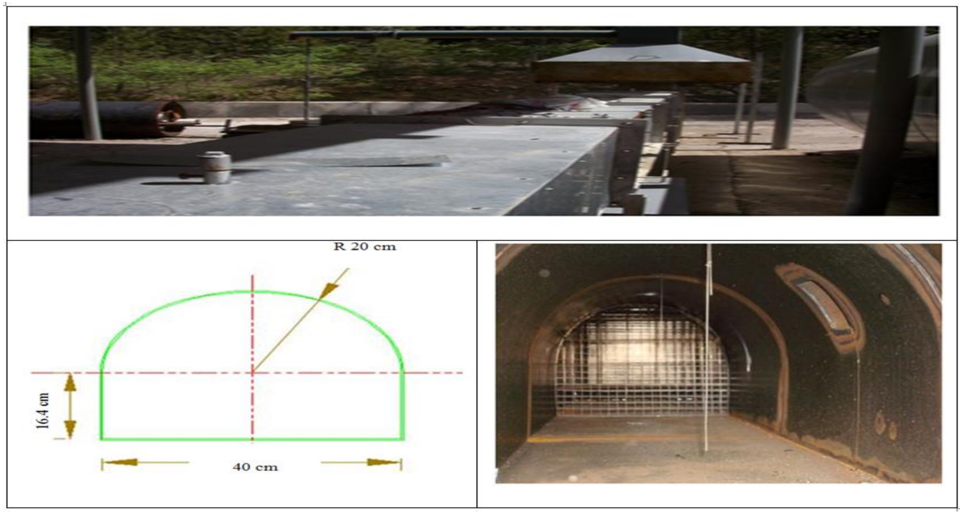


Figure 1. Model tunnel

The mass of the burning model in the tunnel is measured by A&D GF 20 K High Precision Industrial Balance. The modeled is installed on the balance [9] which measures weights up to 20 kg with a precision of 0.1 gr. The data taken from the balance are stored every second. The mass loss rate can be estimated by the following expression [11]:

$$-\left[\frac{dm}{dt}\right]_i = \frac{-m_{i-2} + 8m_{i-1} - 8m_{i+1} + m_{i+2}}{12\Delta t} \tag{1}$$

where m is the model mass (g), t time (s) and i is the data scan number.

Froude scaling technique has been widely used in small scale fire experiments. The scaling relationships based on Froude number for velocity (V) and heat release ($\dot{Q}$) between the model and fuel scale are expressed as follows [12]:

$$\frac{\dot{Q}_M}{\dot{Q}_F} = \left(\frac{L_M}{L_F}\right)^{5/2} . \tag{2}$$

$$\frac{V_M}{V_F} = \left(\frac{L_M}{L_F}\right)^{1/2} . \tag{3}$$

where L_M *and* L_F refer respectively to the model scale length and the full scale length (L_M/L_F = 1/13).

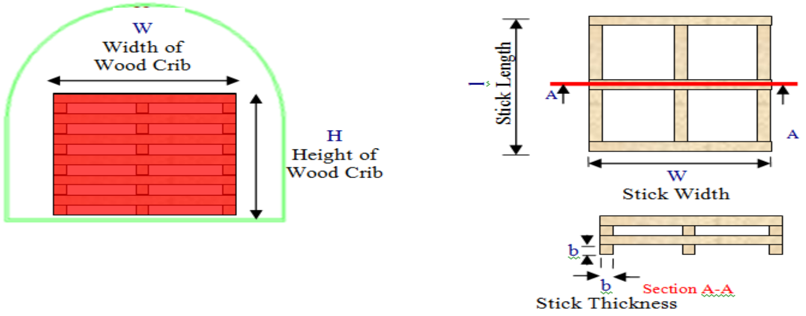
Fire Source and Experimental Design Parameters

The model vehicles are constructed as wood crib structures. The important parameters in the wood crib dimensions are the length of the sticks, spacing between the sticks, number of sticks per layer, thickness of the sticks and height of burning items. A large number of combinations of wood cribs are built by varying the mentioned parameters. In this study, the length and width of the mock-up models change from 10 cm to 30 cm. The number of sticks per layer is selected as 3. The heights of the mockup model vehicles are 12 cm, 18 cm and 24 cm. The thickness of the sticks are selected as 1 cm, 2 cm and 3 cm. The variety of length, thickness and height symbolizes the vehicles with different dimensions and different energy contents. The ventilation velocity inside the model tunnel is the other independent design parameter. In the experimental study, three different ventilation velocities (1 m/s, 2 m/s and 3 m/s) are tested. Design parameters and their ranges are listed in Table 1.

Table 1. Experimental Design Parameters

Design Parameters	*Values*
Stick dimensions (*b x b*)	1 cm x 1 cm /2 cm x 2 cm / 3 cm x 3 cm
Length of sticks (*L*) (Length = Width)	10 cm / 20 cm / 30 cm
Height of the wood cribs (*H*)	12 cm / 18 cm / 24 cm
Ventilation velocity (*V*)	0.5 m/s /1 m/s / 2 m/s / 3 m/s
Number of sticks per layer	3

In Figure 2, experimental design parameters and the wood crib structure construction details are presented.



$$\text{Blockage Ratio} = \frac{\text{Height of Wood Crib x Width of Wood Crib}}{\text{Model Tunnel Cross Sectional Area}} \text{ x } 100$$

Figure 2. Wood Cribs Design Parameters & Blockage Ratio

Before the experiments, the woods are placed in an oven at 100 ^{o}C for 10 hours to extract the humidity. The wood cribs are placed on the platform, the model tunnel ventilation is adjusted and the wood cribs are ignited with 100 ml of ethanol. The masses of the models are sampled every second.

Results and Discussion

The maximum mass loss rate (MLR) values are presented together with the geometrical parameters of the wood cribs in Table 2. There are 5 independent parameters which are thought to be important for the heat release rate. These are the ventilation velocity (V), model height (H), model length (L), model width (W) and stick thickness (T). It is difficult to discuss and isolate the individual influences of these parameters on the mass loss rate. In order to analyze the complex interactions of the geometrical factors and ventilation velocity, a statistical model is developed by using Analysis of Variance (ANOVA) method. This method depicts the variation in the response (here the MLR) by using the predetermined factors (here ventilation velocity and geometry). ANOVA method shows which factors have a significant effect on the response, and how much of the variability in the response is attributable to each factor [13].

Table 2. Experimental Result Table

V (m/s)	H (cm)	L (cm)	W (cm)	T (cm)	Blockage Ratio (%)	$P_{ambient}$ (kPa)	$T_{ambient}$ (^{o}C)	Rel. Hum. (%)	MLR (g/s)
0,5	12	10	10	1	9,3	92,8	18,4	55	2
1	12	10	10	1	9,3	92,5	21,7	34,7	2,25
2	12	10	10	1	9,3	91,4	24,1	31,1	2
3	12	10	10	1	9,3	90,3	27,7	22,1	2,5
1	12	10	10	3	9,3	91,8	20,4	53,4	0,47
2	12	10	10	3	9,3	89,55	34	21,5	0,5
0,5	18	10	10	2	14,0	92,8	17,6	51,3	1,5
1	18	10	10	2	14,0	90,9	25,6	28,9	1,6
3	18	10	10	2	14,0	91,4	30,8	22,7	2
1	24	10	10	1	18,7	90,7	33,3	20,7	3,8
2	24	10	10	1	18,7	90,4	29,8	41,6	3,5
3	24	10	10	1	18,7	91,4	29,7	28	3,84
1	24	10	10	3	18,7	89, 5	37,3	18,3	0,97
3	24	10	10	3	18,7	90,8	19,3	47,8	1,4
2	24	10	10	2	18,7	92	21,7	47,8	2,49
0,5	12	20	20	2	18,7	91,8	29,4	30,2	2,4
2	12	20	20	2	18,7	91	25	46,6	2,1
0,5	12	20	20	3	18,7	91,3	23,1	45	1,75
1	12	20	20	3	18,7	91	19,9	51,9	1,5
0,5	18	20	20	1	28,0	91,3	25,1	38,5	8,5
1	18	20	20	1	28,0	91,4	28,9	41,2	6,55
0,5	24	20	20	2	37,4	91,8	28	32	5,25
1	24	20	20	2	37,4	91,4	21,5	36,4	6
2	12	30	30	1	28,0	91,4	27,5	37,8	5
3	12	30	30	1	28,0	91,4	19,8	53,5	4,51
1	12	30	30	2	28,0	91	19,2	51,4	3,85
0,5	12	30	30	2	28,0	91,7	17,6	59,8	3
0,5	18	30	30	3	42,1	91,8	24,3	41,6	4,35
2	18	30	30	2	42,0	91,4	31,7	38,8	4,42
0,5	24	30	30	2	56,1	91,3	26,2	37,6	9,5
3	24	30	30	2	56,1	91,4	32,6	37,8	2,0
1	24	30	30	1	56,1	91,4	26,8	49,9	10
1	24	30	30	1	56,1	920	23	41,4	12,4
3	18	30	30	1	42,0	91,4	33,7	34,5	5,1
2	24	30	30	3	56,1	91	28,6	45	6,8
3	24	30	30	3	56,1	90,8	21,3	44	5,8
3	18	10	10	3	14,0	92	33,6	25,2	1,2
2	18	10	10	1	14,0	91,4	28,9	41,2	2,25
2	18	20	20	3	28,0	91,4	31,8	38,7	1,4
3	12	10	10	2	9,3	90,4	26,4	50	1,5
2	24	20	20	1	37,4	91,4	27,2	45,3	7,51
3	12	20	20	1	18,7	91,4	33,1	35,2	2,6
3	24	20	20	3	37,4	91,4	25	52	4,49

Table 2. Continued

V (m/s)	H (cm)	L (cm)	W (cm)	T (cm)	Blockage Ratio (%)	$P_{ambient}$ (kPa)	$T_{ambient}$ (^{o}C)	Rel. Hum. (%)	MLR(g/s)
0,5	18	20	20	2	28,0	92,9	18,8	42,4	2,75
3	18	20	20	2	28,0	91	24,8	45,2	1,85
3	12	30	30	3	28,0	91,4	23,7	58	2,35
1	12	30	30	3	28,0	90,7	27,6	29,8	2,5
0,5	24	30	10	1	18,7	92,8	19,8	43,6	12
3	24	30	10	1	18,7	91,4	21,6	49,7	8,5
0,5	24	30	10	3	18,7	92,8	23,3	35,6	2,25
1	24	30	10	3	18,7	92	19,6	65,6	2,31
3	12	10	30	3	28,0	91,4	31,4	23,6	1,46
1	12	10	30	1	28,0	90,7	20,8	50,1	4,28
3	12	30	10	3	9,3	91,4	30,8	31	1,3
1	12	30	10	1	9,3	90,7	25,8	32,7	3,75
0,5	24	10	30	1	56,1	92,8	26,4	23,3	8
1	24	10	30	3	56,1	92	18,9	52,7	2,77

The experiments are grouped into two categories and statistical models are developed for each category:

- Width and length are not equal to each other (W≠L)
- Width and length are equal to each other (W=L)

General linear model with 0.05 level of significance is utilized for this analysis. In order to determine the effect of velocity, length, width, height and stick thickness on MLR, the main effect plots are presented. Figure 3 shows the main effect plot for W≠L.

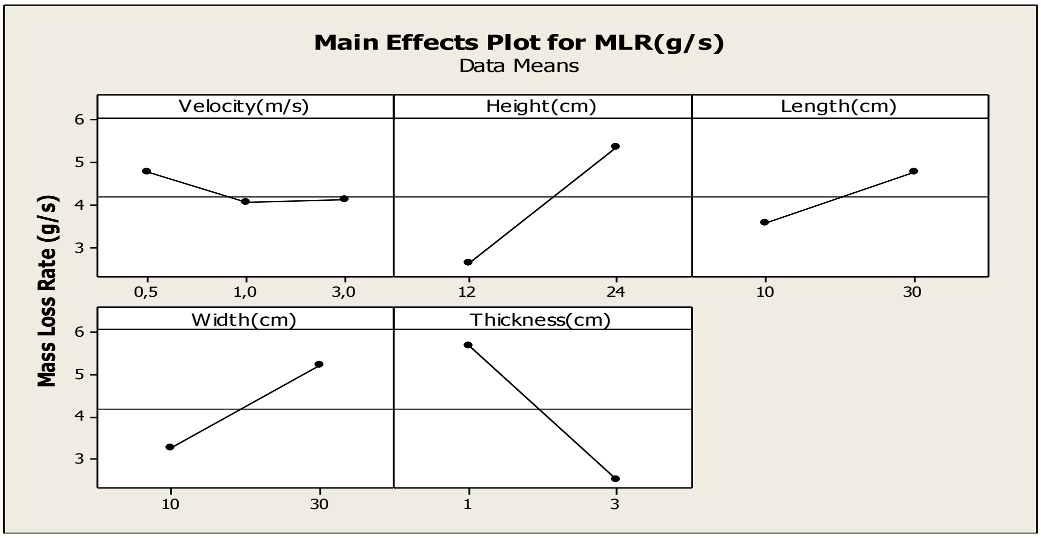


Figure 3. Main Effects Plot for Experiments in MLR (L≠ W)

The velocity has a small influence on MLR. The height, length and width are directly proportional to MLR. However, as the thickness of the sticks increases, the MLR decreases; ANOVA results show that the variation in MLR values is due to (Figure 4):

Height	(23.8 %)
Thickness	(34.9 %)
Width	(10.5 %)
Length	(4.5 %)
Velocity	(1.6 %)
Other	(24.6 %)

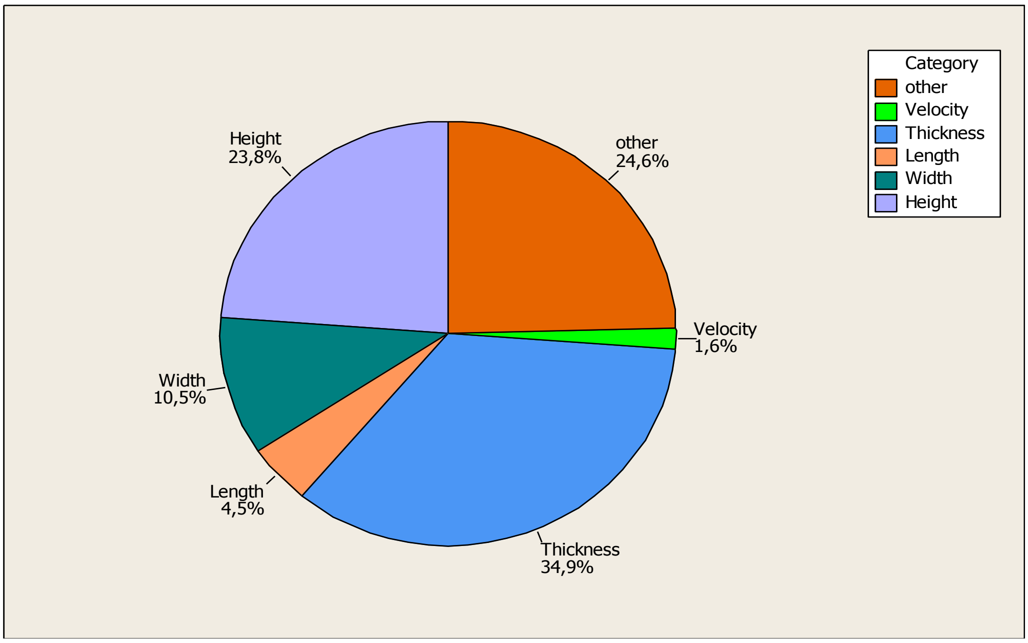


Figure 4. Pie Chart for the Variation Causes in MLR (L≠ W)

It can be noted that the most effective parameter on the mass loss rate is the stick thickness. As the stick thickness is reduced the open surface area is increased and air can penetrate through the model which enhances burning.

The temperature and thickness of the hot layer and the temperature of the upper bounding surfaces have a considerable impact on fire growth due to radiation toward the burning material. Wider burning objects give much higher energy release rates. This is due to the decrease in the distance between the tunnel walls and burning objects. As a result, radiation from the walls to the burning object increases. The heat transfer to the burning object will be greater when the fire is at an enclosure with a low ceiling. This results in a considerable increase in the heat feedback to the combustibles , and a very rapid fire growth. When the height of the object increases, the distance between the tunnel ceiling and burning object is decreasing. This also results in increasing radiation from the tunnel walls to the surface of the burning object.

The results for tests with W=L are presented in figures 5 and 6.

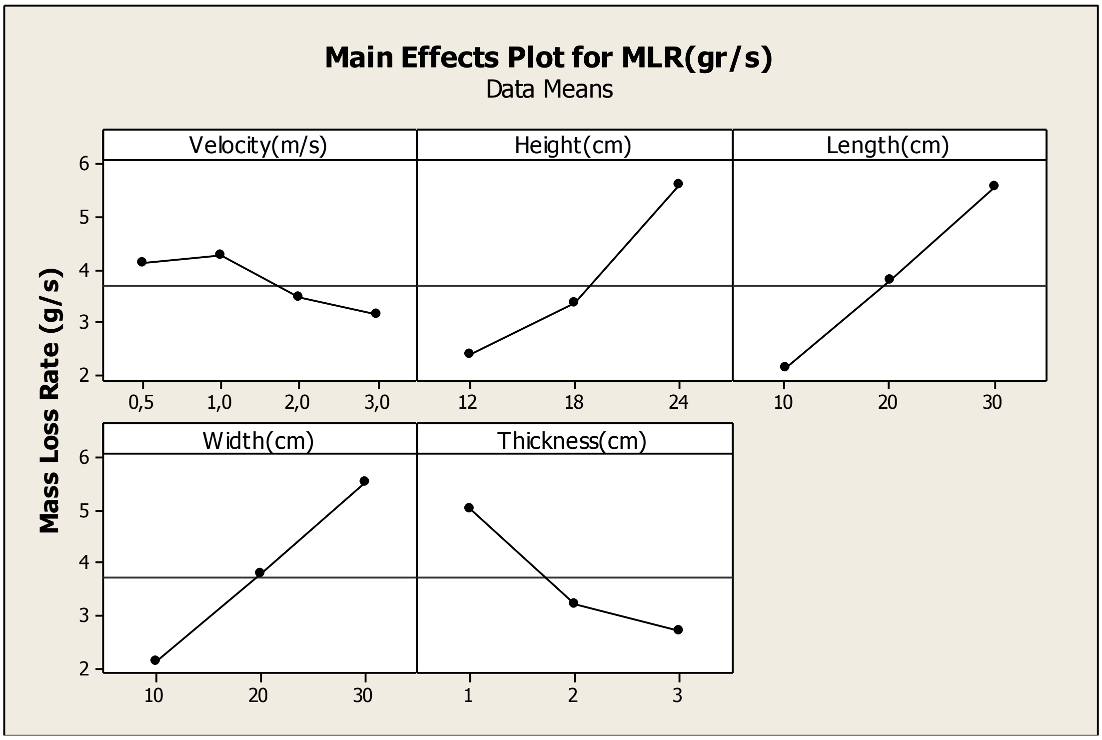


Figure 5. Main Effects Plot of MLR (L= W)

When we examine the main effects plot of V, H, L, W and T on the MLR for L=W cases, we observe the following results. The increase in the height and width of the burning object causes an increase in MLR. The MLR decreases with increasing stick thickness. The ventilation velocity effect is again small; however, for highest velocities the cooling effect of ventilation becomes important and MLR slightly decreases.

Figure 6 shows the interaction plots for the parameters. In this plot it is possible to observe the interaction of the parameter pairs and their combined effect on the MLR. The following conclusions may be reached from the plot. For the velocity and height pairs, MLR increases with height at constant velocity. For the width and velocity pairs, MLR increases with width at constant velocity. For thickness and velocity pairs, thinner sticks give a higher MLR at the fixed velocity. There is no obvious trend for the constant thickness and varying velocity cases. For height and width pairs, the increase in height and width causes an increase in MLR. For thickness and height pairs, the decrease in thickness and the increase in height give a higher MLR. For width and thickness pairs, the decrease in thickness and the increase in width give a higher MLR.

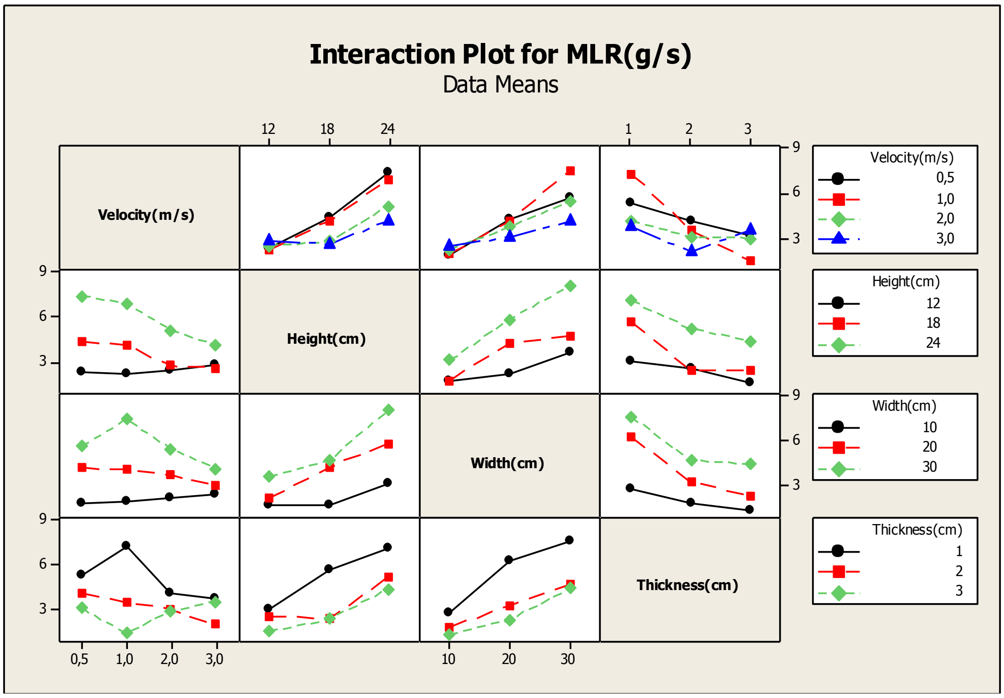


Figure 6. Interaction Plot of MLR (L= W)

To analyse the effect of the blockage ratio (BR) on the mass loss rate, the factors W and H are combined and used as an independent parameter together with V and T. From the main effect plot (Figure 7) it is observed that the MLR increases strongly with the blockage ratio. The results obtained from the full scale tests also show that larger vehicles (hence larger energy content and large BR) have higher mass loss rates in case of a tunnel fire. This effect was also observed in the current experiments and the statistical model. The percentage distribution of the causes for the variations in MLR is shown in Figure 8. The variation in MLR is due to

Blockage Ratio	(81.0 %)
Thickness	(13.1 %)
Velocity	(1.6 %)
Other	(4.3 %)

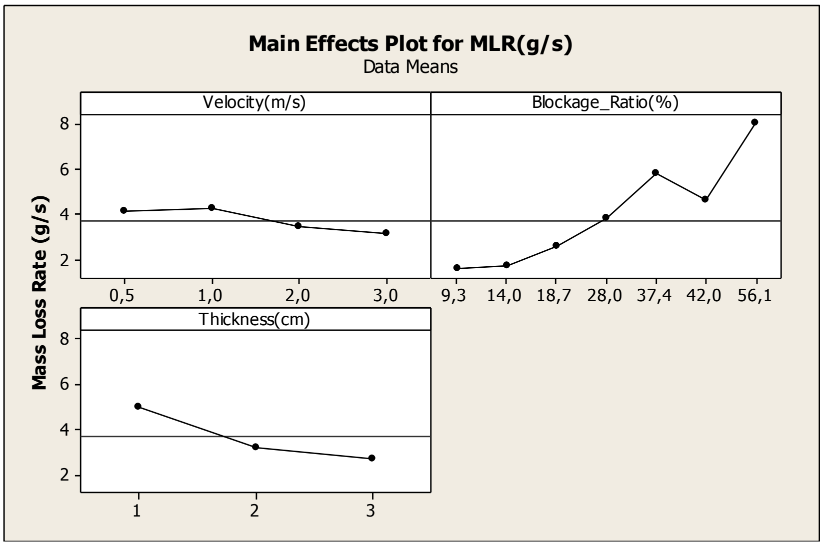


Figure 7. Velocity, Thickness and Blockage Ratio Variation Plot of MLR (L= W)

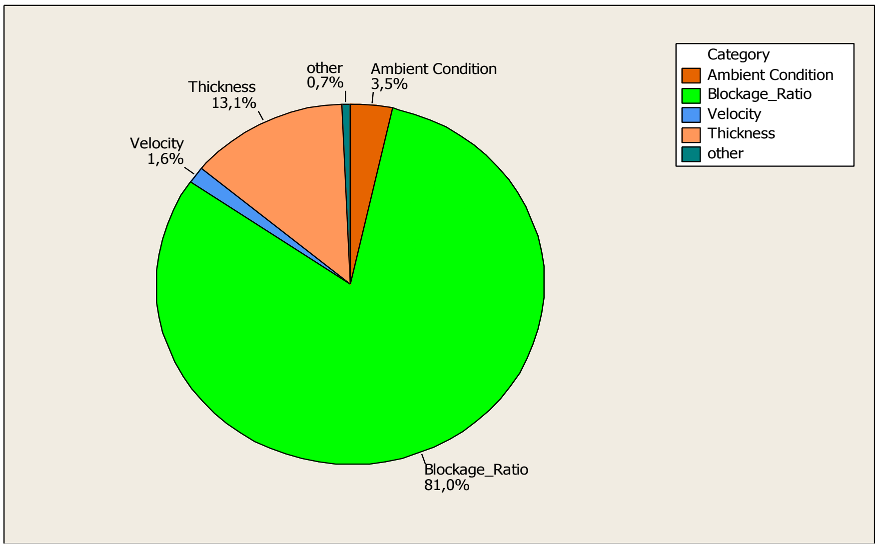


Figure 8. Pie Chart for the Variation Causes in MLR (L=W)

Conclusion

The purpose of this study was to investigate tunnel vehicle blockage effect on the mass loss rate inside the tunnel (that is the burning intensity of the fire) for different ventilation velocities. A set of experiments is conducted in a 1/13 scale model tunnel with various geometrical configurations of burning objects and different ventilation velocities.

According to the mass loss rate results, ventilation velocity does not significantly affect the mass loss rate of the burning object. The mass loss rate is directly proportional to the the variations in height and width of the burning object. As the blockage ratio of the burning object increases, the mass loss rate increases significantly. According to the statistical analysis of the test results, the causes of mass loss rate variations are therefore strongly related to changes in the blockage ratio, and only weakly induced by the changes in the model material thickness (related to the air entrainment rate inside the burning object) and by the changes in the ventilation velocity. These results highlight therefore the importance of the global dimensions of the tunnel and of the blockage ratio caused by the burning objects as the main parameters enhancing the burning rate in a tunnel fire. These parameters should be thoroughly investigated and their effects modelled in future tunnel fire prevention and mitigation studies.

Acknowledgments

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Nomenclature

H	model height
L	length
m	mass
$\dot{Q}$	heat release rate
T	stick thickness
Δt	time interval (s)
V	velocity
W	model width

Subscripts

i	data scan number
M	model scale
F	full scale model

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