POLITECNICO DI TORINO

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Tunnel longitudinal ventilation in case of fire. An easy tool for calculating the number of jet fans

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Contents

1. Introduction

There are two main ventilation scenarios that have to be considered in design of ventilation capacity of every road tunnel. First is operation of tunnel in normal conditions and second one is in the case of fire inside of tunnel. Tunnel ventilation systems must have the capacity to provide fresh air with acceptable quality according to standards during normal operation as well as supporting self-evacuation and rescue phase during an emergency event. [1]

In normal condition of a tunnel the ventilation system first needs to provide enough fresh air to dilute emissions from vehicles, especially Carbon monoxide CO which is considered in many countries as main reference pollutant for measuring exhaust emission toxicity alongside with Nitrogen oxides NO_X , to reach and maintain acceptable air quality in tunnel according to regulations. Also it should guaranty visibility higher than stopping distance of vehicles in design tunnel speed limit. Two source of reducing visibility in tunnels are particles in vehicles exhaust prominently the diesel smoke and non-exhaust particles like re-suspended dust, tire and brake wear and road surface erosion. [1]

To design a tunnel ventilation system required capacity for emergency ventilation (normally during fires) must also be calculated and compared to the normal operation requirements. With the exception of tunnels with very high traffic and long period of congestions fire case is usually the critical one and for that reason it is the subject of this theses. [1]

Although incidence of very large fires in tunnels are relatively rare but there are instances like Mont Blanc tunnel fire on 24th of march 1999.The Mont Blanc tunnel is 11.6 km long and located between France and Italy. The fire started in a truck carrying around 9 tonnes of margarine and 12 tonnes of flour and has approximately 550 liters of diesel fuel behind the first truck the total number 14 heavy good vehicles were stopped. The spread of fire to other vehicles formed a massive fire with peak heat release rate near the first truck estimated between 75 MW to 110 MW and filled 1200 meters of the tunnel with smoke in less than 4 minutes. This fire killed 39 people and damaged the tunnel vault more than 900 meters demonstrating the importance of the adequate ventilation system for tunnels in the case of fire. [2]

After determining the fire case as the critical situation the type of ventilation must be chosen "The general classification of a ventilation system is based on the direction of airflow in the traffic space. Longitudinal ventilation is in the direction of the tunnel axis whereas transverse is perpendicular to the tunnel axis in the plane of a cross section." [3]

Transverse ventilation systems have a supply air duct to introduce fresh air uniformly to the tunnel and an exhaust air duct to remove polluted air from a tunnel. Typically, air is supplied at low level near the road and removed along the tunnel ceiling which provide the advantage of easy extraction of hot smokes in the event of vehicle fire inside the tunnel as shown in the figure 1. [3]

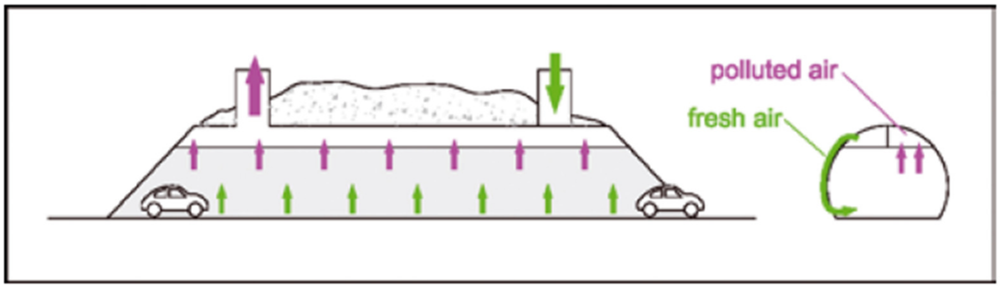


FIGURE 1 - TRANSVERSE VENTILATION SYSTEM
WITH UNIFORM SUPPLY AND EXTRACT OF AIR. [3]

Semi-transverse ventilation systems are systems which in normal conditions, Air flow is either extracted or introduced in a distributed manner in entire length of the tunnel. In figure 2 a semi-traverse system in shown with distributed fresh air injection.

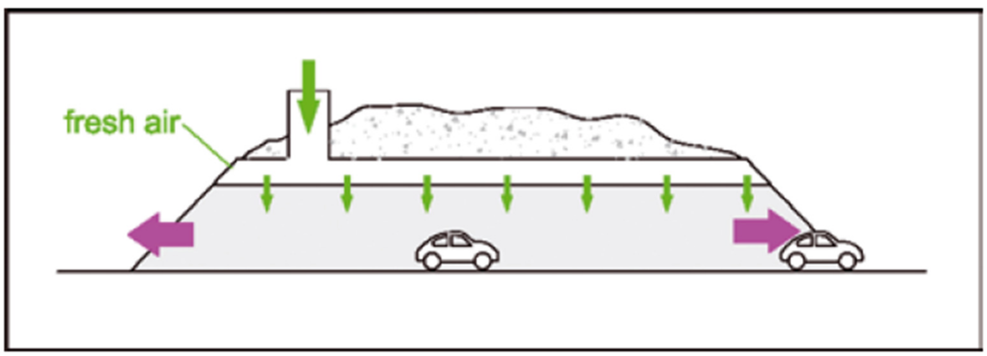


FIGURE 2- SEMI-TRANSVERSE VENTILATION:
DURING NORMAL OPERATING CONDITIONS; FRESH AIR INJECTION [3]

Longitudinal systems supply a longitudinal air flow along the axis of the tunnel. There are several ways to design such a system a common solution is to use system employ celling mounted jet fans to produce the required airflow through the tunnel, as shown in figure 3.

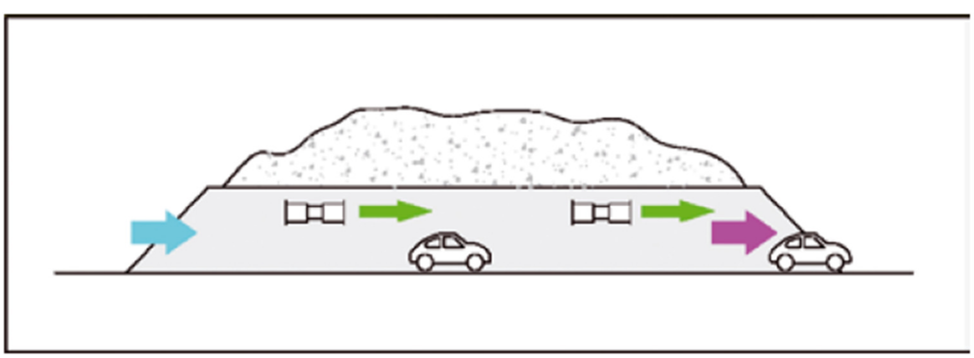


FIGURE 3- LONGITUDINAL VENTILATION WITH JET FANS [3]

The advantage of this type of ventilation is that it can be update and modified fairly easy and inexpensively in comparison with other classes of ventilation systems for this reason the longitudinal ventilation systems is the subject of this theses.

In chapter 2 important definitions and design process of a longitudinal ventilation systems is discussed. In chapter 3 the result of the design process is reported. In chapter 4 the effect of different parameter are compared. Chapter 5 is devoted to the conclusion of this theses and the final chapter will report the Matlab code developed for design of the ventilation system.

2. Important definitions and design process

2.1. Definitions

Before discussing the design process some entities used in this theses should be define.

2.1.1 Design fire

“A design fire is defined as a Heat Release Rate (HRR), in MW, as a function of time. It provides the fire characteristics that are used to establish the sizing of equipment in tunnels.” In road tunnels its value usually is based on fire development in single vehicle and depends on the type of vehicle allowed in them and they value can be seen in table 1. [2]

TABLE 1 TYPICAL PEAK HRRS FOR DIFFERENT ROAD VEHICLES	
Vehicle Type	Peak HRR (MW)
Passenger car	5 – 10
Light duty vehicle	15
Coach, bus	20
Lorry, heavy-goods vehicle up to 25 tonnes*	30 – 50
Heavy-goods vehicles typically 25-50 tonnes*	70 – 150
Petrol tanker	200 – 300
*Depending on the quantity and nature of the load: see Ingason [5] for more specific data [2]	

As the result of this different values some countries choose a range instead of one particular value for design fire in there guidelines like Italy with design fire range of 20-200 WM. [2]

2.1.2. Backlayering

“The phenomenon of the smoke layer flowing against the airflow direction is referred to as backlayering.”[3]

2.1.3. Critical velocity

By increasing of the longitudinal airflow velocity backlayering will decrease and eventually stop completely, the airflow velocity at which the backlayering is completely stops is called critical velocity. [3]

There are different proposals for calculating the critical velocity, Kennedy [6] proposed following formula by relating the increased temperature of hot gasses from fire to fires convective heat release rate:

$$V_c = \left(\frac{gHQ^{\bullet}{}_c}{\rho C_p A T_f Fr_m}\right)^{1/3} \qquad (1)$$

Where H is tunnel height, $Q^{\bullet}{}_c$ is the convective heat release rate from the fire, A is the cross-sectional area of tunnel and ρ is density of upstream air.

Also critical Froude number (Fr_m) can be obtained from following equation [6]:

$$Fr_m = 4.5(1 + 0.0374|\min(grade, 0)|^{0.8})^{-3} \qquad (2)$$

In which grade gradient of the tunnel in percent

And finally and the hot-gas temperature T_f is estimated from the enthalpy conservation equation [7].

$$T_f = \frac{Q^{\bullet}{}_c}{\rho C_p A V_c} + T \qquad (3)$$

The equations (1) and (3) can be coupled and solved with an iterative approaches to evaluate V_c but there is analytical approach to calculate critical velocity directly. By rewriting equations (1) and (3) in following form [7].

$$V_c{}^3 = \frac{gHQ^{\bullet}{}_c}{\rho C_p A Fr_m (T + \frac{Q^{\bullet}{}_c}{\rho C_p A V_c})} \qquad (4)$$

$$(\rho C_p A Fr_m T).V_c{}^3 + (Fr_m Q^{\bullet}{}_c)V_c{}^2 - gHQ^{\bullet}{}_c = 0 \qquad (5)$$

This represents a cubic equation for the critical velocity and when its discriminant is negative ($\Delta < 0$) which is almost always the case with the values of the $Q^{\bullet}{}_c$ that tunnel fires are able to produce then equation has one real root and two non-real complex conjugate roots therefore the real root is critical velocity this leads to [7]

$$V_c = \hat{S} + \hat{T} - \frac{a}{3} \qquad (6)$$

Where

$$a = \frac{Q^{\bullet}{}_c}{\rho C_p A T} \quad (7)$$

$$c = -\frac{gHQ^{\bullet}{}_c}{\rho C_p A T F r_m} \quad (8)$$

$$\hat{Q} = -\frac{a^2}{9} \quad (9)$$

$$\hat{R} = \frac{-27c - 2a^3}{54} \quad (10)$$

$$\hat{S} = \left(\hat{R} + \sqrt{\hat{Q}^3 + \hat{R}^2}\right)^{1/3} \quad (11)$$

$$\hat{T} = \left(\hat{R} - \sqrt{\hat{Q}^3 + \hat{R}^2}\right)^{1/3} \quad (12)$$

In this theses the direct approach is used and critical velocity is calculated by using equation (6)

2.2. Design process

In order to design the longitudinal ventilation system in the case of fire the number of jet fans must be determined to do so the starting point is the conservation of mechanical energy along the tunnel should be satisfied.

$$l_i = \int v dP + \Delta e_P + \Delta e_k + l_w \ (13)$$

Where l_i is shaft or internal work done here by jet fans, $l_w$is the friction work, $\int vdP$ Related to pressure change due to shaft work and $\Delta e_P, \Delta e_k$ are potential and kinetic energy change respectively. Equation (13) can be rewritten for relevant energy sources relevant for inside the tunnel according to equation (14) [8].

$$n_{fan}.\Delta H_{fan} = \Delta \mathrm{H}_{linear} + \Delta \mathrm{H}_{sing} + \Delta \mathrm{H}_{chim} + \Delta H_{veh} + \Delta H_{atm} \quad (14)$$

Where n_{fan} is number of fans ΔH_{fan} is a single fan thrust in real operational conditions $\Delta \mathrm{H}_{linear}$ is the linear pressure losses due to friction $\Delta \mathrm{H}_{sing}$ is the pressure losses due to sudden form changes and air flow obstacle like traffic signs, $\Delta \mathrm{H}_{chim}$ is the chimney effect, ΔH_{veh} is the losses because of parked vehicles inside tunnel and ΔH_{atm} represents pressure difference between tunnel portals that has a random character and includes along many parameters the meteorological conditions in entrance and exit portal of the tunnel.

Every load losses corresponding to different effects along the tunnel should be calculated and they should be compensated with real thrust provided by the jet fans installed. [4] To start the design the following quantities should be evaluated.

2.2.1. Temperature distribution inside the tunnel

The thermal power of the fire is removed by radiation transfer to the walls of the tunnel and by convective transfer to the air of the tunnel. Usually the convective transfer is considered as two third of the total power of the fire $\dot{Q_{tot}}$ and so the average temperature of the air immediately under the fire is determined by equation [9].

$$T_{max} = T_0 + \frac{Q^{\bullet}{}_c}{\rho_0 C_p A V_0} \quad (15)$$

Where ρ_0 is the fresh air density, C_p the specific heat at constant pressure of the air, A the cross section of the tunnel, T_0 the temperature of the fresh air and V_0 the fresh air velocity.

To calculate the air's temperature in any part of the tunnel (T_x) the conduction to the walls should be connected with the equation of the temperature's evolution at the air of the tunnel. A simplified and secure calculation of this temperature can be obtained by using the coefficient of thermal apparent exchange, h_{app}, and the temperature in each point inside the tunnel is also depends on the fire location (x_{fire}).[4]

$$T_x = T_0 + \frac{Q^{\bullet}{}_c}{\rho_0 C_p A V_0} \; . \, e^{-\frac{4 h_{app}}{\rho_0 A.DH.V_0}(x - x_{fire})} \quad (16)$$

The value of h_{app} deppends on the air velocity and the time needed to maintain this velocity in the tunnel. Table 2 [10], shows some of its values most relevant to this theses discussion.

Velocity of the Air	15 min	60 min	120 min
3 m/s	10 $W/m^2/K$	7 $W/m^2/K$	6 $W/m^2/K$
4 m/s	14 $W/m^2/K$	10 $W/m^2/K$	7 $W/m^2/K$

Table 2 the coefficient of thermal apparent exchange for spedific speed and its duration[10].

After calculating the temperature in every point of the tunnel it is possible to evaluate the air density in those points using ideal gas law.

2.2.2. Linear losses

The linear losses along entire tunnel per unit of length (δH) are calculated using following equation

$$\delta H_{linear} = \lambda \frac{\rho V^2}{2} \cdot \frac{\delta l}{DH} \quad (17)$$

Where DH is the hydraulic diameter of the tunnel, δl is the unit length of tunnel considered and λ the friction coefficient. [4]

2.2.3. Losses due to single resistances

The sudden changes on forms (enter and exit of the tunnel, changes of section) or the presence of obstacles of big dimensions (traffic signals or boards for messages) cause a singular load losses. This kind of losses can be calculated by using the following equation

$$\Delta H_{sing} = \varepsilon \frac{\rho V^2}{2} \quad (18)$$

Where ε is the coefficient of singular losses which is different for every obstacle or form change (generally the coefficient of singular losses at the entry of tunnel (ε_e) is considered to be equal to 0.5 and in the exit (ε_e) to 1) [4]

2.2.4. The chimney effect

The chimney effect is the force that tends to move hot and lighter gases upward depending on the gradient of our tunnel this force can work in favor of extraction of smokes of play the resistance force and considered load loss. The effective pressure difference in this phenomena is a function of the elevation difference of the two portals and of the temperatures of the tunnel air and the ambience [11]. For a tunnel of length δl and a slope of grad (positive in rise, negative in descent), this effect is translated by a variation of load per unit of length [4].

$$\delta H_{chim} = \text{grad.}(\rho_0 - \rho).g.\delta l \quad (19)$$

2.2.5. Losses due to presence of parked vehicles inside the tunnel

Every vehicle inside the tunnel exert force on the air mass inside the tunnel. The piston effect(ΔH_{piston}), representing this force and can be evaluated with [4]

$$\Delta H_{piston} = \frac{1}{2}.\frac{C_x\Sigma}{A}\rho.(U-V)|(U-V)| \quad (20)$$

Where $C_x\Sigma$ takes an average of the product of the aerodynamic coefficient of the vehicles and their cross section (so the heterogeneous traffic can be considered), ρ is the density of the air, A the tunnel cross section, U the speed of the vehicles and V the air velocity [4]. In the case of fire in a uni-directional traffic like in case of this theses every car inside the tunnel is parked before the fire therefore U is equal to zero for all vehicles and the piston effect will be considered as a loss due to presence of parked vehicles. Since the density and velocity of air before fire is equal to density of fresh air and critical velocity respectively the equation (18) can be rewritten in the following way to calculate Losses due to presence of parked vehicles

$$\Delta H_{veh} = \frac{1}{2}.\frac{C_x\Sigma}{A}\rho_0.{V_c}^2 \quad (21)$$

2.2.6. The effect atmospheric pressure

The effect of the atmospheric pressure although it has a random character must be included for design of the ventilation system. It is responsible for the natural draught and there is a certain polemic in the technical literature on the form in which it must be evaluated. Generally the phenomenon appears studying separately the effect generated by the difference on temperature between the inside and the outside of the tunnel (at ambient conditions), the height difference between the portals, the barometric differences and the effect of the wind. Since the previous effects are difficult to add generally they get in the calculations as pressures to be overcome by the ventilation system [4].

2.2.7. Thrust of a jet fan

By calculating all the previous effects it is obvious that the ventilation system should overcome all resistance forces in tunnel to guaranty the desired longitudinal air velocity which is equal to critical velocity in case of fire. Therefor the number of fans are determined by dividing the resistance loads to thrust force produced by one single jet fan. It is important to take into account that the thrust of a jet fan is affected by the environmental conditions at which it is used and so it is not the same as the one from catalogues (F_0).following equation evaluate the thrust of jet fans in their actual environment.

$$\Delta H_{fan} = \mathrm{k}\frac{F_0}{A} \cdot \frac{\rho}{\rho_{fan}}\left(1 - \frac{V}{V_{jet}}\right) \quad (22)$$

In the expression k is a coefficient of efficiency, ρ_{fan} the air density of reference, V_{jet} the velocity of the air jet density of reference, A the tunnel cross section and ρ and V the air density and velocity at the tunnel respectively.

It is worth mentioning that usually two fans will be added to this number which are for redundancy to guaranty the ventilation system is able to provide sufficient air velocity even in the case of failure of one or two of them.

3. Results

A simple tool was developed using Matlab to perform the design process in this chapter the features of this tool alongside the results obtaining from it is reported. Firs a generic tunnel was selected and a parametric study was performed to calculate the contribution of every phenomenon effecting the pressure inside the tunnel. The tool can be used for design of longitudinal ventilation system of every tunnel. First in section 3.1 the characteristics of selected tunnel and environment is reported then in section 3.2 the results are shown.

As mentioned design fire in Italy has a range of 20 to 200 MW to see the results in different points of this range three design fire were selected one in low range of heat release rate (HRR) equal to 30 MW one in the middle of the range with HRR equal to 100 MW and the last one at the other limit of the range in 200 MW.

3.1. Tunnel and Environment characteristics

Before reporting the results the characteristic of the tunnel and environment surrounding it should be defined.

3.1.1. Tunnel characteristics

This chapters results are obtained with a tunnel having following characteristics.

1. Cross-section area A = 70 m^2
2. Hydraulic diameter DH = 8.5 m
3. Friction coefficient $\lambda = 0.025$
4. Tunnel length L = 1500 m
5. Coefficient of singular losses at the entry of tunnel ε_e = 0.5
6. Coefficient of singular losses at the exit of tunnel ε_s = 1
7. Slope of the tunnel grad = 2 %
8. The tunnel is uni-directional traffic
9. The height of tunnel H = 6 m

3.1.2. Environment characteristics

1. Environment temperature $T_0 = 300\ K$
2. Environment air density $\rho_0 = 1.2\ \frac{Kg}{m^3}$
3. Air heat capacity in constant pressure $C_p = 1040\ \frac{J}{KgK}$
4. Acceleration of the gravity $g = 9.822\ \frac{m}{S^2}$

3.1.3. Traffic characteristics

1. Maximum number of vehicles in 1000 m $Nveh\_\max = 120$
2. Percentage of heavy-good vehicles in traffic $HGV = 18\ \%$
3. Average of the product of the aerodynamic coefficient of the vehicles and their cross section $C_x\Sigma\_v \quad = 0.9\ m^2$
4. Average of the product of the aerodynamic coefficient of the heavy-good vehicles and their cross section $C_x\Sigma\_HGV = 4.5\ m^2$

3.1.4. Fan characteristics

1. Coefficient of fan efficiency k = 0.85
2. Thrust of one jet fan $F_0 = 900\ N$
3. Air density of reference $\rho_{fan} = 1.2\ \frac{Kg}{m^3}$
4. Velocity of the air Jet at $\rho_{fan}.$, $V_{jet} = 35\ \frac{m}{s}$

3.2. Results

3.2.1 Temperature distribution

In this section the temprature distribution for 3 design fire is reported in figure 4,5 and 6 with the fire position fixed at 500 meter from tunnel entrance. In order to calculate the temperature distribution the air velocity should be defined in tunnel in the case of fire this value should be above the critical velocity to ensure no backlayering occurs inside the tunnel. The critical velocity of air in the case of fire with HRR equal to 30 MW is 1.93 $\frac{m}{s}$ and for fires with HRRs equal to 100 and 200 MW the critical value of speed is 2.56 and 2.89 $\frac{m}{s}$.

Figure 4 Temperature distribution inside the tunnel Q_t = 30 MW

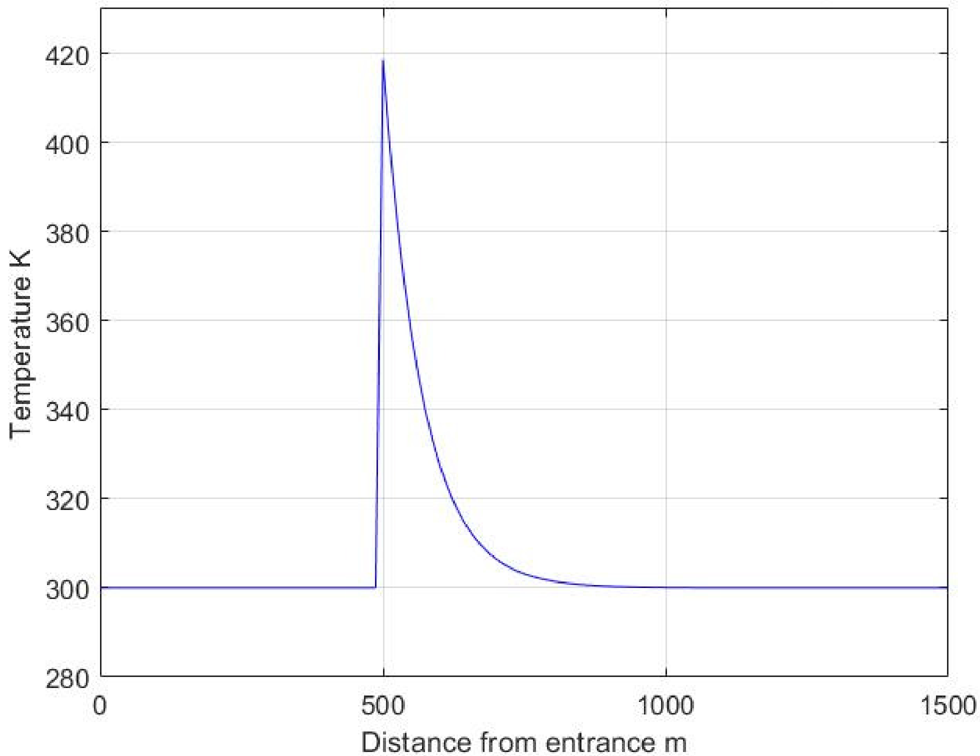


Figure 5 Temperature distribution inside the tunnel Q_t = 100 MW

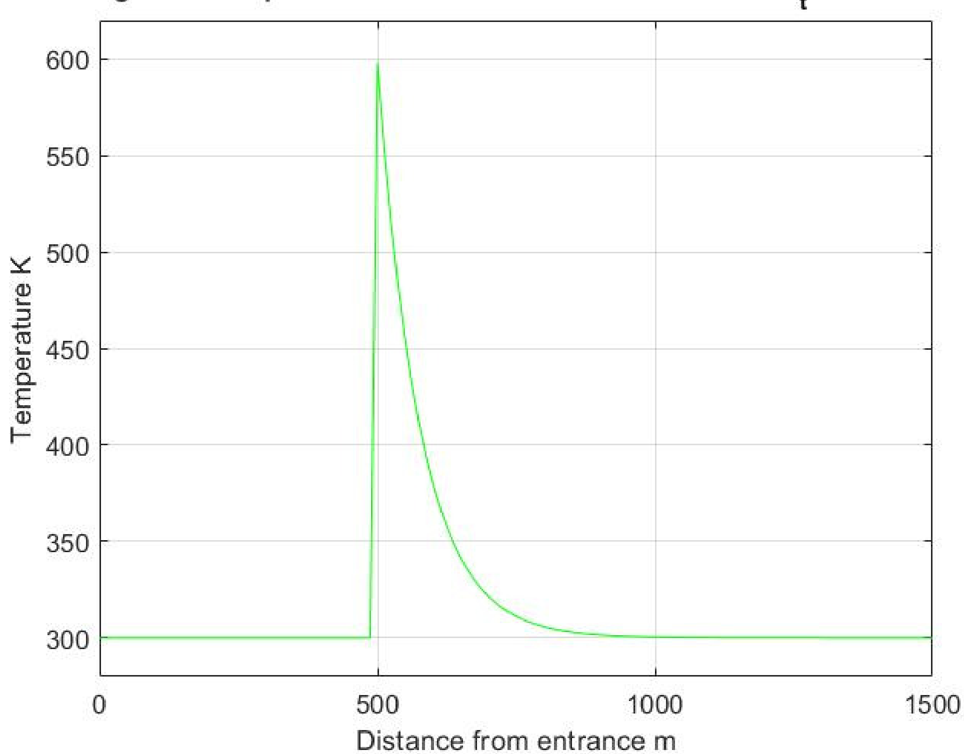
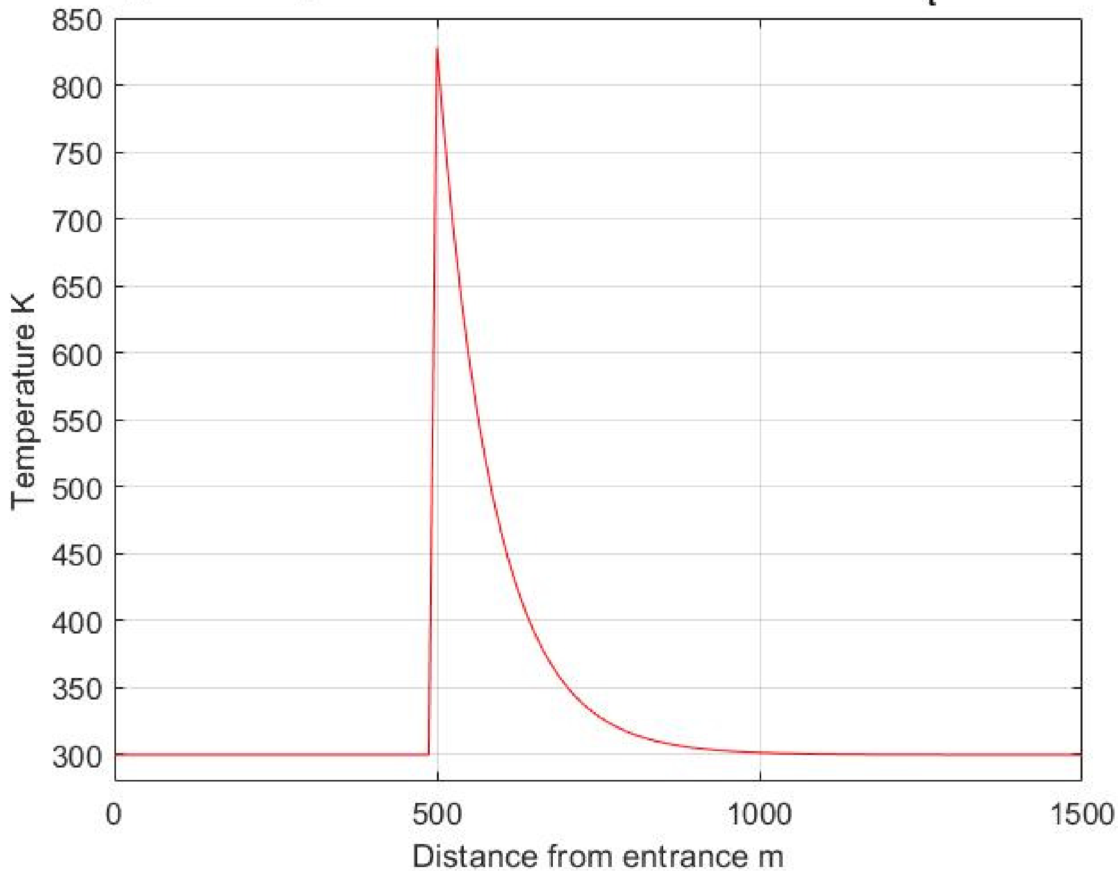


Figure 6 Temperature distribution inside the tunnel Q_t = 200 MW



In figure 4 the maximum temperature reaches to 418 K and after approximately 160 m temperature decreases to 310 K in the case of figure 5 the temperature right above fire is around 598 K and it takes about 270 m to reach air with around 310 K and for the most powerful fire of figure 6 the maximum temperature is 828 K and after 340 m air temperature cools down to 310 K.

3.2.2 Air density distribution

From temperature distribution and by using ideal gas law it is fairly easy to get the air density distribution. Figures 7, 8 and 9 will illustrate this results for respective temperature distributions.

Figure 7 Air density distribution inside the tunnel Q_t = 30 MW

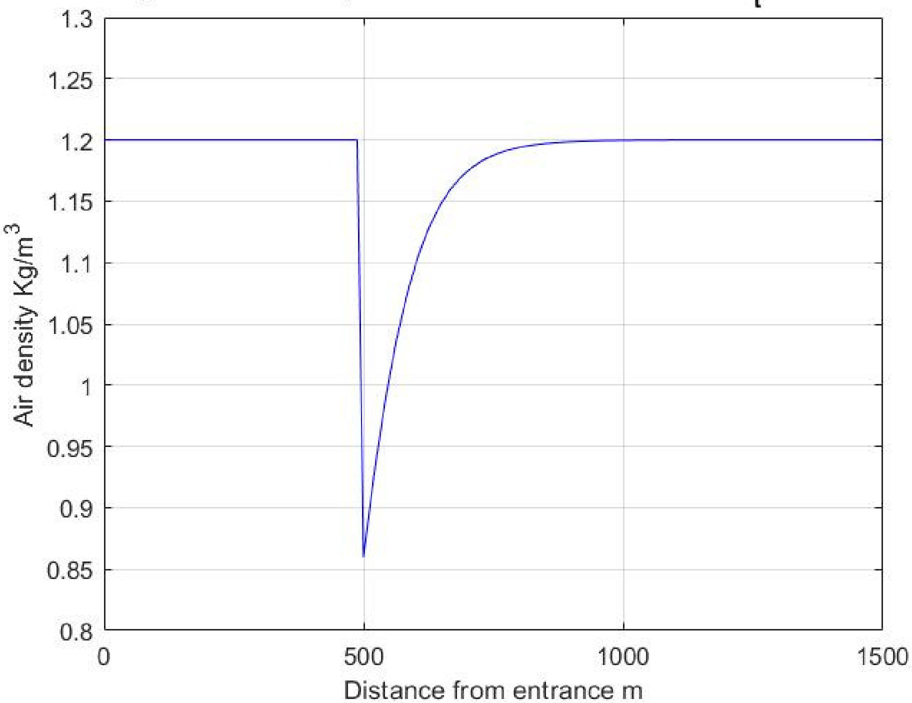
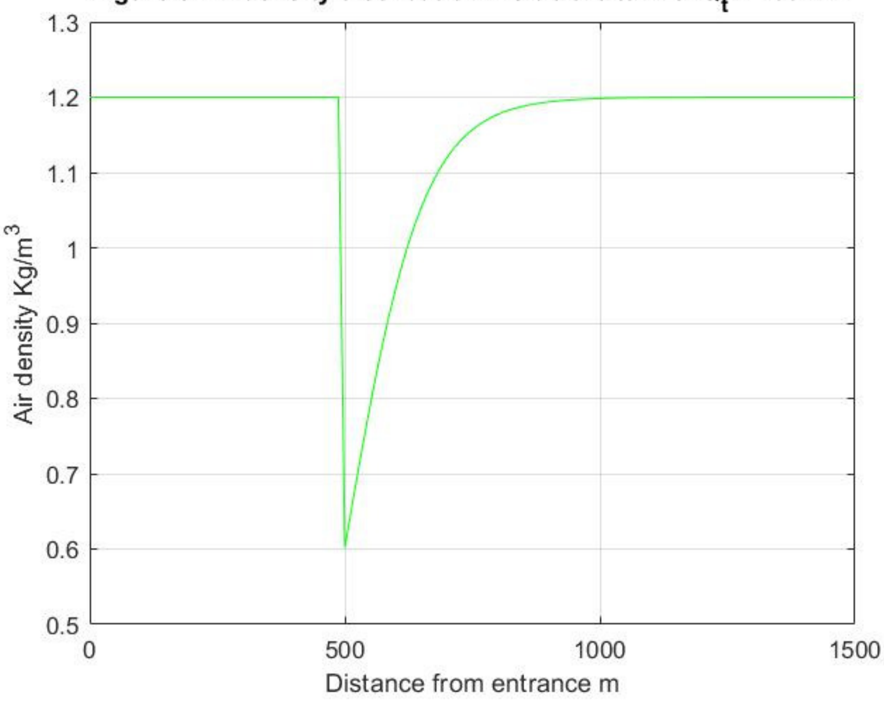
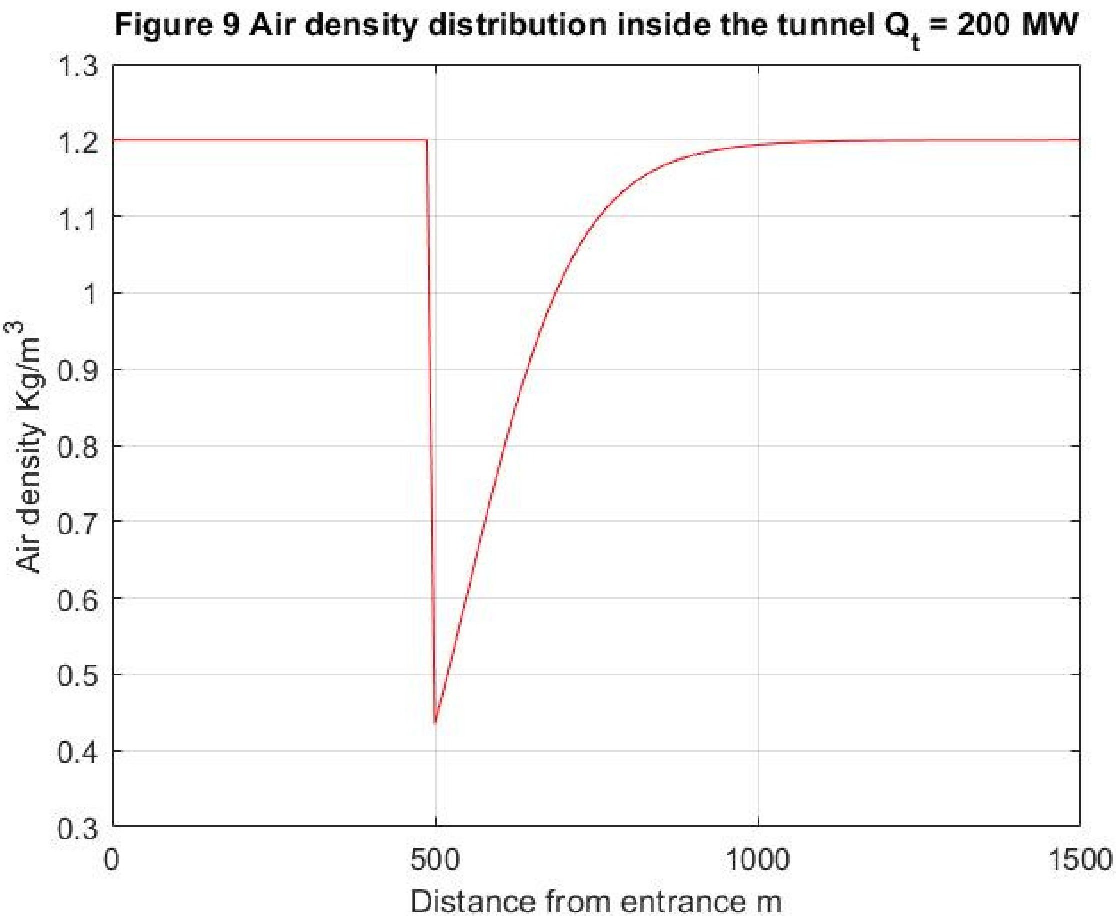


Figure 8 Air density distribution inside the tunnel Q_t = 100 MW





The minimum air density correspond to the highest temperature and are 0.86, 0.60 and 0.43 $\frac{Kg}{m^3}$ respectively for figures 7, 8 and 9.

3.2.3 Air velocity distribution

From conservation of mass law ($\rho_x V_x A_x = constant$) we can calculate the air velocity distribution inside the tunnel. Near the fire increased temperature will decrease the air density and since the constant cross section of tunnel is constant the velocity of air near fire will increase. Figures 10, 11 and 12 will illustrate this results for respective velocity distributions.

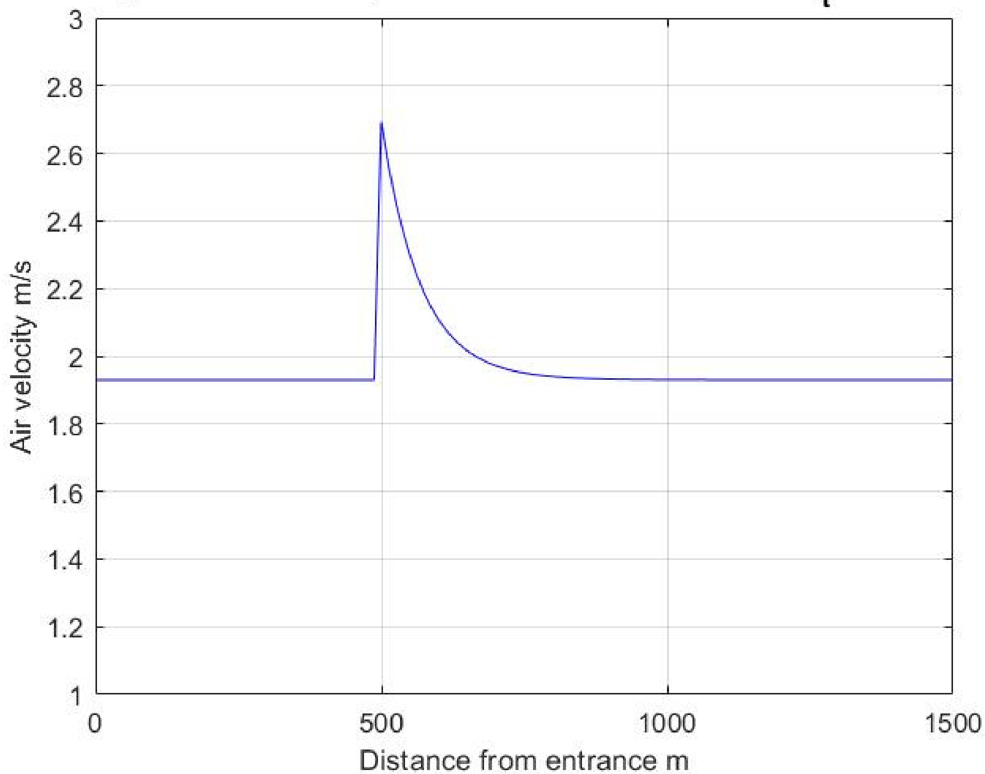


Figure 10 Air velocity distribution inside the tunnel Q_t = 30 MW

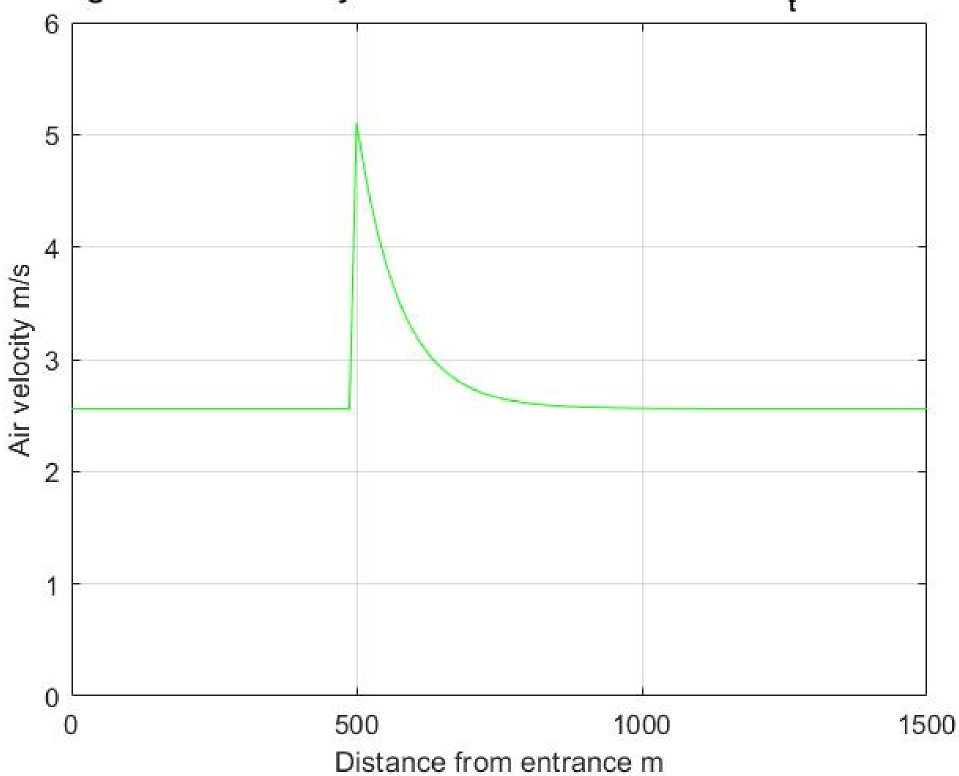
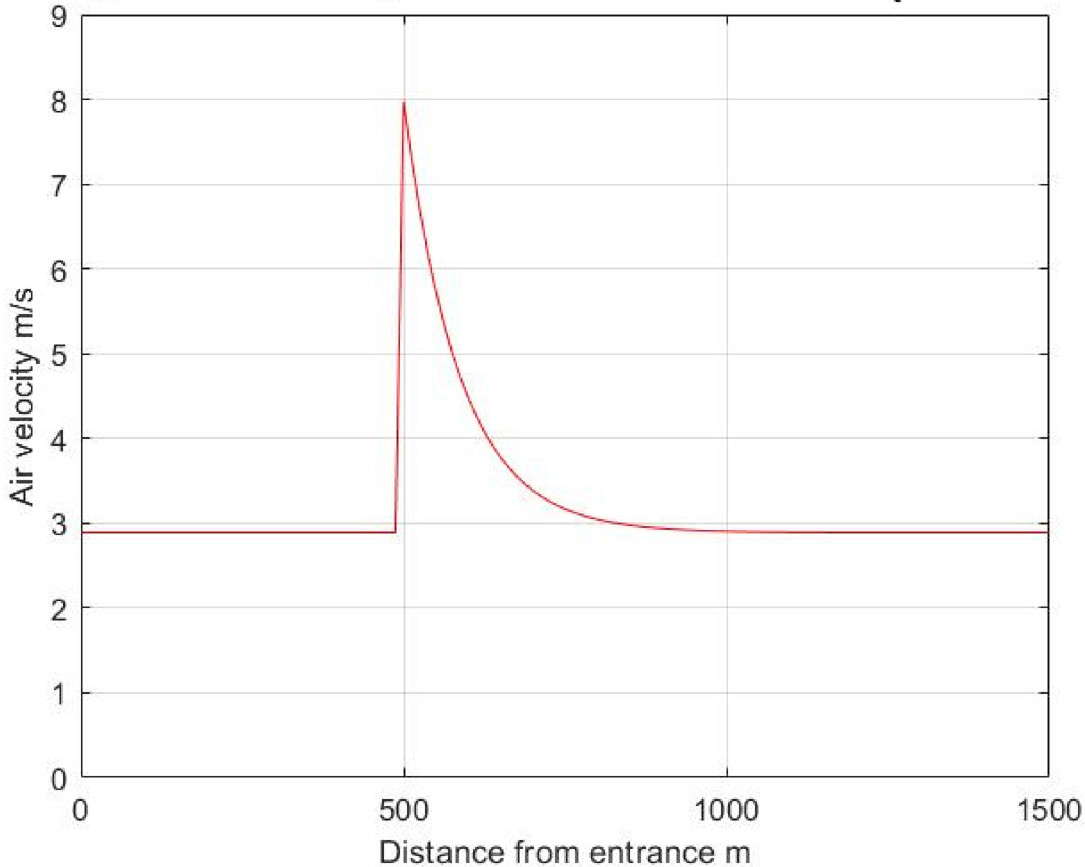


Figure 11 Air velocity distribution inside the tunnel Q_t = 100 MW

Figure 12 Air velocity distribution inside the tunnel Q_t = 200 MW



Maximum speed corresponds to the maximum temperature and are reported for figure 10, 11 and 12 as 2.69, 5.10 and 7.98 $\frac{m}{s}$ respectively.

3.2.4 Linear losses across the tunnel

Figure 13, 14 and 15 report the total linear losses across the tunnel for the different fire heat release rate and also the fire position is changed from 50 to 1450 with 100 m steps to study its effect too.

Figure 13 Linear losses across the tunnel for different fire positions Q_t = 30 MW

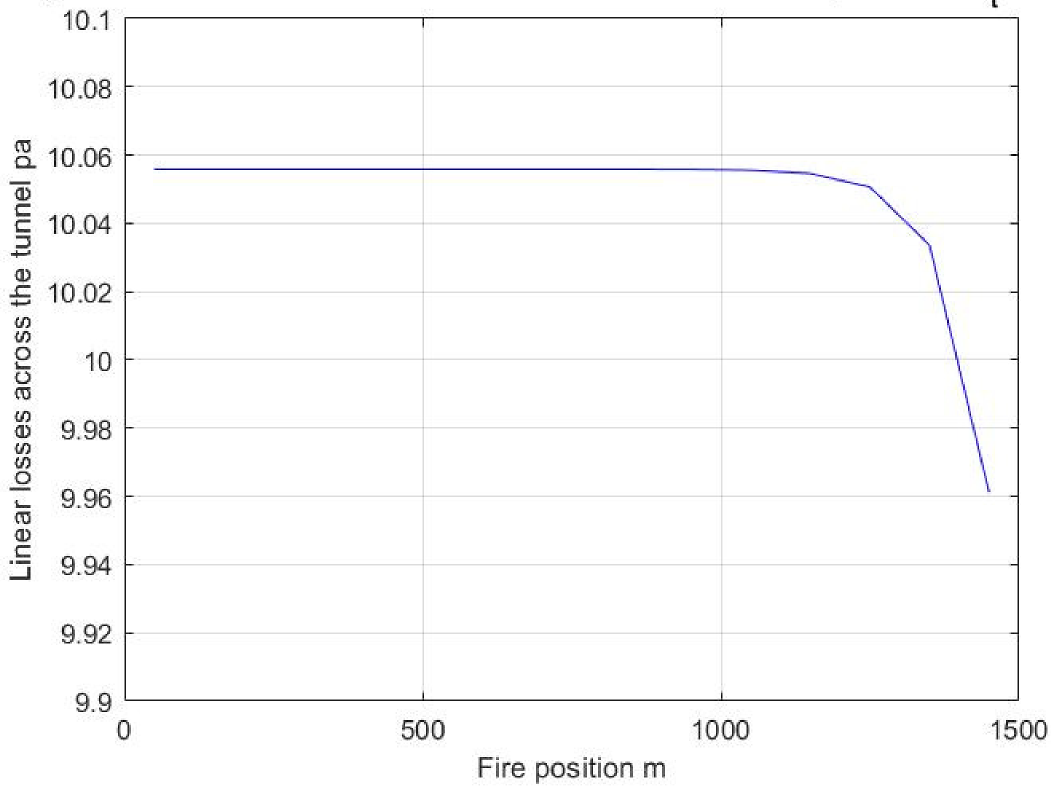


Figure 14 Linear losses across the tunnel for different fire positions Q_t = 100 MW

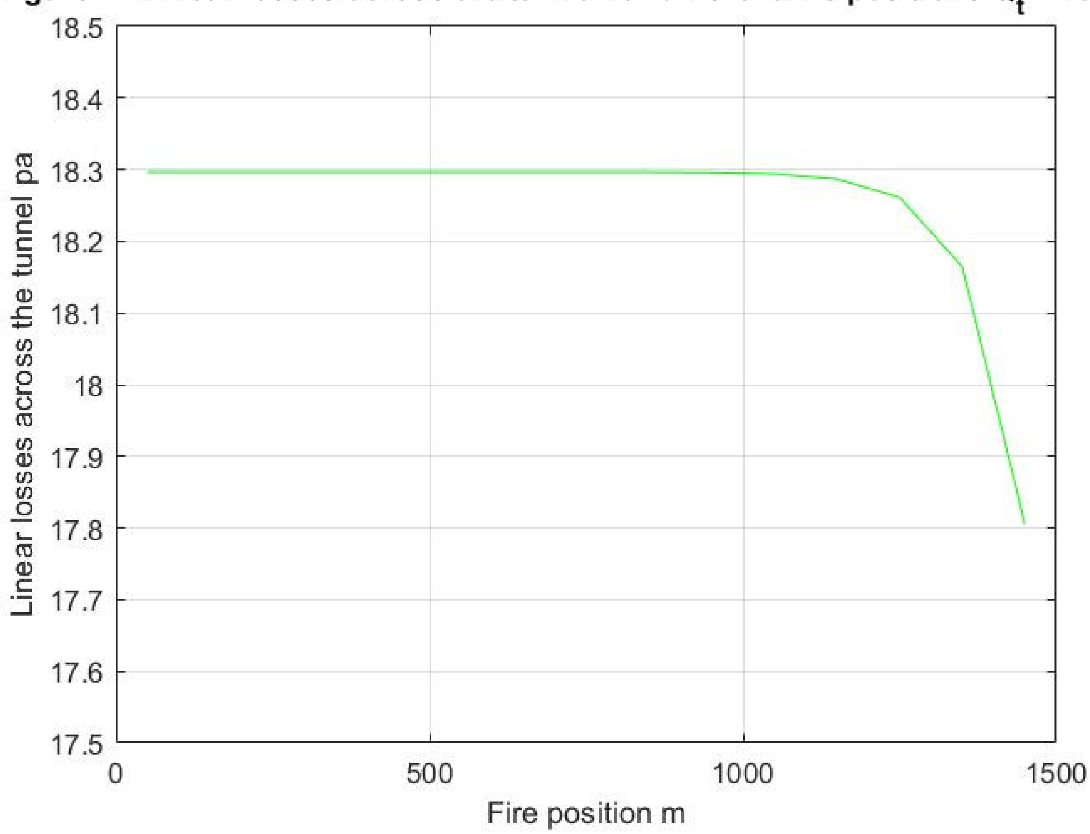
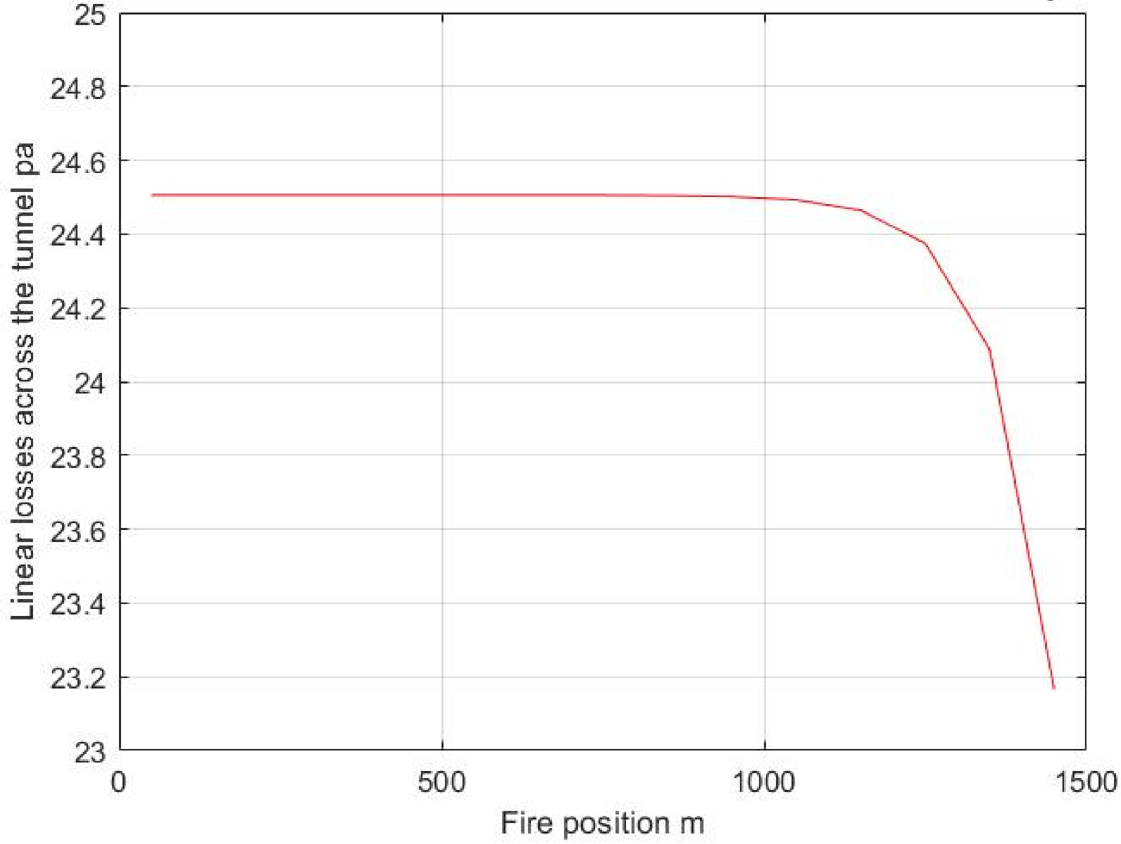


Figure 15 Linear losses across the tunnel for different fire positions Q_t = 200 MW



If fire starts in entrance of tunnel the loss will be 10.06, 18.3 and 24.51 respectively for figures 13, 14 and 15 which demonstrate that this kind of losses are very dependent on the velocity of air inside the tunnel .

If fire starts at the end of the tunnel the losses are 9.96, 17.8, and 23.17 respectively. From figure 13 can be seen that by changing fire position the value of the losses are bigger with fire near the entrance but only 1 percent this value for figure 14 and 15 is 2.7 percent and 5.4 percent showing linear losses can be considered slightly affected by fire position.

3.2.5. Singular losses

Singular loss of tunnel does dependent on air velocity therefore it is smaller for the scenario with smallest fire HRR and is equal to 3.35 if the fire occurs near the entrance of tunnel, and it will increase to 5.90 for fire with HRR equal to 100 MW and 7.52 for the last design fire. If fire occurs near the exit of tunnel the air density at exit portal decreases but the air velocity increases since the singular loss is more sensitive to the velocity it will increase and reach 3.78, 7.93 and 12.45 pa for fire designs with 30, 100 and 200 MW heat release rate. Figures 16, 17 and 18 will illustrate the singular losses against fire position.

Figure 16 Singular losses across the tunnel for different fire positions Q_t = 30 MW

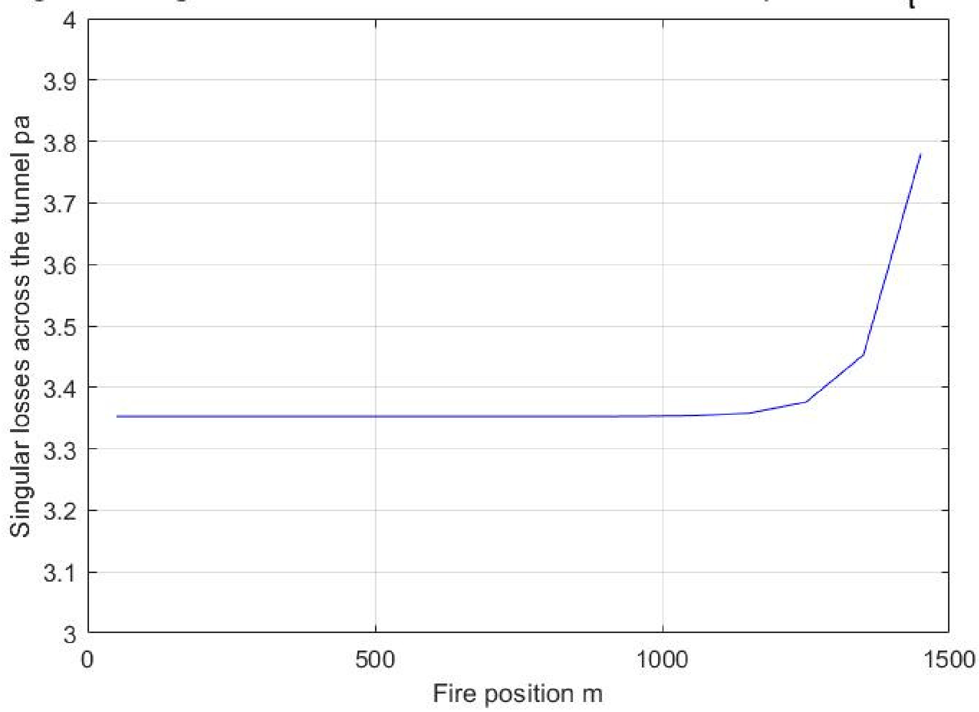


Figure 17 Singular losses across the tunnel for different fire positions Q_t = 100 MW

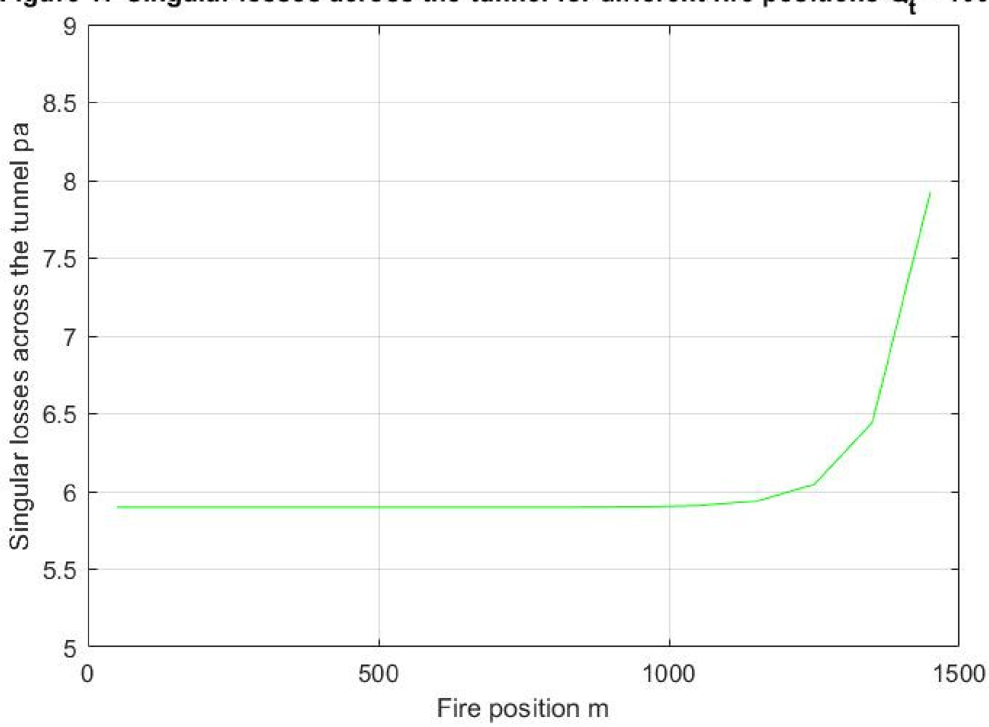
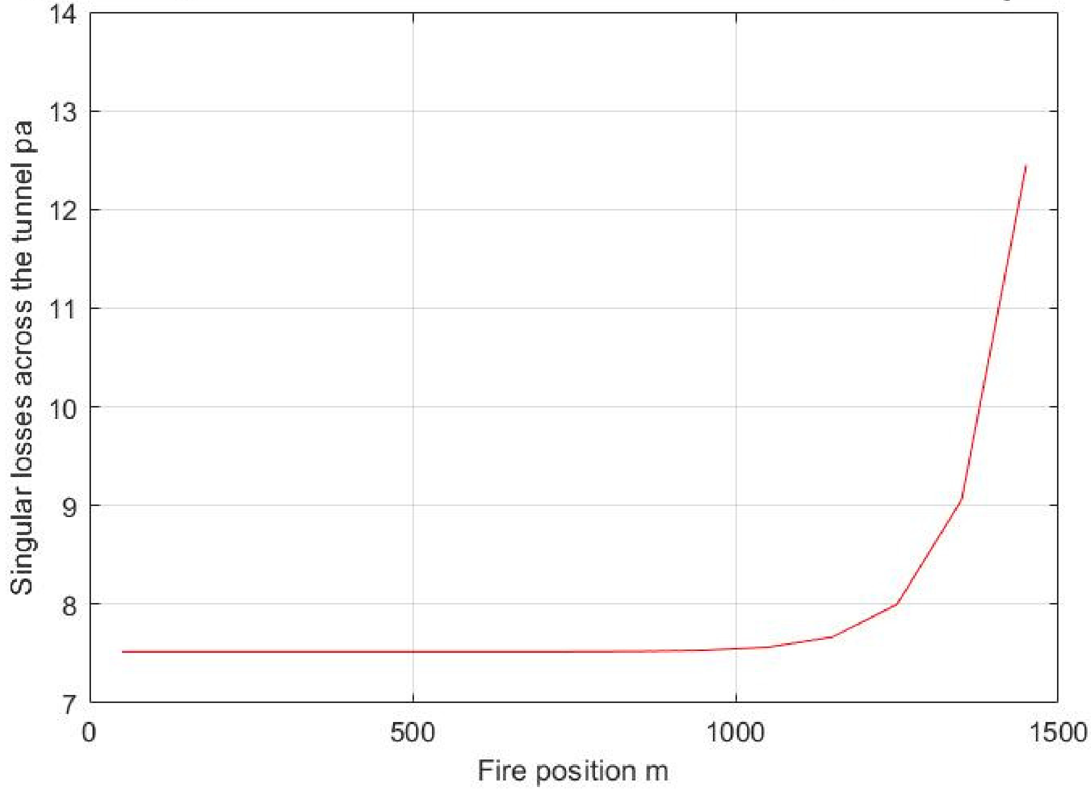


Figure 18 Singular losses across the tunnel for different fire positions Q_t = 200 MW



3.2.6. Chimney effect

Figure 18, 19 and 20 are dedicated to illustrate the chimney effect for different fire positions and fire heat release rate.

Since tunnel slope is positive so chimney effect does work in favor of smoke extraction therefore its values are negative. In figure 19 which has the smallest HRR the chimney effect changes from -5.84 with fire near entrance to -2.75 pa with fire near the exit, in figure 20 these value change to -13.13 and -5.16 and finally in figure 21 from -21.53 to -6.9 pa. Which shows 53 percent loss of favorable chimney effect in figure 19 and 60 and 68 percent for figure 20 and 21 respectively also the maximum chimney effect for the highest HRR is 3.7 times bigger than the maximum chimney effect for the lowest HRR.

Figure 19 Chimney effect across the tunnel for different fire positions Q_t = 30 MW

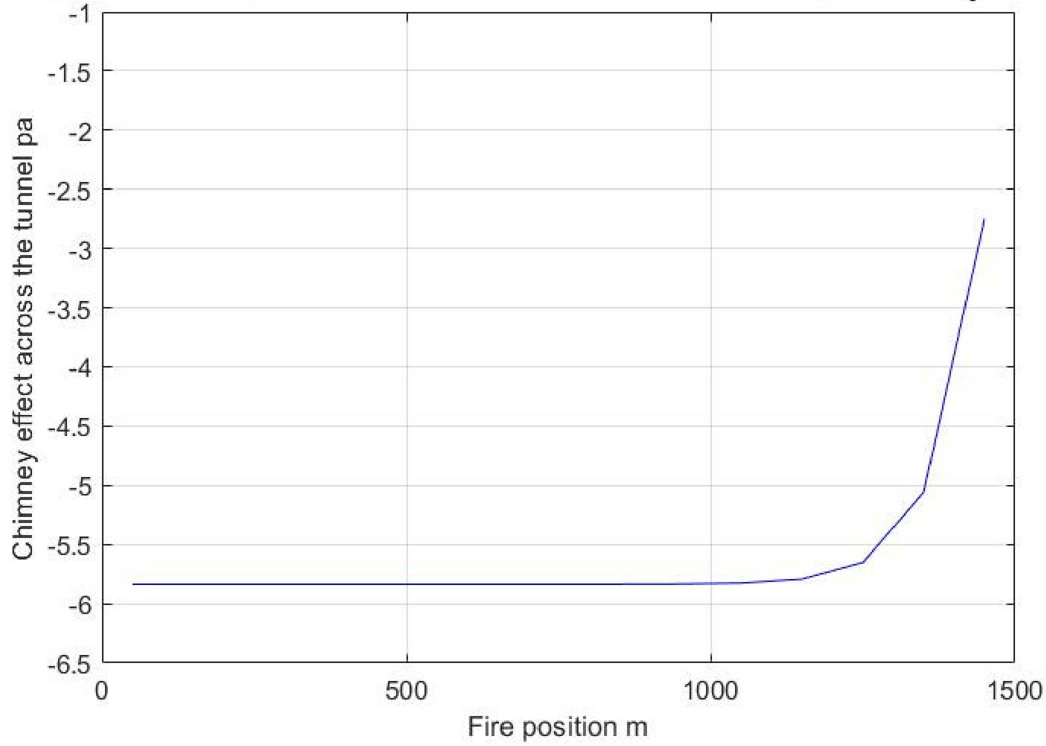
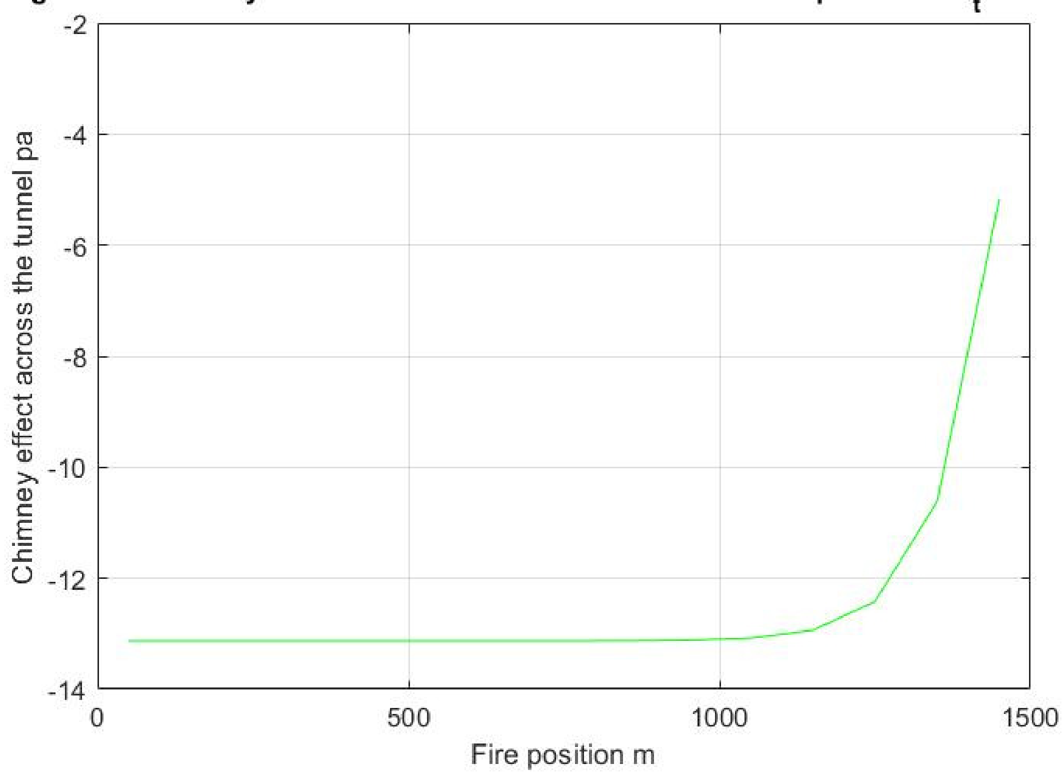
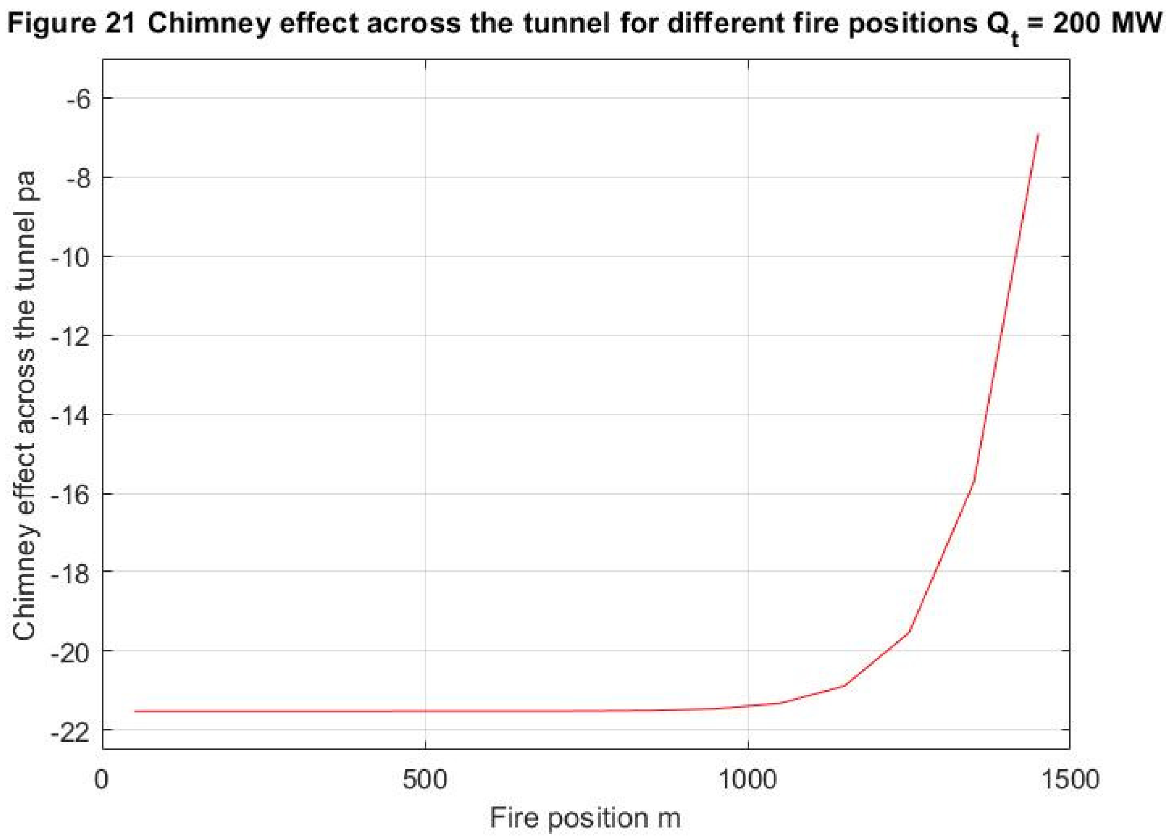


Figure 20 Chimney effect across the tunnel for different fire positions Q_t = 100 MW





3.2.7. Losses due to presence of parked vehicles inside the tunnel

Since the tunnel is uni-directional traffic in case of fire inside it the vehicles are parked before the fire and vehicle velocity in equation 17 is equal to zero also since here all of the vehicles are before the fire air density will be environment air density therefore piston effect is only depends on number of vehicles and air velocity . Figure 22 will illustrate its value across the tunnel against fire position for 30MW fire and figure 23 and 24 for 100 and 200 MW fire.

Figure 22 Vehicle Losses across the tunnel for different fire positions Q_t = 30 MW

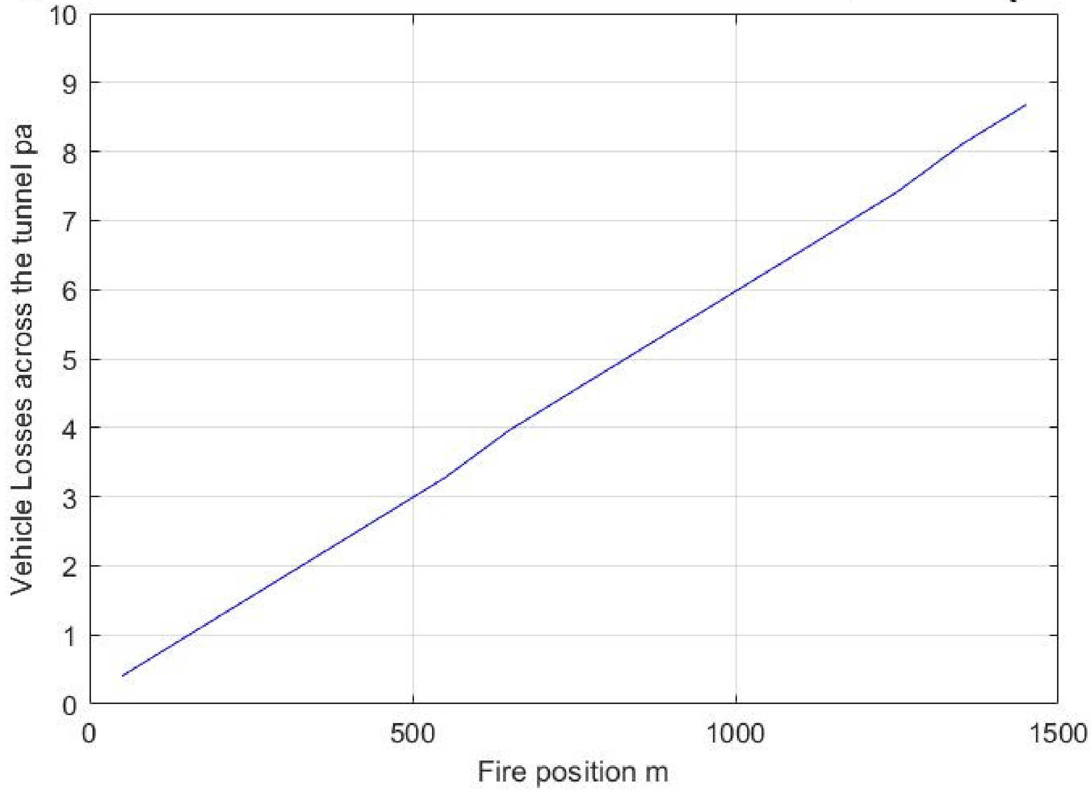


Figure 23 Vehicle Losses across the tunnel for different fire positions Q_t = 100 MW

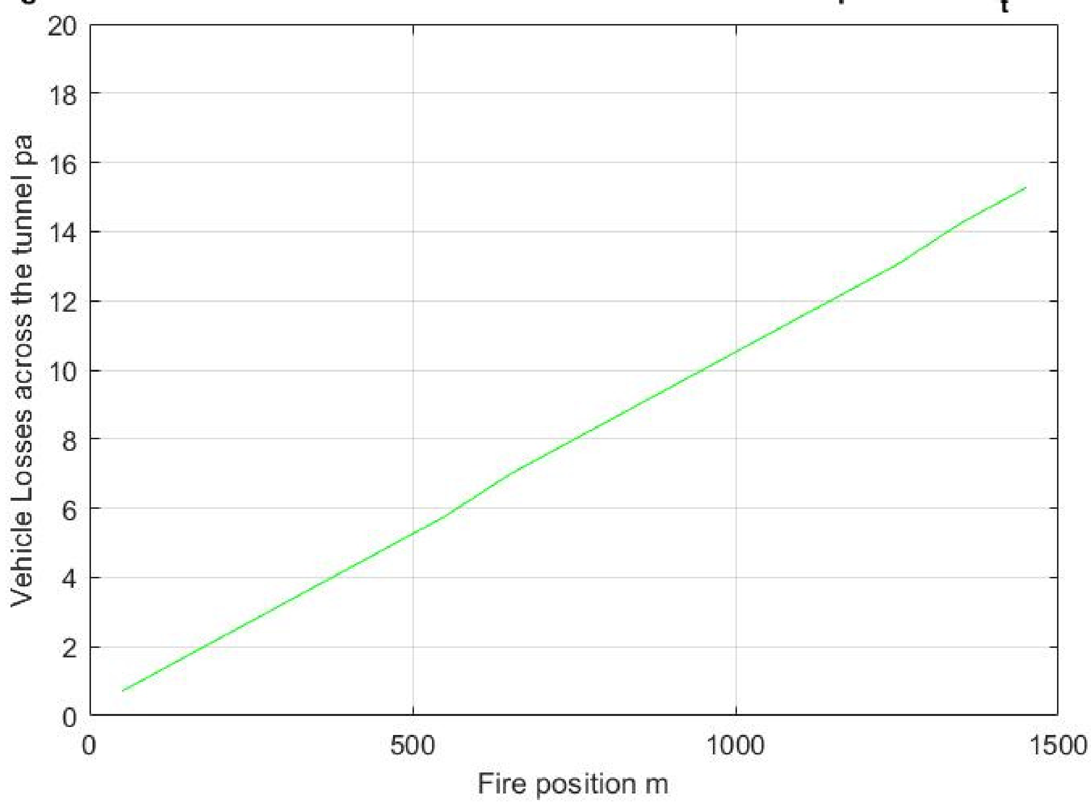
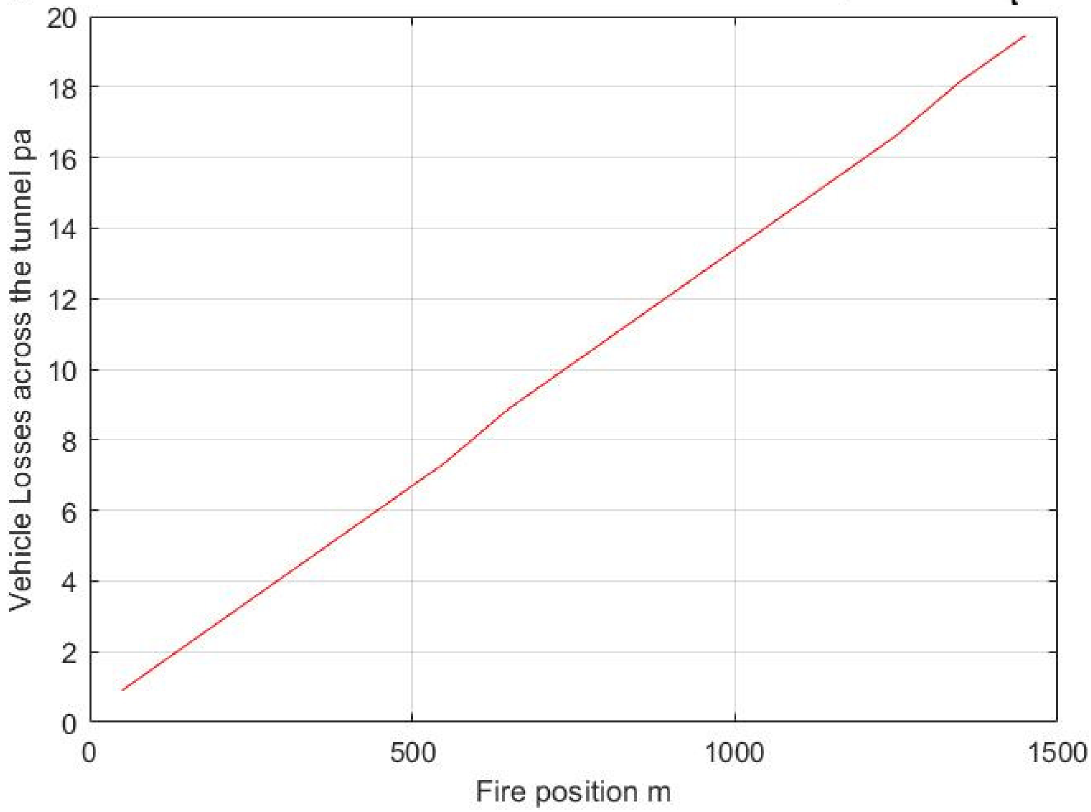


Figure 24 Vehicle Losses across the tunnel for different fire positions Q_t = 200 MW



Vehicle loss values in figure 22 are 0.40 pa with fire near entrance and 8.68 pa with fire near the exit. In figure 23 and 24 they change to 0.71 and 0.9 when fire is near the entrance and 15.27 and 19.46 in the case of fire near the exit respectively.

3.2.8. The effect atmospheric pressure

This is constant effect and here is considered to be equal to 25 pa for wind effects the pressure difference which is purely due to elevation difference is already considered in Chimney effect.

3.2.9. Thrust of a jet fan

By using the average air density inside the tunnel the thrust of a fan can be calculated with different fire positions the value of thrust only increase when the fire position getting close to tunnel exit. Obviously by increasing the fire HRR the thrust of fans decreases.

Figure 25 Fan thrust across the tunnel for different fire positions Q_t = 30 MW

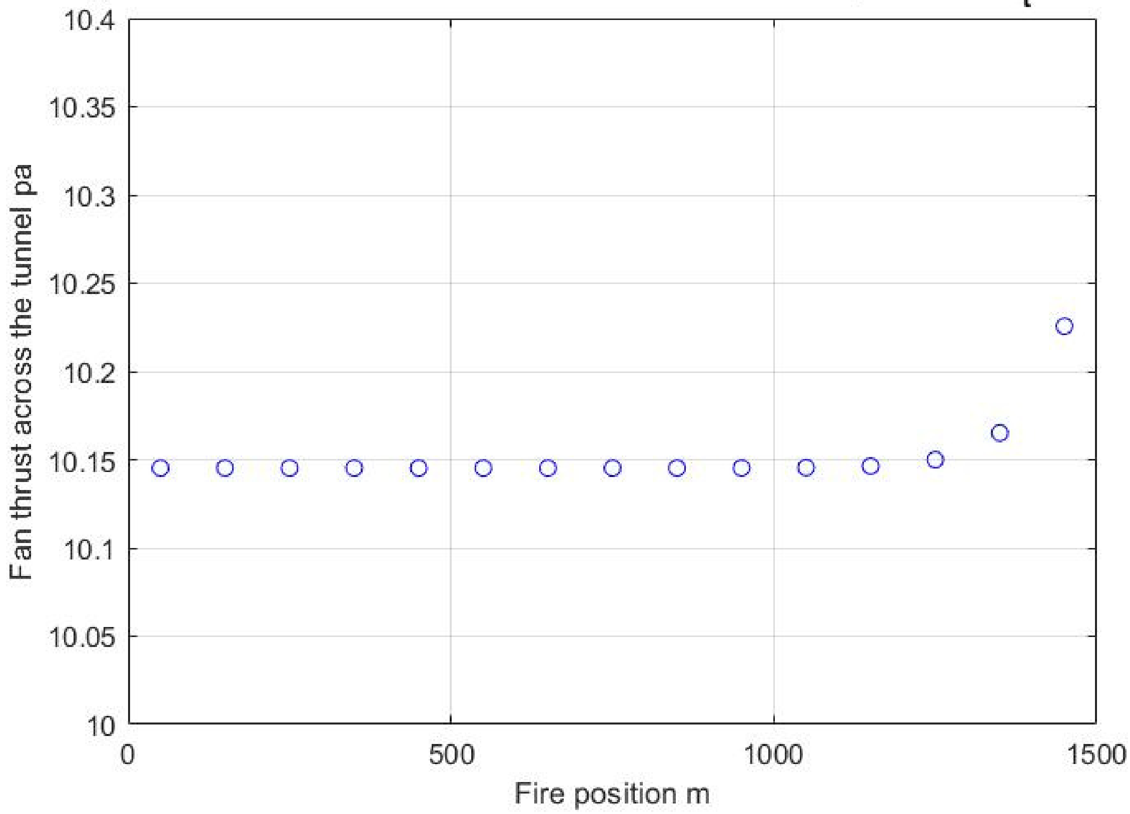


Figure 26 Fan thrust across the tunnel for different fire positions Q_t = 100 MW

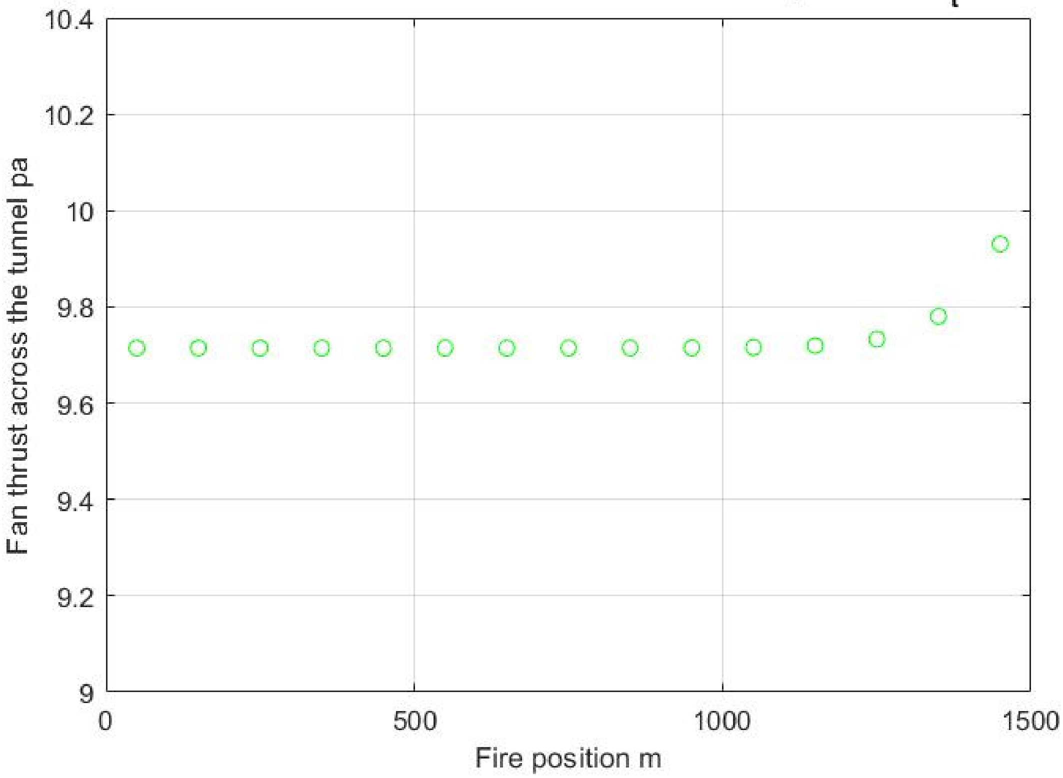
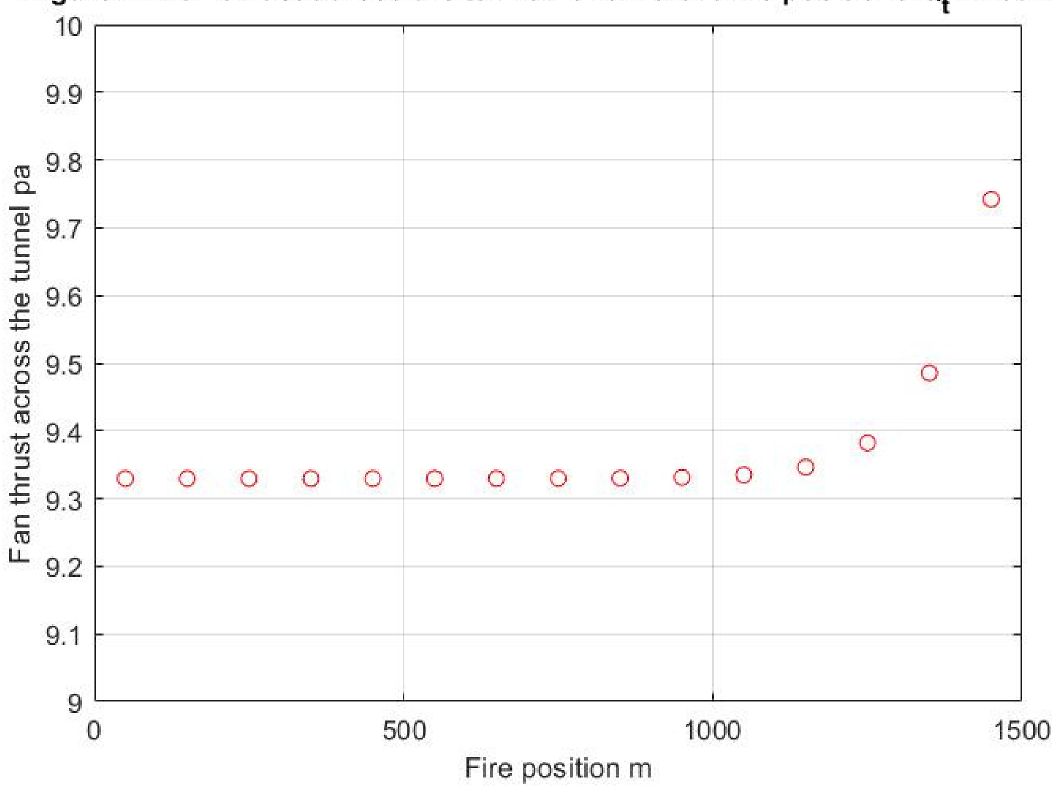


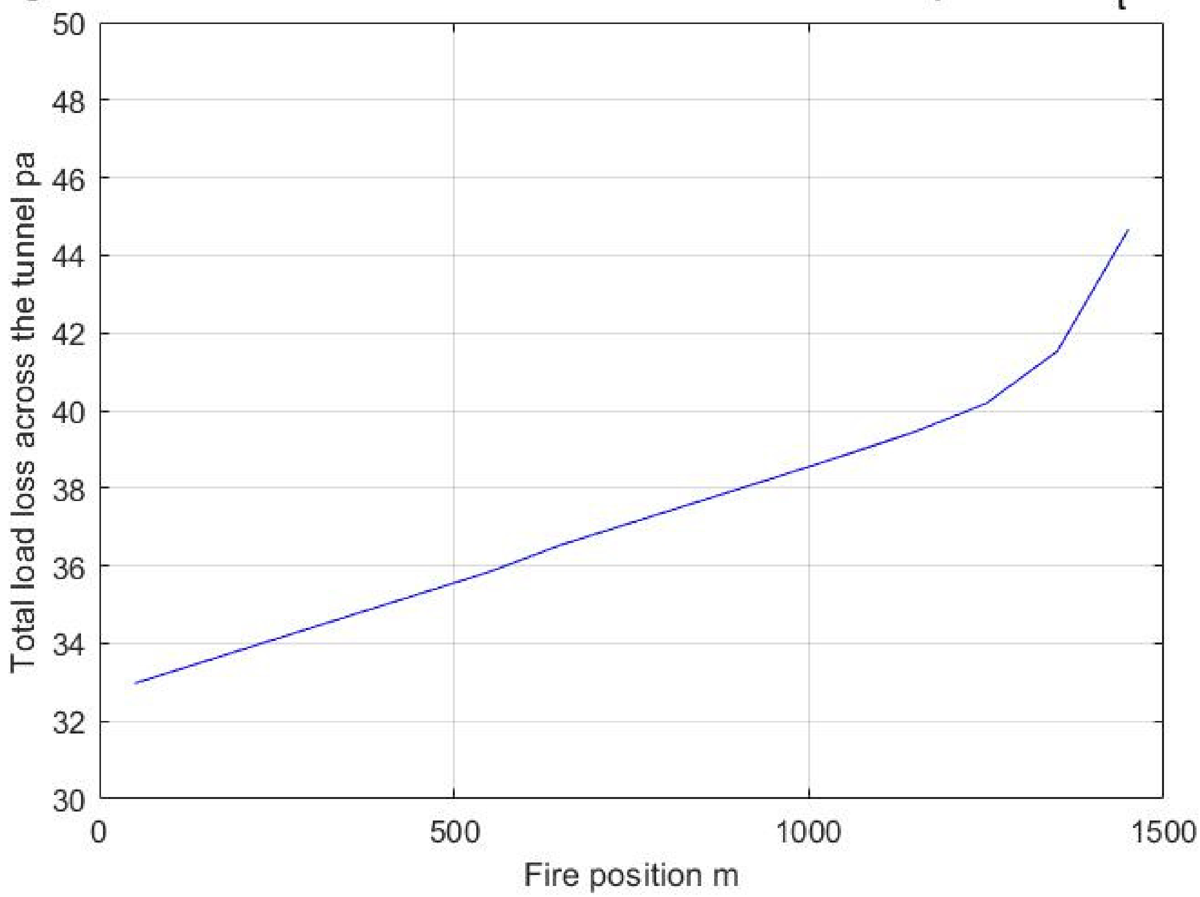
Figure 27 Fan thrust across the tunnel for different fire positions Q_t = 200 MW



3.2.10. Total load loss

By adding the all the above mentioned effect the total load loss can be obtained. Figure 28, 29 and 30 will show the total load loss.

Figure 28 Total load loss across the tunnel for different fire positions Q_t = 30 MW



It is obvious from the figures that with every fire HRR losses are higher when the fire occur near the exit port of the tunnel also by increasing fire HRR the losses will obviously increase.

Figure 29 Total load loss across the tunnel for different fire positions Q_t = 100 M

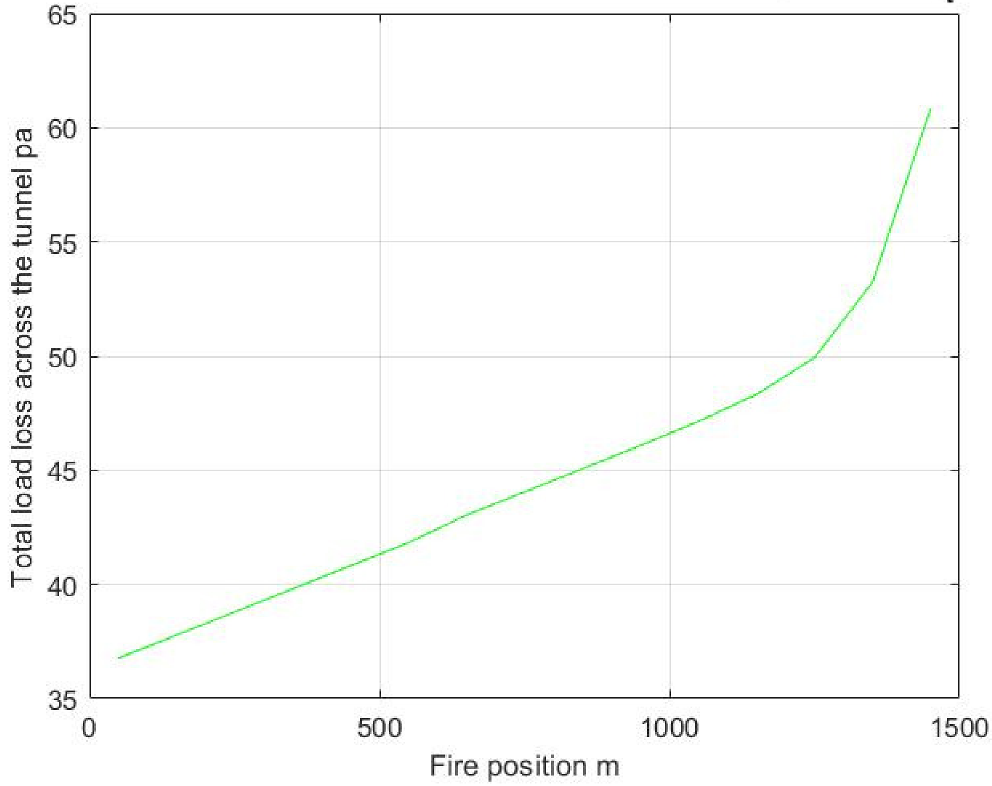
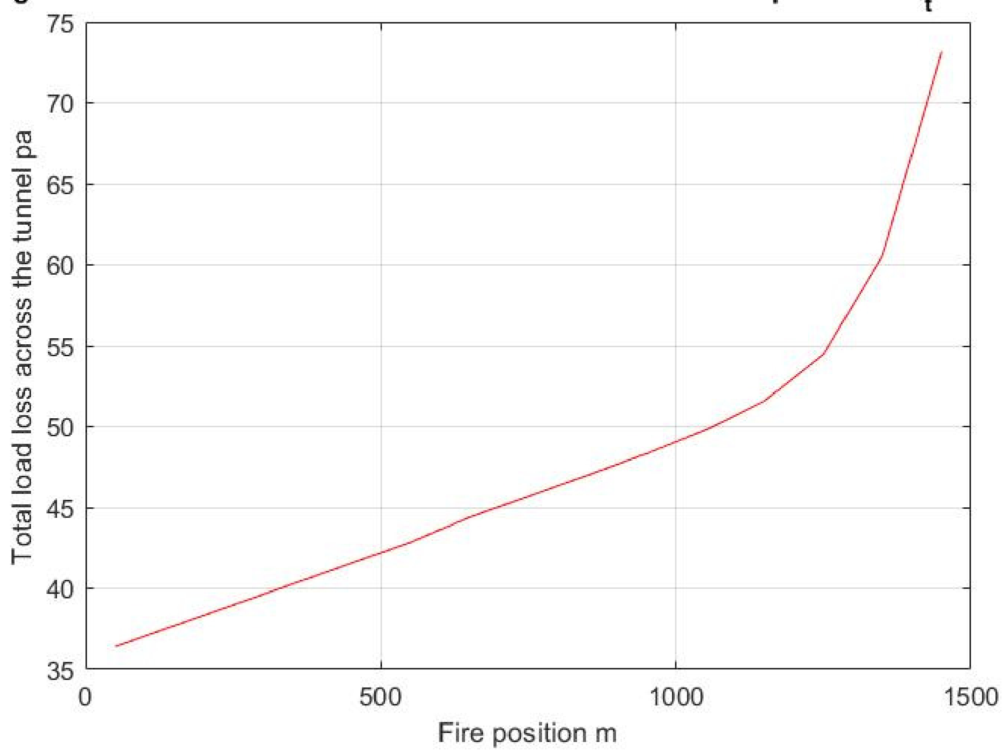


Figure 30 Total load loss across the tunnel for different fire positions Q_t = 200 MW



3.2.11. Number of fans

Finally the number of fans can be obtained by comparing the total pressure losses and single fan thrust in real working environment figures 31 to 23 are showing the number of fans needed for different fire positions.

Figure 31 Number of fans needed for ventilation system for different fire positions Q_t = 30 MW

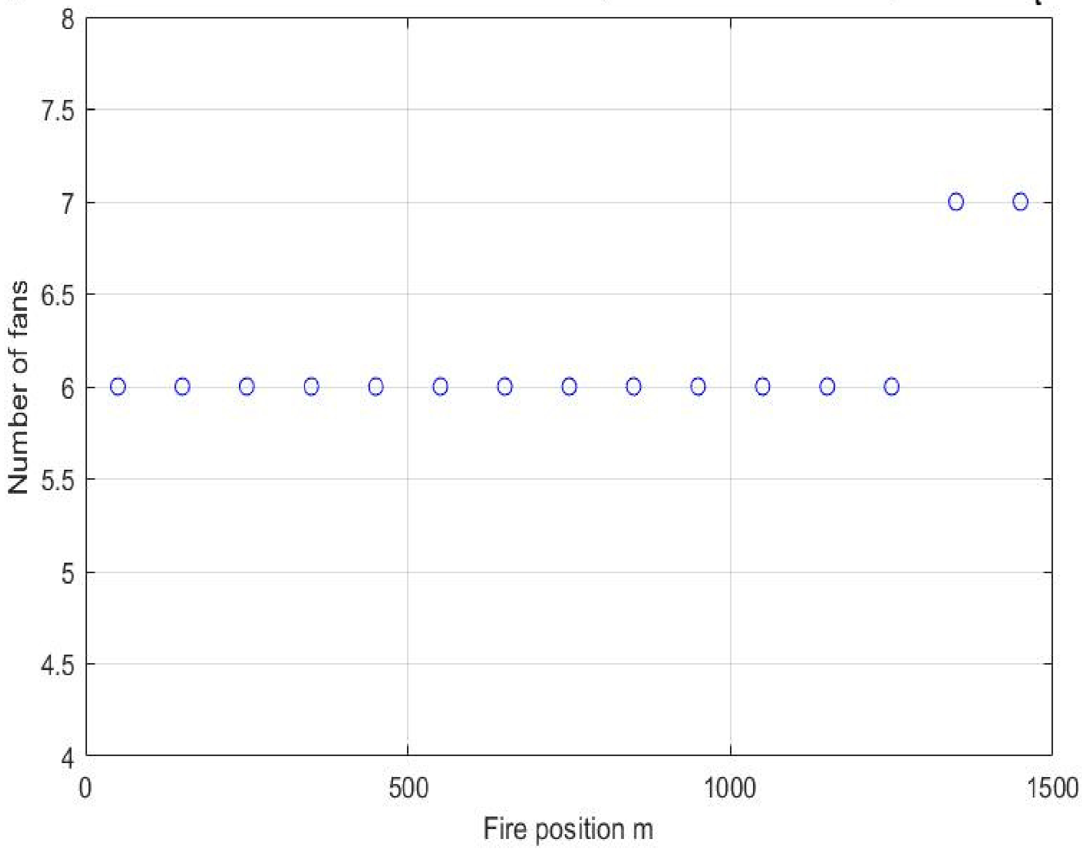


Figure 32 Number of fans for ventilation system for different fire positions Q_t = 100 MW

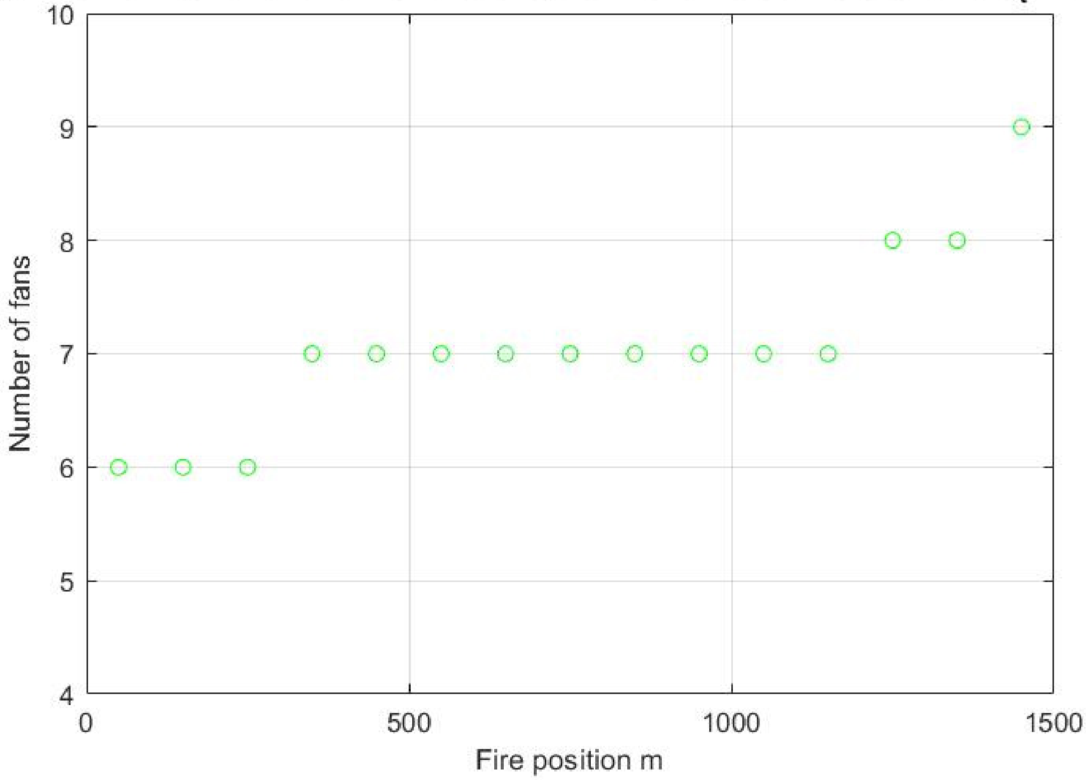
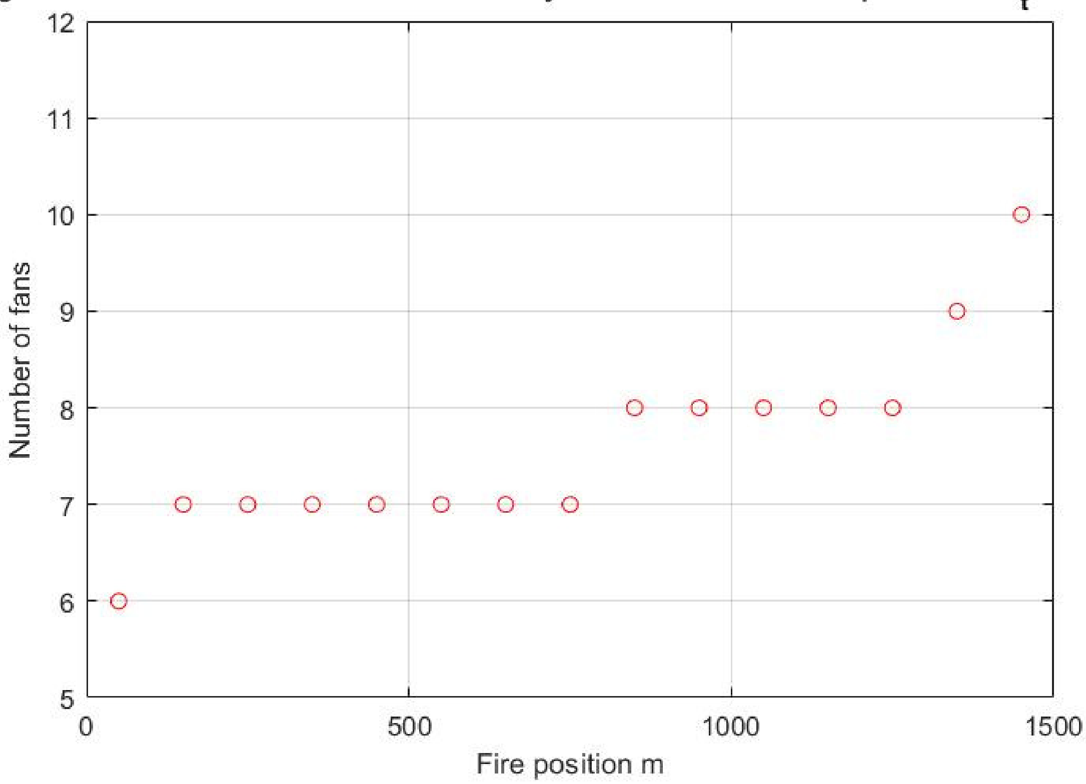


Figure 33 Number of fans for ventilation system for different fire positions Q_t = 200 MW



4. Comparison of parameters effect

In this chapter the fire Heat release rate is considered constant and equal to 100 MW and one other parameter changes to find some insight about what are the most important parameter in design of a longitudinal ventilation system capacity.

4.1 Critical air velocity

Longitudinal tunnel ventilation systems must provide air velocity equal or higher than the smoke critical velocity to prevent backlayering of smoke inside the tunnel in the case of fire. In this section the effect of over estimation of critical air velocity is calculated for fire with HRR of 100 MW. When critical air velocity increases from 2.56 $\frac{m}{s}$ to 3 $\frac{m}{s}$ we will find the following values. Figure 34 and 35 will show the difference in total load loss and number of fans required for ventilation after this change.

Figure 34 Total load loss across the tunnel for different fire positions V_c = 3 m/s

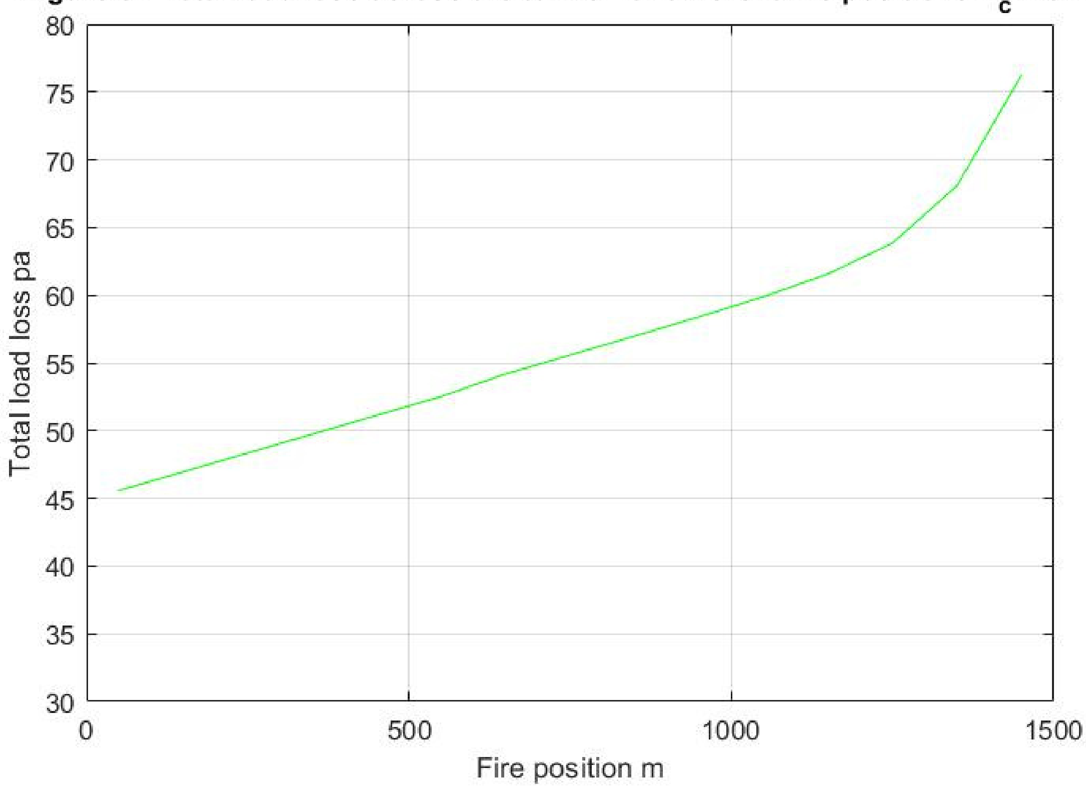
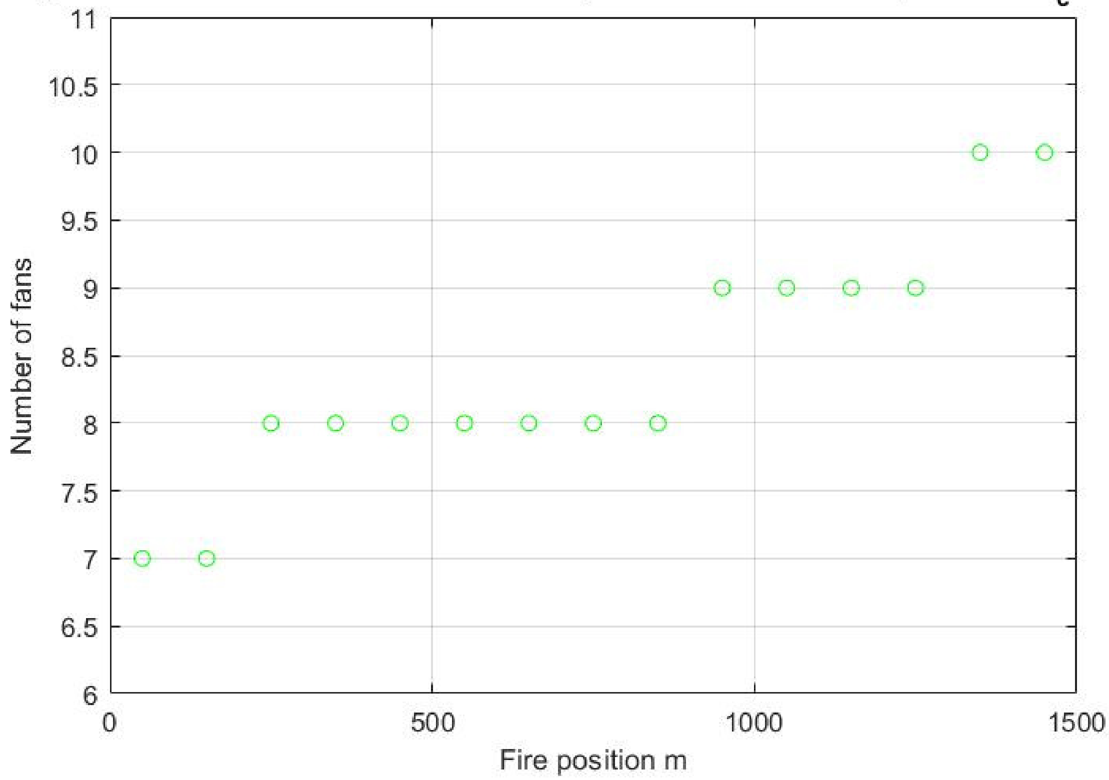


Figure 35 Number of fans for ventilation system for different fire positions V_c = 3 m/s



From the figures it can be obtained that maximum load loss increases 60.84 to 76.25 pa and number of fans needed is also increased from 9 to 10.

4.2. Slope

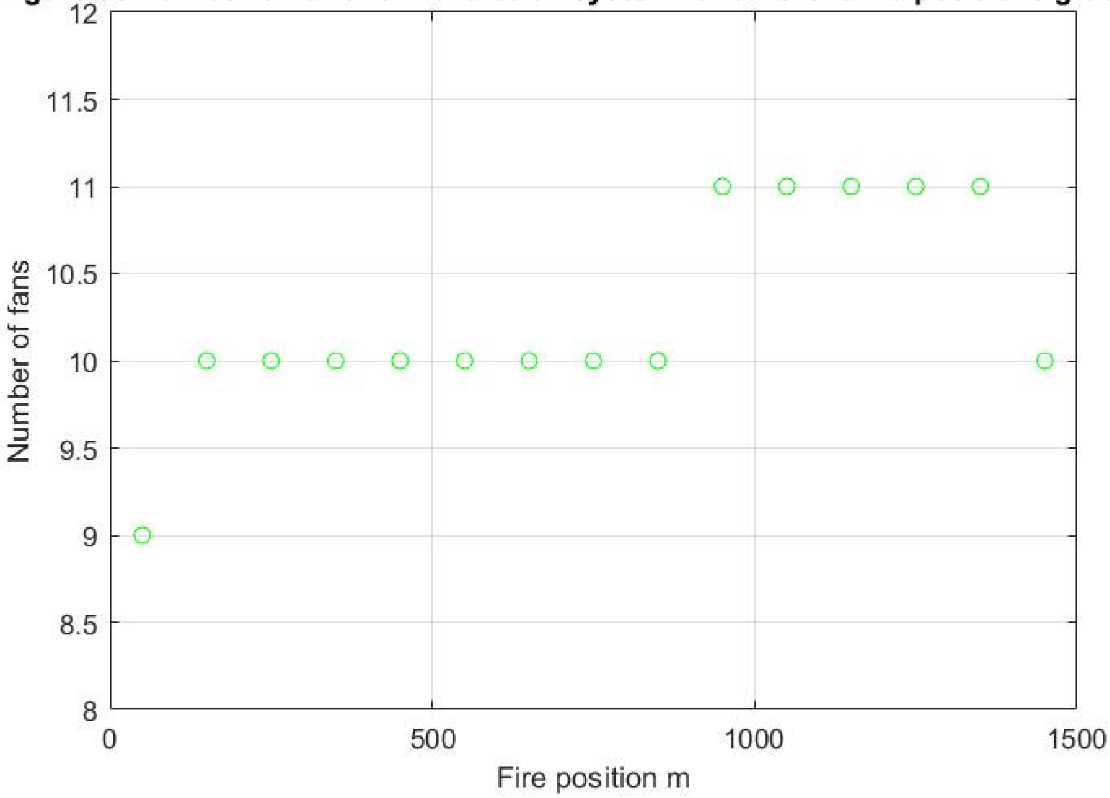
The effect of slope of the tunnel can be seen mainly in critical velocity and chimney effect first the positive 2% slope of tunnel changed to zero and then to -2% the new results for chimney effect and number of fans is reported in following lines.

The critical speed for tunnel with positive and zero slope is the same and equal to 2.56 $\frac{m}{s}$ it will increase to 2.76 $\frac{m}{s}$.

When the tunnel has a positive gradient the chimney effect does work in favor of extracting smoke and has value of -13.13 pa when fire is near entrance and -5.16 pa when fire is located near exit but with 0 slope there is no chimney effect and for slope of -2% these value change to 13.36 and 4.99 pa respectively.

Finally number of fans needed for the tunnel with positive 2 percent gradient is 8 which become 9 for flat tunnel and increases to 11 for tunnel with negative 2 percent gradient as shown in figure 31.

Figure 36 Number of fans for ventilation system for different fire positions grad=-2%



4.3. Friction coefficient

The friction coefficient affects the linear losses of the tunnel by doubling it from 0.025 to 0.05 for the tunnel with 2 percent positive gradient and with critical speed of 2.56 set as the air speed inside the tunnel the maximum linear loss will increase from 18.3 to 36.6 which was predictable from equation 14 with this change 2 fan must be added to the ventilation system which make total number of 10 fans.

4.4. Traffic composition

Piston effect is mainly depend on number of cars inside tunnel and their aerodynamic coefficient plus their cross section so adding less aerodynamic and bigger heavy-good vehicles add to this kind of losses in this section their percentage in tunnel traffic were raised from 18 % to 40% . Due to presence of more heavy-good vehicles in traffic maximum piston loss increased from 15.27 pa to 22.95 pa which translate to adding one more fan to the system and bringing the total number of fans to 9 .

5. Conclusion

An easy tool for calculating the number of jet fans in longitudinal ventilation system was created using matlab then this tool used to evaluate the effect of different parameters in the case of fire inside the tunnel. By using this tool number of jet fans were calculated for three different design fires in the tunnel and 15 different position of fire. Eventually by changing one specific parameter and fixing all the others the sensitivity of the system to that parameter were tested .From the data gathered in this theses it can be shown fire position near the exit poet of the tunnel is the critical one and the capacity of ventilation system have very high sensitivity to design air speed inside the tunnel and tunnel gradient.

6. Matlab Codes

The tools created by matlab for this theses are reported here.

6.1. Critical velocity

```
%%%%%%%%%%%%%%%%%%%%% constant parameters %%%%%%%%%%%%%%%%%
H = 6 ;%% Height of the Tunnel in m
grad = 2; %% Tunnel gradient in percent
A = 70; %%Tunnel cross section Area in m^2

Ro_0 = 1.2; %% Density of Ambient Air in kg/m^3
T_0 = 300; %% Ambient Temperature in K
C_p = 1040 ;%% Heat Capacity at constant Pressure in J/(KgK)
g = 9.822; %% Gravitational Acceleration in m/s^2

Q = 100000000;%% Fire total Heat release rate in W
Qc = (2/3)*Q; %% Fire convective Heat release rate in W
%%%%%%%%%%%%%%%%%%%%% constant parameters %%%%%%%%%%%%%%%%
Grad = abs(min(grad,0));
Gradeffect = (1 + (0.0374 * (Grad ^ 0.8))) ^ -3;
Fr_m = 4.5 * Gradeffect ;%%Critical Froude number
Qc_1 = (Ro_0 * A * C_p * T_0) / 2;
Qc_2 = sqrt((27* g * H)/ Fr_m);
Qc_max =( Qc_1 * Qc_2 )/ 1000000 ; %% Upper limit on the fire
convective Heat release rate in MW
a = Qc / (Ro_0 * A * C_p * T_0);
c = -(g * H * a)/ Fr_m ;
Q_bar = -((a^2)/9);
R_bar = (-27*c - (2*(a^3))) / 54 ;
S_bar1 = sqrt((Q_bar^3)+(R_bar^2));
S_bar = nthroot((R_bar + S_bar1),3);
T_bar = nthroot((R_bar - S_bar1),3);
Vc = S_bar + T_bar - (a/3);  %% Critical Velocity in m/s
```

6.2. Number of fans

```
%%%%%%%%%%%%%%% constant parameters %%%%%%%%%%
T_0 = 300;%% Ambient Temperature
Ro_0 = 1.2; %% Density of Ambient Air in kg/m^3 and fan
reference air density
C_p = 1040 ;%% Heat Capacity at constant Pressure in J/(KgK)
g = 9.822; %% earth gravitational acceleration in m/s^2

A = 70; %%Tunnel cross section Area in m^2
DH = 8.5 ;%% the hydraulic diameter in m
happ = 6 ;%% the coefficient of the Thermal apparent exchange in
W*K/m^2
L = 1500 ; %% Tunnel length
Slop = 2 ;%% slop of the Tunnel in percent
P = 32.5; %% Tunnel cross section perimeter in m
Landa = 0.025; %% the friction coefficient

Q = 100000000; %% Fire Heat release rate in W
Qc=(2/3)*Q; %% Fire convective Heat release rate in W
V_critical = 2.56; %% Air flow velocity in m/s

epsilon_e = 0.5; %%coefficient of Singular losses at Tunnel
entry
epsilon_s = 1 ;  %%coefficient of Singular losses at Tunnel exit

N_maxnormal_veh = 120;%% max number of vehicles in 1000 m of the
Tunnel
N_normal_veh = floor((N_maxnormal_veh * L)/1000); %% max number
of vehiecles in the Tunnel
HDV = 40;%% the percentage of the heavy duty vehicles
CxZigma_veh = 0.9;%%product of aerodynamic resistance and cross
section area of vehicles
CxZigma_HDV = 4.5;%%product of aerodynamic resistance and cross
section area of heavy duty vehicles

Ka= 0.85 ;%%coefficient of fan efficiency
F_0 = 900;%% thrust of one jet fan in N
V_jet = 35; %% the velocity of the air Jet at R_0 of fans in m/s
Fan_add = 2; %% number of redundant fans

deltaL = 12.5 ; %% Tunnel length steps
dH_atm = 25; %%the pressure difference between entrance and exit
of a Tunnel
k=1;
```

```
%%%%%%% prealocation of vector sizes %%%%%
x_fire_vec=zeros(1,15);
dH_fire_vec=zeros(1,15);
dH_linear_vec=zeros(1,15);
dH_singular_vec=zeros(1,15);
dH_chimney_vec=zeros(1,15);
dH_veh_vec=zeros(1,15);
dH_total_vec=zeros(1,15);
dH_atm_vec=zeros(1,15);
dH_fan_vec=zeros(1,15);
Nfan_vec=zeros(1,15);
for x_fire = 50:100:L %%Position of the Fire
dH_atm = 25; %%the pressure difference between entrance and exit
of a Tunnel
X = 0 : 12.5 : L ;
X_fire = x_fire.* ones(length(X),1)';
Position = X - X_fire;
Fireposition = size(find(Position < (deltaL/2)),2);%setting the
fire position
N_vel1 = floor((N_normal_veh /L).* X);
N_vel_total = N_vel1(Fireposition);
N_HDV = ceil((HDV/100)*N_vel_total);% calculating heavy-good
vehicles number
N_veh = N_vel_total - N_HDV;%calculating vehicles number
P_R = T_0*Ro_0;
T_conv1 = Position ((Fireposition+1:end));
T_conv2 = ((-
4*happ)/(Ro_0*A*DH*V_critical)).*ones(1,size(T_conv1,2));
T_conv3 = T_conv2.*T_conv1;
T_conv4 = exp(T_conv3);
T_conv = T_0 + ((Qc/(Ro_0*V_critical*A*C_p)).*T_conv4);%
calculating Temperature  after the fire
T_amb = T_0.* ones(1,Fireposition-1);%calculating Temperature
before the fire
T_fire = T_0 + (Qc/(Ro_0*V_critical*A*C_p));%calculating fire
Temperature
Temp = [T_amb T_fire T_conv ];%Temperature Distribution
Ro = P_R./Temp;
V_critical_vec = V_critical.* ones(length(X),1)';
V=(Ro_0./Ro).*V_critical_vec;
dH_linear1 = ((Landa.*(V.^2).*deltaL)./(2*DH)).*Ro;
dH_linear = sum(dH_linear1 (1:end-1));
Ro_entry = Ro(1);
Ro_exit = Ro(end);
V_entry = V(1);
V_exit = V(end);
dH_entry = 0.5 * epsilon_e * Ro_entry * (V_entry^2);
```

```
dH_exit = 0.5 * epsilon_s * Ro_exit * (V_exit^2);
dH_singular = dH_entry + dH_exit;
Ro_0vec = Ro_0.* ones(length(X),1)';
Ro_chimney = Ro_0vec - Ro ;
dH_chimney1 = (deltaL * (-1*Slop/100) * g) .* Ro_chimney;
dH_chimney = sum(dH_chimney1 (1:end-1));
dH_veh=((0.5*Ro_0*(V_critical^2)/A)*N_HDV*CxZigma_HDV)+((0.5*Ro_
0*(V_critical^2)/A)*N_veh*CxZigma_veh);
Ro_avr = sum(Ro) / size(Ro,2);
V_avr = sum(V) / size(V,2);
dH_total = dH_veh + dH_chimney + dH_singular + dH_linear +
dH_atm;
dH_fan = ((Ka * F_0 * Ro_avr) * ( 1- (V_avr/V_jet)))/(A * Ro_0
);
N_fans = ceil((dH_total/dH_fan)) + Fan_add;
x_fire_vec(1,k) = x_fire;
dH_linear_vec(1,k) = dH_linear;%linear losses
dH_singular_vec(1,k) = dH_singular;%singular losses
dH_chimney_vec(1,k) = dH_chimney;%chimney effect
dH_veh_vec(1,k) = dH_veh;%piston losses
dH_total_vec(1,k) = dH_total;%total losses
dH_fan_vec(1,k) = dH_fan;
dH_atm_vec(1,k) = dH_atm;
Nfan_vec(1,k) = N_fans;%number of fans
k=k+1;
end
```

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Ringraziamenti

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