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Research Article

Numerical Simulation Study of the Effect of Sloping up Tunnels and Sloping Down Tunnels on the Smoke Management at Truck Fire with Flammable Loading

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Abstract In this study CFD simulations are conducted on two parts of sloping tunnel to study the effect of slope of tunnels on the smoke management at truck fire taking in consideration that ventilation system is semi-transverse ventilation system, background velocity direction which effects the smoke movement when the direction is in the same direction of tunnel slope or in the opposite direction, ANSYS Fluent program is used to investigate the temperature and velocity variations along tunnel length, the tunnel used to be case study is Dartford west tunnel which its slope is 4 %, the heat released rate (HRR) of the truck fire with flammable loading is 30 MW which is the general case according to PIARC 1999, also truck fire is considered one of the big dangerous fires that may happen in any tunnel, the results shows that the slope of tunnel effects the smoke movement along tunnel length and this effect depends on many parameters such as direction of air and direction of slope if it is up or down, etc.

Keywords Slope of Tunnels; Smoke Management; Semi-Transverse Ventilation; Background Velocity; Heat Released Rate

1. Introduction

Countries now are on the direction of going through far and difficult access places due to need for new cites to reduce population in center and to open new communities., Vehicle roads are the first step for this action so they face many difficulties like rivers or mountains so that leads to constructing bridges or tunnels but Bridges are used commonly because of its simple design and construction.

Route tunnels are used in most complicated areas which there is not enough space for bridges so tunnels are the way to solve this problem

Ventilation system in tunnels is the most important parameter for people life in the tunnel during normal ventilation or fire or accident.

Classification of smoke control systems in tunnels

Natural ventilation

This is caused by natural effects in tunnels without any mechanical systems such as fans and classified into two types.

Induced by the air temperature and meteorological conditions

This type of ventilation is caused by wind speed due to air pressure difference between the two opposite portals in tunnel and may be by height difference between portals that causes chimney’s effect.

Induced by traffic

Which is called "piston effect" this is a natural effect which is caused by pushing air into tunnel by vehicles drag force due to vehicles velocity. Piston effect has its own effect when the tunnel is unidirectional and air velocity depends on number of vehicles entering the tunnel and vehicle's speed.

Mechanical ventilation

This type of ventilation system is used when natural ventilation is not enough for controlling smoke in tunnels during fire and it is classified into three types.

Longitudinal ventilation system

This type of ventilation system depends on pushing air from entrance tunnel portals and exits smoke from exit tunnel portal making uniform longitudinal air direction and velocity. This way is very simple and cheap due to its simple design and construction.

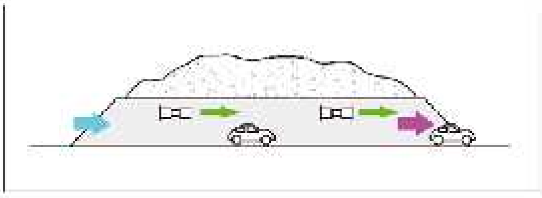
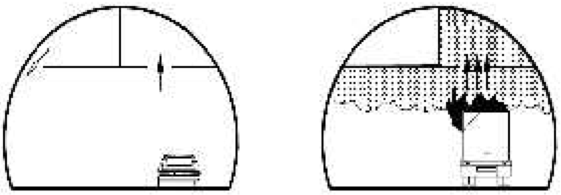


Figure 0.1: longitudinal ventilation with jet fans [1].

Full transverse system

In fully transverse ventilation systems in tunnels fresh air is introduced to the tunnel by one or more ducts along the tunnel length by some air louvers at side walls of the tunnel and there are one or more ducts at the opposite side walls which extracts smoke from the other side by some exhaust louvers but at fire supply fans are turned off and only exhaust fans are still working.



Normal ventilation Fire case

Figure 0.2: Smoke movements with full transverse ventilation system [2].

Reversible Semi transverse system

In semi transverse ventilation system in tunnels air is introduced to the tunnel by one or more supply ducts with supply air louvers along the tunnel but there are no exhaust ducts and air is extracted by the two portals of the tunnels making uncontrolled longitudinal air flow through the tunnel length.

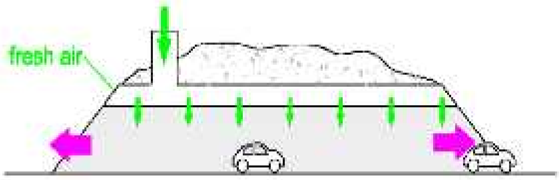


Figure 0.3: Air direction with semi transverse ventilation [1].

In reversible semi transverse system supply fans are reversed to be exhaust fans and air is extracted from supply louvers out from the tunnel and fresh air is introduced to by the two portals of the tunnel as shown on figure 1.4.

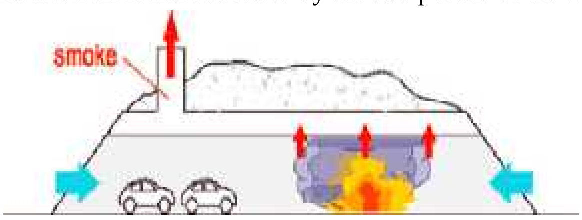


Figure 0.4 Smoke movements with reversible semi transverse ventilation at fire [1].

2. Case study

CFD ventilation analysis of Dartford west tunnel

Dartford west tunnel was opened in 1963 with 1.5 km long and 6.5 m height with unidirectional traffic in two lanes going from Kent in south to Essex in north at east of London. The tunnel has a diameter 8.6m and its capacity is 130,000 vehicle/day.

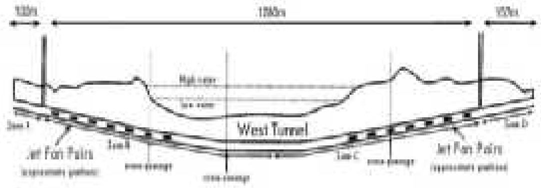


Figure 0.1: Diagram of West tunnel showing the relative positions of the jet fans and extract shafts [4].

Different ventilation scenarios at fire case

The designers of the ventilation system in Dartford west tunnel designed that at fire there are 4 scenarios that may happen.

At zone A (if the fire occurs between south portal and south extract shaft)

Ventilation system was designed to activate all jet fans blowing air from south to north and activating exhaust shafts at south and north but keeps all supply fans off.

At zone B (if the fire occurs between souths extract shaft and midpoint of the tunnel).

Ventilation system was designed to activate all jet fans blowing air from south to north and activation of northern exhaust shaft but setting southern extract shaft and all supply fans off.

At zone C (if the fire occurs between midpoint of the tunnel and northern extract shaft).

Ventilation system was designed to activate all jet fans blowing air from south to north and activation of southern supply and northern extract shaft but setting northern supply fan and southern extract shaft off.

At zone D (if the fire occurs between northern extract shaft and northern portal of the tunnel).

Ventilation system was designed to activate all jet fans blowing air from south to north and activation of all supply fans but setting all extract shafts off.

The fire is critical when it occurs in zones B and C which is difficult for people to escape because Dartford west tunnel is long with about 1500 meters and when fire occurs jet fans are activated with high velocity which forces smoke distributes along tunnel length according to jet fans design and type so this study concentrates on activating fire in zones B and C are.

Design of fire in Dartford west tunnel

According to piarc 1999 the general case of fire in route tunnel is lorry with burning goods with 30 MW heat released rate.

Dartford west tunnel located in united kingdom so according to piarc 2017 measurements are conducted on tunnels to get the relation between lorry fire with time so in this study lorry fire with flammable loading is firing and stands for 10 minutes which is applicable in this tunnel.

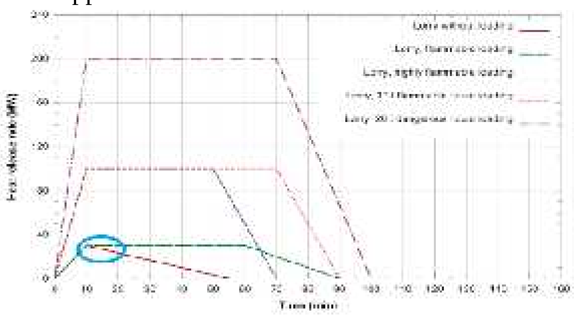


Figure 0.2: Design of lorry fire in United Kingdom [3]

Mesh sensitivity test

Firstly CFD simulations using ANSYS Fluent program is done on normal ventilation analysis on zone B when activating 7 jet fan pairs existing in zone B and getting velocity variations at center point of tunnel which the air flow seems to be steady because that at center of Dartford west tunnel there are no jet fans so comparing mesh sensitivity test at this point is optimum at this case.

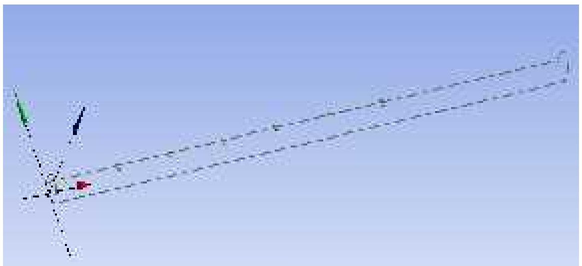


Figure 0.3: Wire frame geometry simulation of zone B in ANSYS Fluent program

Getting the velocity variation at different mesh elements to get the optimum number of mesh elements which is compatible with this study as following:-

A- Dividing zone B into 1,000,000 elements for 700 iterations the resulted background velocity ranges from 3.5 m/s to 4.7 m/s at end of zone B.

B- When dividing zone B into 2,000,000 elements for 700 iterations the resulted background velocity is 3.25 m/s at end of zone B.

C- When dividing zone B into 2,500,000 elements for 700 iterations the resulted background velocity is 3.25 m/s at end of zone B.

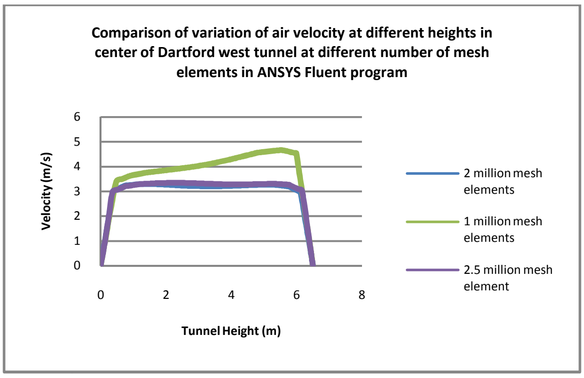


Figure 0.4: Comparison of variation of air velocity at different heights in center of Dartford west tunnel at different number of mesh elements in ANSYS Fluent program

The results shows that increasing number of mesh elements enhances the solution at end of zone B, but when using 2,500,000 elements, the variation of air velocity with tunnel heightis almost similar to the results when using 2,000,000 mesh elements.

So all numerical simulations are conducted using 2,000,000 mesh elements in ANSYS Fluent program at all studies in this research.

3. Results and discussion

Jet fan design

Dartford west tunnel has 14 jet fan pairs (28 jet fan) with diameter 0.8 m and 1.6 m long with distance 1 m from center

Calculating jet fan thrust force

Jet fan air flow rate 8.9 m^3/s

Jet fan air velocity 17.8 m/s

Air density 1.2 kg/m^3

Force= Flow rate x velocity x density

Tj= Q x V x ρ

Tj= 8.9x17.8x1.2=237.63 N/m^3

Jet fan thrust force = 237.63 N/m^3

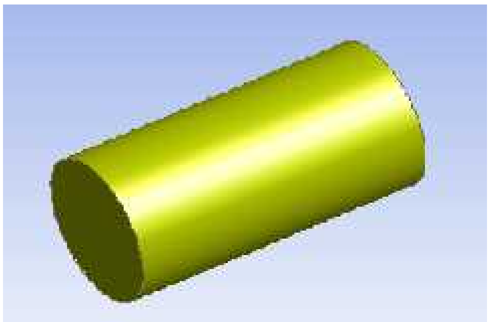


Figure 0.1: Jet fan geometry in ANSYS Fluent program

Comparison between sloping zone B in Dartford west tunnel and non-sloping zone B

Zone B in Dartford west tunnel begins from southern exhaust shaft and middle point in the tunnel with slope 4 % as shown in figure 2.1 , zone B has 7 jet fan pairs (14 jet fans) each has thrust force equal 237.63 N/m^3 with distance 50 m between them.

In this section CFD simulations are conducted on zone B and getting velocity and temperature variations at different tunnel heights along length of zone B and comparing this results with non-sloping zone B, the results shows the effect of slope on temperature and velocity along distance of zone B taking into consideration that air is introduced to tunnel from southern portal and exits from northern portal of the tunnel.

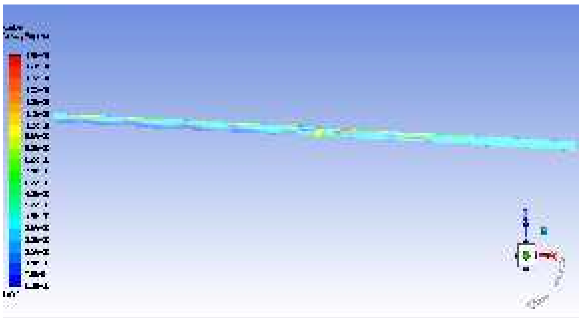


Figure 0.2: Velocity contours at center of zone B sloping 4 %.

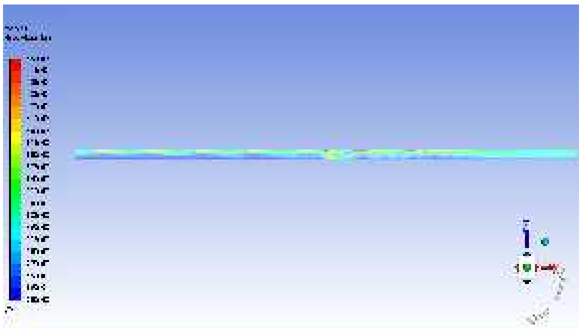


Figure 0.3: Velocity contours at center of zone B non-sloping.

The range of Velocity contours along zone B is from 0 m/s to 15m/s so overall velocity along length of zone B with slope 4 % is lower than non-sloping zone B especially at high levels as shown on figure 3.2 and figure 3.3.

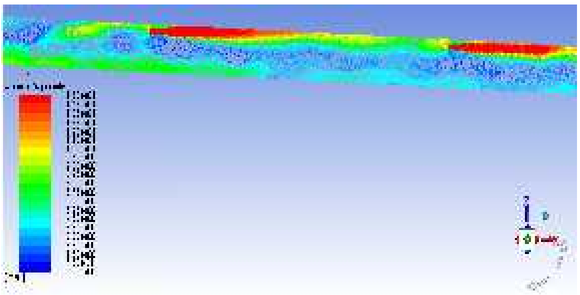


Figure 0.4: velocity vectors at sixth and seventh jet fan pairs (after fire) at zone B with slope 4 %.

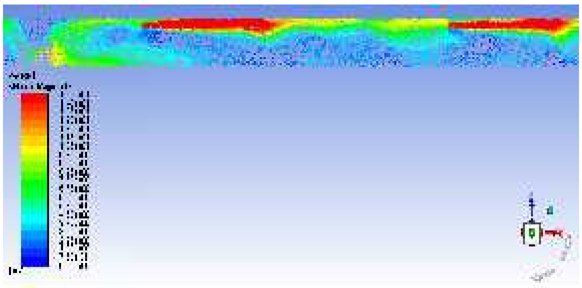


Figure 0.5: Velocity vectors at sixth and seventh jet fan pairs (after fire) at non-sloping zone B.

Slope of the tunnel effects the direction of air or smoke enters the jet fan because that jet fan pushes smoke to tunnel bottom which is opposite of nature of smoke which have low density that goes up not down but slope of the tunnel affects this nature causing turbulence at jet fans inlet and outlet as shown on figure 3.4.

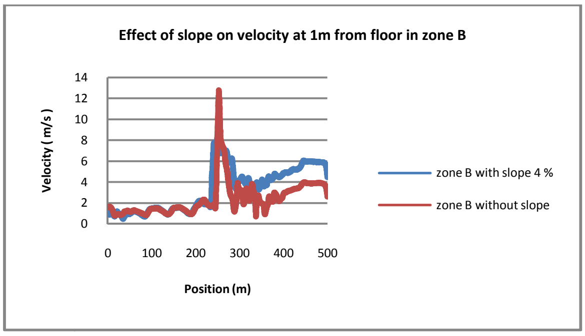


Figure 0.6: Velocity variations at 1m height in zone B with slope 4 % and 0 %.

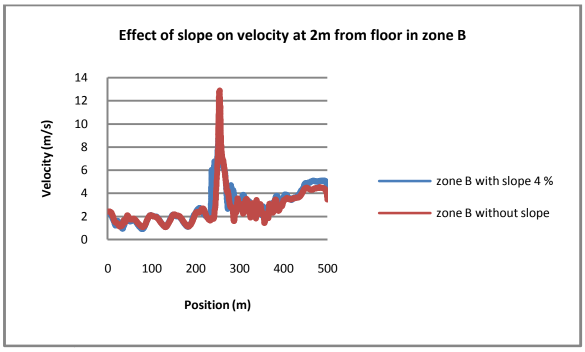


Figure 0.7: Velocity variations at 2m height in zone B with slope 4 % and 0 %.

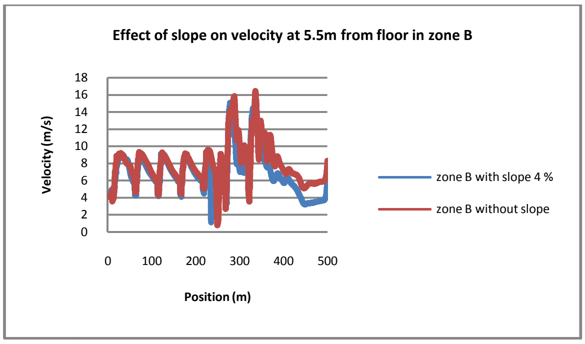


Figure 0.8: Velocity variations at 5.5m height in zone B with slope 4 % and 0%.

Comparing between velocity values at different heights along zone B length, at people levels which are between children height 1m and adults' level 2m from floor. Figures 15 and 16 shows that at slope 4 %, velocity after fire is higher than at slope 0 % inverses at jet fans height which is 5.5m which is logic according to effect of tunnel slope.

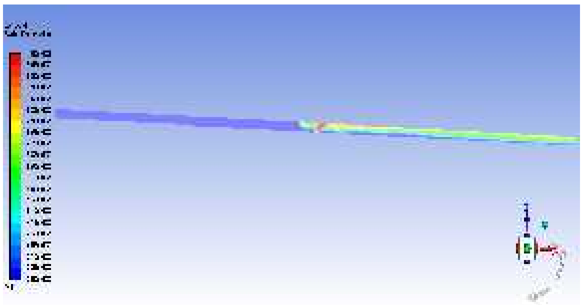


Figure 0.9: Temperature contours at center of zone B sloping 4 %.

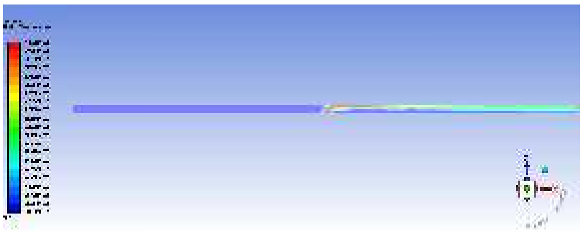


Figure 0.10: Temperature contours at center of zone B non-sloping

The range of temperature scale is from 300 kelvin to 1000 kelvin and same in two cases, jet fans derives air from south to north which is the same direction of slope of zone B so air is introducing in the direction of tunnel center point, as shown on figure 3.9 and figure 3.10 temperature contours at zone B sloping 4 % is higher than non-sloping one that may harms people life.

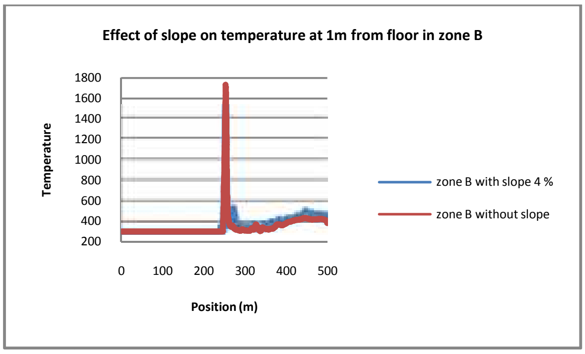


Figure 0.11: Temperature variations at 1m height in zone B with slope 4 % and 0 %.

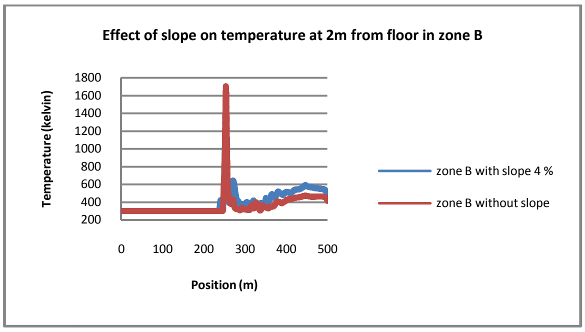


Figure 0.12: Temperature variations at 2m height in zone B with slope 4 % and 0 %.

At human levels from 1m to 2m, slope of the tunnel makes a negative effect on temperature variations that sloping tunnel increases temperature at human levels causes harmful effect to people life as shown on figures 3.11 and 3.12.

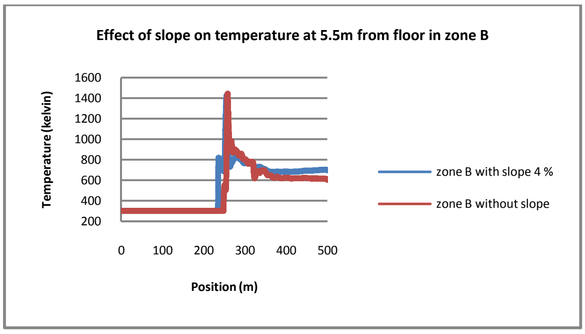


Figure 0.13: Temperature variations at 5.5m height in zone B with slope 4 % and 0 %.

At high levels of zone B temperature at sloping tunnel is higher than non-sloping one as shown on figure 3.13. Heat retention is a general case when the direction of delivering air is the same direction of tunnel sloping down so increasing number of jet fans may be a good way for sloping down tunnels to overcome the negative effect of the slope.

Comparison between sloping zone C in Dartford west tunnel and non-sloping zone C

Zone C of Dartford west tunnel begins from center point of the tunnel to eastern exhaust shaft

In this section CFD simulations are conducted on zone C with slope 4 % raising up opposite of zone B and comparing velocity and temperature results with assumption of non-sloping zone C to get the effect of slope when the direction of delivering air is from south to north raising up same as slope of zone C.

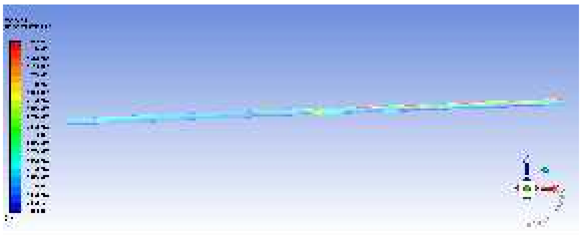


Figure 0.14: Velocity contours at center of zone C sloping 4 %.

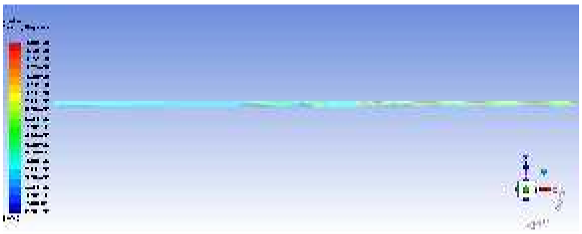


Figure 0.15: Velocity contours at center of zone C non-sloping

The velocity contours at zone C sloping 4 % is very high at jet fans level comparing with the same range at non-sloping zone C this relation is reversed at lower levels which the velocity of sloping zone C is lower than non-sloping one which describes the positive effect of slope when the direction of air is the same as the direction of slope raising up as shown on figures 3.14 and 3.15.

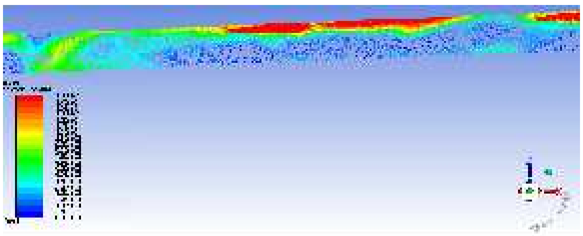


Figure 0.16: Velocity vectors at sixth and seventh jet fan pairs (after fire) at zone C with slope 4 %

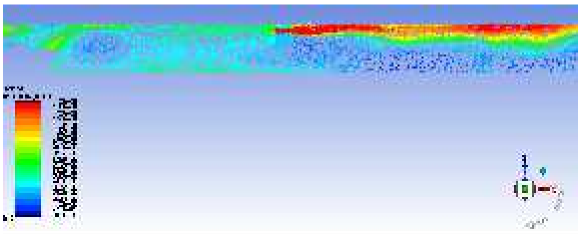


Figure 0.17: Velocity vectors at sixth and seventh jet fan pairs (after fire) at non-sloping zone C

Slope of tunnel affects the velocity vectors at inlet and outlet of jet fans which differs between if the direction of background velocity is the same direction of tunnel sloping up or the direction of background is the same direction of straight tunnel, so velocity vectors around jet fans are smoothing at inlet or outlet when tunnel is straight but they are more turbulent when the tunnel is sloping up.

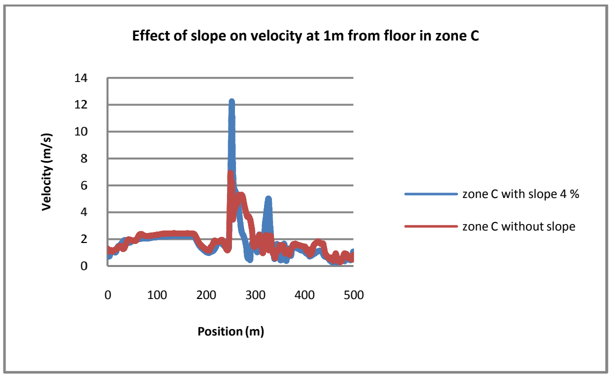


Figure 0.18: Velocity variations at 1m height in zone C with slope 4 % and 0 %.

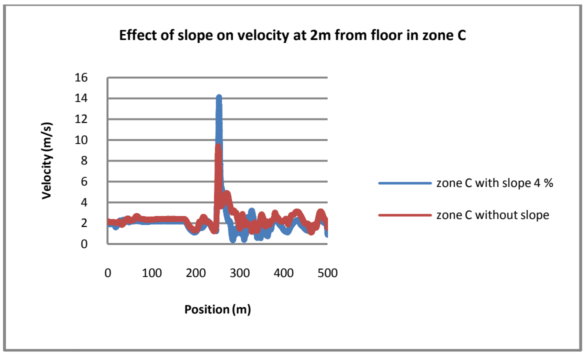


Figure 0.19: Velocity variations at 2m height in zone C with slope 4 % and 0 %.

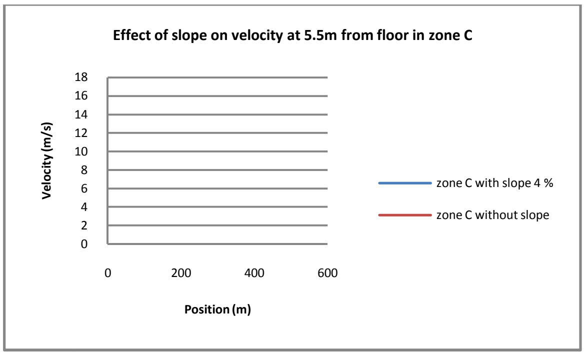


Figure 0.20: Velocity variations at 5.5m height in zone C with slope 4 % and 0%.

At human levels from 1m height to 2m height from floor the velocity variations when zone C is sloping up with 4 % is lower than when zone C is non-sloping because of when tunnel is sloping up the direction of air movement is going to raise up but at high levels such as 5.5m from floor which is the center of jet fans the velocity variations when zone C is sloping is higher than non-sloping one and this describes the effect of sloping up tunnel on velocity variations which is higher at high levels than straight tunnel and lower at low levels than straight tunnel.

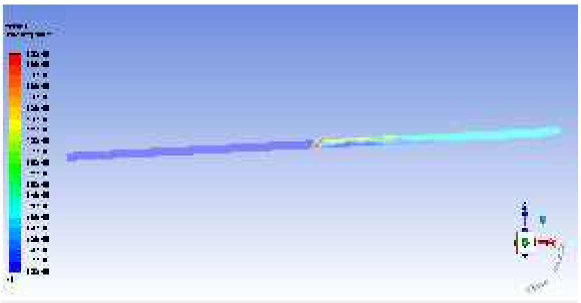


Figure 0.21: Temperature contours at center of zone C sloping 4 %.

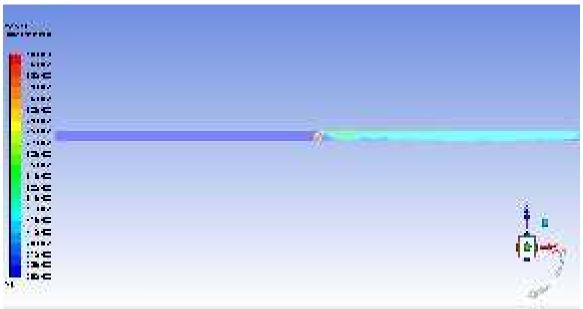


Figure 0.22: Temperature contours at center of zone C non-sloping.

CFD simulations of truck fire with heat release rate 30 mw for 10 minutes at sloping and non-sloping zone Z when the background velocity is the same of sloping up zone C shows that temperature values are better at human levels especially after the fire position when the tunnel is sloping than non-sloping one as shown on figure 3.21 and figure 3.22.

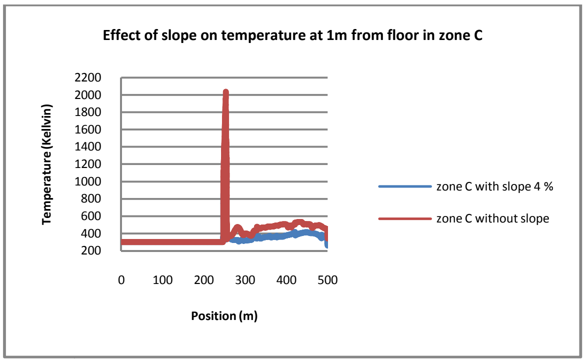


Figure 0.23: Temperature variations at 1m height in zone C with slope 4 % and 0 %.

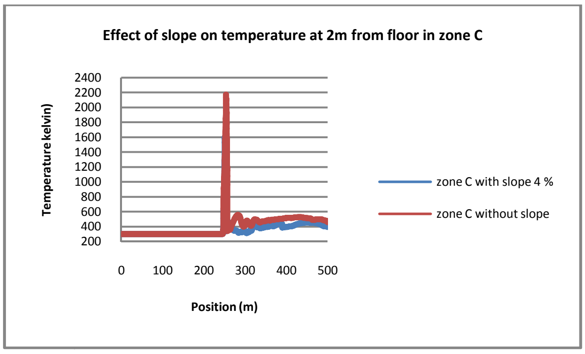


Figure 0.24: Temperature variations at 2m height in zone C with slope 4 % and 0 %.

At adults heights which are from 1m to 2m the range of temperatures at sloping and non-sloping zone C are from 380 K to 550 K which are very risky to people life but the slope of zone makes a positive effect to temperature values but still the range of temperatures are dangerous.

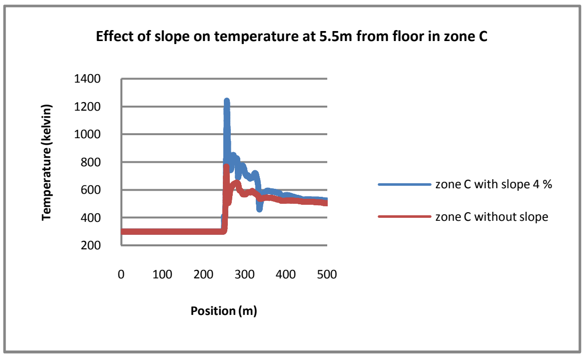


Figure 0.25: Temperature variations at 5.5m height in zone C with slope 4 % and 0 %.

At jet fans center the range of temperatures are higher when the tunnel is sloping up because the slope makes a positive effect to smoke which may rise up smoother than at straight tunnel.

Temperature variations improvement is the general case when the direction of pushing air is the same direction of tunnel rising up so the number of jet fans at this region may be reduced to save cost.

4. Conclusions

CFD simulations are conducted here on Dartford west tunnel at zone B and zone C with the same slope 4 % and the ventilation system controlling smoke is semi-transverse but the direction of pushing air differ because that at zone B the slope is going down but at zone C the slope is going up according to direction of traffic and background velocity and theses CFD simulations shows the following:

1- At zone B the slope of tunnel makes negative effect on velocity at human levels from 1m to 2 m especially at positions northern the truck fire which is increased by about 2 m/s.
2- Along the length of zone B temperature is higher comparing with straight tunnel at lower levels and high levels because heat retention is happened in this case because of negative effect of sloping down tunnel on temperature.
3- At zone C the tunnel is sloping up and CFD simulations shows that velocity and temperature are enhanced at human levels

Finally , the slope of the tunnel effects the performance of smoke control systems in route tunnels so it should be taken in consideration at designing the smoke control system of sloping tunnels

5. Recommendations for future work

In this study CFD simulations are conducted on Dartford west tunnel when truck fire with 30 mw is activated for 10 minutes when the tunnel is ventilated by semi-transverse system so in the future, other systems should be studied to get the effect of slope of tunnels in performance of controlling smoke

According to PIARC 1999 report the general fire case in the tunnels is truck fire with 30 MW heat release rate but studying more dangerous fire is useful that clarifies more dangerous accidents that may happen in tunnels

Slope of tunnel is a very important parameter to be taken in consideration when designing smoke control system in route tunnels, so studying different slopes in tunnels is very important.

References

[1]. PIARC Technical Committee 3.3 Road Tunnel Operation Road Tunnels: “Operational Strategies for Emergency Ventilation” (2011)

[2]. Didier LACROIX, PIARC Committee on Road Tunnels (C5) “FIRE AND SMOKE CONTROL IN ROAD TUNNELS” 137- 151, (1999)

[3]. PIARC Technical Committee 3.3 Road Tunnel Operation Road Tunnels “Design fire characteristics for road tunnels” (2017)

[4]. F. Colella, G. Rein, R. Carvel , P. Reszka, J.L. Torero , “Analysis of the ventilation systems in the Dartford tunnels using a multi-scale modelling approach’’ Tunnelling and Underground Space Technology 25 423–432,(2010)

[5]. Chin Ding (Edmund) Ang , Guillermo Rein , Joaquim Peiro Roger Harrison “Simulating longitudinal ventilation flows in long tunnels: Comparison of full CFD and multi-scale modelling approaches in FDS6” Tunnelling and Underground Space Technology 52 119–126,(2016)

[6]. Izabella Vermesi , Guillermo Rein, Francesco Colella c, Morten Valkvist d, GrundeJomaas “Reducing the computational requirements for simulating tunnel fires by combining multiscale modelling and multiple processor calculation” Tunnelling and Underground Space Technology 64 146–153,(2017)

[7]. PIARC Committee on Road Tunnels “VEHICLE EMISSIONS AIR DEMAND ENVIRONMENT LONGITUDINAL VENTILATION” 47-60, (1995)

[8]. PIARC Technical Committee on Road Tunnel Operation (C5) World Road Association “ROAD TUNNELS: VEHICLE EMISSIONS AND AIR DEMAND FOR VENTILATION” 9-27, (2004)

[9]. Soufien Gannouni, Rejeb Ben Maad “Numerical analysis of smoke dispersion against the wind in a tunnel fire” Journal of Wind Engineering and Industrial Aerodynamics journal 61-68, (2016)

[10]. Antonio Costantino, Marilena Musto “Numerical analysis for reduced-scale road tunnel model equipped with axial jet fan ventilation system” Energy Procedia 45 1146 – 1154,(2014)

[11]. Zhongyuan Yuana, Bo Leia, HaiquanBia “The Effect of Fire Location on Smoke Temperature in Tunnel Fires with Natural Ventilation” Procedia Engineering 121 2119 – 2124,(2015)

[12]. CHEN Juan-juan, FANG Zheng, YUAN Jian-ping “Numerical Simulation about Smoke Vent Arrangement Influence on Smoke Control in Double-decked Tunnel” Procedia Engineering 52 48 – 55, (2013)

[13]. Jian-ping Yuan, Zheng Fang, Zhi Tang, Qi Li, Jun-heng Wang “Influence of smoke damper configuration on point extraction ventilation system of an urban tunnel” Procedia Engineering 135 99 – 106,(2016)