Jet fans as Stratified Tunnel Fire Suppressants

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Abstract. The very first tunnel was developed about 4000 years ago and since then the art of tunnelling has evolved to a great extent. With advancement in the field of science and technology tunnels have grown from a mere defence strategy to something that can carve its way to places that were once unapproachable. However, there are various problems associated with tunnels that are yet to be addressed, fires being one of the major ones. Astonishingly, 70% of deaths during a fire are caused by smoke inhalation and only 30% of deaths are the result of the fire. Every year an enormous amount of money, effort and time is put into research to prevent such fires and minimize the damage it causes and yet no significant result has been obtained till now. This is primarily because of the diversified nature of fires which results in heterogeneous heat and mass transfer. A jet fan is a mechanism that can extract smoke quickly, safely, and efficiently. The present work focuses on testing the effectiveness of Jet fans to suppress these fires and minimize the accumulation of smoke, thereby bringing down the number of deaths to a significant amount. In this paper, a numerical study is carried out using FDS SMV. Multiple parameters such as HRRPUA, volume flow rate, etc. are varied and the corresponding change in the temperature, velocity, the heat generated, etc. is observed. The key controlling parameters are taken and varied proportionally to see how each one affects the performance of the jet fans. Consequently, a conceptual design has been proposed specifically for tunnel fires. This study aims to understand the potency of jet fans with changes in various parameters and to utilize them effectively to suppress not just tunnel fires but also building fires, fires in aviation etc.

1. Introduction

With the increase technological development across the world, the amount of fire related accidents has grown exponentially. According to WHO violence and injury prevention, globally 180000 deaths across the globe are caused due to fires alone. The 2015 Global Health Estimates states that, 95% of deadly fire-related accidents happen in low-and middle-income countries. along with the high number of deaths, millions more are left with deep-rooted incapacities and distortions. As indicated by the National Fire Protection Association (NFPA), most fire deaths are the consequence of smoke inhalation instead of burns. NFPA noticed that in every 20 seconds in the United States a fire department responds to a fire. Every one minute, a fire breaks out in a home or other structure. Actual flames and burns just record for around 30 percent [6] of fire-related deaths and wounds.
Fires being heterogeneous in nature have been an issue not just on land but in the aviation industry in general. In 26 years of time 95 fire related accidents in civil passenger aircrafts have been recording which has claimed around 2400 lives. Many deaths are caused due to fire/smoke and yet no comprehensive solution has been obtained.

It has been reviewed and revealed that more than 44% of deaths caused by aircraft crashes are because of fires. It is assessed that aircraft fires cost the global airline industry well more than 2 Billion Dollars. Aircraft fires noticeable all around are one of the riskiest situations that can be confronted with. A fire onboard an aircraft can prompt the calamitous loss of the aircraft inside an exceptionally short span of time.

1.1 Literature Survey

Tunnel fires have been a major issue ever since the tunnels came into existence and a comprehensive solution for the problem is yet to be attained. Figure 3 consists a list of some of the major tunnel fire accidents that occurred in between the year 2001 to 2010.

The fires are an issue not just in road tunnels but also in rail tunnels. The investigation of the UNECE (United Nations Economic Commission for Europe) named "Hazard Analysis of Accidents in Tunnels" noted 176 cases of mishaps including trains in tunnels or underground rail lines [4]. Of these, 49% included fires.
Figure 2. Data highlighting (a) aircraft fire accidents density (b) corresponding fatality rates.
| Year | Tunnel | Country | Tunnel Length, m (ft) | Fire Duration | Damage |
|------|--------|---------|----------------------|---------------|--------|
| 2001 | Propontis | Italy | 4409 (14,463) | — | 19 injured, 1 truck, Serious |
| 2001 | Gleiensee | Austria | 8320 (27,293) | — | 5 dead, 4 injured |
| 2001 | Ville Marie Tunnel | Canada | 8400 (27,560) | — | — |
| 2001 | Goldborg-sund | Denmark | 460 (1,509) | — | 5 dead, 6 injured |
| 2001 | St. Gotthard | Switzerland | 16,990 (55,450) | Over 2 days | 11 dead, 2 tracks, 23 vehicles, Serious |
| 2002 | Tauern | Austria | 6401 (21,080) | — | 1 dead |
| 2002 | A76 | France | 618 (2,028) | 6 hr | 2 dead, 1 car, 1 motorcycle |
| 2002 | Ted Williams | United States | 2600 (8,530) | — | 1 bus |
| 2002 | Homer | New Zealand | — | — | 3 injured, 1 bus |
| 2003 | Locica | Slovenia | 800 (2,625) | — | 1 track, 1 car |
| 2003 | Fløyfjell | Norway | 3100 (10,111) | —10 min | 1 dead, 1 car, Limited |
| 2003 | Gelovec | Slovenia | 500 (2,297) | — | 1 bus |
| 2003 | Baregg | Switzerland | 1390 (4,560) | — | 2 dead, 21 injured, 4 trucks, 3 fire engines, Serious |
| 2004 | Baregg | Switzerland | 1080 (3,543) | — | 1 dead, 1 injured, 1 track, 1 car, Serious |
| 2004 | Dullin | France | 1500 (4,921) | — | 1 bus |
| 2004 | Kinkem-pois | Belgium | 600 (1,969) | — | 1 track, Slight |
| 2004 | Frejus | France/Italy | 12,990 (42,323) | — | 1 track |
| 2005 | Frejus | France/Italy | 12,900 (42,323) | 6 h Diesel leakage in HGV loaded with tires | 2 dead; 21 treated for smoke inhalation; 4 HGVs, 3 fire fighting vehicles 1. load: Tires 2. load: cheese 3. load: scrap 4. load: glue; Serious damage, tunnel closed |
| 2006 | Viamala | Switzerland | 760 (2,493) | 9 dead, 6 injured | 1 bus, 2 cars |
| 2006 | Crap-Teig | Switzerland | 2171 (7,122) | — | 1 HGV with wooden pallets, Limited structural, electrical damage |
| 2007 | Burnley | Australia | 2900 (9,514) | 3 dead | 4 HGVs, 7 cars, Slight |
| 2007 | Caldecott | United States, Canada | 1028 (3,372) | — | 1 car |
| 2007 | Santa Clarita 1-5 [25] | United States, Canada | 165 (544) | 3 dead | 23 injured, 33 tractor/semi-trailer, 1 car |
| 2007 | San Martino | Italy | >45 min | 2 dead, 10 injured | 1 HGV |
| 2009 | Eiksaund | Norway | 7700 (25,262) | 5 dead | 1 HGV, 1 car |
| 2009 | Gutrist | Switzerland | — | 4 injured | 2 cars |
| 2010 | Trojane | Slovenia | 885 (2,900) | 5 injured | 1 HGV |
| 2010 | Wuxi Linhu | China | — | 24 dead, 19 injured | 1 shuttle bus |

Figure 3. Tunnel fire accidents between the year 2001 to 2010.

Collected from numerous sources: ASHRAE Handbook (25).
Figure 4. Causes of incidents involving trains in tunnels or underground railways.

According to the National Fire Protection Association in the United States local groups of fire-fighters reacted to 1,291,500 fires in 2019 [3]. These fires caused about 3,700 civilian deaths, 16,600 civilian injuries, and $14.8 billion in property harm. At regular intervals, a local group of fire-fighters in the United States reacted to fire somewhere in the country. Majority of the deaths and injuries were caused by home fires.

Figure 5. Fires by Incident Type in US: 1980-2019 (NFPA 2020).
Figure 6. Distribution of estimated deaths from fire, heat and hot substances (WHO 2016).

Figure 5 shows a study carried out by world fire statistics. It indicates the number of deaths in various countries due to fire. The list shows all the countries that have encountered more than 300 deaths per year.

2. Motivation and Objectives

Fires are a potential source of irreplaceable loss of mankind, resources, property and every year huge amount of economic investment is made on the safety. Fires start when a flammable or combustible material, in blend with an adequate amount of oxidizer, for example, oxygen gas or another oxygen-rich compound is exposed to an adequate amount of heat or ambient temperatures above the flashpoint for the fuel/oxidizer mix and can support a pace of fast oxidation that creates a chain reaction. This is alluded to as the fire tetrahedron. Fire can’t exist without these components set up and in the correct proportions.

In order for a fire to burn and propagate it consumes a significant amount of available oxygen reducing its levels for the individual to remain conscious and exit. The process is so fast that the individuals have very little time to react and are therefore unable to make an exit. The NFPA’s chart shown in figure 8 shows what an individual experiences at different levels of oxygen. As the oxygen levels drop to nearly half the normal levels, it becomes difficult for one to react normally.
To completely eliminate the possibility of fire outbreak is an impossible task. In order to reduce the damage due to fire any one of the four elements of the fire tetrahedron shown in figure 7 has to be removed. The only element under control is the amount of oxygen present. As illustrated in figure 8 the amount of oxygen if left unregulated can cause the person to die even before the fire actually reaches him/her. Due to gravity the oxygen is convected toward the fire thereby increasing its strength. In the initial stages of fire little heat may be generated but a lot of thick toxic smoke is released making it difficult for an individual to escape. In order to address these problems, there has to be some sort of ventilation that needs to be provided [10].

In such conditions, unless the exhaust smoke can be cleared, it is very difficult to escape or control the situation. The available solutions to the problem are not complex, however, the use of a specific technique, understanding and implementation of the same demands for a specialized knowledge. One of the solutions that has not been worked upon is fast and effective removal of hot exhaust using an efficient ventilation system. A ventilation system can provide ample oxygen to keep the fire going but it reduces the toxicity in the environment. To overcome the disadvantage of a normal ventilation the use of jet fans has been proposed. Because of the heterogeneous and unpredictable nature of fires, no successful solution has been obtained for even for a problem of this intensity. All the measures that are taken to this day are just precautionary or preventative in nature. Although these measures were able to bring down the frequency of accidents, the origin of fire cannot be eliminated altogether. Therefore, a solution needs to exist in case a fire actually breaks out to minimize the damage that it can cause to life and property.
Jet fans induce forced convection unlike a simple opening for ventilation thereby reducing the forward heat transfer. Present work explores the feasibility and spontaneity of Jet fans as an efficient fire safety tool. A jet fan is a fan configuration which largely ingests in the polluted air and divert it to a specific manifold. They are primarily used as an exhaust and pollution control systems for fast evacuation of toxins and pollutants. Jet fan utilization details from early 1960 and have been proven effective in car parking and tunnels. The operation involves easy installation, usage, cost effective and covers minimum space.

Jet fans are likely to be very effective in fast removal of hot toxic exhaust gases minimizing the forward heat transfer. Reduced forward heat transfer minimizes fire spreading which in turn increases the control time for the necessary actions to for evacuation procedures thus, minimizing the damage.

In order to understand the potency of jet fans to reduce the damage caused by fires, a numerical study has been carried out in order to better understand the functionality of jet fans. The main objectives of the study are:

• To examine the role of key controlling parameters.
• To study the variation of heat, transfer along with the contribution of each of the component’s conduction, convection and radiation in order to better understand the working of jet fans and test their effectiveness.
• To propose a conceptual design to suppress tunnel fires and thereby significantly reduce the time taken to extinguish them.
• To highlight the importance of jet fans to repress these fires and minimize the accumulation of smoke, thereby bringing the loss of life and property to a significant amount.

3. Numerical Simulations and Solution Methodology

Systematic numerical simulations were carried on Fire Dynamics Simulator (FDS)–Smoke view (SMV) which is a Large eddy simulation (LES) computational fluid dynamics (CFD) model of low-speed fire driven fluid flow. The simulations emphasize on boundary condition oriented Navier Stokes equations for heat transfer from concerned fire systems.
For selected open or confined fires, the governing equations are discretized in spatial and temporal domain. The spatial iterations are performed on a structured grid, with second order, central differencing or upwind schemes depending on the parameter. The temporal iterations are guided with second order, predictor-corrector method. The predictions are well supported by depiction of tracer particle flow, gas phase contours, temperature and flow vectors highlighting flow direction and magnitude in each plane computed from soot densities. Parametric variation of HRRPUA (Heat release rate per unit area), volume flow rate and reaction soot yield are thoroughly investigated to extract good physical insight. The numerical predictions are verified and validated with the conventional fire and heat transfer theory. An Enclosure (10m x 4m x 4m) was selected as a prototype for the numerical experimentation (Figure 11).

![Figure 11. Jet fan placed in an enclosure](image)

The base case selected was HRRPUA = 1000 kW/m\(^2\), reaction soot yield=0.2, volume flow = 0.8 m\(^3\)/s, area = 0.04 m\(^2\) with Mesh size = 50,20,20. The simulations were carried out for 10 seconds. HRRPUA, reaction soot yield, volume flow rate and area were varied. For each case 20 iterations were performed. The variations of maximum velocities, maximum temperature, gross Heat release rate, conduction, convection and radiation heat release rates were plotted in y axis.

### 4. Results and Discussions

A parametric numerical simulation was carried out by varying HRRPUA, volume flow rate, reaction soot yield and area. Variation in area however didn’t show any significant results but changing the other three did. Three plots for each case were plotted- maximum temperature, maximum directional velocity and componential heat release rate.

The heat release rate per unit area (HRRPUA) was varied systematically from 1000 kW/m\(^2\) to 10500 kW/m\(^2\). HRRPUA directly signifies the size of the fires. Figure 12 shows the obtained variations with varying HRRPUA. It is to be noted that the other three parameters are kept constant during the variation of any one parameter.
Figure 12. (a) Variation of maximum temperature (b) Variation of componental Heat release rate (c) Variation of directional velocities with varying HRRPUA

Figure 13. Temperature Variation contour within the enclosure

The plot of maximum temperature is expected to increase exponentially with the increase in HRRPUA in case no jet fan is present. However as one can notice from figure 12(a) the exponential rise in temperature has been clearly inhibited. Any change in the nature is observed only due to the presence of jet fan. The rate of change in temperature is higher initially and gradually decreases around HRRPUA=3000 kW/m². As the maximum temperature increases the possibility of fire propagation also increases. Jet fans control maximum temperature hence reduce propagation of fire. The rate of increase of the maximum temperature was initially 0.29 K/kW and finally it became 0.008 K/kW. The percentage increase in maximum temperature initially was 26% which later came down to 0.35%.
Figure 14. (a) velocity vector for HRRPUA=1000 kW/m² (b) velocity vector for HRRPUA=10500 kW/m²

Figure 12(b) shows the variation of componential heat transfers with varying HRRPUA. The rate of change in Gross heat release rate (GHRR) significantly reduces. This reduction can only be attributed to jet fans. Negative heat transfer signifies heat out of the system which is observed in the case of radiation and conduction as diffusion flame. Forced convection induced by jet fans being positive attempts to stabilize.

The variation of directional velocity is plotted in figure 12(c). The velocity vector can be seen for the first and last iteration in figure (14). It is evident that jet fans tend to suck in the air and throw it out of its outlet thereby reducing the forward heat transfer. Any significant changes in the velocity vector comes due to the presence of the jet fans.

Figure 15 shows the variations on changing volume flow rate. The volume flow rate of jet fans was increased in a systematic manner and the results were plotted. Volume flow rate was particularly plotted to test the effectiveness of jet fans. It is however important to note that the size of the fire i.e. the HRRPUA and the reaction soot density remains constant.

As the amount of air thrown out by the jet fan increases the maximum temperature begins to drop as shown in figure 15(a) and becomes almost constant towards the end. The gross heat release rate also decreases (figure 15(b)). These changes are brought about only by increasing the volume flow rate through the jet fan.
Figures 16 and 17 show the temperature contours for the first and the last iteration. The contours clearly indicate how the temperatures have been reduced even though the size of the fire has been kept constant. The maximum temperature zones have shifted towards the jet fans which clearly supports that the jet fans act positively in suppressing fires. The maximum directional velocities constantly increase which is to be expected as the area is kept constant throughout.

The reaction soot yield of the fire was varied next to test different types of combustion with the different kinds of fire. Varying soot density gives a direct idea on how the smoke and toxicity of the fire would affect in a practical scenario. Soot yield corresponds to the type of combustion taking place.
In the absence of jet fans, the increase in soot yield would have resulted in an increase in the maximum temperature. As seen from Figure 18(a) this is not the case at all. The temperature profile almost remains constant owing to the presence of the jet fans. The gross heat transfer also follows a nearly constant path until the last iteration where it encounters a sudden drop. It is to be noted that after a soot yield of 0.8 the carbon in the combustion was exhausted for the taken HRRPUA.

As the amount of smoke increase, the time taken to remove it by the jet fan of the same capacity also increases. This is visible by figures 19 and 20.

Another phenomenon that was observed during the study was the formation and propagation of recirculation zones.
Figures 21 to 23 show the formation of recirculation zone for a particular case at different time steps. Recirculation zones are formed when due to the variation of temperatures in different regions of enclosures. Jet fans prevent the formation of these zones directly above the source of fire by propagating them farther away from the source. This clearly shows how jet fans work towards inhibition of forward heat transfer. The strength of the zones increases as with increase in size. As the time increases the recirculation zones become stronger.
5. Conceptual Design

Based on the results obtained from the numerical study, a conceptual model to minimize tunnel fires is proposed as shown in figure 24.

Figure 24. Conceptual Design for Tunnel Fires

The silver arches as seen in the figure contain movable jet fan inlets which direct the flow to a centralized primary jet fan responsible for exhausting the hot plume. This prevents the amplification of forward heat transfer which in turn prevents the propagation.

The size of the inlets and main jet fans could be varied depending on the length and usability of the tunnel. Jet fan, in a confined space work by generating recirculation zones, which gains momentum and increases in size.

Merits of the design:

• Movable structure
• Long Shell Life
• Adaptable and adjustable
• Less maintenance cost
• Reduced time to extinguish fires
• Increased road safety

6. Conclusion

In case of a fire outbreak, it is not hard to extinguish a fire, the hard part is to prevent the fire from spreading or reducing the forward heat transfer.

From the numerical study that was carried out by varying various parameters and studying their effects, it was confirmed that a jet fan is an effective fire suppressant. Presence of jet fan matters and it affects the propagation of fire positively. As the HRRPUA increases or the size of the fire increases the rate of change of maximum temperature drops indicating jet fan is more suitable for medium and large fires. Further variation of volume flow rate indicated that the effectiveness of jet fans directly increases with increase in
volume flow rate. Negative heat transfer signifies heat out of the system which is observed in the case of radiation and conduction as diffusion flame. Forced convection induced by jet fans being positive attempts to stabilize.

The conceptual design proposed is not just limited to tunnels but could be expanded for other compartment fires, building fires, structure fires and aviation fires also. The design is capable of reducing the fires by curbing the forward heat transfer thereby reducing the time taken to extinguish the fire. Using this design the deaths and injury caused by fires could be reduced to a significant amount.

Jet fans could not only curb the forward heat transfer and reduce fire but also act as a ventilation system as seen from the reaction soot yield thereby bringing down the death rate significantly.

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