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Short Communication

Investigating the Throttling Effect in Tunnel Fires

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Abstract. Critical ventilation velocity remains the most studied phenomenon in the tunnel fire literature. But focus on the velocity as the principal parameter may hide other features of the interaction between a fire and tunnel flow. The throttling effect was identified in the 1960s and described in the 1970s, yet it seems to be generally overlooked these days. In essence, the throttling effect is the tendency of a fire in a tunnel to resist the airflow; the larger the fire, the greater the resistance. Thus, while it has been shown that no increase in longitudinal flow velocity is required to control smoke from fires larger than the 'super critical' limit, in practice, an increasing number of ventilation devices are required to achieve this flow, and hence control the smoke from a fire, as the fire size grows. A CFD modelling study using the FDS model has been carried out to demonstrate this effect. It is clearly demonstrated that for fires larger than the 'super critical' limit, an increasing number of jet fans are required to control the smoke from increasingly larger fires. The results of the modelling study are presented.

Keywords: Critical ventilation velocity, Smoke management, CFD modelling, Fire size

1. Introduction

As discussed by Ingason at the 9th IAFSS symposium [1], critical ventilation velocity (CVV) remains the most studied phenomenon in the tunnel fire literature. The fundamental concept of smoke management in longitudinally ventilated tunnels is that, for a given size of fire, there exists a 'critical' ventilation velocity sufficient to blow all the smoke produced by a fire to one side of the fire location only. If the ventilation flow is below this level, a layer of smoke may extend away from the fire location in the upstream direction, this is commonly referred to as "backlayering".

The origins of the CVV concept can be traced back to Thomas in the 1950s [2], with notable refinements and alternative formulations being proposed by Heselden in the 1970s [3] and Danziger and Kennedy in the 1980s [4]. The 1995 work by

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Oka and Atkinson [5] is the most influential paper in the literature and was the first to adequately define the ‘super critical’ ventilation velocity (SCVV) concept. In their experiments, Oka and Atkinson observed that there is a relationship between fire size and CVV up to a certain limit, but that beyond this limit no increase in ventilation would be required to control the smoke from fires with larger heat release rates (HRR). This can be seen clearly in Figure 1. For many typical road tunnels, the SCVV is found to be about 3 m s^{-1}, so many emergency ventilation strategies for longitudinally ventilated tunnels aim to achieve a longitudinal flow of about 3 m s^{-1} in the event of any fire, in order to control smoke. Ventilation studies since 1995 have tended to build on the work of Oka and Atkinson, adding various complexities relating to features such as tunnel slope [6], aspect ratio [7, 8] and the presence of blockages [9, 10], and the SCVV concept has become widely accepted in the industry.

When designing the ventilation system for a tunnel, the design engineer considers a prescribed ‘design fire’ (generally expressed as a constant HRR) and specifies the capacity of the fans, etc. on the basis of this, taking into account the possible presence of vehicles and other blockages in the tunnel. Historically, design fires in the range 20 MW to 50 MW have been relatively common for road tunnel ventilation design, although recent design guidance [e.g. 11] suggests that heavy goods vehicle fires could be in the range 70 MW to 200 MW, while fuel tanker fires could be higher still. For most tunnels, fire sizes above about 30 MW fall above the super critical limit, so it might be tempting for a tunnel designer to use a design fire of, say, 50 MW as the basis of the design, as the required longitudinal flow would be no different for this than for a larger size of fire.

This line of reasoning, however, does not take the ‘throttling’ effect of a fire into account. The throttling effect appears to have been known anecdotally in the mine ventilation industry since at least the 1960s [12], but does not appear to have been studied systematically until Lee et al. in the late 1970s [13, 14]. In essence, Lee et al. found that a fire in a tunnel tended to change the resistance of the tun-

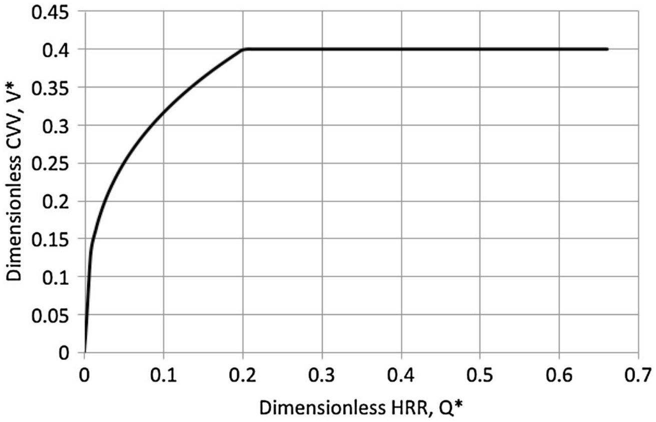

Figure 1. An example of the variation of CVV with HRR, based on Oka and Atkinson [5].

nel to ventilation flow, with larger fire sizes exhibiting greater resistance to flow than smaller fires. The phenomenon was dubbed the 'throttling' effect as a section of tunnel containing a fire effectively behaved as a section of tunnel with a reduced bore size; that is, the fire appeared to 'throttle' the flow. Thus, if a fixed ventilation flow rate is desired, the power of the ventilation devices supplying the flow will need to be greater if there is a larger fire, even though the resulting upstream flow velocity will be the same.

The practical meaning of this is that if, for example, six jet fans are required to achieve a critical flow of 3 m s^{-1} in a given tunnel to control the smoke from a 50 MW fire, if an 80 MW fire should occur, six jet fans will be insufficient to generate the required 3 m s^{-1} flow, and smoke control will not be achieved.

The throttling effect, while discussed and detailed in the late 1970s, does not appear to have been discussed in the tunnel ventilation literature since then. Once the discussion of smoke control became expressed in terms of HRR and CVV, the question of the number or power of ventilation devices being used dropped out of the discussion. Experimental studies of CVV utilised variable speed ventilation devices, which were rarely used at peak flow capacity [e.g. 15, 16], meanwhile computational fluid dynamics (CFD) modelling of tunnel fires has commonly imposed a fixed velocity flow as a boundary condition on the computational domain, rather than explicitly incorporating the capacity of the fans [e.g. 17, 18].

Recent modelling studies by Colella et al. [19, 20] employed a multi-scale modelling approach to tunnel ventilation and explicitly modelled the ventilation devices as well as blockages and fires in the tunnel, without imposing flow as a boundary condition. In this way the throttling effect was essentially 'rediscovered'.

This paper presents the results of a simple modelling study which seeks to demonstrate that while the CVV required to control smoke does not vary with fire size beyond a certain limit, the number of ventilation devices required to generate the critical flow continues to increase with increasing fire size. The aim is, essentially, to demonstrate numerically the throttling effect of fire.

2. Methodology

As the intent of the project was to demonstrate an effect, not to model a specific realistic tunnel configuration, a simple rectangular tunnel geometry was chosen, and a relatively short computational domain was used for most of the simulations. The limitations of these assumptions will be discussed below. The project used the Fire Dynamics Simulator (FDS), version 5.5.3 [21] for all simulations. The tunnel modelled was 100 m long, 8.0 m wide by 6.5 m high (52 m^2 cross-section). The upstream and downstream domain boundaries were specified as open at atmospheric pressure, while all the tunnel surfaces were defined as adiabatic, using the default surface roughness for concrete.

The adiabatic surface assumption is generally discouraged in modelling of tunnel fires as it leads to unrealistic model predictions in terms of the gas temperatures and flow velocities calculated. For most CFD studies of tunnel ventilation interactions with fire, consideration of the heat losses is essential as, using the adiabatic assumption, the gases remain hotter than realistic, and hence any calculations relating to the capacity of ventilation devices will overestimate the fan power required. In the present study, absolute predictions of temperature or flow velocities are not of primary interest, it is only the trends in behaviour that are important. Thus, for the purposes of this study, an adiabatic assumption is appropriate. Of course, given this, it is likely that the results presented below will tend to exaggerate the throttling effect, and the effect itself will be clearly evident.

The fire source in the majority of simulations was modelled as a burner of fixed dimensions (3 m wide × 4 m long × 1 m high), positioned symmetrically in the middle of the tunnel, but closer to the 'upstream' portal than the 'downstream' one. The centre of the fire source was positioned 32 m from the upstream portal and 68 m from the downstream one. Seven ceiling mounted jet-fans were modelled, side by side, at 25 m upstream of the fire. These were considered to be 0.5 m high by 0.5 m wide and were positioned 0.5 m below the tunnel ceiling. A typical configuration of the fans is shown in Figure 2. It is acknowledged that this is an unrealistic configuration of fans, but it is stressed that the design of the tunnel has been chosen to demonstrate an effect, not to represent a realistic tunnel configuration.

Rather than impose a prescribed airflow at the domain boundary, the flow within the domain was generated entirely by the jet fans within the domain. Each fan was modelled as an object of zero thickness, through which air can pass, with a fixed airflow velocity at the downstream surface, in the manner suggested in the FDS user guide [21]. After a few preliminary simulations, the outlet velocity was fixed at 35 m s^{-1} for each fan, as this provided sufficient flow to investigate smoke control for fires ranging from 10 MW to 90 MW. In these simulations, jet fans were considered either 'on' or 'off', no fans were modelled as operating at reduced capacity in any of the simulations.

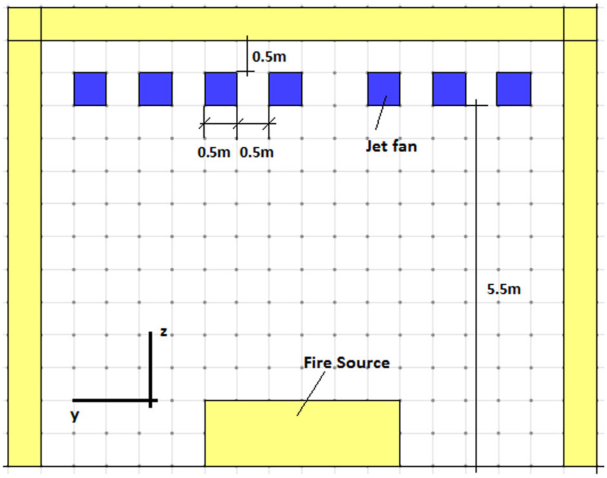

Figure 2. An example configuration of jet fans in the model tunnel.

In each simulation, the fire was specified as having a fixed HRR from t = 0 and for the duration of the simulation time, which was 840 s in each case. In each simulation, the fire and all seven jet fans were initiated at time t = 0, and the jet fans were then switched off at 120 s intervals thereafter. The jet fans were switched on and off in such a way that each combination of fans was reasonably symmetrical across the width of the tunnel.

In line with good modelling practice, a grid refinement and sensitivity study was carried out. As a result of this it was found that a computational mesh of 0.25 m × 0.25 m × 0.25 m cells was required in the vicinity of the fans and around the fire location, but a coarser mesh could be used downstream of the fire (from the tunnel midpoint to the downstream portal). In most simulations, the domain contained about 225,000 cells.

An array of virtual velocity probes was positioned 2 m upstream of the edge of the fire object, as shown in Figure 3. Backlayering was deemed to have been eliminated in a given simulation (that is, the flow was deemed to be above CVV) if the flow was found to be positive at all measurement points.

3. Results

Nine simulations were carried out for fire HRR of 10 MW, 20 MW, 30 MW, ..., 80 MW and 90 MW. Figure 4 shows a summary of the results for the minimum fan combinations required to prevent backlayering. Using the method derived by Wu and Bakar [7], the SCVV for the simulated tunnel was calculated to be 3.4 m s^{-1}, corresponding to fires of 30.3 MW and above.

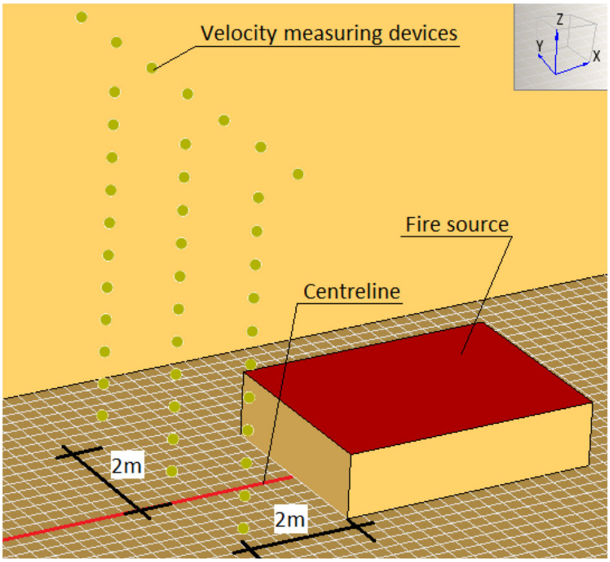

Figure 3. Location of the velocity probes in the model.

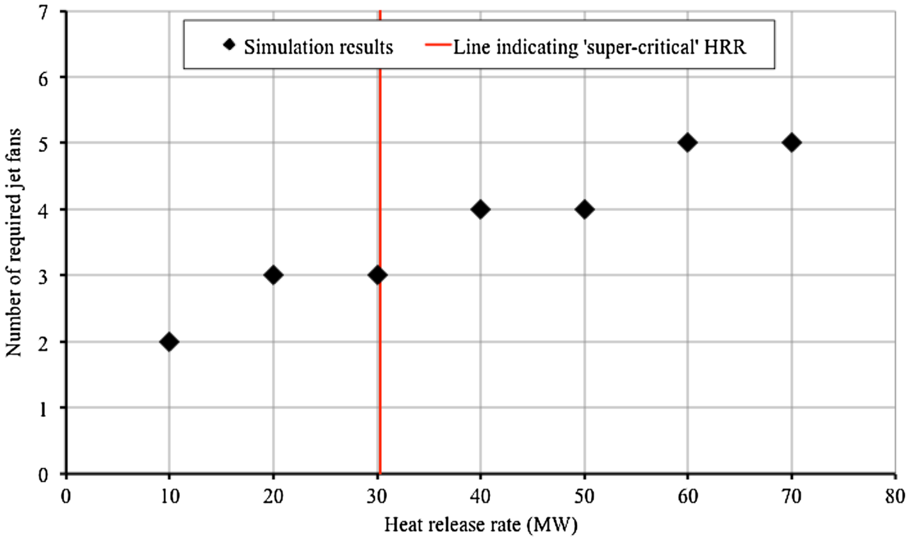

Figure 4. Minimum jet fan combinations required to prevent backlayering, fans 25 m away from fire.

It is clear from Figure 4 that the number of jet-fans required to control smoke continues to increase with increasing fire size above the HRR corresponding to the SCVV, thus the throttling effect is evident.

In the 80 MW and 90 MW simulations, not included in Figure 4, there was a small negative flow at the lowest measurement points, even with all seven jet fans active, see Figure 5a, so backlayering was not deemed to have been eliminated in these scenarios, even though the flow in the upper parts of the tunnel was positive. This phenomenon is thought to be due to the close proximity between the fire and the fans, as will be discussed below.

As can be seen in Figure 5a, the flow in the tunnel generated by the jet fans is significantly far from uniform at locations near to the fire. Thus a second series of simulations were carried out using a longer computational domain, with a 50 m distance between the jet fans and the fire location. This results in a considerably more uniform flow field at the location of the fire, as shown in Figure 5b.

The minimum jet fan combinations were also assessed using the 50 m longer computational domain, and the results are broadly similar to the first series of simulations, see Figure 6.

Each of the results presented so far comes from a model which assumes the fire load is evenly distributed across a fixed fuel area of 12 m^2. That is, the heat release rate per unit area (HRRPUA) varies between each simulation, while the surface area does not. This results in differences in the Froude number (or the non-dimensional HRR, Q*) between simulations. A final series of simulations were carried out in the longer computational domain, varying both the area and the HRRPUA between simulations, in order to keep the Froude number constant between tests.

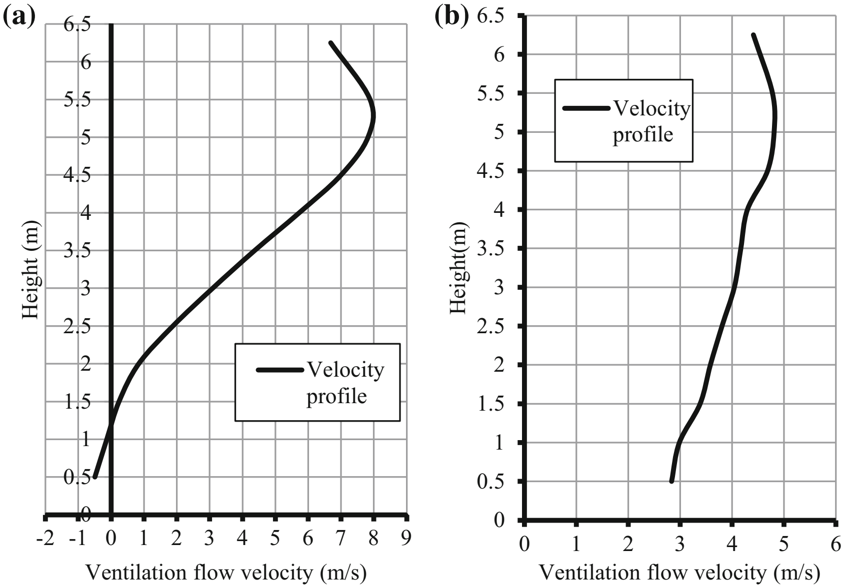

Figure 5. Ventilation flow profiles for (a) a 90 MW fire and all seven jet fans active, 25 m upstream of the fire, and (b) a 60 MW fire with five jet fans active, 50 m upstream of the fire.

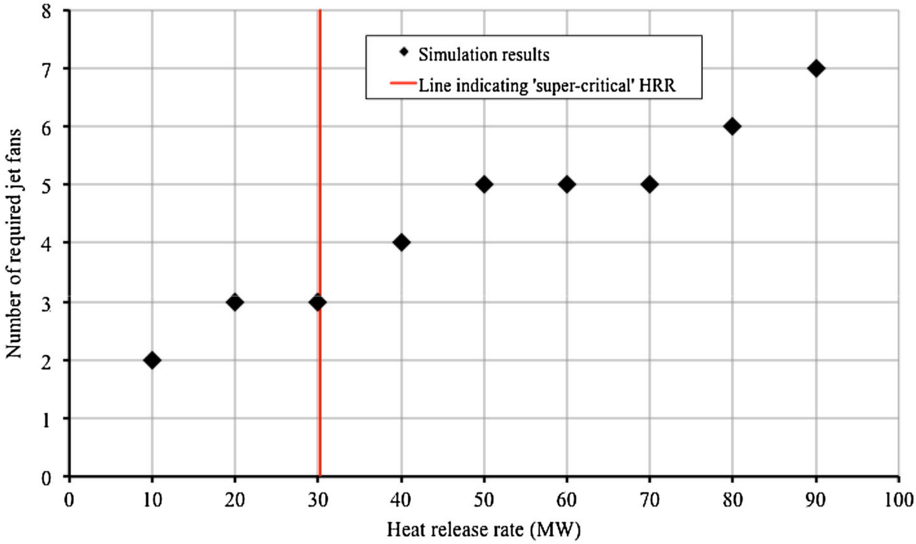

Figure 6. Minimum jet fan combinations required to prevent backlayering, fans 50 m away from fire.

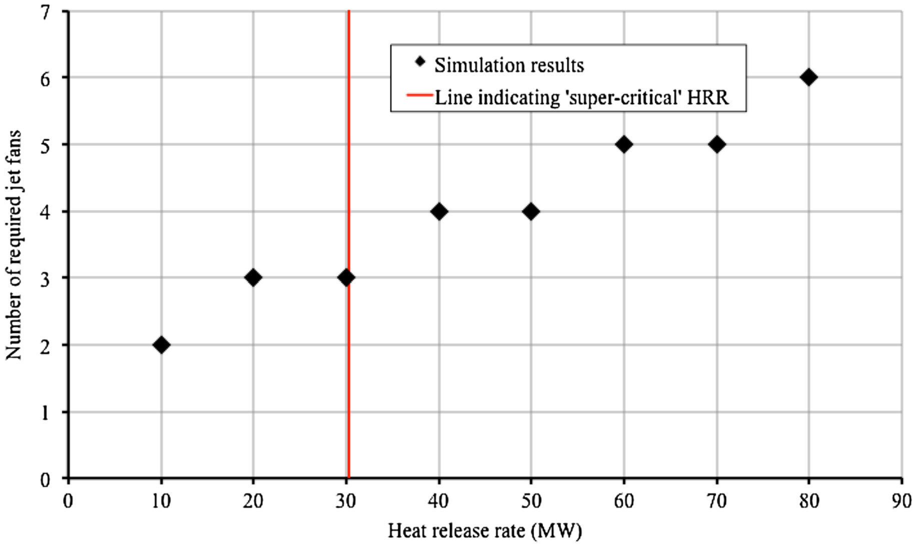

Figure 7. Minimum jet fan combinations required to prevent backlayering, fans 50 m away from fire and varying fire area.

(The Froude number is a non-dimensional number which is a characteristic of flows where buoyant effects are important. The Froude number is, essentially, the ratio of inertial to gravitational or buoyant forces. It is common in fire engineering analyses to consider flow scenarios with the same Froude number as being similar, provided the flow is turbulent and the Reynolds number remains high.)

In this instance, the same broad pattern is observed, as shown in Figure 7. No minimum fan combination is recorded for the 90 MW fire in this instance (33 m^2 and 2722 kW/m^2) as the maximum seven fan combination was not quite able to control the smoke.

4. Discussion and Concluding Comments

These results were presented for the first time at the 6th International Symposium on Tunnel Safety and Security, Marseille, in March 2014 [22]. During that presentation, the author asked the audience for a ‘show of hands’ to indicate who in the audience was aware of the throttling effect and who was not. Aside from the conference chairman, nobody in the audience indicated that they previously knew about the throttling effect. While consideration of this effect has not been totally lost by the industry (the reviewers of this paper were familiar with the concept, at least), the influence of the throttling effect has commonly been overlooked in modelling practice, when airflow velocities have been imposed as boundary conditions instead of properly considering the pressure differences provided by jetfans and other ventilation devices in tunnels.

As noted above, it is likely that the simulations presented will have slightly exaggerated the magnitude of the throttling effect, due to the adiabatic surface assumption. However, it is stressed that the throttling effect is not an artefact of this specific model, but a real effect that can be (and has been) observed in real tunnel fire situations and other numerical studies. The effect was clearly evident in the small scale experiments presented by Lee et al. [13, 14], who first described the phenomenon, and in the full scale Runehamar tunnel fire tests [23], where the flow was throttled by about 30 % (from about 3 m s^{-1} to just over 2 m s^{-1}) as the fire grew to its maximum size. The effect was also identified numerically by Colella [19, 20], using a different model, with very different geometry and input parameters to the simulations described here.

The results presented show that if, for example, a ventilation system design can be demonstrated sufficient to control the smoke from a 50 MW fire, this does not mean that the ventilation system would be sufficient to control the smoke from fires larger than this limit, even though the required airflow velocity is the same for larger fires.

The primary conclusion from this study is therefore that ventilation system design should not be made on the basis of a ‘critical’ ventilation velocity, independent of fire size considerations, but rather should be made on the basis of the size of the largest credible fire scenario for the specific tunnel in question.

In other words, in tunnel design for fire safety, the throttling effect must be considered.

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