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Major fire spread in a tunnel with water mist: A theoretical model

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ABSTRACT

A model of the effect of water mist on major fire spread in a tunnel is described. It employs the concepts of non-linear dynamical systems theory and identifies the onset of instability with major fire spread in a tunnel. The purpose is to identify the thermo-physical and geometrical conditions which lead to instability and sudden fire spread. It uses as a starting point one of the non-linear models for major fire spread which have been developed by the author over many years and assumes that a water mist system operates.

The case considered assumes the existence of a longitudinal forced ventilation and predicts the critical heat release rate needed for a fire to spread from an initial fire to an item with a given assumed shape; in the presence of water mist. There is assumed to be no flame impingement on the target object. The target object may be taken to approximate a vehicle. The illustrative case approximating fire spread from an initial fire to a heavy goods vehicle (HGV) is presented; it is not restricted to this case, however. The model is being identified with the name FIRE-SPRINT C1, which is an acronym of *Fire Spread in Tunnels*, *Model C*, *Version 1*. It has been developed from an earlier model, FIRE-SPRINT A3 and considers a case where, in the absence of a fire fighting system, there is the potential for a major fire.

1. Introduction

During the last two decades there has been a considerable increase in the construction of both road and rail tunnels throughout the world and this has raised many concerns. For a comprehensive account of the range of issues involved in the field of fire safety see the 'Handbook of Tunnel Fire Safety', (Beard and Carvel, 2012). In particular the construction of the Channel Tunnel between France and England stimulated both theoretical and experimental work. In more recent years there has been the body of work carried out under the aegis of UPTUN (an acronym for 'Cost-effective, Sustainable and Innovative Upgrading Methods for Fire Safety in Existing Tunnels'), see (Both, 2012), relating to the up-grading of tunnels. At the present time many tunnels are either under construction or in the design phase. Also, over the last two decades, there have been a number of serious tunnel fires. Probably the most serious to date took place in the Baku underground railway system in Azerbaijan on October 28th 1995. In that fire approximately 300 people lost their lives. Many very serious fires have involved heavy goods vehicles (HGVs), in both road and rail tunnels. For example, in November 1996, a fire took place in the Channel Tunnel connecting France and England; this involved a train carrying HGVs. By good fortune, the location of the initial fire was a considerable distance from the amenity coach carrying the lorry drivers and there were no deaths; had the location been closer to the amenity coach the result may well have been very different. Since then there have been very serious fires in the Channel Tunnel, in 2006 and 2008. There have, also, been very serious fires involving HGVs in road tunnels, for example, in the Mont Blanc Tunnel, 1999 and St Gotthard Tunnel, 2001; see chapters 1–4 of Beard and Carvel (2012). It has become apparent that a HGV fire in a tunnel may reach about 200 MW or more (Ingason and Lonnermark, 2012).

There has also been a serious tunnel fire in Australia, i.e. the fire in the Burnley Tunnel, Victoria, in 2007. This case is distinguished from the others, however, in that effective action by control room staff operating a conventional, larger droplet, water sprinkler deluge system, certainly stopped this fire becoming much more serious and probably saved many lives, see Dix (2011) and Dix (2012). Also, it would have greatly reduced property damage and disruption of operation. More recently, Ingason and his co-workers have carried out tests with a large-droplet, low-pressure, deluge sprinkler system which employs the water supply system designed for the fire brigade (Ingason et al., 2014). They make the point that this has reduced costs. Also, they say that the system was effective at preventing spread to a target object for the conditions investigated.

In addition to larger droplet water sprinkler systems, water mist systems have come into use in tunnels and it has been claimed by

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Nomenclature

Latin symbols

C_{EVAP}	latent heat of evaporation of water
C_{H2O}	specific heat of water
C_v	specific heat at constant volume of the hot gases in the control volume
D_{m1}	water discharge rate density
D_{m2}	water discharge rate into the CV
G	rate of gain of energy of the gases in the CV
L	rate of loss of energy of the gases in the CV
L_o	length of the control volume (CV)
L_1	length, within the CV, of the target object
L_2	target height
L_3	target width
M_{fun}	un-enhanced fuel mass loss rate
N_{DNLS}	fraction of water discharged into the CV which does not hit lower surfaces
N_{DSW}	fraction of water discharged into the CV which is transported downstream and out of the CV; i.e. is 'swept away'
N_{DEV}	fraction of water discharged into the CV which evaporates
N_{TRED}	temperature reduction factor; see Appendix A
N_{x1}	factor used as part of estimating T_{ve}
N_{x2}	factor used as part of estimating T_{vet}
N_{x3}	factor used as part of estimating T_{vef}
t	time
T	temperature of the gases in the control volume (CV)
T_a	temperature of ambient air
T_f	flame temperature
T_{ve}	temperature of the surface of the target, other than for top and front
T_{vet}	temperature of the top of the target
T_{vef}	temperature of the front of the target
T_{WS}	temperature at which water changes to vapour
V	volume of the CV

Greek symbols

λ, λ_i	eigenvalues
ρ	density of the gases in the control volume (CV)

manufacturers that they are effective in combating fires. There are, however, serious questions about the effectiveness of water mist systems, particularly in relation to their value in real tunnel fire scenarios, see Wu and Carvel (2012). As far as this author is aware, no water mist system has yet been deployed in a real tunnel fire situation.

2. Modelling major fire spread in tunnels

Major fire spread in tunnels has been modelled in a series of papers by this author; see chapters 10 and 16 of Beard and Carvel (2012) for a summary. The case considered has been to assume a tunnel similar in size to the Channel Tunnel, with a longitudinal ventilation, and to assume spread from an initial fire to a target object. The principles of non-linear dynamical systems theory have been used to identify a point of thermal instability and this has been identified with the point of spread to the target. Non-linear dynamical systems theory has been applied to many systems which exhibit 'jump' phenomena (Thompson and Stewart, 1986) and, within the field of fire modelling, has been applied to the jump associated with flashover in a compartment fire; see, for example, Beard (2010) and major fire spread in a tunnel; see, for example, Beard et al. (1995) and chapters 10 and 16 of Beard and Carvel (2012). The flashover and major fire spread phenomena are strongly suggestive of a non-linear 'bifurcation point' and lend themselves to such modelling.

(For much more on the basic concepts, see Bishop et al. (1993)). As early as 1928 Semenov had employed non-linear concepts to modelling spontaneous ignition (Semenov, 1928). Much later, Thomas et al. associated such concepts with modelling flashover in compartment fires (Thomas et al., 1980) but non-linear dynamical systems theory was not applied to fire development in a way which might have definite practical implications until Beard et al. initiated research in this area in 1990. Since then the concepts have been applied to flashover in compartments and tunnel fires, extending over a large number of papers. In the application to tunnel fires, a comparison between theory and experiment has been carried out and reported on Beard (2007).

For tunnel fires, the critical heat release rate for fire to spread from the initial fire to the target object has been calculated. Three models have been created which assume there is no flame impingement on the target object, making different assumptions about the extent of flame and smoke. The fire spread in these models would correspond to spontaneous ignition of the target. The three models have been identified with the acronyms FIRE-SPRINT A1, FIRE-SPRINT A2 and FIRE-SPRINT A3. The model which assumes the greatest extent of flame is FIRE-SPRINT A3 (Beard, 2006) and using this model the critical heat release rate for the case considered was found to be between 30 and 40 MW, with a ventilation velocity of 2 m/s. The case considered was that of a tunnel similar to the Channel Tunnel and a separation of 6.45 m.

A model which assumes flame impingement on the target object does exist has also been created (Beard, 2003) and this has been identified with the acronym FIRE-SPRINT B1. Flame impingement greatly reduces the calculated critical rate of heat release, by the order of 60–70%. A comparison between theory and experiment for these models has been carried out using results from the only large-scale experiment to date to measure major fire spread in a tunnel (Beard, 2007); as known to the author. Far more large-scale experimental tests examining the conditions for major fire spread in tunnels need to be conducted, and these should be carried out by independent organizations.

A question which emerges is: if a water-mist system were to be operating, what would be the calculated critical heat release rate (HRR) for fire spread? Specifically, for the case where there is no flame impingement on a target object, what would be the calculated critical HRR in the presence of water mist? The presence of water mist may be assumed to create extra heat losses in the system. In relation to the FIRE-SPRINT models created: if water mist were to be incorporated into FIRE-SPRINT A3, to create another model, what values for the critical HRR would be found? This is the question addressed in this paper. The case considered is that of a fire which, without fire fighting of some kind, has the potential to become a major fire, with a HRR of the order of tens or even hundreds of megaWatts.

3. Water mist systems

Water mist systems produce droplets which are much smaller than those for a conventional sprinkler system and a large part of