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Fires in Ducts: A review of the early research which underpins modern tunnel fire safety engineering

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A B S T R A C T

Much of the early research which now underpins tunnel fire safety design was carried out experimentally, using small scale ducts. This paper reviews such experiments, mostly carried out in the 1960s, 1970s, and 1980s, highlighting the assumptions and limitations of the early studies, which may have been forgotten as the equations developed have been applied in practice in the subsequent years. The review covers three primary topics; fire propagation under 'turbulent slug flow' conditions, stratification & flame spread, and backlayering & critical ventilation velocity.

1. Introduction

The problem of tunnel fires is one of the most complex and interesting areas of modern fire research. The demand on existing road and rail infrastructure has increased dramatically over the past few decades, forcing existing tunnels to take more traffic, leading to more congestion than ever. New tunnels, built to accommodate extra traffic and to reduce travel times, are now being made wider, longer and more complex than ever before. In order to engineer fire safety solutions for these tunnels, the interactions of vehicle fire loads, ventilation systems and tunnel geometry must be fully understood.

Tunnel fires have attracted an increasing amount of attention in recent years, following a series of catastrophic fires which occurred in European road and rail tunnels at the turn of the century (Carvel and Marlair, 2005), and more recent fire disasters in road tunnels in China (http://www.scmp.com/news/china/article/1447749/31-killed-truck-collision-turns-chinese-tunnel-fiery-death-trap; http://www.chinadaily.com.cn/china/2017-05/11/content_29296643.htm); resulting in many fatalities. Additionally, the cost of tunnel construction can be exorbitant, meaning there is demand for tunnels to have inherent fire safety to minimise the investment risk. Despite this, sufficient interest in tunnel fire research is still somewhat lacking, resulting in some study areas, such as critical velocity, receiving extensive research (Ingason, 2008), while significant gaps in understanding remain in others.

Several full-scale tunnel fire experiments have been carried out across the past five decades, including pool fire experiments carried out in Switzerland in 1965 (Haerter, 1994), in the UK in 1970 (Heselden and Hinkley, 1970), in Austria in 1975 (Pucher, 1994), and in the USA in 1995 (Memorial Tunnel Fire Ventilation Test Program, 1996), as well as solid fuel and occasional vehicle fire experiments carried out in Japan in 1980 (Mizutani et al., 1982), Finland in 1985 (Keski-Rahkonen et al., 1986), Norway in 1992 (Fires in Transport Tunnels: Report on full-scale tests, 1995), Japan in 2001 (Stroeks, 2001), and The Netherlands in 2001 (Project 'Safety Test'). Recent full-scale tunnel fire experiments have tended to focus on simulated truck loads, such as the Runehamar tests in Norway in 2002 & 2013 (Ingason and Lönnermark, 2005; Ingason et al., 2014), and metro carriages, such as the Metro project in Sweden in 2011 (Lonnermark et al., 2012) and tests carried out in Canada in 2011 (Hadjisophocleous et al., 2012). While each of these tests has contributed to knowledge, the enormous expense of full-scale tests is often hard to justify, especially as the contribution to knowledge of any individual test is often minimal. For this reason, much recent research in tunnel fire behaviour has been carried out using small scale 'tunnel apparatuses' in established test centres like RISE in Sweden (formerly SP) (Li et al., 2016) and the State Key Laboratory of Fire Science (SKLFS) in China (Chen et al., 2015). These recent small-scale experiments are carrying on the tradition established in the pioneering research carried out using ducts in the 1960s and 1970s, which is the main focus of this paper.

The issue of underground fire safety is not a new one and pre-dates most of the significant fire incidents in vehicle tunnels. Much of the early research began in the 1960s in response to a large number of fatal fires in mines (Keenan, 1963). This research consisted of both theoretical and experimental studies, often driven by mining associations, such as the Safety in Mines Research Establishment in the U.K. and the U.S. Bureau of Mines. Due to the obvious expense and safety issues associated with large-scale tunnel experiments, many of the studies were carried out using small-scale ducts. Assuming similarities in the fire dynamics between full scale and reduced scale, meant that the results from duct experiments could be applied to full size mines and this

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Nomenclature

A	tunnel cross-sectional area (m^2)
c_i	local mass concentration of gas species i
$c_{i,avg}$	average mass concentration of gas species i
$\bar{c}_p$	average specific heat capacity of the gases (kJ/g)
E	energy (kJ)
Fr	Froude number
g	gravitational acceleration (m/s^2)
H	height of duct (m)
H_{vap}	latent heat of vaporisation (kJ/mol or kJ/kg)
k_1, k_2	proportionality constants, Eqs. (4) and (5) (–)
L	length scale (–)
L_b	length of the backlayer (m)
$\dot{m}_A$	mass flow rate of ventilation air (kg/s)
M_f'	mass of fuel per unit length (kg/m)
Q	heat release rate (kW)
$\dot{Q}'$	heat release rate per m width of tunnel (kW/m)
$\dot{Q}_L$	rate of heat loss into the walls (kW)
Q^*	dimensionless heat release rate (–)
r	stoichiometric ratio of fuel/air
R	tunnel radius (m)
t	time (s)
T	temperature (K)
T_o	ambient temperature (K)
T_{avg}	average downstream temperature (K)
T_{sm}	temperature of the smoke layer (K)
u	ventilation velocity (m/s)
v_c	critical velocity (m/s)
v^*	dimensionless velocity (–)
V	flame spread rate (m/s)
V_{avg}	average downstream ventilation velocity (m/s)
$Y_0^{(0)}$	oxygen supply rate (mol)
ε	emissivity (–)
ρ_0	ambient density of air (kg/m^2)
ΔH_c	heat of combustion of the fuel (kJ/mol or kJ/g)
ΔT_{cf}	temperature difference due to stratification (K)
ΔT	local gas temperature rise (K)
ΔT_{avg}	average gas temperature rise (K)

Subscripts

F	full scale
M	model scale

research yielded many valuable observations and theories. Research in this field lost momentum as the mining industry waned, until it was revived with the recent concern over transportation tunnel fire safety.

The behaviour of fires in tunnels can be directly related to this early research in mines and ducts; however, many of these early studies appear to have been overlooked in recent research (Vaitkevicius et al., 2014, 2016). One reason for this may be that researchers, understandably, prefer to compare their theories to large-scale experiments, due to the problems and complexities of scaling laws. However, in some cases, this may have led to the theories themselves being overlooked and not investigated further. Another explanation is that the similarities between the subjects and the full extent of this research have not been fully appreciated, which may have resulted in some research being repeated.

The aim of this literature review is to produce a comprehensive overview of the historic theoretical and experimental research which was carried out regarding duct fires. This is intended to act as a summary of the pioneering work that was carried out on this subject and it is hoped that it will be a useful reference for the current tunnel fire safety engineering community. Particular attention is focused on early studies that are not widely referenced in modern research; since these are likely to be less familiar to the audience they are therefore of greater interest. By examining the concepts discovered in these early studies, the roots of different modern branches of tunnel fire science can be uncovered. This paper is presented as an overall narrative of the development of this subject, from research on fires in ducts to the modern research in transportation tunnel fires.

This literature review has been broken down into three broad themes. Section 2 examines the study of flame propagation in ducts under "turbulent slug flow". This is further divided into the fuel-rich and oxygen-rich mechanisms of flame propagation to compare the similarities and differences between these. The theoretical and mathematical models developed to describe these mechanisms are examined and compared to the results of early duct fire experiments. In Section 3, the effects of stratification on flame spread are examined. Models based on the concept of Froude number correlations are compared to examine the ability of the Froude number to predict the degree of downstream stratification and the composition of the gas species within the stratified layers. Section 4 provides a summary of the phenomena of backlayering and critical ventilation velocity. These topics, which have gone on to be widely researched with regard to tunnel fire safety, originated in the general study of duct fires. A short summary of the scaling theory, required to convert the results of small-scale experiments for application to full-scale tunnels, is provided in Section 5.

The scope of this literature review has generally been limited to the study of fires in ducts, building corridors and model-scale tunnels; however, research on large-scale tunnels and mine shafts is also included where it provides a foundation for the understanding of the subject as a whole. Literature reviews on the subject of tunnel fire research have been covered in depth by several other authors elsewhere (Ingason, 2008; Hansen, 2009; Lönnermark, 2005), and so it is not the purpose of this work to reproduce their findings.

2. Flame spread with turbulent slug flow

This section focuses on the mechanisms governing flame spread in a duct under "turbulent slug flow", a condition first introduced by de Ris (1970). This condition is the assumption that the gases are fully mixed within the duct cross-section and therefore the effects of stratification can be neglected. It was first used in order to develop a solvable mathematical model to describe the mechanisms occurring in a duct fire, and was adopted by many of the other researchers of the time as it greatly reduced the complexity of the problem.

This assumption was shown to be sufficiently accurate for fires in small-scale tunnels and ducts (Newman and Tewarson, 1983), since their small height prevents significant stratification. However, in larger-scale ducts, stratification is much more likely to occur as the temperature variation of the gases within is greater. This condition is discussed in more detail in Sections 3 and 4. The equations and concepts derived for turbulent slug flow, presented below, have occasionally been applied to full scale tunnels, apparently without consideration that the assumptions might not apply. The extent to which turbulent slug concepts can be applied in real tunnel conditions has yet to be adequately explored.

2.1. Modes of propagation

Much of the earliest research on duct fires focuses on flame propagation in continuously lined ducts (Roberts and Kennedy, 1965). Here, the term "fire propagation" is used to describe the continuous propagation of the burning region along the fuel (not to be confused with fire spread, where the burning region grows in size) either from an