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Influence of fire suppression on combustion products in tunnel fires

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ABSTRACT

A series of model scale tunnel fire tests was carried out to investigate effects of the fire suppression system on production of key combustion products including CO and soot. The key parameters accounted for in the tests include fuel type, ventilation velocity and activation time. The results show that fire suppression indeed has influence on production of combustion products especially for cellulose fuels. In case that the fire is not effectively suppressed, e.g. when the water density is too low or activation is too late, the CO concentration and visibility could be worse than in the free-burn test. From the point of view of production of combustion products, only fire suppression systems with sufficient capability and early activation are recommended to be used in tunnels.

1. Introduction

Nowadays use of water-based fire suppression systems in tunnels has attracted much attention and the regulations and standards are also changing with regard to its use [1]. Despite this, there are still numerous issues needed to be clarified before quantitative guidelines can be made.

The Swedish Transport Administration (STA) plans to construct a new highway connection through the western part of Stockholm called the Stockholm bypass, due for completion in 2025. A new type of water based fire suppression system will be installed in the tunnel. In earlier studies within the frame of the EU co-funded project (TEN-T), a concern was raised that if the system activates late, an increase of toxic substances and smoke could be produced. The impact of this effect could be mitigated by activating the system early. Further research was needed to investigate the implication of this observation in future testing [2]. The work presented here is directly related to the research question raised.

There have been many full scale fire suppression tests carried out in tunnels [2–10]. These tests have been mainly concerned about the design fires in tunnels with focus on specific fire suppression systems. Model scale tests have also been performed to systematically investigate the design fires with different fire suppression systems [11], and interaction between water mist and hot gases [12]. Tests with automatic suppression systems in tunnels have also been carried out in model scale [13].

At present it is clear that by equipping a tunnel with a deluge water-based fire suppression system of enough capacity, e.g. greater than 10 mm/min for a water spray system, the design fire can be reduced to a lower level [14]. It is, however, not clear how the combustion products are released in such cases. As the fire is suppressed due to the intervention of the water sprays, strong interaction between the combustion and water sprays exist. This results in changes in the production of combustion products, which in turn changes the environment in the tunnel. Therefore this issue is very important for analysis of evacuation in a tunnel fire after activation of a suppression system. A scenario similar to the use of water-based fire suppressions is the fire-fighting operation in a tunnel fire. Note that fire fighters use fire hoses to suppress and extinguish the fire. The agent used can be water, foam, or mixture of water and foam, but for attacking solid fuel fires water is mostly used. In such cases, the same adverse effect as that using a fixed water-based fire suppression system exists. Clearly, this issue has to be clearly addressed from the point of view of both tunnel safety designs and fire-fighting operations.

The main objective of the work is therefore to investigate effects of a deluge water-based fire suppression system on combustion products in tunnel fires. The focuses are on CO concentration, CO yield, soot yield and visibility.

2. Theory

2.1. Scaling

The Froude scaling technique has been applied in this work. Although it is impossible and in most cases not necessary to preserve all

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Nomenclature

a	constant
C	extinction coefficient in Eq. (2) (1/m)
d	water droplet size (mm)
E	energy content (kJ)
ΔH_c	heat of combustion (kJ/kg)
I	received light intensity
I_o	emitted light intensity
l	length scale (m)
L	light path length (m)
m	fuel mass (kg)
$\dot{m}$.	ss flow rate (kg/s)
M	molecular weight (kg/kmol)
p	pressure (Pa)
$\dot{Q}$.	at release rate (kW)
$\dot{q}_w$	water flow rate (L/min)
$\dot{q}''_w$	water density (mm/min)
t	time (min)
Δt	time step (min)
T	gas temperature (K)
u	velocity (m/s)
v	frequency factor
V_{is}	visibility (m)
$\dot{V}$	volume flow rate (m^3/s)
X	volume concentration
Y	yield of combustion product (kg/kg)

Subscripts

CO	Carbon monoxide
CO_2	Carbon dioxide
eff	effective
f	fuel
F	full scale
HCN	hydrogen cyanide
M	model scale
o	ambient air (incoming flow)
O_2	oxygen
g	smoke flow
i	ith layer
s	soot

Greek symbols

ρ	density (kg/m^3)
σ_s	specific mass extinction coefficient (m^2/kg)
φ	volume concentration (ppm)
ϕ	oxygen depletion factor
α	Constant

the terms obtained by scaling theory simultaneously, the terms that are most important and most related to the study are preserved. The thermal inertia of the involved material, turbulence intensity and radiation are not explicitly scaled, and the uncertainty due to the scaling is difficult to estimate. However, the Froude scaling has been used widely in enclosure fires, e.g. Refs. [15,16]. Our experience of tunnel fire tests shows there is a good agreement between model scale and large scale test results on many focused issues [17–19]. Despite the radiation terms cannot be simply preserved, some previous researches, e.g. Ref. [20], showed that the radiation from flames and gases to surroundings was reasonably well preserved. For water sprays, if the droplet size scales well, most non-dimensional terms related will be well preserved, aside from the radiation term which only relatively well preserved [1]. Furthermore, the water droplet may not strictly scale as the ½ power of the length scale for geometrically scaled nozzles, however, this effect is considered to be insignificant for such a scaling ratio as pointed out by Heskestad [21]. Experimental work conducted by Yu et al. showed that the cooling effect of the fire suppression systems and the gas temperatures were well scaled in moderate scales for gaseous fires [22,23] and wood crib fires [24], respectively, indicating that the global heat transfer including convection and radiation heat transfer was reasonably well scaled. There is limited work on scaling of visibility and extinction coefficient, but the experimental work conducted by Li et al. [25] showed that the measured maximum extinction coefficients from the train carriage fire tests in 1:3 scale correlated very well with the full scale test data.

The model tunnel for the study presented here was built in a scale of 1:4, which means that the size of the tunnel is scaled geometrically according to this ratio. The scaling correlations for other variables such as the heat release rate, flow rates and the water flow rate can be obtained in Table 1.

Wood pallets were used as one fuel type in the tests and scaling of the wood pallet fires was applied in this work, see Ref. [26].

Visibility, V_{is} (m), can be directly estimated using the extinction coefficient [27]:

$$V_{is} = \frac{a}{2.3C} \tag{1}$$

where the parameter a is a constant related to the characteristics of the evacuation sign and the smoke.

The extinction coefficient, C (1/m), can be obtained by the following:

$$C = \frac{1}{L}\log\left(\frac{I_o}{I}\right) \tag{2}$$

where L is the light path length, I_o is the intensity of the incident light and I is the intensity of light through the smoke.

Note that the average extinction coefficient can also be estimated using [1]:

$$C = \frac{\dot{m}_f Y_s \sigma_s}{\dot{V}_g} \tag{3}$$

where $\dot{m}_f$ is fuel mass loss rate (kg/s),Y_s is soot yield (kg/kg), and $\dot{V}_g$ is volume flow rate of the tunnel flow (m^3/s). The specific mass extinction coefficient, σ_s (m^2/kg), is considered as a constant 3300 m^2/kg for flaming combustion [28]. The above correlation in reality indicates that there is a linear correlation between the soot density, $\dot{m}_f Y_s/\dot{V}_g$, and extinction coefficient, C.

It is assumed that the same fuel type is used in model scales. Also, note that the fuel mass burning rate and smoke mass flow rate are supposed to scale as 5/2 power of the length scale. Therefore the average extinction coefficient scales as:

$$C \propto Y_s \propto l^0 \tag{4}$$

This suggests that the average extinction coefficient and the visibility scale as the soot yield. Note that in most cases the soot yield is insensitive to the scale, that is, the average extinction coefficient and the visibility scales as zero order of the length scale. In other words, they are approximately the same in all scales.