A QUALITATIVELY MODEL TO DESCRIBE THE INFLUENCE OF BOUNDARIES ON THE ENERGY DENSITY BY CONSIDERING THE ENERGY LEAKAGE, AND ITS EXTENSION ON THE SYSTEM VENTILATION AND FIRE FIGHTING SYSTEMS

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Abstract

Abstract In this paper constitutive models based on physical laws are derived that allow the energy flows and the release of energy to be described and predicted for fires in enclosed spaces and tunnels in particular. The models are generally formulated but are also specifically formulated for practical applications, e.g. for considering the effect of limited burning due to insufficient oxygen supply or the effect of firefighting systems. The solutions agree with the experimentally obtained results in (Carvel et al, 2001 and Carvel et al, 2005). Accordingly, the methods and solutions derived here can be considered adequately validated.

Keywords: tunnel fire, heat release rate (HRR), energy density, ventilation

INTRODUCTION

A number of serious tunnel fires, such as those in the Eurotunnel, the Mont Blanc Tunnel and the Tauern Tunnel (Carvel, 2010, Lacroix, 2001Leitner, 2001,Brousse, 2001), have contributed to the existing interest in methods for determining energy release rates and temperature development in enclosed space. Such methods are of importance not only for tunnel design and, by extension, the economic consequences of fires, but also in the assessment of various rescue scenarios. As part of an international research project (EUREKA) a number of fire scenarios, including a truck fire, were experimentally investigated (Swedish National Testing, 1994,Ingason, 2003, deNenno et al, 2002). Significant differences to known fire scenarios were identified in these experiments in terms of structuial engineering. Fire development was much faster, and the temperature gradient at the starting point of the fire was therefore significantly steeper. Significantly higher temperatures were also reached in some cases. In this context, the question was also posed regarding which effect the tunnel geometry or the special conditions of the fire within the tunnel have on the rate of energy release or temperature development. On the basis of experimental investigations, empirically observable relationships were derived taking this effect into consideration (Ingason et al, 2005, Carvel et al, 2005, Carvel et al, 2010, Dehn et al, 2011). Also on the basis of the experimental investigations, temperature-time curves specifically applicable to tunnel structures were incorporated into relevant regulatory guidelines (e.g. ÖVBB, 2005, RABT, ZTV, 2010) in order to enable future tunnel structures to be constructed with adequate safety in terms of the expected fire load. At the same time, construction materials (see e.g. Dehn et al,2007Dehn et al, 2008) that can withstand the relevant temperature load without loss of integrity and solutions for existing structures or for passive fire protection (see Bergmeister et al, 2003, Clement, 2010). This paper derives constitutive models on the basis of physical laws that allow the energy flows and rates of energy release, and, in turn, temperatures and smoke development, in closed spaces and tunnels in particular to be determined for various boundary conditions. The models are generally formulated and are then further specified for practical applications. The solutions agree with the experimentally obtained results in (Carvel et al, 2005) and (Carvel, 2010), meaning that the methods formulated here (Carvel, 2010, Carvel et al, 2005, Carvel et al, 2004, Dehn et al, 2001) or closed solutions can be considered to be adequately validated.

1 THEORETICAL PRINCIPLES FOR THE MODEL

Generally a normal fire is too complex for an analytical approach that is why a simpler source is normally constructed. This source is a superposition of a diffusion source and a radiation source of energy. That is on the first view a strong simplification for the thermal convection, but the thermal convection is the superposition on a direct and an undirect part and so the only mistake of this description seems, to be the handling of the directed part.

The radiation field can thus be described in the following form with the normalization constant (N) and the radius (r).

$$f_{rad}(r) = \frac{1}{N}\begin{cases} (2-r^2), & 0 \leq r \leq 1 \\ \frac{1}{r^2}, & 1 < r \end{cases} \tag{1}$$

and the diffusion field of energy with the following equation

$$f_{dif}(r) = \frac{1}{N} e^{-\frac{1}{2}r^2} \tag{2}$$

The blending is shown in equation (3) and Fig. 1.

$$f(r) = a\, f_{rad}(r) + (1-a) f_{dif}(r), a \in \ [0,1] \tag{3}$$

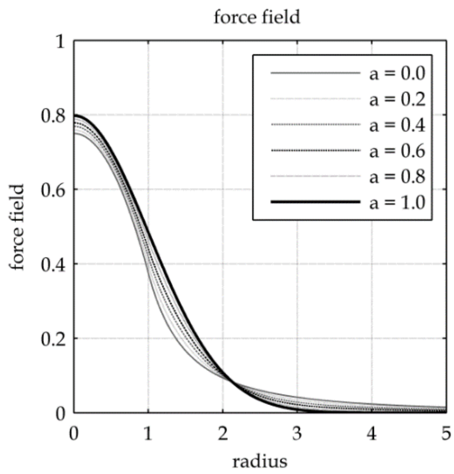

Fig. 1 Transition between a diffuse energy source (a = 1) and a radiative energy source (a=0)

The energy as a field generator size is concentrated in the center, similar to the mass for the gravitational field. In figure Fig. 1 it can be seen more than 80 % of the energy field is in a sector between r = 0 and r =2 for a source with the radius 1. For a non-spherical approximation for energy density is this good ratio to calculation.

To calculate the leaks the following basis model can be used. A confined space has a border. And on a infinitesimal small borderline the energy has two possibilities, the energy can leave the system (transmission $\tau \epsilon [0,1]$) or the energy can go back into the system (reflection$\rho \epsilon [0,1]$). Every time the energy beak flow (E_b) to the system is to calculated by the following general equation (E_s Energy of the Source, E_l over the leak lost energy)

$$E_b = E_s \underbrace{(\rho + \tau)}_{=1} \overbrace{\left(1 - \frac{E_l}{\underbrace{E_s}_{=\tau}}\right)}^{=\rho}. \tag{4}$$

This process will be repeated indefinitely and so the energy density increases by a factor of

$$\Phi = \sum_{i=0}^{\infty} (1-\tau)^i = \sum_{i=0}^{\infty} \rho^i. \tag{5}$$

For a time interdependent spherical geometry it is possibly to calculate the effect of the energy leaks with the equations (4) and (5). For a non-spherical system with some simplifications, such as that the walls are lambertian emitters, that the geometry is easy and that the energy transport from the walls is diffuse, it is possibly to solve the problem analytically.

For a confined non-spherical space the problem is not only defined by the leak, it is as well defined by the ratio of the radii of the source and the confined space. That means that a for flat radiation source the infinitesimal visable surface is a function of the angle $\sphericalangle_{rad}$between the normal of the surface and vector between the center of the surface and the point of view. A weak or non-visible surface can be neglected for the energy balance. For a radius higher than the double source radius, the field gradient (Fig. 1) is zero. Or in other term, the reflected energy density is low. For calculating the increasing factor the special case that the confined space has the double radius of the source will be applied. The reason is simple, in this special

case 95 % back flowing energy is captured for $\sphericalangle_{rad} = 45°$. The solution for the energy transfer back to confined space form surfaces with greater distances (in a non-spherical system) and a higher angles $\sphericalangle_{rad}$amount nearly zero and can be neglected. For a lower ratio between the radii, it needs to be used $\sphericalangle_{rad}$ higher than 45 ° and for higher ratio the angle is lower. So, for the approximation the ratio between confined space and source radius of 2:1was used. That makes it simple to approximationΦ.
With all this simplifications, the energy density can be written as (r_s radius of source)

$$\begin{gathered}\rho_{E,s} r_s^3 = E = \rho_{E,2s} r_{2s}^3. \\ \underbrace{\rho_{E,2s} r_s^3}_{E^*} = \underbrace{\rho_{E,s} r_s^3}_{E} \underbrace{\left(\frac{r_s}{r_{2s}}\right)^3}_{=\frac{1}{8}}\end{gathered} \tag{6}$$

To solve this is very easily with a little trick, one writes for $E^* = \frac{\Phi}{n} E$. In this case it is directly to see that $n = 8\,\Phi$. In the studies of Caravel and all [Carvel et al, 2001 Carvel et al, 2005 Carvel, 2010] is $= 24$. And for this experiment is $\Phi = 3$by $E_l = \frac{1}{3} E_s$.

As result of the superposition on source and reflection term one obtains (r_{la}radius of limited area)

$$\dot{E}^* = \dot{E}_s (8\,\Phi + 1) \underbrace{\left(\frac{r_s}{r_{la}}\right)^3}_{=\alpha^3} \tag{7}$$

The studies of Carvel are for tunnel. In this special case to calculateE_l is only a geometrical problem. The greatest angle it is to regard is 45 ° and ratio between the radii of source and confined space is 1:2. In following the leak is calculated for cylindrically symmetrical problem.The leak surfaces(A_τ) and the reflective surfaces $\left(A_\rho\right)$ are

$$A_\tau = 8\,\pi\, r_s^2 \text{ and } A_\rho = 16\,\pi\, r_s^2 \tag{8}$$

The ratio τbetween $E_l$and $E_s$is ratio between the closed surface$A_\tau + A_\rho$ and leak surface A_τ

$$\begin{gathered}\frac{E_l}{E_s} = \frac{A_\tau}{A_\tau + A_\rho} = \tau = \frac{1}{3} \\ \Phi = \sum_{i=0}^{\infty} \left(1 - \frac{1}{3}\right)^i = 3\end{gathered} \tag{9}$$

The effect of ventilation and fire fighting systems can be approximated by the Arrhenius equation ($E_A$activation energy, Runiversal gas constant, Ttemperature)

$$\kappa = e^{-\frac{E_A}{R\,T}} \tag{10}$$

and the ideal gas law (p pressure, Vvolume, $n$amount of substance)

$$p\, V_0 = n\, R\, T \tag{11}$$

The ventilation can be approximated with the free volume $V_\Delta = V_0(1 - \alpha^3)$ (that means the volume of the system without the volume of the source), that can vary in the ratio to the source from 1to∞. For this reason, the total volume V_0 from equation (11) must be corrected with a weighting term of $\frac{V_0}{\alpha^3}$. With this approximation the exponent of Arrhenius equation can be written as follow:

$$\frac{E_A}{R\,T} = \underbrace{\frac{n\,E_A}{p\,V_0}}_{\beta} \frac{\alpha^3}{1-\alpha^3}. \tag{12}$$

The effect of ventilation an the HRR (heat release rate) is

$$\dot{E}^* = \dot{E}_s(8\,\Phi + 1)\alpha^3 e^{-\beta\frac{\alpha^3}{1-\alpha^3}} \tag{13}$$

For the fire fighting systems the same procedure can be applied. These systems can reduce the system energy ($E_r$amount of the energy reducing) or the free volume (γ^3 expression of the reducing of the free volume). That can written as an Arrhenius exponent in the following form:

$$\frac{E_A}{R\,T} = \beta \frac{\alpha^3}{1-\alpha^3} \frac{p\,V_0}{p\,V_0 - E_R} \frac{\gamma^3}{1-\gamma^3}. \tag{14}$$

In this case one can write equation (13) in the following form:

$$\dot{E}^* = \dot{E}_s(8\,\Phi + 1)\alpha^3 \left(e^{-\beta\frac{\alpha^3}{1-\alpha^3}}\right)^{\frac{p\,V_0}{p\,V_0 - E_R}\frac{\gamma^3}{1-\gamma^3}} \tag{15}$$

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