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Ventilation effects in confined and mechanically ventilated fires

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ABSTRACT

The main objective of this work is to study underventilated and highly underventilated fires in a compartment equipped with a mechanical ventilation network. Heptane and dodecane pool fire experiments are performed in a reduced-scale room. A changing-scale analysis is performed in order to obtain species concentrations and temperature levels at a larger scale. Carbon dioxide concentration increases linearly with the decreasing of oxygen concentration. Heat release rate depends on ventilation condition in the compartment and we can distinguish three cases. The first one corresponds to sufficiently ventilated fires, where heat release rate is higher or equal to the one of an open fire and where the reaction is almost complete. The second one includes underventilated fires for oxygen concentration ranging between the Minimum Oxygen Concentration of the given fuel and around 7% (this value corresponds to the Minimum Oxygen Concentration of carbon monoxide). At this percentage of oxygen, the Heat Release Rate is lower than the one of an open fire and the carbon monoxide production is proportional to oxygen concentration. The third one corresponds to very underventilated fires for oxygen concentration lower than 7%, and where the fire can stop due to a lack of oxygen. In this case, carbon monoxide concentration increases strongly with the decrease of oxygen concentration.

1. Introduction

Many investigations were conducted on unburnt gas production during compartment fires. This production depends on the amount of oxygen supplied. Carbon monoxide and oxygen concentrations produced during fires have been measured by several authors (Beyler [1], Tewarson [2], Morehart et al. [3], Gottuk [4] and Utiskul [5] among others). Pitts [6] has summarized a large number of investigations conducted for carbon monoxide production. The transport of exhaust gases to another compartment has also been investigated (Lattimer et al. [7], Wieczorek [8], Lassus [9]). In many of these investigations, available oxygen is considered using global equivalence ratio. Beyler has shown that the carbon monoxide level generated during a fire is correlated to fuel type [1]. The main objective of the present work is to study the ventilation conditions during a fire in a reduced scale room, and especially the production of some species, such as carbon monoxide and carbon dioxide. As pointed by Viskanta [10], such experimental data are important to increase the efficiency of Computational Fluid Dynamics (CFD)-based fire dynamics models. The use of laboratory-scale experiments requires the confirmation of the validity of the similarity between the original full-scale compartment and the scaled model. In this paper, scaling laws are proposed for pool fires in a compartment. Fire investigations have been previously conducted in full scale compartments, such as the International Collaborative Fire Model Project (ICFMP) conducted by Rowekamp et al. [11], Full-Scale Enclosure (FSE) fires performed by Pitts et al. [12] in order to extend the earlier reduced-scale enclosure (RSE) study carried out by Bryner et al. [13] and FLIP test presented by Melis and Audouin [14] for the study of vitiation effect on Heat Release Rate (HRR). A comparison between these full-scale fires and the reduced-scale room fire performed in this work is also given. The aim of the paper is to study the validity of scaling laws and to check the validity of our enclosure to reproduce the behavior of bigger enclosures. A description of the different combustion regimes is also given. Section 2 is devoted to the derivation of the scaling relations. Material and methods are presented in Section 3 and the results and discussions in Section 4.

2. Scaling relations

Investigations on fire compartment require experiments. It is often necessary to quantify temperature, pressure, species

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Nomenclature

ACPH	air change per hour
c_p	specific heat (J kg^{-1} K^{-1})
D	fire diameter (m)
Fr	Froude number
g	acceleration of gravity (m s^{-2})
h	fuel height in the pan (m)
h_{conv}	heat transfer coefficient (J m^{-2} K^{-1} s^{-1})
L	characteristic length (m)
$\dot{m}''$	burning rate per unit area (kg m^{-2} s^{-1})
MOC	Minimum Oxygen Concentration of fuel (% vol.)
$\dot{q}_{\mathrm{cond}}$	conductive heat flux (J s^{-1})
$\dot{q}_{\mathrm{conv}}$	convective heat flux (J s^{-1})
$\dot{q}_{\mathrm{rad}}$	radiative heat flux (J s^{-1})
$\dot{Q}$	heat release rate (kJ s^{-1})
Re	Reynolds number
S	fuel pan surface area (m^2)
t	time (s)
T	temperature (K)
u	gas velocity (m s^{-1})
λ	thermal conductivity (J m^{-1} K^{-1} s^{-1})
δ	thermal penetration distance within wall (m)
ΔH_c	heat of combustion (J kg^{-1})
ε	emissivity
ρ	gas density (kg m^{-3})
σ	Stefan–Boltzmann constant (J m^{-2} K^{-4} s^{-1})
ϕ	global equivalence ratio
τ	flow time scale
μ	dynamic viscosity (N s m^{-2})

concentration and to consider parameter influences such as ventilation flow or HRR. Two cases of fire tests can be considered: fire tests in full-scale room and in reduced-scale room. Experiments in full scale are expensive, that limit the numbers of tests. It may be difficult to analyze results in these conditions. With reduced-scale room, more tests may be carried out but the scale reduction must respect several scaling laws adapted to the studied problem. In many works, Reynolds number analogy is used to insure similarity between the prototype and the full-scale compartment. However, fire requires the preservation of too many groups to ensure complete similarity. Partial scaling is made by establishing dimensionless variables from the conservation equation. Scaling relations for compartment fires have previously been proposed by Heskestad [15], Emori and Saito [16], Quintiere [17] and others. This work is based on the one of Quintiere [10] and a particular attention is devoted to heat loss.

With constant temperature and pressure from small scale to full scale, Reynolds and Froude numbers cannot be preserved simultaneously. In this study, fire compartment tests have been conducted at a smaller geometric scale, maintaining the Froude number, $Fr = u^2/gL$, constant. Reynolds number is large enough to ensure the turbulence of the flow. The Froude number is then made constant by $u_r = l_r^{1/2}$ that comes from dimensionless variable of momentum conservation. Flow time scale is obtained from mass conservation by $\tau \propto l_r/u_r \propto l_r^{1/2}$. Since the ventilation flow rates (ACPH) is the inverse of τ, it scales with $l^{-1/2}$.

Pool fire is a phenomenon with a low Mach number that has a nearly constant pressure. By neglecting pressure variation, the energy equation (1) in mono-dimensional form can be expressed by:

$$\tilde{\rho}\cdot\left[\frac{l_r}{u_r\cdot\tau}\cdot\frac{\partial\tilde{T}}{\partial\tilde{t}}+u\cdot\frac{\partial\tilde{T}}{\partial\tilde{x}}\right] = \frac{\mu}{\rho_0\cdot u_r\cdot l_r}\cdot\frac{\lambda}{\mu\cdot c_p}\cdot\frac{\partial^2\tilde{T}}{\partial\tilde{x}^2}+\frac{\dot{Q}'''\cdot l_r}{\rho_0\cdot u_r\cdot c_p\cdot T_0} \tag{1}$$

The last term, which corresponds to the source term, contains the Zukoski number $\Pi_{Zu} = \dot{Q}/\rho_0\cdot F_r\cdot l_r^{5/2}\cdot g^{1/2}\cdot c_p\cdot T_0$ [18] that can lead to the heat release rate scaling by preservation of the term Q^2/L^5. Hottel [19] with the results of Blinov and Khudiakov [20], Thomas et al. [21] and Yumoto [22] concluded that flame radiation plays the most important role in fuel combustion.

Heat can be exchanged by radiation and convection at the bounding surfaces. Convective heat flux can be expressed by:

$$\dot{q}_{\mathrm{conv}} = h_{\mathrm{conv}}\cdot S\cdot(T-T_{\mathrm{wall}}) \tag{2}$$

From Zukoski number and the preservation of the Froude number, a dimensionless term appears:

$$\Pi_{\mathrm{conv}} = \frac{h_{\mathrm{conv}}}{\rho_0\cdot c_p\cdot g^{1/2}\cdot l_r^{1/2}} \tag{3}$$

In order to preserve this number, heat transfer coefficient must ensure $h_{\mathrm{conv}}\propto l_r^{1/2}$, the convective heat flux scaling is therefore obtained if $\dot{q}_{\mathrm{conv}}\propto l_r^{5/2}$. This condition is automatically obtained with HRR scaling.

The conduction term can be scaled if a condition is applied on the wall thickness. Indeed, from Fourier equation and Zukoski number, another dimensionless term appears:

$$\Pi_{\mathrm{cond}} = \frac{\lambda_{\mathrm{wall}}}{\sqrt{\tau\cdot\left(\frac{\lambda}{\rho\cdot c_p}\right)_{\mathrm{wall}}}\cdot\rho_0\cdot c_p\cdot g^{1/2}\cdot l_r^{1/2}} \tag{4}$$

Combined with the scaling laws for flow time ($\tau\propto\sqrt{l_r/g}$), this relation can be preserved if $(\lambda\cdot\rho\cdot c_p)_{\mathrm{wall}}\propto l_r^{3/2}$. Except specific heat of steel, specific heat of solids are nearly constant. Thus, the proportionality $c_{p\mathrm{wall}}\propto l_r^0$ appears. Assuming that thermal conductivity and gas density of a material have similar trends, we obtain: $\lambda_{\mathrm{wall}}\propto\rho_{\mathrm{wall}}\propto l_r^{3/4}$. Conductive heat flux scaling requires the preservation of wall thickness by the following dimensionless term:

$$\Pi_{\mathrm{wall}} = \frac{\delta_{\mathrm{wall}}}{\delta} = \left(\frac{\lambda_{\mathrm{wall}}}{\rho_{\mathrm{wall}}\cdot c_{p_{\mathrm{wall}}}}\right)^{-1/2}\cdot\left(\frac{g}{l_r}\right)^{1/4}\cdot\delta_{\mathrm{wall}} \tag{5}$$

where δ is the thermal penetration distance within wall.

In order to preserve this number, the following proportionality relation on wall thickness must be obtained:

$$\delta_{\mathrm{wall}}\propto\frac{\lambda^{1/2}\cdot l_r^{1/4}}{\left(\rho_{\mathrm{wall}}\cdot c_{p_{\mathrm{wall}}}\right)^{1/2}} \tag{6}$$

Using the proportionality relation of thermal conductivity, the gas density and Eq. (6), we get the requirement: $\delta_{\mathrm{wall}}\propto l_r^{1/4}$. If this term is preserved, conductive flux scaling is scaled with: $\dot{q}_{\mathrm{cond}}\propto l_r^{5/2}$ and this condition is obtained with HRR scaling.

Assuming that walls are black bodies, radiative heat flux can be expressed with the Stefan–Boltzmann law:

$$\dot{q}_{\mathrm{rad}} = \varepsilon\cdot\sigma\cdot S\cdot\left(T^4-T_0^4\right) \tag{7}$$

Using Zukoski number and the preservation of Froude number, a dimensionless term appears: