Flame extinction properties of solids obtained from limiting oxygen index tests

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ABSTRACT

Extinction theory is used in this work to determine from the limiting oxygen index test (LOI), widely used in industry, flame extinction properties such as the critical mass flux at extinction and its dependence on oxygen concentration. A method for characterizing the chemistry related to extinction, namely activation energy and pre-exponential factor, for an assumed one-step global Arrhenius reaction rate is also presented. In previous work, we showed how the LOI is related to key flammability properties of a material as measured by thermogravimetric analysis, differential scanning calorimetry, and cone calorimetry. In this work, even though the chemical kinetics for practical materials are unknown, we use results from a slightly modified LOI apparatus to derive the material extinction properties, including chemistry effects, by assuming a one-step global Arrhenius reaction rate for extinction. The extinction of flames on a solid surface depends on the flow field through both the heat transferred to the solid and the straining of the flame near stoichiometric conditions. The heat transferred to the solid is determined using a convective heat transfer coefficient, because flame radiation near the surface is small at extinction, and the strain rate affecting the flame reactions is expressed by a characteristic flow time. These flow parameters depend on the local flow conditions. For a counterflow situation, these parameters have been identified in our previous work, whereas for other flow situations, they can be determined from the specific flow field. The ratio of the flow time to the chemical time is used to determine a modified Damköhler number, together with the activation and flame temperatures. The heat transfer coefficient is used to determine the dimensionless mass flux at extinction, which is a function of the Damköhler number.

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1. Introduction

The oxygen index (OI) measurement is a small-scale standard test for characterizing the flammability tendency of materials by burning a vertical strip of this material after it is ignited at its top using a pilot candlelike diffusion flame. It allows the determination in an oxygen/nitrogen mixture of the minimum oxygen volume concentration, the so-called limiting oxygen index (LOI), required to just support the downward burning on the vertically mounted test specimen. The specimen's dimensions are between 70 and 150 mm in length, 6.5 mm in width, and 3 mm in thickness. The sample is placed in the center of a glass chimney where the oxygen/nitrogen gas mixture flows upward. After a 30 s purge of the chimney with the mixture gas, the top of the specimen is ignited using a diffusion pilot flame and the burning of the sample is observed until it stops as the oxygen concentration decreases. The LOI test is standard worldwide [1,2].

The LOI is expressed in terms of the oxygen and nitrogen volume concentrations (respectively $[O_2]$ and $[N_2]$) at extinction as

$$LOI = 100 \times \frac{[O_2]}{[O_2] + [N_2]}. \tag{1}$$

The two clear advantages of the LOI are that (a) it is a reproducible test that only requires small samples and (b) it provides a single figure that can be used for a presumed flammability ranking of materials.

In recent work [3], it was shown that the second premise is not applicable, because the LOI is related, in a complex way, to other key flammability properties, as well as to flow conditions such as the convective heat transfer coefficient. This conclusion is supported by experiments in a modified apparatus [4] designed to study the LOI of polymethylmethacrylate (PMMA), polystyrene (PS), and polyoxymethylene (POM). The authors in [4] investigated the effects of the initial sample temperature and external heat flux and found that the LOI decreases with an increase in either of these external parameters. These trends were predicted in our recent work [3], along with the estimation of LOI measurements of five polymers using their key flammability properties. Some important

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Nomenclature

c	sample specific heat (kJ kg^{-1} K^{-1})
c_p	gas specific heat (kJ kg^{-1} K^{-1})
Da	Damköhler number
Da$_m$	modified Damköhler number
h_c	effective heat transfer coefficient at zero mass flux rate (kW m^{-2} K^{-1})
M	molecular weight (g mol^{-1})
$\dot{m}''$	mass pyrolysis rate per unit area (kg m^{-2} s^{-1})
$\dot{q}''$	heat flux (kW m^{-2})
$\tilde{T}$	temperature (K)
T	normalized temperature
Y_{FT}	normalized fuel concentration in the supplied fuel (equal to 1 in the fuel supply)
$\tilde{Y}_{FT}$	fuel mass fraction in the supplied fuel
$\tilde{Y}_{0\infty}$	ambient oxygen mass fraction
$Y_{0\infty}$	normalized oxygen concentration at infinity

Greek

α	normalized temperature difference between wall and ambient
β	defined as $\beta = (\pi/2)^{0.5} + I(\chi_s) = (\pi/2)^{0.5} + \int_0^{\chi_s} \exp(-t^2/2)dt$
ΔH_c	heat of combustion per unit fuel mass (kJ kg^{-1})

ΔH_p	total heat of gasification per unit fuel mass (kJ kg^{-1})
v	stoichiometric coefficient in combustion reaction
ρ	density (kg m^{-3})
σ	Stefan–Boltzmann constant (kW m^{-2} K^{-4})
τ_{ch}	chemical time
τ_f	flow time
χ_S	normalized mass flux at the wall

Subscripts

a	activation
c	convective
e	external
ext	extinction
fl	flame
FT	fuel
o	oxygen
rr	re-radiative
w	wall
0	initial
∞	ambient

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discrepancies were noticed in [3], which are further studied in this paper, leading to the determination of flame extinction properties near the surface of a solid material.

Specifically, in the present paper we use the results in the standard [3] and modified LOI apparatus [4] to deduce flame extinction properties, including chemical effects. The method is based on a flame extinction theory [5] developed for a counterflow stagnation situation of the oxidizer flowing against the solid material. Even though the counterflow stagnation is different from LOI combustion conditions, this flame extinction theory [5] can be applied to other flow geometries as long as one identifies the relevant effective heat transfer coefficient, the Damköhler number, and the flame temperature.

The extinction of flames on a solid surface depends both on the heat transferred to the solid and on the strain of the flame sheet. The heat transferred to the solid is expressed by a convective heat transfer coefficient, h_c, because flame radiation is small at extinction near the surface, and the strain rate affects the flame reactions in a way expressed by a characteristic flow time. These parameters will depend on the local flow conditions. For a counterflow situation, these parameters have been identified in our previous work [5,7,8], whereas for other flow situations, they can be identified from the specific flow field. We have found that at high strain rates, solid combustion cannot be sustained at any pyrolysis rate. In the infinitely fast kinetics regime, an appropriate scaling has been developed that collapses all the heat flux curves onto a single one. In addition, the critical pyrolysis fuel mass flux exhibits a universal behavior for variation in various model parameters when plotted versus a modified Damköhler number, and becomes constant when the latter is sufficiently high, as shown analytically, numerically, and experimentally [5,7,8].

2. Extinction theory for the low oxygen index test

Burning of a solid material involves interaction between the combustion of the pyrolyzed gases and the thermal degradation of the solid. After the ignition of volatiles generated from the solid decomposition, the burning can be sustained by additional heat from the flame. For this process to be fully investigated, it is desirable that gas and solid phases be taken into account simultaneously, assuming that the kinetics of pyrolysis and gaseous combustion is known. Such a task is rather difficult for a practical solid material, where the chemistry is usually unknown. In order to simplify this complex process and develop a practical method, flame extinction near the sample surface in the LOI test is studied using a model where the gas phase phenomenon is separated from the solid phase phenomenon; i.e., gaseous heat transfer is considered separately from mass balance on the sample surface [3]. The next sections present a summary of the new methodology [5–8] and results from the previous work [3] useful for deducing extinction properties, as well as new relations for the flame temperature. This new methodology takes into account the variation in the critical mass flux at extinction with oxygen concentration, which was not the case for the previous method presented in [3].

2.1. Gas phase heat transfer

Near extinction, the mode of heat transfer from the flame to the sample is essentially convection, because radiation caused by a flame that is nearly blue is negligible. Using a porous pool type burner with an ethane–nitrogen system, it was measured and later modeled that the convective heat flux from the flame to the sample increases as the fuel supply rate decreases, reaching a maximum value at a critical mass flux, at which extinction occurs for a pyrolyzing fuel [6]. For a gaseous fuel, however, with a further decrease in the mass flux that is independent of the heat from the flames, the convective heat flux decreases because of quenching of the chemical reactions as the flame approaches the surface, before extinction occurs. As an analogy with the pyrolysis of a solid material, the mass supply of the fuel in the porous burner is related to the rate of mass pyrolysis.

The convective heat flux to the surface, $\dot{q}''_c$, for a counterflow situation is [5–10]

$$\dot{q}''_c = \frac{h_c}{c_p} \Delta H_c (Y_{0\infty} - \alpha) \exp\left(-\frac{\chi_s^2}{2}\right), \tag{2}$$