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Auto-extinction of engineered timber: Application to compartment fires with exposed timber surfaces

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ABSTRACT

A series of compartment fire tests with multiple exposed timber surfaces have been undertaken to explore the effect of exposed timber on the fire dynamics and the potential for auto-extinction. A test with exposed wall and ceiling achieved auto-extinction after approximately 21 min. Firepoint theory is applied using temperature data at the charline, is shown to predict a mass loss rate dropping below the critical value at 20–21 min, and thus is successful in predicting auto-extinction. Additional uncertainties caused by delamination are explored, and recommendations for the use of auto-extinction in design are given.

1. Introduction

Engineered timber products are continuing to increase in popularity, with factors such as sustainability, speed of construction, and aesthetics becoming ever more important. With the development of products such as cross-laminated timber (CLT) acting as structural wall and floor slabs, buildings are being constructed with the load-bearing structure formed predominantly from structural, engineered timber. The architectural aspiration for such buildings is often to have some of this structural timber exposed. The effect of exposed combustible compartment linings challenges many assumptions used in the assessment of compartment fire behaviour. One method to support robust design is to ensure that the timber linings auto extinguish after the compartment fuel load has been consumed. This requires an understanding of the energy balance at the char line, and an investigation of the critical factors at large scale. This presents an opportunity to explore the effects of multiple exposed timber surfaces within a compartment on the compartment fire dynamics. This paper focusses on the contribution of exposed timber surfaces to the fuel load during the cooling phase of a compartment fire, and interrogates the condition(s) under which the burning timber is expected to auto-extinguish.

2. Combustion of timber

Timber begins to pyrolyse upon exposure to an external heat source, producing flammable and inert gases, tars, and a rigid, carbonaceous char layer [1]. Flaming ignition of these flammable gases will occur when the generated mixture falls within the flammability limits, i.e. the air to fuel ratio falls within the correct range and the gases have sufficient energy. Smouldering ignition is also possible, but does not usually occur simultaneously with significant flaming combustion [1,2]. As a result, under flaming conditions, the char layer will continue to increase in thickness [1], reducing the rate of heat transfer to the virgin timber and resulting in a subsequent gradual decline in pyrolysis rate and hence mass flux of pyrolyzate [3].

2.1. Extinction

The “opposite” of flaming ignition is flaming extinction, which occurs when volatiles cease being produced in sufficient quantities to form a stable flame. This can be expressed in terms of the Damköhler number (the ratio of diffusion phenomena to kinetic timescales), which increases as a function of flame temperature and residence time (the duration the pyrolyzate remains in the reaction zone). Extinction will occur if the Damköhler number drops below a critical value, which can be achieved by reducing either the flame temperature or the residence time. Extinction can therefore occur due to external suppression (most commonly due to the application of water to cool the reaction zone); burnout of the pyrolysing fuel; or a reduction in the net energy supplied to the remaining unburned fuel. This will in turn result in a reduction in the mass of volatiles produced, which, if sufficient, will result in extinction. Due to the aforementioned decline in pyrolysis rate due to

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Nomenclature

A	area (m^2)
C_p	specific heat capacity (kJ/kg K)
E	energy consumed per unit mass (kJ/g)
ΔH_c	heat of combustion (kJ/g)
k	thermal conductivity (W/mK)
H	height (m)
L	latent heat (kJ/g)
$\dot{m}''$	mass flux (g/m^2s)
M	molar mass (kg/kmol)
$\dot{q}''$	heat flux (kW/m^2)
O	opening factor ($m^{-1/2}$)
Q	heat release rate (kW)
S	extinction parameter (kW/m^2)
T	temperature (°C)
W	molecular mass (g/mol)
x	position (m)
X	volumetric concentration

Greek

ϕ	critical ratio

subscripts

a	air
c	char
CLT	CLT contribution
cr	critical
e	external
f	final
f	flames
g	gasification
$H2O$	water vapour
i	initial
in	incoming air
int	internal
l	losses
n	net
$O2$	oxygen
p	pyrolysis
t	total
v	vaporisation
v	ventilation
w	wood
∞	ambient

the build-up of a char layer, a burning timber sample has the potential to auto-extinguish naturally. To understand this condition in more detail, firepoint theory can be used to analyse the energy balance between the char and the virgin timber.

2.2. Firepoint theory

Rasbash et al. [4] present firepoint theory as a means of determining ignition criteria for PMMA. They conducted a series of experiments on PMMA samples heated from above with a radiant panel to determine the effects of incident heat flux, air flow and oxygen concentration on the critical mass flux for ignition. In a range close to the critical heat flux for piloted ignition ($12\ kW/m^2$ to $19\ kW/m^2$), the critical mass flux was found to increase as a function of heat flux, from about $3.8\ g/m^2s$ to $5.2\ g/m^2s$; thereafter becoming independent of external heat flux. This initial variation was attributed to the variations in flame behaviour with lower heat fluxes. The effects of airflow around the sample were also investigated; an initial drop from around $5.3\ g/m^2s$ at 0lpm airflow to $3.2\ g/m^2s$ at 30 lpm, rising again to around $5.0\ g/m^2s$ at 60 lpm was observed. Reducing the oxygen concentration below ambient values resulted in a sharp increase in critical mass flux from around $3.3\ g/m^2s$ to $10.4\ g/m^2s$ at 19% O_2.

Rasbash et al. [4] concluded that firepoint theory may be used to determine if a material will continue to burn in the absence of a supporting heat flux:

$$S=(\phi\Delta H_c - L_v)\dot{m}''_{cr} + \dot{q}''_e - \dot{q}''_l \tag{1}$$

where ϕ is the critical ratio of convective heat transfer to the heat of combustion of the volatiles, ΔH_c is the heat of combustion of the solid, L_v is the heat of pyrolysis, and $\dot{q}''_e$ and $\dot{q}''_l$ are the external heat flux and heat losses respectively. If $S > 0$, the flame will be sustained, but if $S < 0$, extinction will occur.

This equation has previously been applied to small-scale spruce/fir timber samples in a fire propagation apparatus (FPA) [5,6], where it was shown that timber samples will auto-extinguish when the mass flux of volatiles drops below $3.48\ g/m^2s$ (at ambient oxygen concentrations), and can be predicted using the firepoint equation. In the FPA setup, this value was reached at incident heat fluxes at or below $31\ kW/m^2$ – however it should be noted that in a compartment fire setup, heat losses, oxygen concentrations, and boundary conditions may differ, so the same critical heat flux should not necessarily be expected. As with the experiments in [4] the critical mass flux for extinction increased with a reduction in oxygen concentration, but airflow was found to have no noticeable effect. In similar tests on Australian softwoods, Emberley et al. [7] found a critical mass flux of $4.0\ g/m^2s$.

2.3. Compartment fire behaviour

Considerable research has been undertaken on compartment fires, the key aspects of which are summarised by Drysdale [8]. Wooden cribs are typically used as the fuel load, as they have been shown to be representative of typical room furnishings [9], and have good repeatability. Numerous correlations exist for the burning rate of cribs, and this is typically related to the opening factor of a compartment – calculated by:

$$O = \frac{A_t}{A_v\sqrt{H_v}} \tag{2}$$

where A_t is the total internal surface area excluding the floor and the opening, A_v is the ventilation area, and H_v the ventilation height.

Compartment fires can be said to follow three main stages: 1) the initial growth phase, in which burning is fuel-controlled; 2) the fully-developed, post-flashover phase, in which burning is ventilation-controlled (Regime 1), and any excess fuel will be burned outside the compartment in an external plume; and 3) the decay phase, in which the burning will transition back to fuel-control (Regime 2) before extinction is achieved due to burnout of the fuel load.

2.4. Compartment fires with combustible surfaces

A compartment with exposed combustible surfaces such as timber presents an additional complexity due to the additional fuel load present. The existing empirical correlations were tested in situations where the fuel load was spread over the floor, and may not necessarily be valid when part of the fuel load is on the walls or ceiling. In a compartment with combustible surfaces, these will ignite, and the flames from these large exposed areas will produce additional heat which may increase the rate of burning of the compartment fuel load. The involvement of exposed combustible surfaces will also increase the total heat release rate, thus reducing the time to flashover.