ARTICLE IN PRESS

Fire Safety Journal xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Fire Safety Journal

journal homepage: www.elsevier.com/locate/firesaf

Critical heat flux and mass loss rate for extinction of flaming combustion of timber

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A R T I C L E I N F O

Keywords:
Heat transfer
Self-extinction
Timber
External heat flux
Cross laminated timber
Critical mass loss rate

A B S T R A C T

The critical mass loss rate and critical heat flux for self-extinction of flaming combustion during steady-state burning of timber was measured in this study for a range of timber species. A vertical mass loss calorimeter was used to provide the external heat flux and to measure the mass loss of the timber samples. The results showed that the critical mass loss rate was dependent upon the timber species but did not show a clear dependency with the timber density. Critical mass loss rates and heat fluxes for self-extinction exist for each of the timber species tested for both the solid timber and cross laminated timber (CLT). Debonding of both the char layer and the individual lamella of the CLT caused increased mass loss rates, re-ignition after self-extinction and increased flame lengths. Both char and ply fall-off were observed.

1. Introduction

The most significant aspect that differentiates steel and concrete buildings from timber structures is the combustible nature of timber. Structural design for burnout of a compartment fire has been a fundamental assumption since 1928 and as such self-extinction of flaming combustion of timber is a critical aspect to achieve this implicit requirement. Self-extinction controls the structural and fire performance of a timber structure and should be considered an inherent principle of their fire safety.

Originally, fire resistance and real fires were equated through the use of the equal area method. In the equal area method, the area under the standard time-temperature curve was set equal to the area under the time-temperature curve of a real fire. This was created as an attempt to compare building products. By using the entire burning time in a real fire, the equivalent fire resistance is directly linked to complete burnout of the fuel load of a fire. The concept of fire resistance in a standard furnace testing [1,2] was first linked to fuel load by Ingberg in 1928 [3]. By increasing the fuel load the burning duration of the fire was increased. Ingberg then linked fuel loads to equivalent times in the standard furnace. However, this is an over-simplification of the burning rate behavior in a compartment fire. Burning rates are a complex function of factors including ventilation, geometry and the type of fuel. Each of these are specific to the compartment in question. The results from Ingberg entered codes and standards and are currently in use today. Building codes classify the amount of fuel as well as the burning rate on the type of occupancy based on the types of fuel typically found in the occupancy [4]. Nevertheless, what still remains is the fundamental assumption that the compartment reaches burnout.

To maintain structural integrity through the entire duration of a compartment fire, flaming combustion has to cease after the fuel load has been consumed. The phenomena of self-extinction of flaming combustion of timber is an intrinsic quality of timber which has been observed several times in studies designed to research other aspects of combustion. Petrella [5] and Tewarson and Pion [6] studied the ideal burning rate for a wide range of combustible materials as well as several species of timber. In their studies, they calculated surface heat losses from the materials and compared them to the calculated heat flux provided by the materials' flames. For timber, the heat fluxes provided by the flames was calculated as an extremely wide range from 23.9 kW/m^2 (Douglas fir) [6] to 77.5 kW/m^2 (White oak) [5]. However, even with the wide range, the heat losses from the surface of the burning timber were approximately equal or greater than the heat flux provided by the flames and thus were calculated to not be sufficient to sustain burning. Therefore, for flaming combustion to continue, an external heat flux was required to keep the burning rate above a critical limit for flaming combustion. This is in stark contrast to other solids and liquids tested which had significantly higher flame heat fluxes than heat losses.

Babrauskas [7] reviewed and compiled data from 110 years of tests on the ignition of timber and heat fluxes necessary for ignition. The ignition temperature varied widely due to experimental set-up (i.e. piloted vs. auto-ignition and heat flux intensity, etc.). The minimum

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http://dx.doi.org/10.1016/j.firesaf.2017.03.008
Received 15 February 2017; Accepted 15 March 2017

Please cite this article as: Emberley, R., Fire Safety Journal (2017), http://dx.doi.org/10.1016/j.firesaf.2017.03.008

Nomenclature

c_p	specific heat
ΔH_c	heat of combustion
ΔH_p	heat of pyrolysis
k	thermal conductivity
m	mass loss
q	heat
s	shaded length
T	temperature
t	time
U	velocity
x	distance

Greek

∞	ambient
ρ	density
δ	reaction thickness

subscripts

c	characteristic
$char$	char layer
ext	exterior
f	fuel
g	generation
$loss$	energy losses from surface

heat flux for ignition was measured between 4.3 and 50 kW/m^2. Babrauskas [7] detailed a previously unpublished work of his on self-extinction of timber. Timber was placed in direct contact with a flame for 1–5 min and every time the flame was removed, self-extinction of flaming combustion was observed. Furthermore, Drysdale [8] observed that small pieces of wood (thermally thin) sustain burning while larger pieces of wood (thermally thick) self-extinguish. The interaction between the applied energy to the system and the heat losses was clearly demonstrated.

The increasing thickness of the char layer, the changing thermal properties, and the surface regression of the sample away from the thermal energy source all reduce the amount of the energy the pyrolysis front receives. As the energy decreases, the resulting burning rate decreases as well. Concurrently, during the decay phase of a fire as the fuel load is consumed and the burning rate decreases, the heat fluxes incident to timber components in the compartment decrease as well. Self-extinction of flaming combustion of timber occurs when the heat flux reduces enough to decrease the burning rate below a critical value for combustion. While self-extinction has been observed in previous studies, each of the studies listed above only analyzed the scenario where the external heat flux was completely removed. Continued burning in this scenario relies solely on the heat flux provided by the flames and is the best case scenario for self-extinction.

The main objective of this study is to provide a systematic analysis of the self-extinction properties of both engineered and solid timber in the context of ensuring structural integrity during the decay phase of a compartment fire. While numerous studies have been conducted on charring rates under imposed heat fluxes from standard fire resistance furnaces [9,10] and constant heat flux exposures [11], no study has sought to establish a repeatable methodology to measure self-extinction. The objective of this research project was to construct a methodology to quantify the critical mass loss rate and critical heat flux for self-extinction of flaming combustion for both solid and engineered timber as well as for several different species of timber in the context of structural integrity. The parameters affecting the burning rate are detailed in the following section as a demonstration of which variables to study.

2. Theoretical background

The variables affecting the burning rate, and thus the principle of self-extinction, can be quantified through a formulation of the energy balance over the char layer. Fig. 1 (left) depicts the energy balance over the char layer. The char layer is represented as the diagonal hatched area. Energy enters the control volume from an external energy source and oxidation of the char adds an energy generation term to the energy balance. Energy is lost from the control volume in terms of surface losses (i.e. radiation and convection) and heat is conducted into the pyrolysis layer. Energy is then stored in the char layer which increases the local temperatures of the char layer. The energy balance of the char layer is shown in Eq. (1).

$$\dot{q}''_{ext} + \dot{q}''_{g} - \dot{q}''_{loss} - \dot{q}''_{char} = \frac{\partial q''}{\partial t} \tag{1}$$

The amount of energy leaving the char layer enters the pyrolysis layer and is used to decompose the timber into char and combustible gases. A portion of the energy is not used for pyrolysis and is transferred through conduction into the virgin timber deeper into the cross section. The entire energy balance is dependent upon the heat of pyrolysis, thermal conductivity and the energy gradient leaving the pyrolysis layer. The energy balance is formulated in Eq. (2) and shown in Fig. 1 (right).

$$\dot{q}''_{char} - \left(-k\frac{dT}{dx}\bigg|_{x=x_{char}} \right) = \Delta H_p \dot{m}''_f \tag{2}$$

Eqs. (1) and (2) can be combined to form Eq. (3) which shows the various terms which represent the burning rate of timber. An analysis of each of the specific terms demonstrates which terms are critical in understanding self-extinction.

$$\dot{m}''_f = \frac{1}{\Delta H_p}\left[\dot{q}''_{ext} + \dot{q}''_{g} - \dot{q}''_{loss} - \left(-k\frac{dT}{dx}\bigg|_{x=x_{char}} \right) - \frac{\partial q''}{\partial t} \right] \tag{3}$$

The mass loss rate of timber has two distinct regimes of burning: transient and steady-state. Fig. 2 demonstrates a generalized curve of the two regimes. During the transient stage of burning, a peak mass loss rate occurs. The mass loss rate during the transient stage is inherently higher than the steady-state burning rate as the char layer is thin; therefore, the energy stored in this layer is small. Most of the energy is transferred through the char and used to decompose the timber or is conducted into the unburnt wood. In order for steady-state burning to occur, the various terms of Eq. (3) need to reach steady-state conditions as well. First, steady-state conditions indicate that the energy storage term (last term) in Eq. (3) is approximately zero. The energy generation by the oxidation of the char layer is incorporated in

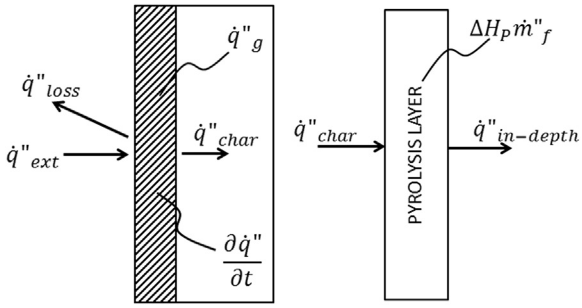

Fig. 1. Energy balance over both the char layer and the pyrolysis layer.