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Contribution to flashover modelling: Development of a validated numerical model for ignition of non-contiguous wood samples

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ABSTRACT

A computational model of flashover is presented that closely follows the experimental setup at CNRS-ENSMA-Poitiers. A propane burner with thermal power of 55 kW is used as a primary source of fire and square beech wood samples (30 mm × 30 mm × 5 mm) as fire spread targets. The computational model describes the wood pyrolysis with a progress variable. Using the conservation of heat fluxes at the solid–gas interface, the thermal diffusion in the wood samples is coupled with the convective and the radiative heat transfer in the ambient gas phase. The incoming heat flux at the upper surface of the wood samples reaches values between 20 and 30 kW/m^2. With the ignition and subsequent combustion of the pyrolysis volatiles, the heat flux increases by approx. 12 kW/m^2. The results show that the ignition of the wood samples is triggered at an approx. surface temperature of 650 K. Due to large local variations in incident heat flux, significant differences in the ignition times of the wood samples are observed. The comparison of the calculated and the experimentally measured temperature shows a good agreement for the first wood sample and the model predicts the ignition time very well. But for the second and the third wood samples the model overpredicts the temperature, which leads to a premature ignition of these wood samples.

1. Introduction

A fire in a confined space can be divided into three distinct stages based on fuel and oxygen consumption, heat release and variation of average gas temperature. These stages are usually described as the fire growth period, fully developed fire and decay period. Flashover is a short period of transition from a localized initial fire to the fully developed fire where all fuel surfaces within the compartment start to burn [1]. During the pre-flashover stage, the fire develops from its origin, forming a hot layer of combustion products below the ceiling of the enclosure. Thermal radiation from the fire and the hot layer raises the surface temperature of the surrounding combustible material. The material starts to pyrolyse [2], releasing volatiles that may ignite. The ignition of the combustible volatiles results in a rapid flame spread from a localized fire to all combustible surfaces. A more detailed description of this phenomenon can be found in [1,3,4].

From the fire-fighting perspective, flashover is a critical stage of fire growth. Namely, when flashover takes place, the probability of survival of occupants rapidly decreases. As the transition from the initial localized fire to the general conflagration takes usually less than a minute [5], fatalities are very likely to occur. Also, flashover creates a large increase in the rate of combustion; therefore, significantly greater effort is needed to reduce the burning material below its ignition temperature [6].

Due to the hazard associated with flashover, the subject has received a fair amount of attention in the literature. Drysdale [1] collected probably the most comprehensive overview of experimental studies. More recent analysis of flashover experimental data can be found in [5] and [7]. Although, the emphasis of this paper is on computational modelling of flashover, it is also important to mention a full-scale experiment conducted by White et al. [8], where a train fire was allowed to become fully developed, involving all combustible materials within the train.

Computational models used to analyse flashover can be classified into zone and field models. The theoretical background of zone models is the conservation of mass and energy in a compartment fire. The simulation domain is divided into separate zones and the conditions in each zone are assumed to be constant. Most often the fire is described with two zones (lower cold layer and upper hot layer). As such description of a complex

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Nomenclature

Latin letters

A_p	pre-exponential factor of the pyrolysis reaction
c_p	specific heat
C_A	Eddy dissipation model parameter
D	molecular diffusivity
E_p	activation energy of the pyrolysis reaction
f	mass flux
F_1, F_2	SST model blending functions
g	gravitational acceleration
G	turbulence production term due to buoyancy
h	enthalpy
I	radiation intensity
k	thermal conductivity, turbulence kinetic energy
k_g, k_{HCg}	empirical parameters of the radiation model
K	radiation coefficient
ℓ	wall distance
m	mass flow
M	molar mass
p	pressure
P	turbulence production term due to stresses
Pr_t	turbulent Prandtl number (= 0.9)
q	heat flux
r	spatial dependence
R	gas constant, reaction rate
s	ray path length
S	source term, surface, invariant of the strain rate
Sc_t	turbulent Schmidt number (= 0.9)
t	time
T	temperature
v	velocity
V	volume
x, y, z	spatial coordinates

Greek letters

α	progress variable of the pyrolysis reaction, heat transfer coefficient
α_1, α_3	SST model parameter
β^*, β_3	SST model parameters
δ	Kronecker delta function, wall thickness
ε	emissivity, turbulence eddy dissipation
ζ	molecular concentration
θ	angle
λ	wave length
μ	dynamic viscosity
ν	stoichiometric coefficients
ξ	mass fraction
ρ	density
$\sigma_{\omega 2}$, σ_{k3}, $\sigma_{\omega 3}$	SST model parameters
Ψ	volume fraction
φ	angle
Ω	angle
ω	turbulence frequency

Subscripts/superscripts

0	starting radiation intensity
a	absorption
b	blackbody
b_{1g}, b_{2g}	radiation model parameters
c	char, component, convection
comb	combustion
g	gaseous phase
i	irradiation
insul	insulation
p	pyrolysis
rad	radiation
ref	reference state
s	solid, scatter
stat	static
t	turbulence
v	volatiles
w	wood

Symbols

$'$	fluctuation from a time average
—	time average

phenomenon is rather coarse, zone models have to incorporate empirical observations regarding fire dynamics and smoke movement. Some of the applications of zone models to flashover scenario were published by Spearpoint et al. [4], Lou et al. [9], and Chow [10]. More recently, Novozhilov [11] presented an analysis of flashover development under fire suppression conditions using a zone model.

In comparison to zone models, field models offer much larger modelling flexibility due to local, Eulerian field description of physical variables. Initial applications of field models to fire spread over solid surfaces were published by Atreya [12] and Fredland [13]. Nevertheless, a numerical prediction of transient behaviour of flashover that incorporates flow dynamics, convective and radiation heat transfer, thermal and chemical decomposition of solid material is still a challenging task. Although more recent applications [9,14,15] show better prediction of magnitude and trends during flashover, large discrepancies in comparison to experimentally obtained values still exist [16].

The present paper describes an experimental investigation conducted by the group at CNRS-ENSMA-Poitiers and modelling work performed by ANSYS Europe Ltd. The motivation behind the experimental work was to re-create a situation similar to flashover in a controllable (and repeatable) laboratory environment. The experiments contain all the elements of flashover although on a much smaller (and less hazardous) scale. The experimental data were obtained for a thick solid material in order to validate the developed mathematical model.

Using a comparison of the collected experimental and simulation results, the paper discusses the suitability of the considered modelling technique to predict flashover, analyses weaknesses of the model and gives recommendations for further development.

2. Description of the experiment

Five experiments were performed under identical conditions to get a representative set of results. In these experiments a primary fuel source – a gas burner – was located in a zone of fresh air underneath a hood. A fire plume is generated above the burner and reaches into the hood, generating a zone of vitiated gas and soot. The distance between the burner and the hood was set so that insufficient air is entrained into the plume. Sufficient fuel is