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Transition from smoldering to flaming fire in short cotton samples with asymmetrical boundary conditions

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ABSTRACT

The transition from smoldering to flaming fire in cotton has been investigated for two different boundary conditions: (a) open boundaries and (b) a lightweight concrete block covering one side of the sample. In the experiments, cotton was exposed from below to an electrically heated hotplate. The cotton sample was 0.15 m × 0.15 m × 0.15 m, with density between 20 and 100 kg/m^3.

The boundary condition affected the transition from smoldering to flaming. No transition to flaming was observed with open boundaries. For cases with a lightweight concrete block, transition to flaming was observed in samples with densities 60, 80 and 100 kg/m^3, but not for 20 and 40 kg/m^3. The transition from smoldering to flaming occurred when smoldering and secondary char oxidation coexisted. This coexisting occurred in 1 of 5 experiments for each of the densities 60, 80 and 100 kg/m^3. A necessary condition for this coexistence to occur seems to be different smoldering velocities in different parts of the sample. Based on the experiments, the following scenario for the transition from smoldering to flaming fire is suggested: The smoldering front moves app. 0.5 mm/min faster through the parts of the sample far away from the lightweight concrete block, than through the parts closer to it. Due to differences in smoldering velocity, a porous char (500–600 °C) forms in parts of the sample far from the block while closer to the block the cotton will be hot but not combusted (200–300 °C). Oxygen is easily transported into the char, and secondary char oxidation occurs. The secondary char oxidation ignites combustible gasses generated by the smoldering process in other parts of the sample resulting in a flaming fire.

The experiments indicate that smoldering and secondary char oxidation must coexist in a sample for the transition from smoldering to flaming to occur. The block seems to be crucial to obtain different smoldering velocities in the sample leading to smoldering and char oxidation occurring simultaneously.

1. Introduction

Transition from smoldering to flaming fire is a hazard that has been experienced in forest fires [1], air craft fires [2], dust explosions [3] and building fires [4]. Mechanisms for spontaneous transition from smoldering to flaming fire have been investigated by several researchers. The transition from a surface reaction between solid fuel and oxygen during smoldering to a flaming fire involving gas-phase reactions, requires the appropriate amount of gaseous fuel, oxygen and a sufficient heat source [5]. Sato and Sega studied different burning modes in pure cellulose, and found that in standard air containing 21% O_2 only smoldering occurred. At higher oxygen concentrations both smoldering and flaming can occur, and a transition from smoldering to flaming fire is possible [6]. Another phenomenon that is linked to the transition from smoldering to flaming fire, as the ignition source, is secondary char oxidation as reported by Tse et al. [7], Putzeys et al. [8], Ohlemiller and Lucca [9] and Pitts [10]. Ohlemiller [11] observed transition to flaming fire when a sample with a smoldering front was affected by walls, while Alexopoulos and Drysdal reported transitions in narrow gaps [12]. Babrauskas [13] and Pitts [10] described the transition to flaming as a stochastic phenomenon, which only occurred in some of the experiments carried out. 64% of the smoldering fires in upholstered furniture had a transition to flaming when ignited with cigarettes [13]. Smoldering in a mix of May tall fescue and pine needles resulted in transition into flaming in 50% of the experiments, while smoldering in pine needles transitioned into flaming in all test [10]. These results indicate that the transition from smoldering to flaming fire is a complex process where several mechanisms are coupled.

This article investigates how variations in the boundary conditions affect the transition from smoldering to flaming fire, as reported by Ohlemiller [11]. The work in this article is an extension of Hagen et al. [14], where it was concluded that density is an

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important variable for the onset of smoldering fire. The present article focuses on variations in sample density and boundary conditions with possible effects on the transition to flaming fire. In Section 2 the experimental set-up and procedure will be presented, followed by experimental results in Section 3 and a discussion in Section 4.

2. Experimental set-up

2.1. Sample and experimental set-up

Both sample material and experimental set-up are described by Hagen et al. [14], and will only be discussed briefly. The sample material used in these experiments was cotton batting. Cotton was chosen since it represents a group of cellulose-based materials that are prone to smoldering. During experiments, the ambient temperature was 15–25 °C and the relative humidity 40–50%.

The experimental set-up is shown in Fig. 1. The sample was 0.15 m × 0.15 m × 0.15 m. The chosen height and width are discussed in Refs. [14,15]. A hotplate was chosen as the ignition source, since it allows reproducible heating scenarios. The power output from the hotplate was set to 12.8 kW/m², leading to a temperature rise on top of the hotplate of 20–30 °C/min. The heat input was determined by dividing the electrical input of 285 W by the areal of the center tile of the hotplate (app. 0.0223 m²), giving 12.8 kW/m². To monitor the temperature, a type-K thermocouple was placed directly on top of the hotplate. In addition, 35 thermocouples were used to measure the temperature in the sample.

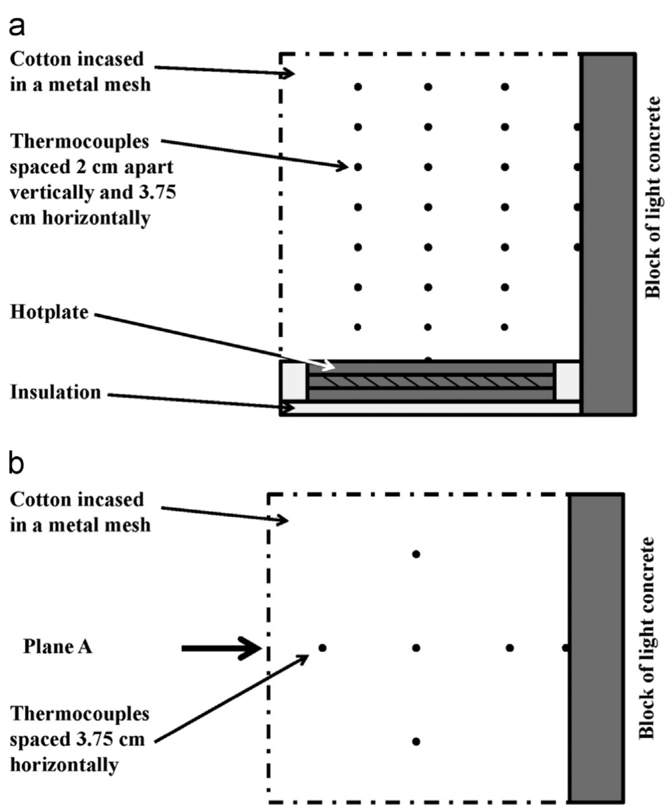

Fig. 1. Experimental set-up: the cotton sample is incased in a metal mesh with a lightweight concrete block as a vertical wall at one of the boundaries. At every 2 cm vertically there are placed five type-K thermocouples forming a cross. The thermocouples in each layer are placed 3.75 cm from each other horizontally. The hotplate consists of three ceramic tiles, with an electrical hot-wire wound around the middle one. Plan A is the vertical cross-section as shown in part (a) Side view cross-section, (b) Top view cross-section.

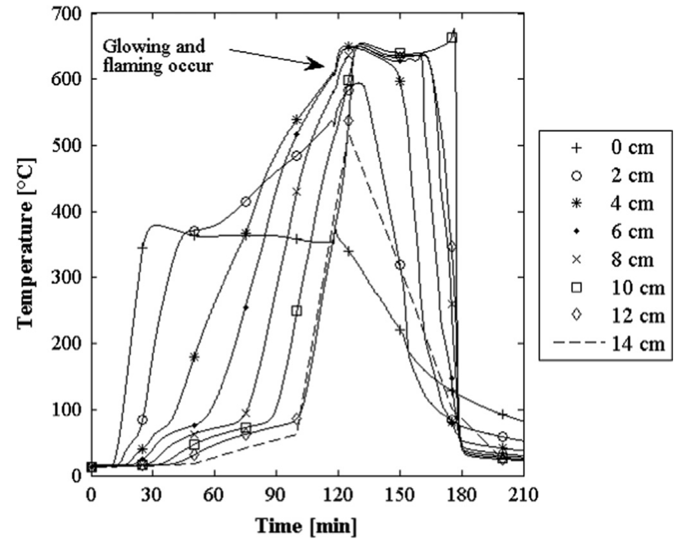

Fig. 2. Temperature at the vertical centerline as a function of time for cotton with density 80 kg/m³ for a case were secondary char oxidation occurred at 117 minutes followed by flaming at 118 minutes.

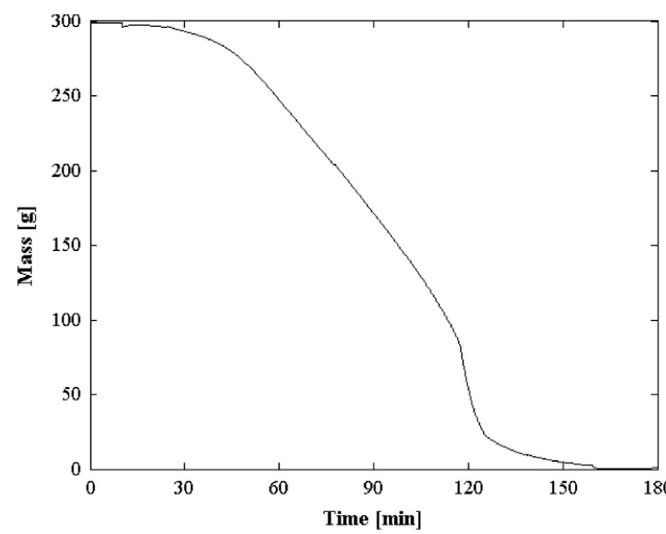

Fig. 3. Sample mass as a function of time for density 80 kg/m³ for a flaming case. The flaming occurred at 118 min. The change in mass at 10 minutes occurred when the power to the hotplate was increased from 0 to 12 kW/m².

At every 2 cm vertically, five thermocouples were placed forming a cross (see Fig. 1b); one thermocouple was placed at the vertical centerline of the sample and four thermocouples where placed 3.75 cm from the centerline. The temperature was also measured at four points on the surface of the sample, near the block used to impose a certain boundary condition (see Section 2.2). The points were at levels 6, 8, 10 and 12 cm above the hotplate-level. The thermocouples used had a diameter of 0.5 mm including the outer casing. In order to reduce effects of air currents, the sample was placed within a container (1.2 m × 0.7 m × 0.6 m) made of light plastic sheets. Before each experimental run, cotton was packed to a predefined density and thermocouples placed within the sample.

2.2. Boundary conditions

Two different boundary conditions have been investigated, representing cases where differences are expected both for heat transfer and transport of oxygen into the cotton.