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Effects of heat flux scenarios on smoldering in cotton

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ABSTRACT

The onset of smoldering in cotton has been investigated under six different heating scenarios: A. High heat flux (12.8 kW/m²) followed by cooling, B. Medium high heat flux (4.5 kW/m²) followed by cooling, C. Medium low heat flux (2.2 kW/m²) followed by cooling, D. Low constant heat flux, E. High heat flux (12.8 kW/m²) followed by low constant heat flux, and F. Multiple heating and cooling of the same sample. In the experiments, cotton was exposed to an electrically heated hotplate. The cotton sample was 0.15 m × 0.15 m × 0.15 m, and the density of the cotton was varied between 20 and 100 kg/m^3.

Both density and heat flux affect the temperature for onset of smoldering. A difference of 19 °C was found in the ignition temperature between high heat flux followed by cooling (Scenario A) and low constant heat flux (Scenario D) for cotton with density 100 kg/m^3. Furthermore, a difference of 36 °C was found in the ignition temperature between cotton with density 40 and 100 kg/m^3 when heated with low constant heat flux (Scenario D). An ignition model has been developed that estimates the ignition temperature of cotton to ±7% of the experimental results. In combination with a one-dimensional heat transfer model, the ignition model is capable of determining the time to and temperature at onset of smoldering for a semi-infinite slab to, respectively, 24% and 2% of the experimental results.

The work presented in this article indicates that both low constant heat flux and density should be included in material tests for onset of smoldering.

1. Introduction

Smoldering is a slow, low-temperature, flameless form of combustion. The combustion is self-sustained due to heat generated by an exotherm reaction between oxygen and solid fuel [1]. Smoldering is a complex process affected by particle size, permeability, density, moisture, initial temperature, ignition source and air movement through and around the material [2,3].

The ignition temperature describes how susceptible a layer is to ignition. The minimum ignition temperature for dust (MIT) is based on experiments with layers 5 mm thick and a constant-temperature ignition source [4]. However, it has been shown that ignition sources with constant heat flux both represent a more realistic ignition scenario and give lower ignition temperatures compared with constant temperature ignition sources [5,6]. Hensel et al. [5] also showed that increased layer thickness leads to reduced ignition temperature. Solids has not been found to have a minimum ignition temperature, since the smoldering process is affected by a number of factors as described above [7].

During tests, samples are usually subjected to only one type of heating: constant heat flux [5], constant temperature [8,9], or an initially cold surface that is rapidly heated and then held at constant temperature [10]. We are not aware of work where different types of heating have been used with the same material and experimental set-up.

In this article, the effect of different heat flux scenarios on the ignition of smoldering in cotton is studied both experimentally and theoretically. The work is an extension on the work by Hagen et al. [11], which concluded that density is an important variable when ignition temperature is to be determined. In the present article both density and heat flux are systematically varied.

Below, experimental results for six different heat flux scenarios are presented and in addition a one-dimensional ignition model. In Section 2 the experimental set-up and procedure will be discussed, followed by experimental results in Section 3 and the ignition model in Sections 4 and 5. A discussion of the results is given in Section 6.

2. Experimental set-up

2.1. Material and experimental set-up

Both sample material and experimental set-up are described by Hagen et al. [11], and will only be discussed briefly here. The sample material used in these experiments was cotton batting.

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Nomenclature

A	pre-exponential factor (s^{-1})
b	negative slope of the linear temperature profile (K/m)
E	activation energy (J/mol)
ΔH_C	heat of combustion (J/kg)
k	thermal conductivity (W/m/K)
l	characteristic length (m)
l_r	reaction layer thickness (m)
$\dot{q}''$	heat flux pr. area (W/m^2)
$\dot{q}'''$	heat production pr. volume (W/m^3)
R	universal gas constant (J/K/mol/)
$T(z)$	sample temperature at height z (K)
T_a	ambient temperature (K)
T_m^p	temperature at mode m at time step p (K)
T_{High}	upper bound for temperature-interval where ignition occur
T_{Low}	lower bound for temperature-interval where ignition occur
T_{avg}	estimated temperature for onset of smoldering based on the average of the lower (T_{Low}) and the upper bound (T_{High}) of the ignition interval
t_{avg}	estimated time for onset of smoldering based on experimental results and the estimated temperature for onset of smoldering (T_{avg})
$\Delta\tau$	time step (s)
V	volume of the sample (m^3)
z	height within sample (m)
Δz	distance between nodes (m)
α	thermal diffusivity (m^2/s)
ρ	density (kg/m^3)

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 dimensions are discussed in Ref. [11]. A hotplate was chosen as the ignition source, since it allows reproducible heating scenarios. Depending on scenario, the power output from the hotplate varied between 1 and 12.8 kW/m^2. 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. If an experiment did not result in smoldering, the cotton was reused. However, the cotton close to the hotplate was replaced after a no-ignition experiment since this layer was partly decomposed. The amount of cotton replaced was based on changes in color and texture. In most cases only the lower 2 cm of the cotton was replaced.

To monitor the temperature, a type-K thermocouple was placed directly on top of the hotplate. In addition, seven thermocouples were used to measure the temperature within the sample. The thermocouples were 2 cm apart along the vertical centerline of the sample. The thermocouples used had a diameter of 0.5 mm including the outer casing. The sample with thermocouples was placed on a balance and the mass and the temperatures were recorded every 2 s.

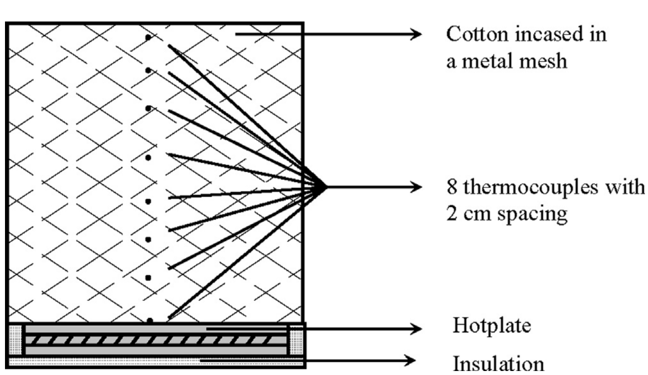

Fig. 1. Experimental set-up: The cotton sample is incased in a metal mesh. There are type-K thermocouples every 2 cm along the center line of the sample. The hotplate consists of three ceramic tiles, with an electrical hot-wire wound around the middle one.

2.2. Heat flux scenarios

Six different heat flux scenarios have been investigated to get a better understanding of how the heating mode affects the ignition temperature (see Fig. 2). Each scenario mimics a real-life situation where a hot object is in contact with a material that easily smolders. Scenario A involves fast heating of a sample with subsequent cooling of the hotplate. This type of heating occurs when an ignition source is in contact with a material and then removed. Scenario D involves slow heating of a sample over a long period. This scenario applies for situations where a material stays in contact with a heated surface for a long time. Scenario B and C are heating scenarios between A and D, with lower heat flux than in scenario A but with heating for extended periods. Scenario E combines scenarios A and D. Scenario F represents materials that are repeatedly heated and cooled, which may occur if a material is close to an engine with repeated starts and stops. The six heating scenarios are described in more detail below.

2.2.1. Scenario A. High heat flux (12.8 kW/m^2) followed by cooling

The hotplate was heated to a pre-determined temperature (called the cut-off temperature), and then switched off. A heat flux of 12.8 kW/m^2 (the maximum allowed by the current set-up) was used, resulting in a temperature rise of 20–30 °C pr. minute at the top of the hotplate (see Fig. 2). In Fig. 3a the power was switched off as the hotplate temperature (upper curve) reached 275 °C, while the maximum recorded hotplate temperature was 303 °C. The temperature profile in Fig. 3a is typical for a non-smoldering experiment: here the hotplate and the sample cool after reaching a maximum temperature. In Fig. 3b the power was switched off as the hotplate temperature (upper curve) reached 280 °C, and the increased hotplate temperature (as compared with the case in Fig. 3a) resulted in ignition. Here the hotplate does not cool, due to the heat production of the smoldering fire, and high temperatures are reached throughout the sample.

2.2.2. Scenario B. Medium high heat flux (4.5 kW/m^2) followed by cooling

The hotplate was heated to a pre-determined temperature, and then switched off. A heat flux of 4.5 kW/m^2 (35% of the flux for scenario A) was used, resulting in a temperature rise of 7 °C pr. minute at the top of the hotplate (see Fig. 2). In Fig. 3c the hotplate was switched off when the temperature reached 305 °C, giving a maximum temperature of 311 °C which did not cause ignition.