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From smoldering to flaming fire: Different modes of transition

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ABSTRACT

Transition from smoldering to flaming fire in cotton is investigated experimentally for five different sample sizes. Two different modes of transition are identified: early and late transition. Early transition to flaming occurs when smoldering combustion forms a hot glowing core inside a sample. As the smoldering burns through to the outside of the sample, air moves more easily into the core, resulting in a change in smoldering direction from reverse to forward smoldering, causing increased heat production and flaming. Late transition to flaming occurs occasionally after most of a sample is consumed by smoldering, and where randomly appearing glowing spots ignite flammable vapor from smoldering processes.

The current setup consists of cotton samples where one side of the sample is situated next to a lightweight concrete block forming a boundary. Cotton samples with density 80 kg/m^3 with dimensions equal to or larger than 0.45 m · 0.45 m · 0.15 m high, consistently give early transition to flaming, while smaller samples have early, late or no transition. By identifying an experimental set-up with a sample size that assures transition from smoldering to flaming, the transition phenomenon can be studied in even more detail.

1. Introduction

Transition from smoldering to flaming fire is an interesting phenomenon within the subject of fire, where weak ignition sources initiate smoldering fires, and transition to flaming fires may occur hours, days or weeks later. The transition to flaming could result in deadly fires or explosions as described by Eckhoff [1], Rein [2], Ogle, Dillon and Fecke [3] and Russo, De Rosa and Mazzaro [4].

Previous research shows that transition from surface reactions (smoldering) to gas phase burning (flaming) is affected by different external factors such as: increased airflow, narrow gaps in the samples or differences in densities. Ohlemiller [5] reported that increased airflow in voids between cellulose insulation and wood frames could cause glowing and transition to flaming in some instances. Tse et al. [6] found that increasing airflows would increase the smoldering rate, causing oxidation of char (secondary char oxidation) left by smoldering of the initial material. Similar observations are made by Anderson et al. [7], with increasing temperature and heat production as secondary char oxidation is initiated. Wang et al. [8] found that increased airflow around samples resulted in increasing smoldering rates and transition to flaming. Alexopoulos and Drysdale [9] reported that transition to flaming in gaps occurred more rapidly in narrow gaps. However, if the gaps became too narrow, they were blocked by expanding smoldering materials and transition did not occur. Hagen et al. [10] found that increasing density in cotton affects the possibility of transition to flaming. Similarly, Wang et al. [11] reported of density affecting smoldering propagation in polyurethane foam. Hadden et al. [12] investigated the effect of sample size on radiant ignition of PU-foam, and found that an increase in sample size reduced the critical radiation heat flux needed for smoldering and flaming.

Importantly, all experiments reported above indicate that transition to flaming is difficult to reproduce. Hagen et al. [13] found that in small-scale experiments (0.15 m · 0.15 m · 0.15 m) only 20 % of cotton samples had transition to flaming, while Morgan et al. [14] found that cotton fabric and cotton batting always resulted in transition to flaming in a 0.3 m · 0.15 m · 0.06 m sample. Stoliarov et al. [15] reported of a probability of 69 % for transition from smoldering to flaming for flexible polyurethane foam samples (0.3 m · 0.15 m · 0.06 m), while Torero and Fernandez-Pello [16] observed consistent transition to flaming for polyurethane foam samples 0.15 m · 0.15 m · 0.3 m high. In spite of all work done on transition from smoldering to flaming fire, experimental set-ups that consistently give transition to flaming have not been developed for other materials than cotton and polyurethane foam. Rein [2] has developed an equation for critical minimum size for sustained smoldering propagation with forced ventilation (see eq. (1)). However, as pointed out by Hadden et al. [12] this equation cannot be used for

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smoldering and transition to flaming under natural flow conditions.

$$L_C = \frac{4\delta}{Q_{sml}} \cdot \frac{U_{loss}(T_{sml} - T_0)}{\dot{m}''} \quad \text{(Eq 1)}$$

where L_c is the critical sample length, δ is the smoldering front thickness, Q_{sml} is the heat of combustion, U_{loss} is the heat loss coefficient, T_{sml} is the smoldering temperature, T_0 is ambient temperature and $\dot{m}''$ is the mass flux of air.

This article investigates the minimum size of cotton samples (width and length) to ensure transition from smoldering to flaming fire under natural flow conditions. By identifying a minimum sample size, more in-depth investigations of the transition from smoldering to flaming fires can be carried out. In section 2 the experimental set-up and procedure are presented, followed by experimental results in section 3. An estimation of minimum sample size for transition to flaming, is presented in section 4. Discussion and conclusion are in section 5 and 6.

2. Experimental set-up

The current experimental work is an extension of the work done by Hagen et al. [13]. While the cotton batting is the same, the experimental set-up is further developed.

2.1. Material

The material used in these experiments was cotton batting with density 80 kg/m^3. Cotton was chosen since it represents cellulose-based materials that are known to smolder, and where transition to flaming has been observed previously [5,17]. The experiments were conducted at ambient temperatures between 10 and 20 °C, and relative humidity of 40–60%. The moisture contents of cotton at these conditions is about 5 % by weight. Due to the lab facilities and cotton's ability to absorb moisture, it was not feasible to conduct experiment with different moisture contents. Moisture contents in different materials have been reported to reduce the propensity of smoldering ignition and reduce fire spread due to heat sink effects [18,19]. It would be reasonable to assume similar effects for the current experiments, but this must be investigated in a more suitable experimental setup.

Transition to flaming in short cotton sample (0.15 m high) with density 60–100 kg/m^3 were observed by Hagen et al. [13]. Expanding on this work, a cotton density of 80 kg/m^3 (porosity 0.944, permeability 2.98×10^{-10} m^2) was chosen for all current experiments. Before each experiment, the cotton was divided into thin fluffy layers. The mass of cotton required to fill a sample volume was measured up. The cotton was than laid out forming the width and the length of the sample. The fluffy cotton was then compacted to the right density and shape. By using a wire mesh container around the sample, spatial uniformity was maintained (See Fig. 1).

2.2. Experimental set-up

The current experimental set-up was used to investigate the effect of sample size (length and width) on transition from smoldering to flaming fire (see Fig. 2). Five different geometries of cotton samples were investigated. Earlier work reported by Torero and Fernandez-Pello [16] indicated that sample height affects transition to flaming, and Hagen et al. [13] found that transition to flaming occur in cotton samples with height 0.15 m. Based on this work, all experiments in the current work were performed with sample height of 0.15 m. The length of the samples was varied from 0.15 m to 0.6 m and the width from 0.15 to 0.45 m, as shown in Table 1. One side of the sample (indicated as width in Table 1) was placed next to a lightweight concrete block. The lightweight concrete block was held in place using the wire mesh container and there was no gap between the cotton and the block. The samples were also placed on top of a lightweight concrete base . The setup is shown in Figs. 2 and 3. The use of a lightweight concrete block is consistent with observations by Ohlemiller [5], where only samples with a solid boundary had transition from smoldering to flaming fire. Fig. 1a shows a photo of the set-up for a large sample (referred to as "L", see Table 1) as transition from smoldering to flaming occurred in the sample. In order to reduce effects of air currents in the laboratory, the sample was placed within a container (1.2 m · 0.7 m · 0.6 m) made of light plastic sheets. On top and center of the plastic container a hole with diameter 0.3 m was cut out, and at the bottom four holes with diameter 0.1 m where evenly spaced. No smoke or gases were observed collecting in the plastic container, and thereby affecting the smoldering experiment.

The temperatures in samples described as small (S), medium (M) and large (L) (See Table 1) were measured using 0.5 mm Type K thermocouples (the diameter includes the outer shield). For temperatures during glowing and flaming, an accuracy of ±10 K is expected. Samples

a) Early transition b) Late transition

Fig. 1. Transition from smoldering to flaming in large sample (part a), sample size: 0.6 m · 0.4 m · 0.15 m and extra small sample (part b), sample size: 0.15 m · 0.3 m · 0.15 m. A lightweight concrete block forms a boundary on one side of the sample, seen on the right of the samples in part a) and b). Part a) is an example of transition early in an experiment, while part b) is a transition occurring late in an experiment.

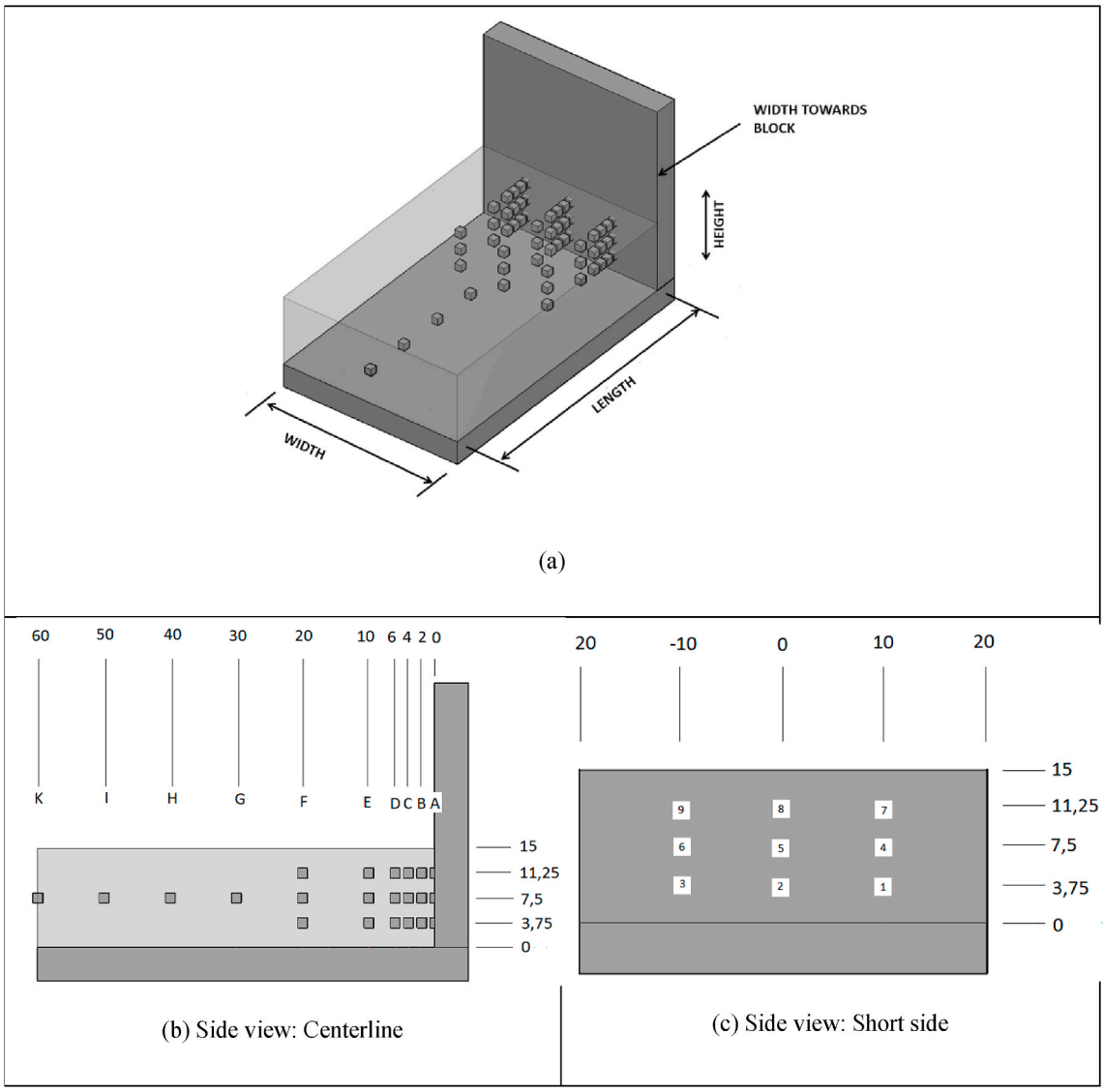

Fig. 2. Experimental set-up with placement of thermocouples for a large sample (L, sample size: 0.6 m · 0.4 m · 0.15 m). NB: The values in the figures are in centimeters.

Table 1
Sample size and number of experiments.

Sample	Length (m)	Width[a] (m)	Height (m)	Number of experiments
Extra extra small (XXS)	0.15	0.15	0.15	5
Extra small (XS)	0.15	0.30	0.15	5
Small (S)	0.30	0.30	0.15	5
Medium (M)	0.45	0.45	0.15	5
Large (L)	0.60	0.40	0.15	5

[a] One of these sides is placed next to the lightweight concrete block.

extra extra small (XXS) and extra small (XS) were run without temperature measurements, just to confirm that the sample size need to be over a certain minimum size in order to consistently get fires with transition to flaming. Details of the placement of the thermocouples are shown in Fig. 2. The nine thermocouples in plane A were sandwiched in placed between the cotton and the lightweight concrete block, as shown in Fig. 2b and c. The nine thermocouples in planes B, C, D, E and F were placed 0.02 m, 0.04 m, 0.06 m, 0.1 m and 0.2 m from the lightweight concrete block, with the locations shown in Fig. 2b and c. One thermocouple was placed at the centerline (ref. thermocouple 5 in Fig. 2c) of the sample for planes G, H, I and K, as illustrated in Fig. 2b (Plane J is not used, for clarity.). In sample S (0.30 m · 0.30 m · 0.15 m high) thermocouples in planes H, I and K were not monitored since they were outside the sample. Similarly, in sample M (0.45 m · 0.45 m · 0.15 m high) thermocouples in planes I and K were not monitored. The placement of the thermocouples is within ±5 mm of the described placement above. The thermocouples were carefully placed at their predetermined position as the cotton sample was put together (see sec. 2.1), and the thermocouple wires were then moved to the outside of the sample.

To achieve smoldering, an electrical hot-wire (0.2 mm, 15.6 Ohm/m) woven around a small piece of lightweight concrete was used as an ignition source. The piece of lightweight concrete had dimensions 0.005 m · 0.01 m · 0.04 m. The electrical wire yielded 50 W, and the power was on for the first 3 min of an experiment and then switched off. The placement of the ignition source is shown in Fig. 3. The ignition source was carefully placed at the predetermined position as the cotton sample was put together (see sec. 2.1).

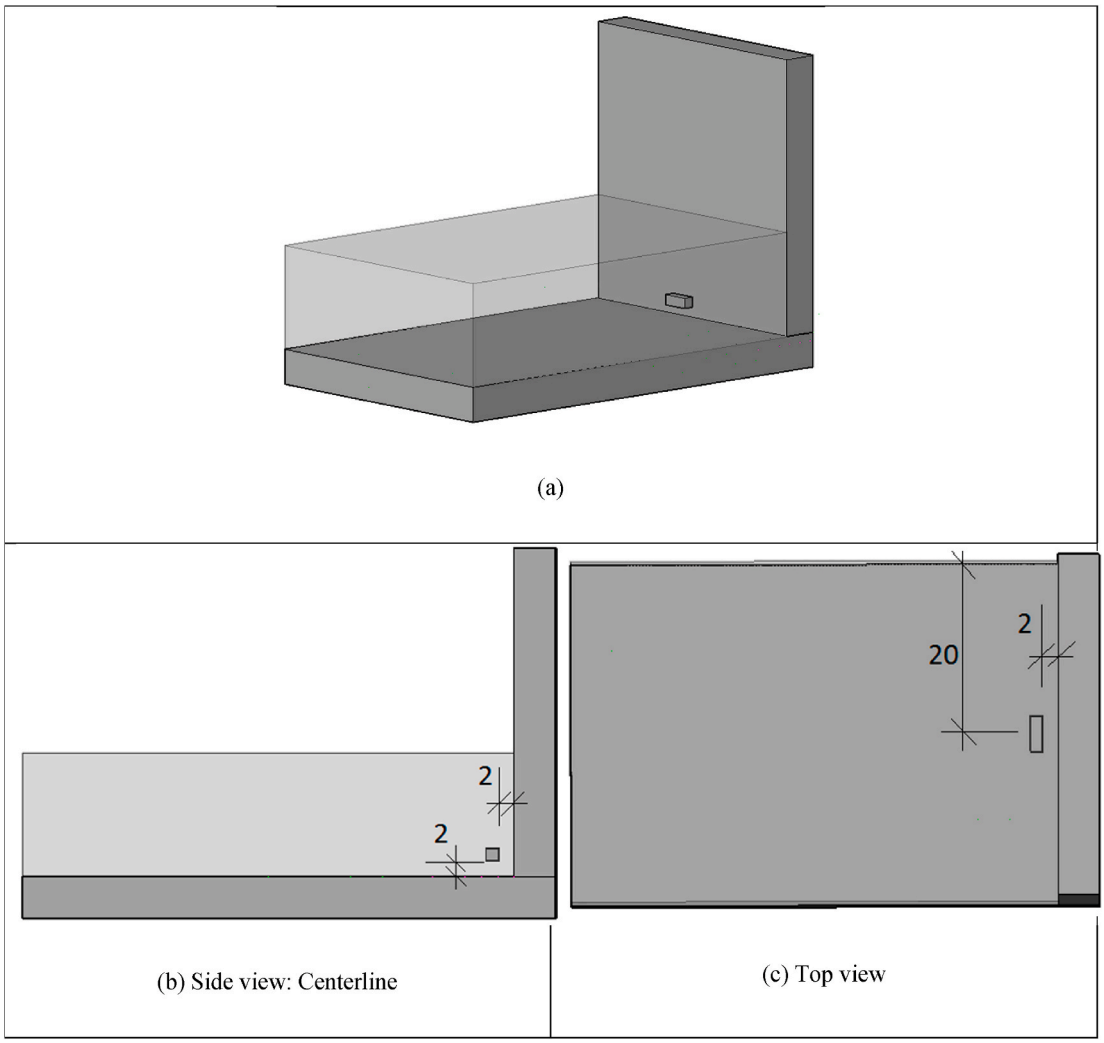

Fig. 3. Experimental set-up with ignition source placed at the centerline of the sample, 0.02 m from the lightweight concrete block and 0.02 m above the lightweight concrete base where the cotton sample is placed. NB: The values in the figures are in centimeters.

2.3. Procedure

Before conducting experiments, the compacted cotton sample was placed in the test rig together with thermocouples and ignition source. After the scale measuring the mass had stabilized (Kern DS, Masx weight 30000 g, accuracy ± 0.1 g), the data acquisition began, and the 50 W ignition source was switched on. The power to the ignition source was switched off after 3 min, and smoldering was observed indirectly by increased temperatures in the sample. Smoldering and smoke were observed in all experiments, and transition to flaming occurred in 16 of 25 experiments (see sec. 3.2). Data acquisition was terminated when all the thermocouples showed less than 50 °C. All experiments were video-filmed.

3. Results

3.1. Recorded data and observations

A representative experiment is introduced to explain the observations during transition from smoldering to flaming. Temperatures in large samples (0.6 m · 0.4 m · 0.15 m) are measured at 58 locations in the cotton using thermocouples as described in Sec. 2. Fig. 4 shows the temperatures at the horizontal centerline (thermocouple 5 in Fig. 2c at planes A-K) for a sample with density 80 kg/m^3. Flaming occurs at 3.3 h, and marks significant changes in the sample. Prior to flaming, temperatures in the cotton increase systematically as the smoldering front moves through the sample, away from the lightweight concrete block. This can be seen in Fig. 4, where the centerline temperatures increase from ambient to approximately 400 °C in succession for thermocouples placed at 0, 2, 4, 6 and 10 cm from the lightweight concrete block; where the characteristic smoldering temperature for cotton is 400 °C. The reduced temperature rise at around 100 °C is associated with evaporation of free water in the cotton. The thermocouples at 20, 30,40, 50 and 60 cm show little or no increase in temperature prior to flaming, indicating that neither heat nor smoldering have reached so far into the sample.

Just before the flames occur (at 3.3 h), the temperatures in the part of the sample closest to the lightweight concrete block (0, 2, 4, 6 and 10 cm) increase from approximately 400 °C to 600–700 °C. Looking at Fig. 5, all temperatures at planes A, B and C have the same increase from 400 °C to 600–700 °C prior to flaming, indicating that there is forming a hot core or volume inside the sample prior to the transition to flaming. The high temperatures within the core is consistent with the observed glowing in the sample just before flames occurred (see Fig. 6).

When flaming has occurred, the temperatures close to the lightweight concrete block continued to increase to 800–900 °C (see Fig. 5). The highest temperatures measured were at Plane A, which is consistent with the opening at the top of the cotton sample (see Fig. 1a) where

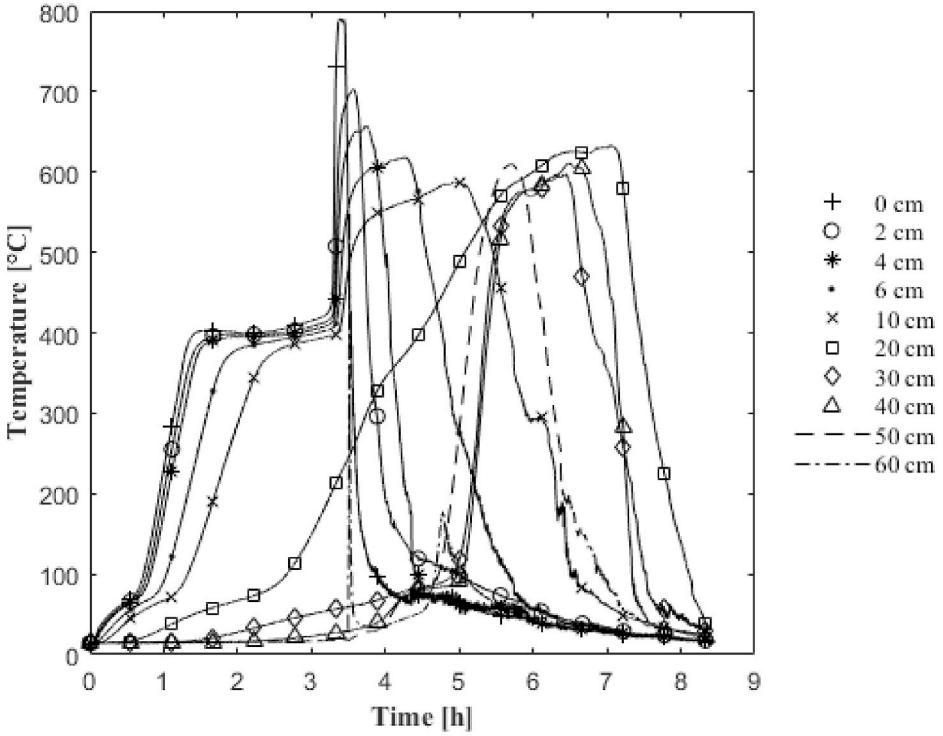

Fig. 4. Centerline temperatures as a function of time (thermocouple 5 in Fig. 2c at planes A-K). Sample size is 0.6 m · 0.4 m · 0.15 m, with density 80 kg/m^3. Flaming was observed after 3.3 h (See Fig. 1a). The legend shows the distance from the lightweight concrete block used as boundary.

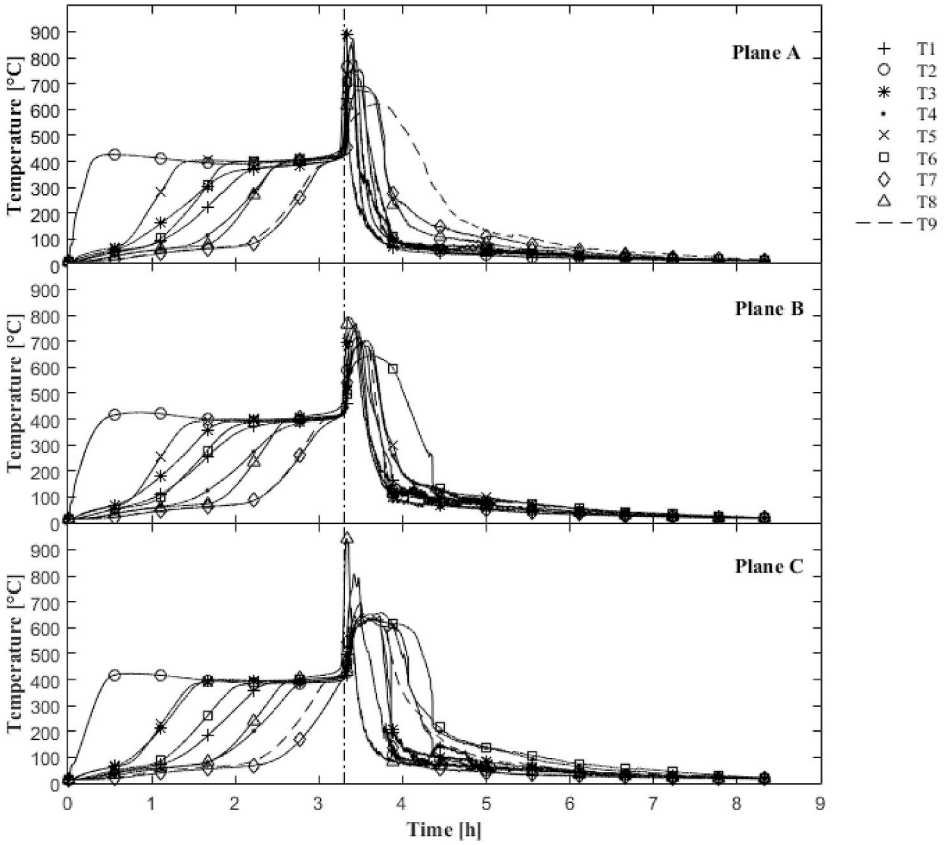

Fig. 5. Temperature as function of time for planes A, B and C (see Fig. 2b) for the same sample as in Fig. 4. The legend shows the thermocouples placement according to Fig. 2c. The temperatures show a strong increasing trend just prior to flaming at 3.3 h. This increase in temperature is consistent with the intense glowing observed inside the sample just before flames occurred (see Fig. 6).

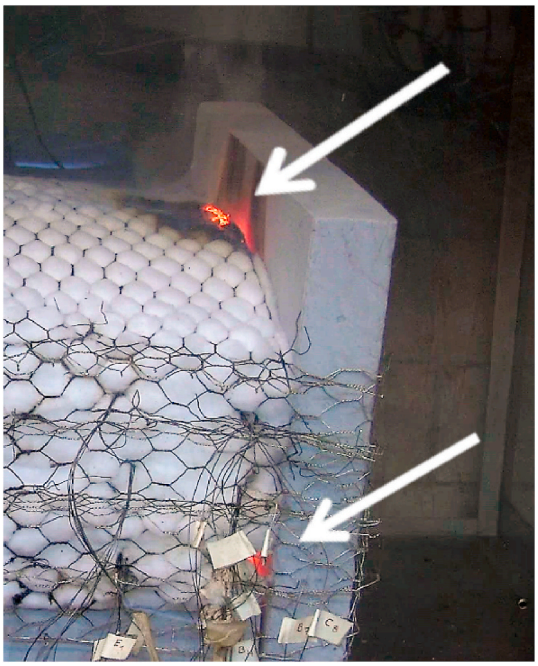

Fig. 6. Intense glowing prior to transition from smoldering to flaming fire. The photo shows the same sample as in Fig. 1a, but 4 s earlier. Notice the glowing both on top and on the side of the sample, as indicated by arrows.

oxygen moves into the sample and flames are ignited. It was observed that the flames moved quickly from the inside of the sample to the top and outside. High temperatures were therefor only recorded within the first minutes after flames occur (see Figs. 4 and 5). This is due to the placement of the thermocouples inside the sample. Fig. 1a shows how the flames have spread from the inside to the top of the sample. Pulsating flamlets were observed at the glowing opening at the side of the sample, and continues flaming were first observed at the side-opening 4 min after the flames emerged from the top of the sample. The opening on the side of the sample is not present in all experiments, and together with flamelets, chimney effects in the sample must be considered (see sec 5.3 for further discussions). After 12 min the flames spread from the top and side-openings of the sample, involving large part of the outside surfaces of the sample (see Fig. 7). This spread is also indicative in Fig. 4 where the temperature at 60 cm have a marked increase as flaming reach the end of the sample.

Flames are observed in the sample for approximately 33 min and then they self-extinguished. The self-extinguishment is surprising, since there was ample air and solid fuel to consume. Self-extinguishment is observed in all samples with transition to flaming early in the experiment. After the flaming, pure smoldering consumed the reminder of the sample. Due to the flame spread and smoldering on the outside of the sample, temperature increase inside the sample became more random as the experiment progressed. This can be seen in Fig. 4, where temperature increase becomes irregular, with a high temperature increase at 50 cm at around 4.5 h; and then increasing more or less at the same time at 30 and 40 cm at around 5 h.

Sample mass as a function of time is recorded, as shown in Fig. 8. The recorded data show that the sample mass decreases systematically with time. When the transition to flaming occurs at 3.3 h, the mass loss rate increases from approximately 13 to 25 g/min (see Fig. 11 for more details). At 3.85 h, the flames self-extinguish and pure smoldering reoccurs with a lower mass loss rate of approximately 13 g/min. An average mass loss rate of 16 g/min can be extracted as a first approximation for the whole experiment, including the mass loss rates during both flaming and smoldering. After each flaming experiments approximately 20 g of a tar substance was left on the wire mesh container. In addition, the lightweight concrete block and base contains water, and some of this evaporated during the experiments giving an overall

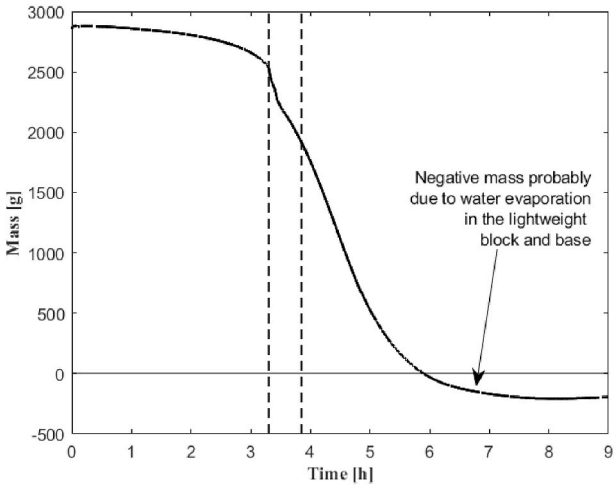

Fig. 8. Mass as a function of time for a large sample (0.6 m · 0.4 m · 0.15 m high, density 80 kg/m^3). Flaming was observed after 3.3 h, and is marked with the dashed vertical line (see Fig. 1a and 4). At 3.85 h (dashed line), the flaming ceases and the mass loss rate changes accordingly.

Fig. 7. Flames have spread from the inside to the outside of the sample. Sample size is 0.6 m · 0.4 m · 0.15 m, with density 80 kg/m^3. This type of flame spread initiated smoldering on a large portion of the surface of the sample, resulting in more erratic temperature increase in the sample.

negative mass loss.

3.2. Transition to flaming

The results of experiments with transition to flaming for different sized samples are shown in Table 2. It is important to notice that transition from smoldering to flaming fire may occur at different stages of smoldering fires; described as early and late transition in this article. In order to get reproducible results with consistent transition from smoldering to flaming fire for the current set-up, the sample size must be greater than a certain minimum.

Transition from smoldering to flaming may occur (see Table 3) early in the experiment, next to the lightweight concrete block as seen in Fig. 1a, or late in the experiment at random positions in the sample as seen in Fig. 1b. Early flaming next to the lightweight concrete block is the transition scenario where samples 0.45 m long, 0.45 m wide and 0.15 m high, and larger, consistently give flaming fires; indicating that the minimum sample size to achieve transition to flaming must be equal to or greater than 0.45 m for the current set-up. 2 of 5 experiments for both small and extra small samples had early transition to flaming, but these smaller sized samples lack the consistency found with the larger. The rest of the experiments with smaller sample sizes have transition to flaming late in the experiment or no flaming at all. When flaming occurs late in an experiment, most of the cotton in a sample is consumed by the initial smoldering fire before secondary char oxidation and transition to flaming occur. This is shown in Fig. 1b where an extra small sample (0.15 m · 0.30 m · 0.15 m high) had transition to flaming at a very late stage of the fire. All the experiments with transition from smoldering to flaming have glowing spots present in the sample as the transition occurs.

3.3. Temperature

Fig. 9 shows the centerline temperatures (Thermocouple 5 in Fig. 2c) as function of time for three different small (S) experiments with three different outcomes: a) pure smoldering (smoldering with no transition to flaming), b) early flaming and c) late flaming. Fig. 10 shows temperature contour-plots for the same three experiments. In the experiment with early transition from smoldering to flaming (see Fig. 9b), a hot core (~400 °C) forms next to the lightweight concrete block (from 0 to 6 cm), and a smoldering front moves outwards from the core to the outer parts of the sample (see Fig. 10b). Transition to flaming occurs when the smoldering front reaches the outside of the sample generating openings where air can move more freely into the hot core. The increase in oxygen content in the core enhances heat production, resulting in flaming. For the experiment in Fig. 10b the smoldering reaches the top first, while for the experiment shown in Fig. 6 smoldering has reached both top and side of the sample prior to flaming. Whether reaching the top or the side of a sample seems less important in the current experiments, as long as the hot core is formed prior to the smoldering front reaching the outer part of the sample.

For pure smoldering and late flaming cases, the smoldering moves to the outside of the sample without forming a hot core. Fig. 10a and c shows the temperature development for two representative experiments. Here the outer parts of the samples have similar or higher temperatures than the core of the sample, resulting in primarily smoldering. The late flaming in Figs. 9c and 10c occurs when glowing spots appear in the later part of an experiment. Here flammable vapor produced by smoldering is ignited by the glowing spots. This late form of ignition and transition to flaming is previously described by Hagen et al. [13].

Table 2
Number of observed transitions from smoldering to flaming fire.

	Sample size				
	Extra extra small (XXS)	Extra small (XS)	Small (S)	Medium (M)	Large (L)
Length (m) and width [a](m)	0.15 · 0.15	0.15 · 0.30	0.30 · 0.30	0.45 · 0.45	0.60 · 0.40
Height (m)	0.15	0.15	0.15	0.15	0.15
Pure smoldering (smoldering with no transition to flaming)	5	1	2	0	1[b]
Early flaming next to block	0	2	2	5	4
Late flaming	0	2	1	0	0
Total number of experiments	5	5	5	5	5

[a] Width towards the lightweight concrete block.
[b] One of the large samples did not transfer to flaming.

3.4. Mass loss and mass loss rate

Mass as function of time for a representative sample is shown in Fig. 8, with associated mass loss rate in Fig. 11. Average mass loss rates for different sample sizes are listed in Table 4. The average mass loss rate for a single experiment is determined from the time it takes to reduce the sample mass from 90 % to 10 % of the initial value. The average mass loss rate for a sample size is the sum of single experiment mass loss rates divided by the number of experiments with the given outcome. The experiments with early flaming have a 40–60 % higher average mass loss rate than pure smoldering and late flaming experiments. The higher average mass loss rate is due to higher mass loss during flaming, as shown in Fig. 11. Comparing the maximum mass loss rate for pure smoldering, early flaming and late flaming experiments (see Table 5), the maximum mass loss rate for early flaming is 40–100 % higher than for the other two scenarios.

The volume that smolders also affects the mass loss rate, as shown in Fig. 12, where the mass loss rate increases with sample volume. However, the average mass loss rate normalized by the initial volume of the sample has a decreasing trend as the volume increases (see Fig. 13). This is consistent with poorer oxygen transport into the sample due to lower permeability as the sample size increases.

3.5. Smoldering velocity

The velocities at which smoldering reaction fronts move along the centerline of the sample are shown in Fig. 14. The velocity is found by using an estimated ignition temperature for smoldering of 309 °C as an indicator for when the smoldering reaction front reached a thermocouple [10]. The velocity is calculated by dividing the distance between two thermocouples by the time it takes for the smoldering front to move between the thermocouples. The smoldering velocity varies from 0.2 to 6 mm/min, with the highest velocities next to the lightweight concrete block forming one of the boundaries. There is no apparent dependency between smoldering velocity and sample size, as seen in Fig. 14. Ohlemiller and Roger [20] reported of smoldering velocities of 2–3 mm/min in cellulose insulation. The current experiments have similar velocities as reported by Ohlemiller and Roger [20] close to the light concrete block, but as the smoldering front moves away from the block, the velocity decreases. The decrease in velocity is consistent with extinction of flames and return to smoldering for the medium and large samples. It is also important to notice that the ignition source was only on for 3 min, and is not affecting the smoldering velocity close to the lightweight concrete block.

4. Estimation of minimum sample size for transition to flaming

The experimental results in Table 2 show that an increase in sample size promote transition from smoldering to flaming fire. Using a simple

Table 3
Time for transition from smoldering to flaming fire. The value in the parenthesis is total experimental time, that is when all thermocouples have reached a temperature less than 50 °C.

	Sample size				
	Extra extra small (XXS)	Extra small (XS)	Small (S)	Medium (M)	Large (L)
Length (m) and width[a] (m)	0.15 · 0.15	0.15 · 0.30	0.30 · 0.30	0.45 · 0.45	0.60 · 0.40
Height (m)	0.15	0.15	0.15	0.15	0.15
Early flaming next to block	–	1.7 ± 0.1 h ([b])	1.7 ± 0.0 h (5.1 ± 0.1 h)	3.3 ± 0.3 h (8.8 ± 1 h)	3.3 ± 0.1 h (8.7 ± 0.8 h)
Late flaming	–	2.7 ± 0.1 h ([b])	3.8 h (5.4 h)	–	–

- No transitions to flaming.
[a] Width towards the lightweight concrete block.
[b] No data for total experimental time is recorded.

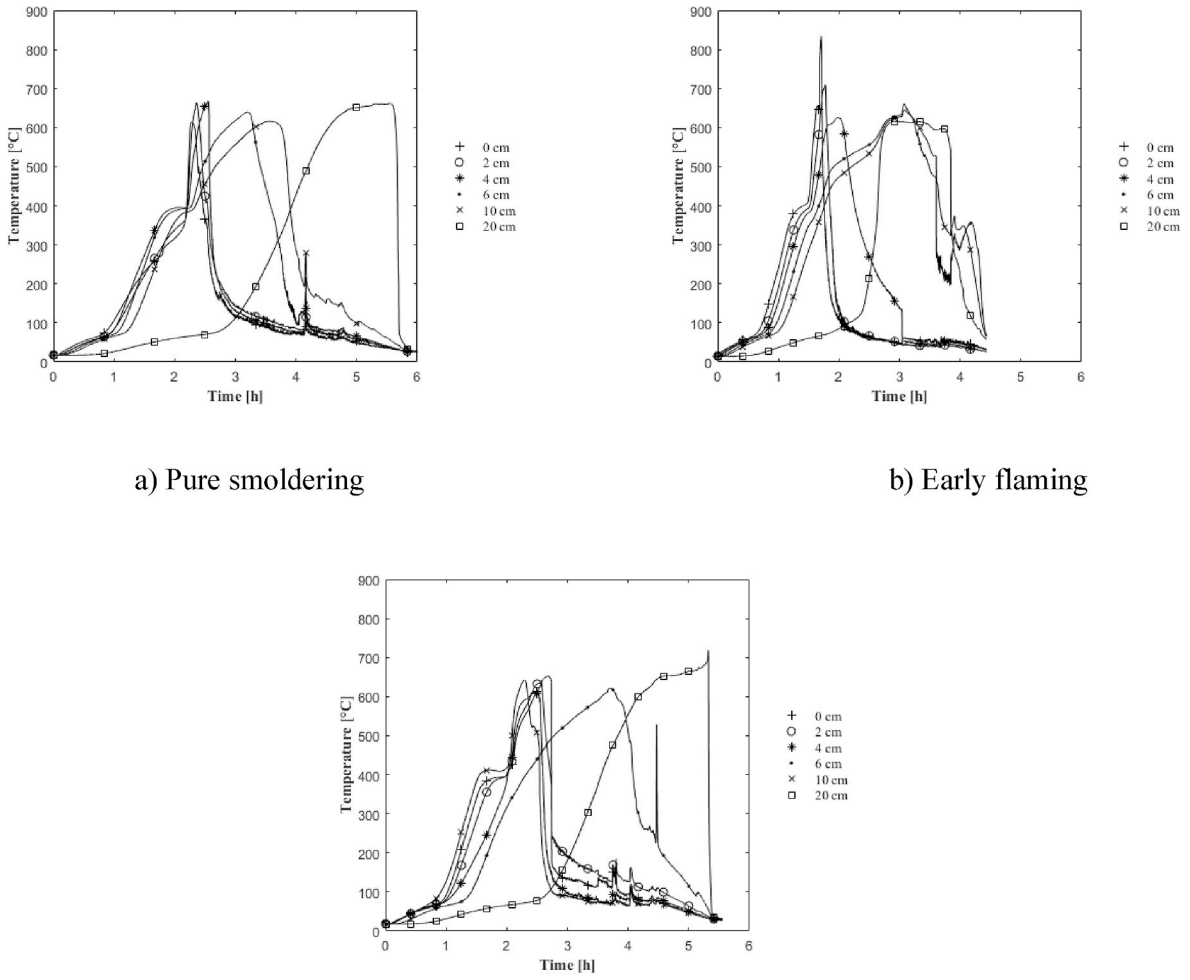

Fig. 9. Centerline temperature (thermocouple 5 in Fig. 2c) as function of time for small cotton samples (0.3 m · 0.3 m · 0.15 m high). Part a) shows results for a pure smoldering experiment, while part b) and c) are experiments with transition to flaming. In part b) early flaming occurred at approximately 1 h 45 min into the experiment, as indicated by the peak in temperature. In part c) the transition to flaming occurred late in the experiment at approximately 3 h and 50 min. This cannot be seen in the plot since the flaming occurred on the outside of the sample.

1D-model for heat transfer and heat generation, the minimum sample size (l) for transition from smoldering to flaming can be calculated theoretically. The main assumptions of the estimation are that the smoldering front moves as a quarter sphere in the sample (1D along the radius), and that as long as flaming has not occurred, heat generated in the sample is transported from the hot core to the cooler parts of the 1D-material. For smaller samples, heat will be lost through the sides of the sample – not forming a hot core, while larger samples will be able to contain heat – forming a hot core, susceptible for transition to flaming when air enters the sample. It is important to notice that this estimate for size does not address the transition itself, but only gives a theoretical minimum size for the sample.

The model is adapted from the work done by Bowes and Townshend [21] and Ohlemiller [22]. The heat flow balance is given in eq (2).

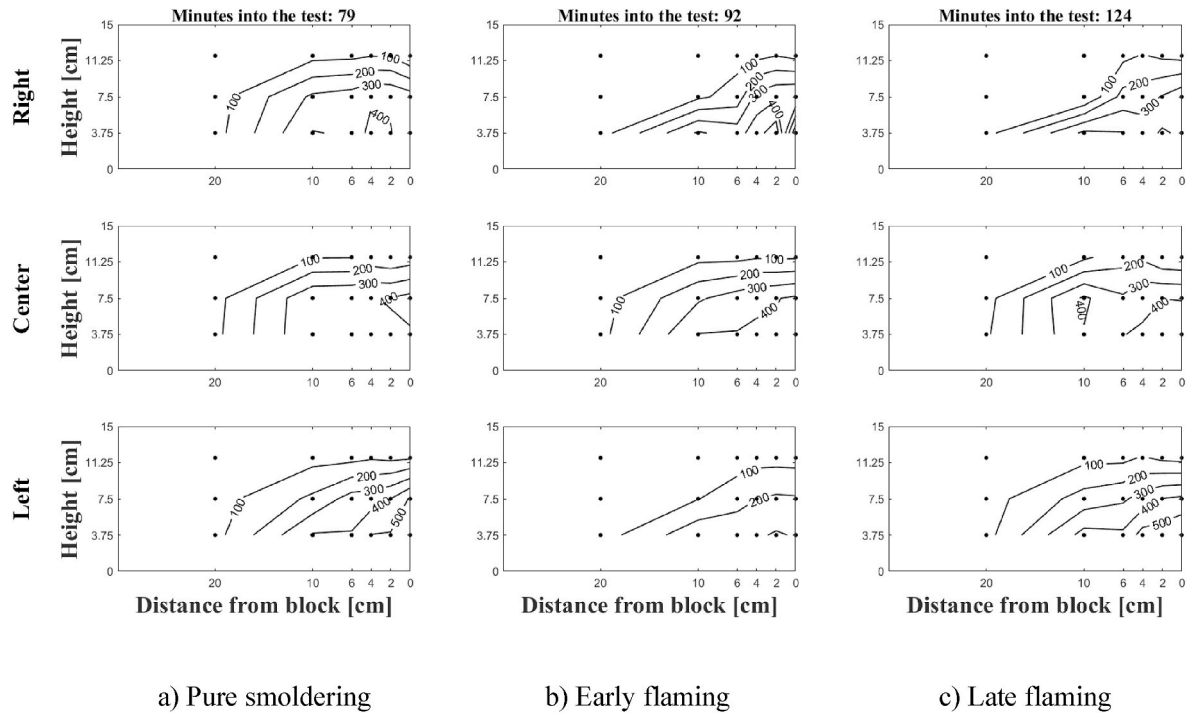

Fig. 10. Temperature contour plots for three different scenarios of smoldering with small cotton samples (0.3 m · 0.3 m · 0.15 m high). Part a) shows the temperature distribution in a sample with pure smoldering as one of the centerline thermocouples exceeds 425 °C (Thermocouple 2, 5 or 8 in Fig. 2c for plane A, B, C and D). Part b) shows temperature plots for a sample with early transition to flaming and part c) shows plots for a late transition to flaming. In part b) a hot core is forming in the middle of the sample next to the lightweight concrete block, with a smoldering front moving outwards from the center of the sample. In comparison with part a) and c), where the highest temperatures are at the outer parts of the sample, and a smoldering front is moving towards the center of the sample. Left is referring to thermocouple 3, 6 and 9 in Fig. 2c, and right refers to thermocouple 1, 4 and 7. (The dots indicate the placement of the thermocouples.)

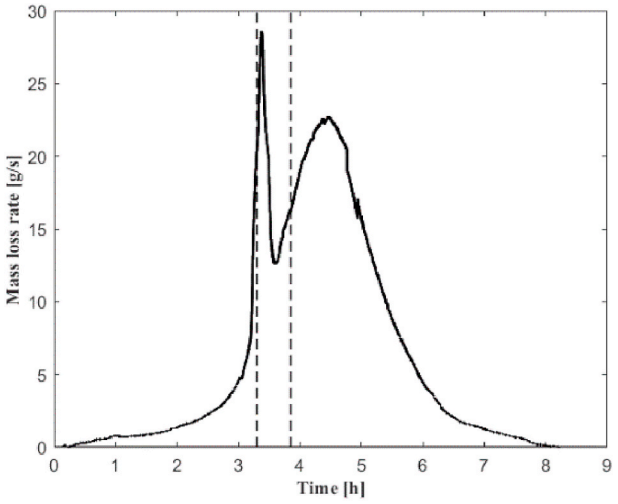

Fig. 11. Mass loss rate as a function of time for a large sample (0.6 m · 0.4 m · 0.15 m high, density 80 kg/m^3), see also Figs. 1a, 4 and 8. The transition from smoldering to flaming fire occurs at 3.3 h, as indicated by the dashed vertical line. The flames cease at 3.85 h (dashed vertical line), as can be seen in the change in the mass loss rate. The mass loss rate has a local minimum at 3.5 h, which could result in the flames going out at 3.85 h.

$$\int_{S1} \dot{q}''_{Source} dS_1 + \int_{V} \dot{q}'''_{Generation} dV = \int_{S2} \dot{q}''_{Loss} dS_2 \qquad \text{(Eq. 2)}$$

The heat flow balance describes the heat transfer in a control volume limited by surface S1 and S2 (See Fig. 15). Surface 1 is the boundary between smoldering cotton and heated cotton, while surface 2 is the boundary between heated cotton and free air. For simplicity, both dS1

Table 4
Average mass loss rate for different sized samples and combustion regimes. The mass loss rate is a first approximation as the sample mass is reduced from 90 to 10 % of the initial value.

Sample	Pure smoldering (g/min)	Early flaming[a] (g/min)	Late flaming (g/min)
Extra extra small (XXS)	[b]	[b]	[b]
Extra small (XS)	[b]	[b]	[b]
Small (S)	7 ± 1	10 ± 4	7
Medium (M)	[c]	13 ± 2	[d]
Large (L)	10	16 ± 2	[d]

[a] Early flaming typically self-extinguished and was followed by smoldering.
[b] No mass measurements performed.
[c] No experiments with pure smoldering.
[d] No experiments with late flaming.

Table 5
Maximum mass loss rate for different sized samples and combustion regimes.

Sample	Pure smoldering (g/min)	Early flaming[a] (g/min)	Late flaming (g/min)
Extra extra small (XXS)	[b]	[b]	[b]
Extra small (XS)	[b]	[b]	[b]
Small (S)	13 ± 3	18 ± 4	16
Medium (M)	[c]	24 ± 4	[d]
Large (L)	14	29 ± 4	[d]

[a] Early flaming typically self-extinguished and was followed by smouldering.
[b] No mass measurements performed.
[c] No experiments with pure smoldering.
[d] No experiments with late flaming.

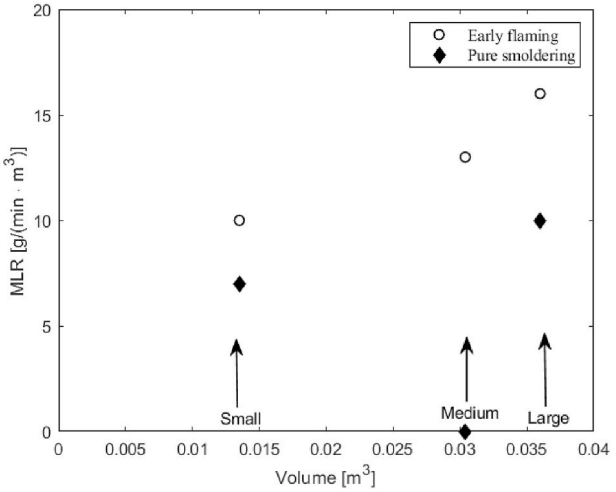

Fig. 12. Average mass loss rate for pure smoldering and early flaming as function of volume. The mass loss rate increases as the volume increases (See Table 4). The short flaming period of each flaming case results in a small increase in the average mass loss rate. Note that medium sized samples did all have early flaming. Sample volume: Small sample: 0.0135 m^3, Medium: 0.0304 m^3, and Large: 0.036 m^3.

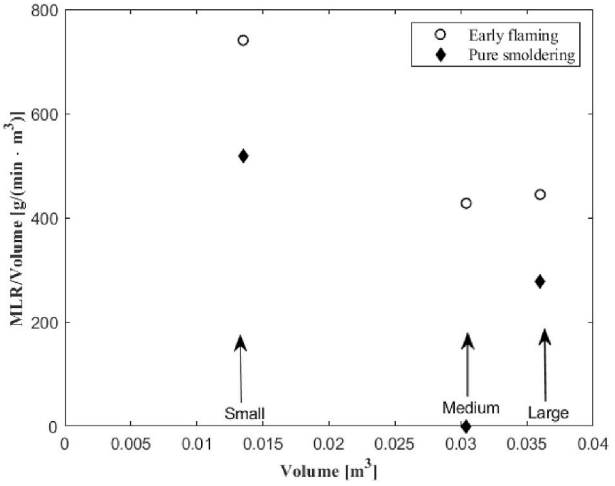

Fig. 13. Average mass loss rate pr. volume for pure smoldering an early flaming as a function of volume. The mass loss rate pr. volume decreases as the volume increases, which is consistent with poorer oxygen transport into the sample. The short flaming period of each flaming case results in a small increase in the mass loss rate pr. volume. Note that medium sized samples did all have early flaming. Sample volume: Small sample: 0.0135 m^3, Medium: 0.0304 m^3, and Large: 0.036 m^3.

and dS2 are assumed to be quadrangular, and a linear cartesian system can be used for the estimation. The first integral is a source term, for example an ignition source, and is assumed to be zero in this model. The second integral is the energy generation within a heated reaction zone, and the third integral is the heat transport and loss through the cotton. The temperature at S1 is assumed to be the same as observed by Hagen et al. (309 °C) [10] for onset of smoldering for cotton with density 80 kg/m^3. The minimum size for the transition from smoldering to flaming is determined as the length (l) between S1 and S2.

The heat generation rate, adjusted by the area (S1 and S2) of the control volume ($\dot{q}' = \dot{q}'''/\mathrm{S1}$), is dependent on the temperature as describe by an Arrhenius function

$$\dot{q}'_{Gen} = \Delta H_c \rho l_r A^* e^{\frac{-E_a}{RT}} \quad \text{(Eq. 3)}$$

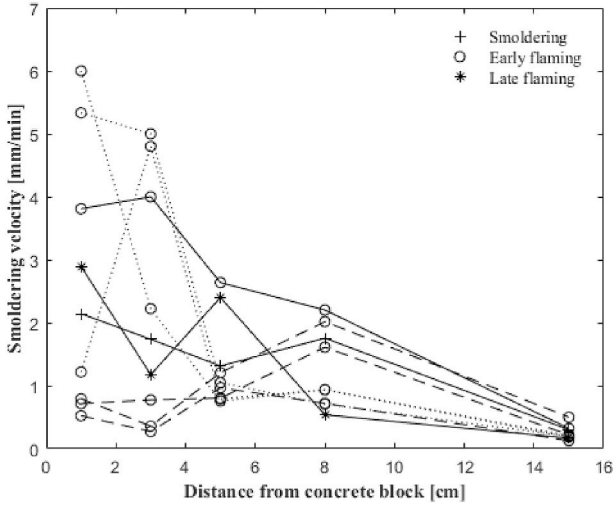

Fig. 14. Smoldering velocity as function of distance from lightweight concrete block for the centerline thermocouple 5 (shown in Fig. 2c). Solid lines (–) are for small samples, dashed lines (–) are for medium samples and dotted lines (…) are for large samples. The smoldering velocity decreases as the distance from the block increases, however the sample size has little effect on the velocity.

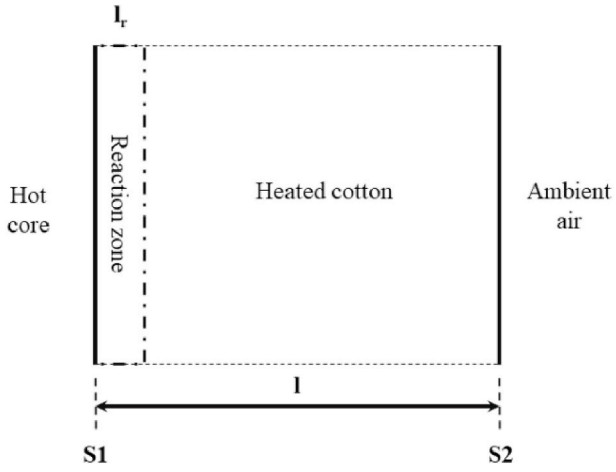

Fig. 15. Illustration of the one-dimensional heat transfer system.

The unit area of the control volume is implicit in the equation, making the heat generation dependent on sample depth only. The symbols in Eq. (3) are defined in Table 6 l_r is the depth of the reaction zone and estimated using eq. (4) [22], where the negative temperature

Table 6
Symbols used in Eq. (3) – Eq. (6).

Variable	Symbol	Property	Unit	Reference
Pre-exponential factor	A^*	6.7×10^5	s^{-1}	[26]
Activation energy	E_a	110×10^3	J/mol	[26]
Convective heat transfer coefficient	h	10	W/(m^2 K)	[23]
Thermal conductivity	k	0.072[a]	W/(m K)	[25]
Heat of combustion	ΔH_c	1×10^6	J/kg	[26]
Universal gas constant	R	8.31431	J/(K · mol)	
Ambient temperature	T_a	293	K	
Temperature for onset of smoldering	T	582	K	[10]
Density	ρ	80	kg/m^3	

[a] Including 5% water.

gradient (b) is calculated using eq. (5) [22].

$$l_r = \frac{RT^2}{bE_a} \quad \text{(Eq. 4)}$$

$$b = (T - T_a)\frac{h}{k}\left(\frac{1}{1 + (h \cdot l/k)}\right) \quad \text{(Eq. 5)}$$

The heat loss through the sample and to the outside is estimated using Fourier's law [23]. The characteristic length (l) can be found by setting heat loss equal to heat generation (see eq. (6)), and where convection is implicit included in eq (6) through eq. (4) and eq. (5). Radiation is not included in the estimation since temperature at S2 is assumed to be close to ambient temperature.

$$\Delta H_c \rho l_r A^* e^{\frac{-E_a}{RT}} = \frac{k}{l}(T - T_a) \quad \text{(Eq. 6)}$$

To solve for l, the boundary between smoldering and no smoldering cotton is used (S1). This boundary will have a temperature similar to the ignition temperature of cotton; 309 °C for cotton with density 80 kg/m^3 [10]. As more robust smoldering combustion models are developed, including better pyrolysis models, the hot core of smoldering can be included in the estimation of minimum size; we are not presently there. The heat of combustion used in the estimation of l, is based on the work by Di Blasi [24], where charring of cellulose at 300 °C is reported with a heat of combustion of 1×10^6 J/kg. The low heat of combustion is associated with the poor combustion of materials in a smoldering fire and should not be compared to heat of combustion for flaming fires. Conduction of cotton with 5% water is estimated using data reported by Tye [25] (0.043 W/(m K)) and conduction of water (0.62 W/(m K)); $k = 0.95 \cdot k_{cotton} + 0.05 \cdot k_{moisture}$. The convection factor ($h \approx 10$ W/(m^2 K)) is from Holman's general recommendation for heat loss due to natural convection over a surface [23].

By solving for l using material values for charring of cellulose (exceeding 300 °C) [26] (see Table 6), a minimum characteristic length of approximately 0.17 m can be found. A quarter sphere with radius of 0.17 m, will give a minimum sample size for the current setup of 0.34 m · 0.34 m · 0.17 m; that is the quarter sphere will reach the top surface of the cotton sample, but not the sidewalls of the sample. The hot core of the sample will then be insulated of the surrounding cotton.. The estimated minimum size is in good agreement with the experimental results; where smaller samples (less or equal to 0.3 m · 0.3 m · 0.15 m) did not support transition to flaming, while larger samples (larger or equal to 0.45 m · 0.45 m · 0.15 m) did.

5. Discussion

The results in section 3 reveal two important findings: there are different modes of transition from smoldering to flaming fire, and a minimum sample size is necessary to assure transition to flaming.

5.1. Types of transition

Two types of transitions from smoldering to flaming have been observed. The mechanisms driving the two transitions are different, however the ignition criteria of fuel, oxygen and ignition source are the same. Early transition to flaming is oxygen controlled and occurs in conjunction with the smoldering front reaching the outer boundary of the sample. Initially, the smoldering front moves from the ignition source and outwards, forming a hot core of charred material. As the smoldering front reaches the boundary of the sample, the smoldering changes direction and start burning back towards the center of the sample. This change in smoldering direction, changes the mode of smoldering from reverse to forward smoldering, as illustrated in Fig. 16 and Fig. 17. In forward smoldering the smoldering rate is increasing as reported by Babrauskas [27], and forward smoldering is known to transition to flaming as reported by Ohlemiller [5]. In addition to changing from reverse to forward smoldering, the now forward moving smoldering front is burning itself into char from previous reverse smoldering, resulting is secondary char oxidation [6]. Secondary char oxidation is reported to have a heat release rate of 8–10 times that of pure smoldering [28]. The change in smoldering direction, including both forward smoldering, and secondary char oxidation, will increase heat production in the sample, leading to flaming.

The early transition from smoldering to flaming fire reported in this article, has a lot common with the observations by Morgan et al. [14] and Stoliarov et al. [15]. In both cases there are complex interactions between smoldering fronts with enough oxygen and pyrolysis areas with less oxygen. Morgan et al. [14] and Stoliarov et al. [15] speculate if the buildup of combustible gases, exceeding the lower flammability limit, could result in ignition by the smoldering fire and transition to flaming fire. While in this article we speculate if the presents of secondary char oxidation (glowing spots, see below) triggers the transition to flaming, as the hot core produces sufficient combustible gasses. There are some differences in the experimental set-ups that could account for the differences in observations and speculations, however it is interesting that for all cases the interaction between smoldering and pyrolysis plays an important role and should be further investigated.

Changes in direction and mode of combustion have been reported

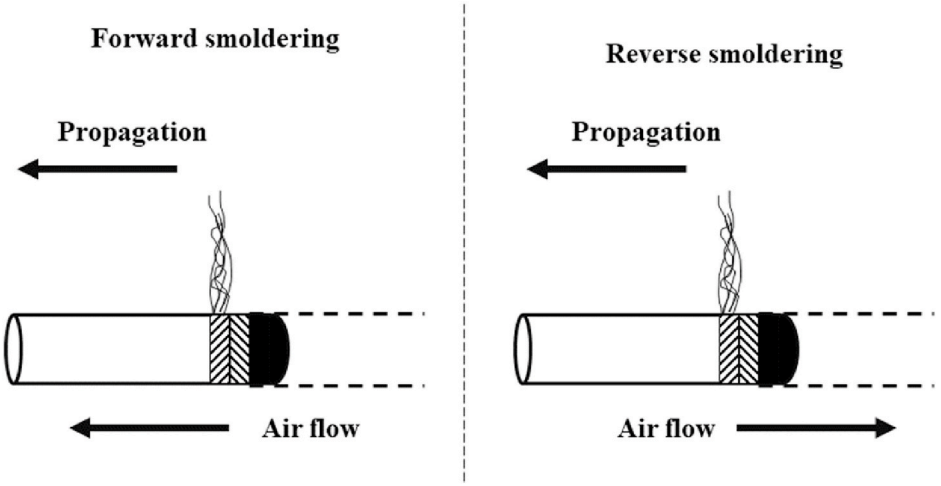

Fig. 16. Illustration of forward and reverse smoldering. Smoldering propagation is related to the direction of air flow, where forward smoldering moves in the same direction as the air, while reverse smoldering moves in opposite direction of the air flow.

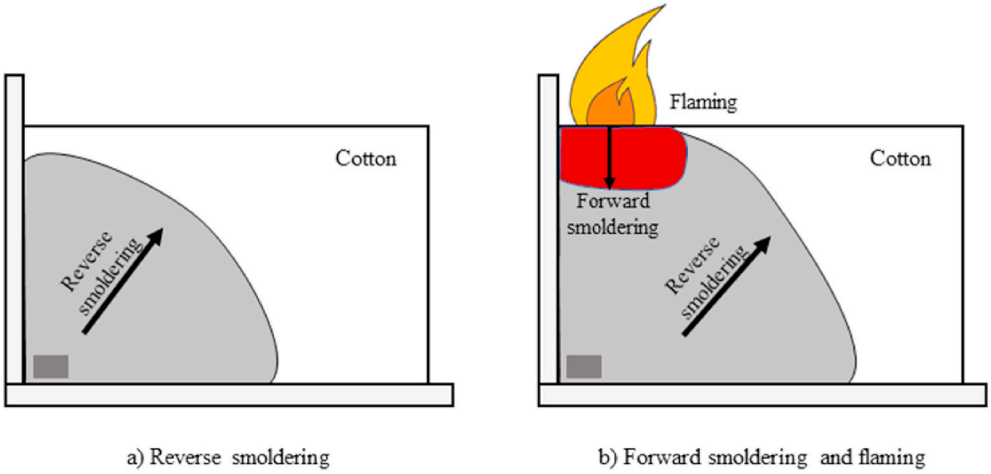

Fig. 17. Change from reverse to forward smoldering resulting in flaming.

earlier by Anderson et al. [7], for smoldering in polyurethane foam. The difference for the current experiments is that the change in direction and mode of combustion, occur at an open boundary of the sample and not deep inside the sample. The change of direction at an open boundary, will give an influx of fresh air to the forward smoldering front, resulting in secondary char oxidation, an increase in heat production and transition to flaming.

Late transition to flaming is much more complex, and is controlled by a combination of enough fuel vapor and a proper ignition source. This late in experiments the samples are quite reduced and open to air; there are no shortage of oxygen at this stage. For late flaming to occur, both enough fuel vapor must be produced by the smoldering of the sample, and glowing spots from secondary char oxidation (ignition source) must coexist in the sample in time and space. In many of the pure smoldering experiments glowing has been observed, but the fuel vapor ~~gas production~~ has not been large enough for flaming to be initiated.

Glowing spots are the result of secondary char oxidation, as reported by Ohlemiller [5], Drysdale [29] and Tse et al. [6], and have been present in all current experiments with transitioning from smoldering to flaming fires. The presents of glowing spots in all current experiments with transition to flaming points to a piloted ignition of the flaming fires. Observation by Alexopoulos and Drysdale [9], Ohlemiller [5], Morgan et al. [14] and Stoliarov et al. [15], all mentions the strong interaction between intense smoldering (glowing) and the transition to flaming. However, it is too early to categorically rule out spontaneous ignition as the ignition mechanism since the gas temperatures are high (>400 °C) and there is enough flammable gas to support an ignition.

The glowing spots occur at different times in the current experiments. In 13 of 25 experiments the glowing spots and transition to flaming occurred early in the experiments, when the smoldering fronts had moved to the outside of the sample making it possible for air to move more freely into the hot core. There are also three experiments where transition to flaming came late and where the initial smoldering fire had consumed most of the cotton fuel. Here the glowing spots occurred in the charred remains of the initial smoldering, igniting flammable vapor produced by smoldering processes. This late transition is similar to the transition described by Hagen et al. [13], even though the initiation of the smoldering is somewhat different. The two modes of transition are quite different: while the first mode requires more air to occur, the second mode requires both an ignition source (glowing spots) and flammable gas concentration exceeding lower flammability limit in order for flaming to occur.

5.2. Sample size

The experimental results show that transition from smoldering to flaming is dependent on the size of the sample. Larger sample sizes (0.6 m · 0.40 m · 0.15 m high, and 0.45 m · 0.45 m · 0.15 m high) have consistent transitions to flaming (see Table 2). When analyzing temperature distributions in samples with early transition to flaming, a hot core of smoldering is present next to the lightweight concrete block prior to transition. In order to generate the hot core, the sample must be large enough for smoldering and glowing to be initiated and insulated. The characteristic length (l) for cotton samples is estimated to approximately 0.17 m. The estimated length indicated that smoldering must be initiated more than 0.17 m from the surface of the sample. For the current experiments, smaller samples than $2\,l$ are not able to insulate the core and will lose heat through the sides. Medium (M) and large (L) samples are however long and wide enough to insulate the core.

The size of the current cotton samples where early flaming consistently occurs is where the length and width of the sample is more than double the height of the sample. This length to height ratio ensures the insulation of the sample core, and transition to flaming occurs as the smoldering front reaches the outside of the sample; making openings where air can move more freely into the core, increasing the heat production, resulting in flaming.

5.3. Chimney effect

For the current flaming experiments, openings either at the top or the sides of the samples would form crevices resulting in transition from smoldering to flaming fires. However, there was not needed a channel for air to flow through the sample (chimney effect) in order to have a transition to flaming; as often reported regarding upholstered furniture and polyurethane foam [18]. Openings at the top will probably be more common for tall configurations like silos. For other types of storage, like flat bulk storage of wood pellets, openings at both top and sides of the stored materials could lead to flaming. Interestingly, current firefighting procedures for smoldering silo-fires recommend breaching the sides of the silo, exposing the smoldering material and extinguishing the fire [30]. This way of opening up silos may result in transition to flaming and explosions [4].

5.4. Concluding remark

From a safety standpoint, both modes of transition to flaming (early and late) are important since they may develop from slow burning smoldering fires to highly hazard flaming fires or even explosions. However, since the late transition to flaming is more random in nature; more emphasis should be put on the early occurring transitions from smoldering to flaming fires in order to investigate and get a better understanding of this phenomenon. Babrauskas and Krasny [31], Hagen

et al. [13] and Stoliarov et al. [15] report of transition to flaming, but only a fraction of the experiments had transition to flaming. To get a better understanding of the transition by experimental work, sample size seems to be an important factor. For consistent transition to flaming, without forced ventilation, the minimum dimensions for cotton samples are 0.45 m · 0.45 m · 0.15 m high, while more experimental work is needed to determine the minimum dimensions for other materials.

6. Conclusion

Transition to flaming in cotton has been investigated experimentally, and two important findings are presented: there are found different modes of transition from smoldering to flaming fire, and a minimum sample size is necessary to assure transition to flaming.

Two modes of transition to flaming have been identified: early and late transitions. Early transitions occur as smoldering combustion forms a hot core in a sample, and then smoldering fronts move towards the outside of the sample (reverse smoldering). As the smoldering reaches the outside of the sample, openings are made where air can move more freely into the sample, thereby changing the smoldering direction from reverse to forward smoldering. The forward smoldering causes increased heat production and flaming. Late transition to flaming occurs more randomly as smoldering and secondary char oxidation (glowing spots) coexist. Here the smoldering produces flammable vapor, and the glowing spots act as ignition sources.

Earlier experimental works have shown that transition to flaming is difficult to reproduce. The current work shows the importance of sample size in order to have experiments with consistent transition to flaming. Cotton samples with dimension equal to or larger than 0.45 m · 0.45 m · 0.15 m high, consistently give transition to flaming. By increasing sample size, transition from smoldering to flaming can be investigated in more details.

CRediT authorship contribution statement

Bjarne C. Hagen: Conceptualization, Methodology, Investigation, Writing - review & editing, Supervision, Funding acquisition. **Anita K. Meyer:** Methodology, Investigation, Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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