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Smoldering combustion as a treatment technology for faces: Sensitivity to key parameters

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Abstract

Poor sanitation results in increased spread of diseases and environmental pollution. In many parts of the globe, treatment of faeces needs an urgent solution that ensures elimination of pathogens using minimal resources. Self-sustaining smouldering combustion of faeces mixed with sand has been has been recently studied as a potential technology. A combination of different experimental parameters is essential to ensure robust operation, where oxidation coexists with pyrolysis and water evaporation. This work presents the results of a series of thirty-two experiments conducted in order to study the sensitivity of the process to the following experimental parameters: moisture content, sand-to-faeces ratio, airflow, sand grain size and ignition temperature. It was found that smouldering temperature and velocity are independent on the moisture content and ignition temperature; while are strongly dependent on other parameters, specially the airflow. The information presented is crucial to control the process, allowing its implementation to a real scenario.

Keywords: smouldering combustion, waste management, faeces, toilet.

Introduction

Proper waste management has been identified as one of the global challenges for this century (UN, 2014). More than 2.5 billion people worldwide routinely practice open defecation due to lack of adequate sanitation facilities (WHO and UNICEF, 2012). In some developing countries, more than 50% of the urban population have no access to basic sanitation (Rahman, 2001). Poor sanitation is directly related to many public health problems. Existing approaches to the destruction of human excreta are limited by cost, ineffective sterilisation capacity or practicality (Katukiza et al., 2012, Pathak, 1999). The lack of affordable and effective sanitation solutions is affecting the health and productivity of billions of people.

Due to the need for rapid destruction and sterilisation of the waste, a combustion treatment is often proposed. However, the high moisture content (MC) of faeces (75%-85%) (Yadav et al., 2010) results in a very low effective calorific value. As a result, faeces requires substantial pre-drying or the use of supplemental fuel to avoid quenching of the combustion reaction (McKay, 2002, Chang et al., 1992); making conventional incineration expensive.

Forward smouldering was previously shown to be effective at treating waste streams such as contaminated soils (Switzer et al., 2009), used tires (Vantelon et al., 2005); and it has been recently studied as an alternative approach for the treatment of faeces (Yermán et al., 2015, Yermán et al., 2014).

Smouldering combustion is a slow, low-temperature and flameless form of combustion driven by the energy released by oxidation of a condensed phase fuel (Rein, 2009, Carvalho et al., 2002).

The most common example is the glowing coal in a barbeque. Smouldering can be characterised by the direction of smoulder propagation relative to the direction of oxygen flow. For example, in forward smouldering propagation the oxygen flow is in the same direction as the movement of the smoulder front (Ohlemiller, 2008). Ignition is governed primarily by heat transfer and chemical kinetics. The heat supplied initiates pyrolysis and other endothermic reactions such as water evaporation before oxidation occurs. Propagation will occur when the oxidation reaction is sufficiently strong to overcome the heat required for pyrolysis. Heat loses are minimum in comparison to flaming combustion, and for this reason the energy efficiency of forward smouldering allows for extended quenching limits (Ohlemiller, 2008). Therefore it can be applied for the treatment of substances with high moisture content, such as faeces.

Smouldering requires a porous fuel as this promotes a high surface area for heat and mass transfer and allows the flow of oxygen to the reaction zone (Switzer et al., 2009). In the case of faeces, they are embedded in a porous inert matrix. Sand is used because it is a low cost commodity and it has been previously been identified as an effective agent for increasing the porosity of fuels for application to smouldering treatments (Pironi et al., 2009).

Yermán *et al* (Yermán et al., 2015) conducted proof-of-concept smouldering experiments of surrogate faeces mixed with sand, as a response to the *Reinvent the Toilet Challenge* project launched by The Bill and Melinda Gates Foundation in 2011 (Mitchell, 2012). Those experiments were part of a new integrated, low cost, on-site sanitation system aiming to disinfect human waste within 24 hours using minimal resources (Fishman et al., 2012, Cheng et al., 2015). The surrogate faeces were used to control the experimental variables; and its equivalence with respect to real faeces was demonstrated. The temperature and time residence achieved during the process ensures elimination of biological hazards. These experiments were the first to demonstrate that smouldering combustion can be applied for the treatment of waste with high moisture content (>70%). Furthermore, authors found a robust self-sustaining (SS) region of different experimental parameters (moisture content, pack height, sand-to-faeces mass ratio (S/F) and airflow rate) where self-sustaining smouldering is possible. It was demonstrated that these limits are not independent; rather they are interdependent in a complex manner.

1.1 Influence of experimental parameters on the smouldering performance.

Several papers about the influence of key parameters on the smouldering performance can be found in literature (Pironi et al., 2009, Pironi et al., 2011, He et al., 2014, Switzer et al., 2014). Under SS conditions, the performance can be assessed by the velocity of propagation of the smouldering front and temperatures. The moisture content of the faeces is an important energy sink that affects the ignition (Rein et al., 2008), and the conditions under which sustained smouldering will occur without quenching (Frandsen, 1997). The effect of moisture content in downward smouldering experiments of corn stalk powder was studied in the range 3-21% (He et al., 2014). Authors found there is no obvious regularity between the oxidation velocity and the moisture content. Nevertheless, the range of MC studied was considerably low compared to that found in faeces.

Pironi *et al*. studied the effect of permeability of the porous medium for the smouldering combustion of coal tar mixed with sand (Pironi et al., 2011). They found that increasing the grain size was shown to increase the velocities and temperatures at low particle sizes (0.75 – 1.34 mm), while it significantly reduced the temperatures and the rate of propagation up to quenching at high particle sizes (6 – 10 mm).

Previous studies on smouldering showed the rate of propagation is directly related to the rate of oxidiser supply to the reaction zone (Ohlemiller, 2008). Switzer et al. studied the smouldering remediation of contaminated materials (Switzer et al., 2014), and found that the remediation time can be controlled by the air injection rate; with higher rates leading to higher propagation velocities. While the correlation seems to be linear, there is no clear evidence, as experiments were performed in different reactor geometries.

All these previous works described here studied the influence of different experimental parameters on the dependence of the smouldering propagation velocity or temperatures; this was never studied in the case of faeces. The simultaneous presence of an inert matrix and, more important, the high moisture content of this kind of fuel make this study unique. This paper presents the effect on the propagation velocity and temperature of the following key parameters: moisture content, sand-to-faeces mass ratio (dry basis), sand grain size, ignition temperature (T_{ig}) and air flux, on the smouldering of surrogate faeces mixed with sand. This is the first time such study is performed with a fuel with such high moisture content. The information presented here is crucial to control the smouldering process, allowing the scaling and implementation of this technology to a faeces treatment system integrated to a toilet.

Experimental methodology

Due to the regulatory challenges of working with real faeces and in order to control the experimental variables, a surrogate faeces based on (Wignarajah et al., 2006) was used. The equivalence of this surrogate formula to real faeces was demonstrated (Yermán et al., 2015). A fresh batch of surrogate faeces was prepared prior to each test and mixed with sand using a food mixer. The columns were filled with the mixture up to 32 cm in all the experiments.

Upwards forward smouldering combustion experiments were carried out using a purpose built column. A schematic representation of the system utilised can be found in Figure 1. Two different column diameters were used for the experiments (internal diameters 6 and 16 cm). The columns are cylindrical, placed over the same stainless steel base which houses the heater (Incoloy-sheathed, 2.2x4.2 mm cross-section, coiled in a spiral) and air diffuser. The air diffuser consists of a ring-shaped tube perforated with six pairs of opposite holes. This is placed in the bottom of the base and covered with layers of gravel and sand to ensure uniform airflow. The heater is embedded beneath the upper surface of the sand layer; and the column is then filled with the sand-faeces mixture up to the desired height. The propagation of the smouldering reaction was monitored by thermocouples (TC) positioned along the central axis of the tube. The first five TCs (TC1 to TC5) are spaced at 1 cm intervals, with TC1 located 2 cm from the heater. The remaining thermocouples (TC6 to TC10) are spaced at 5 cm intervals. Temperatures were recorded every 5 seconds.

At the start of each experiment, the material adjacent to the heater was preheated to a certain temperature (measured at 2 cm - TC1), defined as ignition temperature. When T_{ig} is reached at TC1, the flow of air through the sample was initiated at the desired flow rate controlled using a differential pressure mass flow controller. The heater was switched off when TC1 peaked, and the smoulder was allowed to propagate without additional energy input. Compressed air was switched off when temperatures throughout the column had returned to ambient. This procedure and configuration (one-dimensional, forced, upwards forward smouldering) was chosen as it has been proven to give a robust, repeatable ignition across a wide range of conditions (Switzer et al., 2009, Pironi et al., 2011).

A typical plot of temperature histories throughout the column of a self-sustaining experiment is shown in Figure 2. In this example, the preheating period lasted approximately 100 minutes and is characterised by a gradual increase in temperature up to the desired ignition temperature (400 °C in this example), and a plateau close to 100 °C which corresponds to water evaporation. When the air flow is initiated, the location closest to the heater experiences a sharp increase in temperature up to a peak >600 °C as exothermic oxidation occurs. Heater is turned off when the TC at 2 cm from the heater (TC1) peaks. Adjacent TCs experience a temperature increase due to the convective heat transfer from the reaction zone to the virgin material ahead. The sand-faeces mixture is thus pre-dried ahead of the smouldering front's arrival. As the fuel is consumed and the reaction at that location stops, the temperature falls as it is cooled by incoming air. Temperature histories can also be used to produce spatial temperature distributions. The succession of temperature peaks is observed throughout the sand-faeces mixture is indicative of a self-sustaining smouldering reaction.

The limits where the smouldering combustion of faeces is SS were already studied (Yermán et al., 2015). As the aim of this paper is to find the velocities and temperatures that can be achieved under real conditions, and how to control them, all the experiments performed were in self-sustaining conditions. Nevertheless, the study of the influence of the sand grain size does include experiments in non-SS conditions because these limits, for the smouldering of faeces mixed with sand, were studied here for the first time.

The experimental parameters studied in this work are: moisture content, sand-to-faces mass ratio (dry basis), airflow rate, sand grain size and ignition temperature. The average peak temperatures and the average local velocity of the smouldering front were used to evaluate the performance of the process. The peak temperature is defined as the maximum temperature recorded at one TC. ***The determination of the smouldering velocity is based on that described in (Torero et al., 1993), and the same as that used in (Yermán et al., 2015) . It is calculated from the time lapse of the reaction zone arrival to two consecutive thermocouples, and the known distance between them. Usually, the location of the reaction zone can be defined by the position of the peak temperatures reordered at each TC. However, in many tests this is not sharply defined, thus to reduce uncertainties the location of the smouldering front is defined here by the inflexion point in the temperature histories.*** In both cases, the average values were calculated excluding the data from any TC placed in the first and last 5 cm of mixture. This was done to avoid the influence of the heater and the boundary conditions at the top of the mixture.

All the experiments employed commercial sand (7C filter sand, Riversands Pty, Australia) with a sand grain size between 0.6 mm and 1.2 mm (0.9 mm in average). The same sand was used in all the experiments, except in those were we studied the influence of the sand grain size on the smouldering performance. The ignition temperature was 250 °C in all the experiments, except for the study of the sand grain size (120 °C), and in those experiments were the influence of T_{ig} was studied. The small diameter column (6 cm) was used in the experiments were we studied the influence of the airflow, to allow a larger range in the air Darcy flux of those experiments. The rest of the experiments were performed in the 16 cm diameter column. The S/F ratio was settled at 24 g/g for all the experiments, except when the study of the sand content was carried out.

Thirty-two experiments were carried out to determine the sensitivity of the process to different experimental parameters (see Table 1). ***The repeatability of these experiments was previously demonstrated in (Yermán et al., 2015) for the same sand-waste mixture and under quenching conditions. Here, we perform three repetitions of another experiment under self-sustaining conditions (33% MC, 16 g/g S/F and air Darcy flux 11.7 cm/s). Table 2 summarizes the smouldering velocities and average peak temperature with a 95% confidence interval for those experiments. These values demonstrate the repeatability of these smouldering experiments under a wide range of conditions. Each experiment reported here was repeated twice, assuming the same repeatability than in the repetitions showed in Table 2.*** ~~Each experiment was repeated at least twice to ensure repeatability~~. Experiments 1-5 examine the dependence of the smouldering process on the moisture concentration in the range 64-72%. The influence of the sand content in the mixture was studied varying S/F between 4 and 28 g/g, in experiments 6-13 at 50% MC. Experiments 14-21 examine the influence of the air Darcy flux , between 3.5 and 46.7 cm/s, on the smouldering performance at 50% MC. The effect of varying T_{ig} from ambient temperature to 400 °C was studied with experiments: 27-32 at 67% MC.

Results and discussion

Moisture content

Figure 3 shows the average peak temperature and smoulder velocity as a function of MC for fixed air Darcy flux (3.0 cm/s) and S/F ratio (24 g/g), in experiments 1-5. Average peak temperatures ranged from 481 to 506 °C; while smouldering propagation velocities were found between 0.23 and 0.26 cm/min.

Considering the inherent experimental variability showed in the repetitions of these experiments, these figures can be considered constant. Results presented here showed that, at high moisture content levels (64-73%), and under robust self-sustaining conditions, the smouldering propagation or the temperature does not depend on the initial moisture content of the faeces. In the case of U_S, this independence with respect the moisture content is somehow expected since the propagation of the smouldering front occurs on completely dried and already pyrolysed material (Rein et al., 2008). A similar behaviour is observed for the average peak temperature as a function of MC. Temperatures appear to be constant, although a slight reduction in the average peak temperatures can be observed after 69%.

These results are in concordance with the results observed in (He et al., 2014) for the smouldering of biomass in the range of moisture content 3 – 21 %. However, those experiments were performed with another fuel, in absence of inert porous matrix and much lower moisture content. The impact of MC may not be the same at high values, such as in faeces. Previous studies on smouldering combustion of faeces mixed with sand (Yermán et al., 2015) showed that moisture content was a crucial parameter to consider the self-sustainability of the smouldering. Water recondensation in the above layers of cooler mixture can be significant, increasing the local moisture content levels due to free water flowing down inside the column, which can lead to the reaction quenching (Yermán et al., 2015). As water acts as an energy sink, at higher moisture content, a reduction in the peak temperatures can be expected, as MC increases. It is possible that the slight reduction in the average peak temperatures above 69% MC is due to this phenomenon. Nevertheless, the pack height used in these experiments (32 cm) may allow steam to leave the column seconds after the airflow is initiated, avoiding significant water recondensation.

Sand content

The influence of the sand content on the performance of the smouldering combustion was studied at different S/F ratios in the range 4 – 28 g/g and all other parameters fixed, in experiments 6-13. Results are presented in Figure 4 and showed that both U_S and smouldering temperatures decrease when S/F is increased.

Pironi *et al* studied the influence of the amount of sand in the smouldering of non-aqueous phase liquids (NAPL) (Pironi et al., 2009). They found that smouldering temperatures increase with fuel saturation. On the other hand, the smouldering velocity decreases in a linear fashion when the fuel saturation was increased. It is worthy to notice that this is a completely different fuel, without water, and results can be influenced from any other variables which were not taken in consideration.

In this paper, while the behaviour for the temperature dependence may be similar, results are different –and opposite - for the variation of the smouldering velocity with S/F. As explained above, sand is necessary to provide the porous medium necessary for the propagation of the smouldering reaction. However, sand is not combustible and acts as energy sink as part of the energy released form the oxidation is consumed on heating the sand. As the S/F ratio increases, there is less fuel per length unit, decreasing the energy release rate and the smouldering velocity. Even more, part of this energy is consumed on heating a higher amount of sand. This explains the lower temperatures observed.

The differences observed in the results presented here with those for NAPL highlight the importance of the present study. The amount of experiential variables that have influence on the smouldering performance, their interdependence, and different processes that occur during smouldering make the study of every fuel or mixture unique and necessary when smouldering is intended to be applied as a treatment method.

Airflow rate

Figure 5 shows the average peak temperature and smouldering velocity as a function of the air Darcy flux for experiments 14-21. In all these experiments, the smouldering velocity ranged between 0.25 and 3.5 cm/min. Results showed that increasing the air Darcy flux from 3 to 47 cm/s, while other parameters are fixed, increases the velocity of propagation of the smouldering front in a linear fashion. However, the average peak temperatures do not show such linear trend. Smouldering temperature increases (from 423 to 612 °C) within the range of air Darcy flux from 3 to 38 cm/s and drops to 498 °C at 47 cm/s.

These results demonstrate that higher smouldering velocities do not necessary lead to higher temperatures, as it was observed in Figure 4. This is mainly associated with the fine energy balance between heat transfer and the rate of the exothermic oxidation (Pironi et al., 2009). By increasing the airflow, the amount of oxygen per time unit that reaches the surface of the fuel is also increased. This implies higher oxidation reaction rates and consequently, the energy release rate is also higher, which raises the temperature inside the reactor and the gases produced. On the other hand, the increment in the air flux also produces an increment on the amount of cool gas (mostly inert nitrogen) entering the reactor. Due to the high velocity of the gas inside the reactor, the heat released form the exothermic reaction in the form of hot gases is not efficiently transferred to the sand-faeces mixture. In fact, it was observed that the temperature of the gases leaving the reactor increases with the airflow. Therefore, a higher airflow produces larger amount of gases which are leaving the reactor at higher temperature, which increases the heat losses. At high airflows (air Darcy flux 38 - 47 cm/s) this condition provokes a reduction in the temperatures inside the reactor with respect to lower airflows.

Sand grain size

The influence of the sand particle size on the smouldering temperatures and velocities was determined by performing ten experiments (22 to 26) using the different porous media presented in Table 3. Those experiments were conducted under the same experimental conditions (67% MC, 24 g/g S/F and 7.5 cm/s of airflow). As the study of the sand size limits for the SS smouldering combustion of faeces was not previously studied, this investigation is included in this section. Results obtained are summarized in Figure 6.

Smouldering was observed to be not-SS at sand particle size below 0.5 (fine sand) or above 3 mm (gravel). At low particle sizes, it is presumed that the fine sand does not provide enough air permeability to the sand-faeces mixture. In the experiments carried out with fine sand, the propagation of the smouldering front only reached 5 cm and with temperatures slightly over 300 °C. At the other extreme, when the sand grain size is too high, the hot gases pathway towards the end of the reactor is considerably shorter, having less time to transfer the energy to the medium. As the energy is not efficiently transferred – and this is the key of smouldering combustion - smouldering cannot be self-sustaining. In those experiments, the temperatures hardly reached 160 °C at 3 cm.

Figure 6 also shows the range of average sand particle size where the smouldering of faeces mixed with sand is self-sustaining is between 0.6 and 3.0 mm. Nevertheless, these sand particle limits may slightly vary at different the airflow rates, as the experimental limits were demonstrated to have an interdependent relationship (Yermán et al., 2015). Within that SS range, results in Figure 6 show both average peak temperatures and smouldering velocities decrease when the sand particle size increases. There is a reduction of 23% in the smouldering velocity and of 10% in the temperature when the average sand grain size is increased from 0.9 to 2.2 mm. This can be explained in the same way the experiments at high particle size are not-SS. The residence time of the hot gases inside the reactor is decreased when the sand grain size is increased; increasing the heat loses, and the heat that is transferred to the mixture. Additionally, as the grain size increases, the ratio surface area/volume diminishes. The smouldering reaction takes place in the surface of the sand, hence the heat released per unit volume decrease when the grain size is increased. A similar effect was also observed for mixtures of sand and NAPL (Pironi et al., 2011).

Ignition temperature

For the application of smouldering combustion of faeces to a real scenario, it is desired to operate this technology with the least energy consumption as possible. Ignition temperature, or T_{ig}, is defined as the temperature measured at TC1 (2 cm from the heater) when the air flux is initiated. For example, in the experiment showed in Figure 1, T_{ig} corresponds to 400 °C.

In this work, we studied the influence of T_{ig} on the propagation velocity and temperatures at 67% MC. Figure 7 present the average peak temperature and smouldering velocity as a function of T_{ig} of those experiments (27-32). The range of T_{ig} studied was 25 – 400 °C. Temperature ranged from 474 to 553 °C for the temperature and from 0.35 to 0.47 cm/min for the smouldering velocity.

No pattern is observed in the variation of the velocities or temperatures when T_{ig} is varied. A fluctuation below 8% is observed in the values of U_S and average peak temperature can be attributed to the natural variability of those experiments, as similar fluctuation was observed across experiment's repetitions. The similarity in the values indicates that T_{ig} has an almost negligible effect on the peak temperatures and smouldering velocities.

Results from thermo-gravimetric analysis showed that combustion of the surrogate faeces occurs approximately between 200 and 700 °C (Yermán et al., 2015). Hence, working at ignition temperatures above 200 °C would only imply the consumption of unnecessary energy for ignition, as there is no impact on the performance of the smouldering.

Conclusions

A set of experiments of smouldering combustion of faeces mixed with sand has been conducted under a range of experimental conditions were smouldering is robust and self-sustaining. The smouldering performance has been assessed in terms of smouldering propagation velocity and average temperatures during smouldering as a function of moisture content, amount of sand, sand particle size, airflow and ignition temperature. This is crucial information for the implementation of this technology to a real scenario, such as an on-site sanitation system. Knowing the smouldering velocity as a function of experimental parameters may be used for scaling the smouldering technology, while the temperatures can be used to estimate the energy recovery of the overall process (Cheng et al., 2015).

Results reveal that the smouldering propagation velocity can be easily achievable between 0.2 and 1.0 cm/s, and this can be modulated by changing the airflow because there is a linear relationship between the air Darcy flux and the velocity of propagation. Higher airflows can be used to reach velocities of up to 3.5 cm/s however this would consume more unnecessary energy. While the airflow can be also used to alter the temperatures during smouldering, the amount of sand used has a greater impact on the temperatures achieved during smouldering. It was observed that by changing the sand-to-faeces mass ratio, the temperatures can be modulated within a range of almost 500 °C. On the other hand, the impact of this ratio on the smouldering velocity is not as great as the influence of the airflow, showing differences below 0.4 cm/s for the same range studied. A sand-to-faeces mass ratio equal to 4 can be used and will lead to high temperatures and velocities. However, those high velocities may not be desired if the intention is to smoulder for long periods of time.

The sand grain size has also shown to have some effect on the smouldering temperatures and velocities. However, under the same experimental conditions and within the whole range of self-sustainability, the variation in velocities and temperatures was only 23% and 10%, respectively. This means that, while within that range of particle size, any size of sand can be used with no significant impact on the smouldering process.

The moisture content in the faeces acts as an energy sink and is the most crucial parameter to determine the self-sustainability of the process. Higher velocities and temperatures were registered for dried faeces compared to wet (67%) faeces. While this information is useful to understand how the moisture content affects the performance of the smouldering of faeces, working with dried faeces is unrealistic because a considerable amount of energy is required for drying. Results showed that within the applicability range of moisture content for faeces (65-72%), this seems to have a minimal impact on the smouldering velocity and temperature.

Finally, the ignition temperature did not show a systematic effect in the smouldering velocities or temperatures. As there is no evident influence of the ignition temperature on the smouldering performance, it is recommended to work with an ignition temperature within the range 60-140 C to save energy.

Further experiments should be carried out to systematically study the influence of the reactor size on the smouldering performance and parameter limits. This will allow the balancing of the smouldering conditions to suit the individual community requirement, applied to a real scenario.

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Figure 1. Schematic representation and a photograph of the smouldering reaction system.

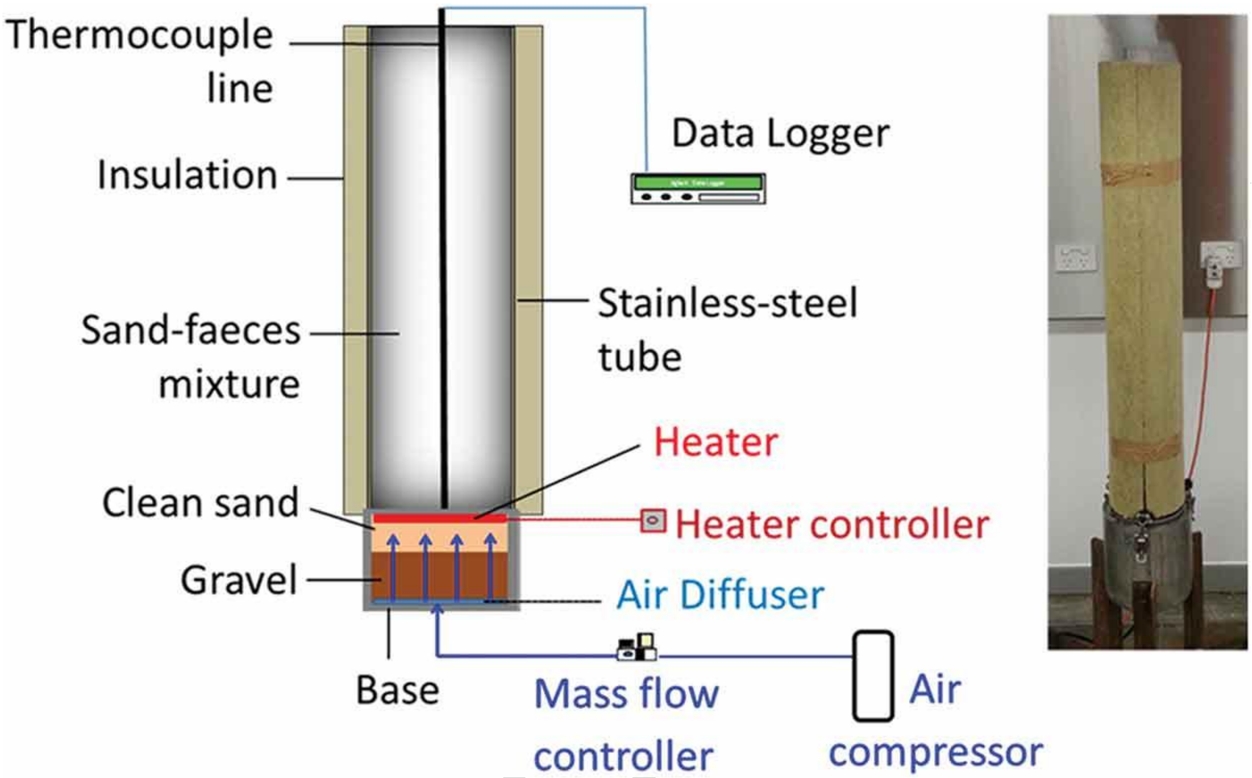

Figure 2. Example of temperature histories for self-sustaining smouldering of faeces mixed with sand.

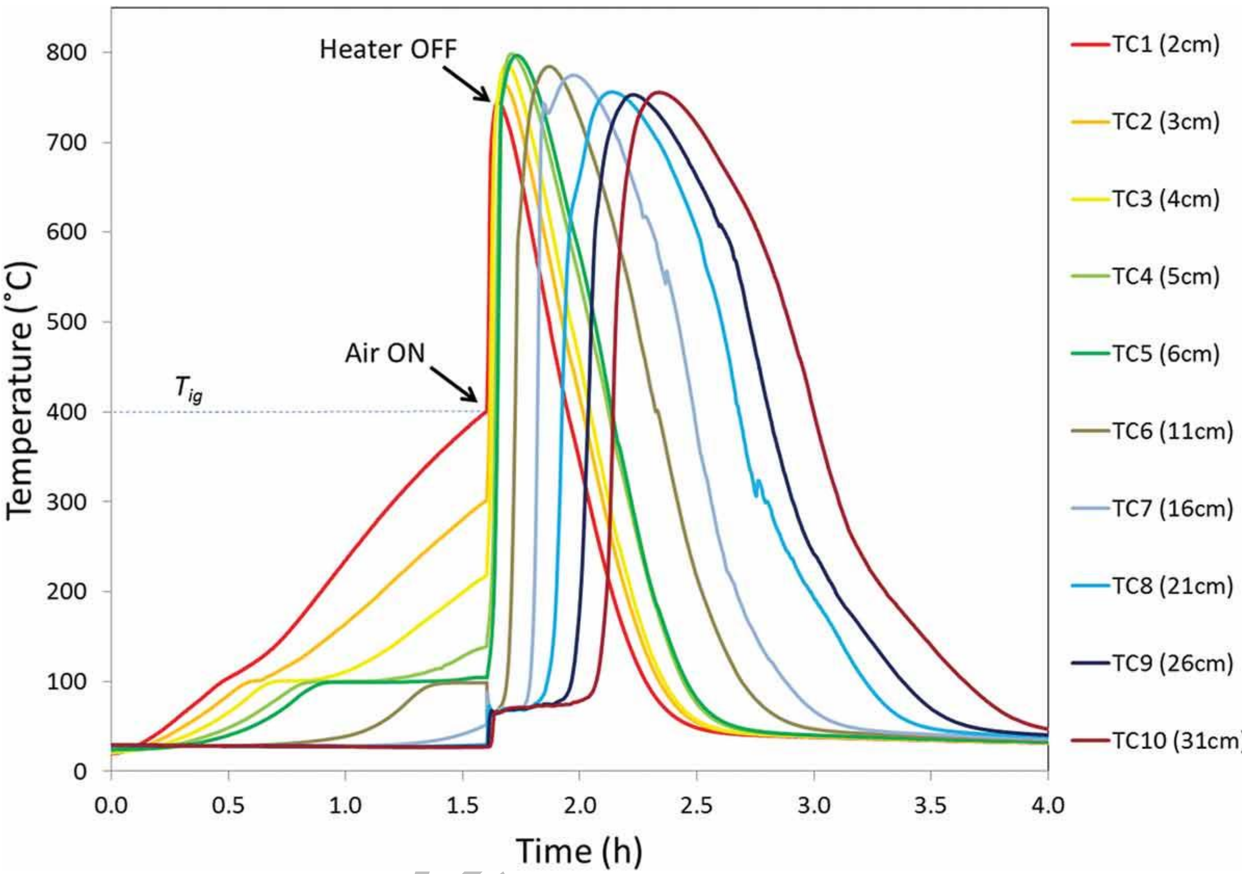

Figure 3. Average peak temperature and smouldering velocity as a function of moisture content.

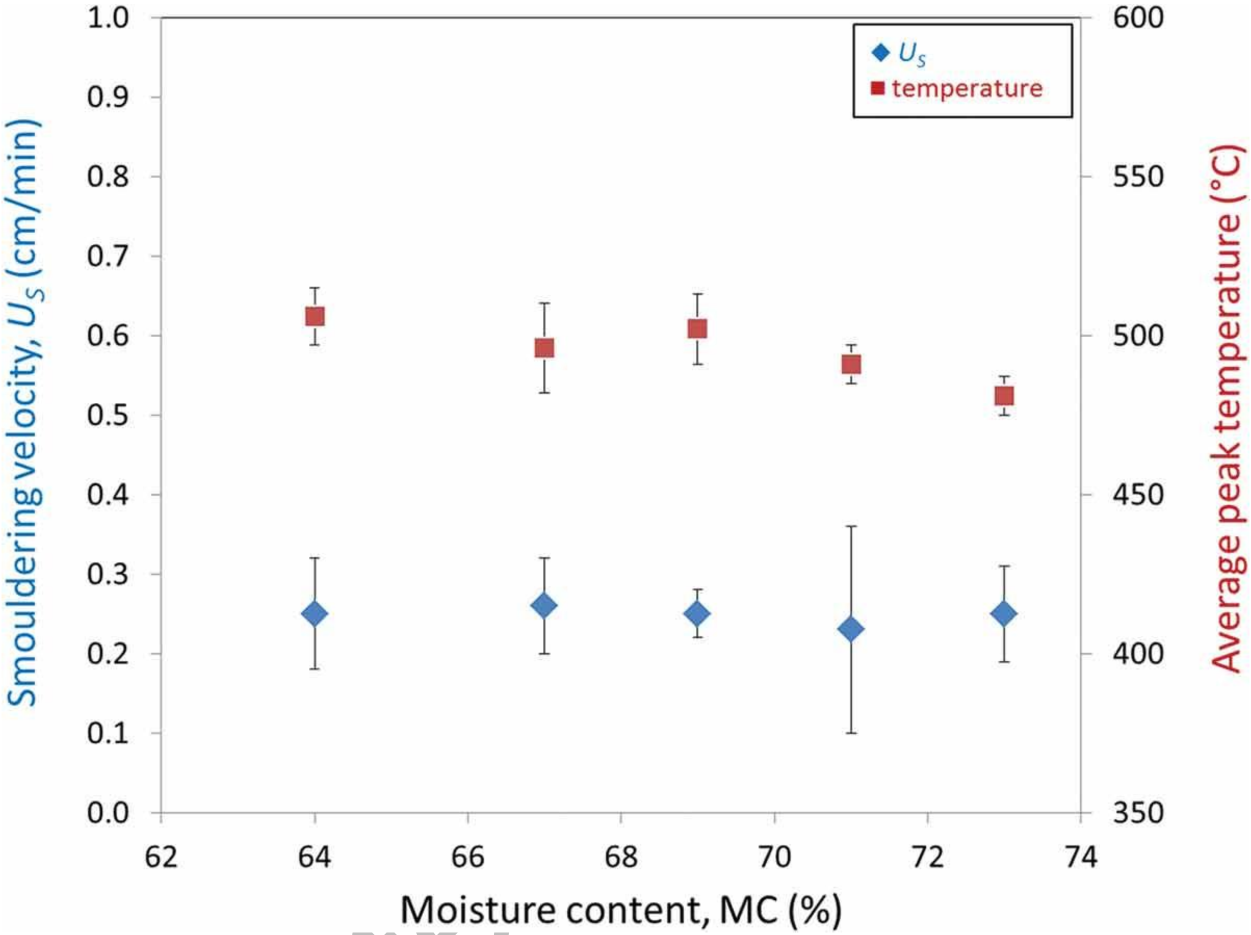

Figure 4. Average peak temperature and smouldering velocity as a function of S/F mass ratio.

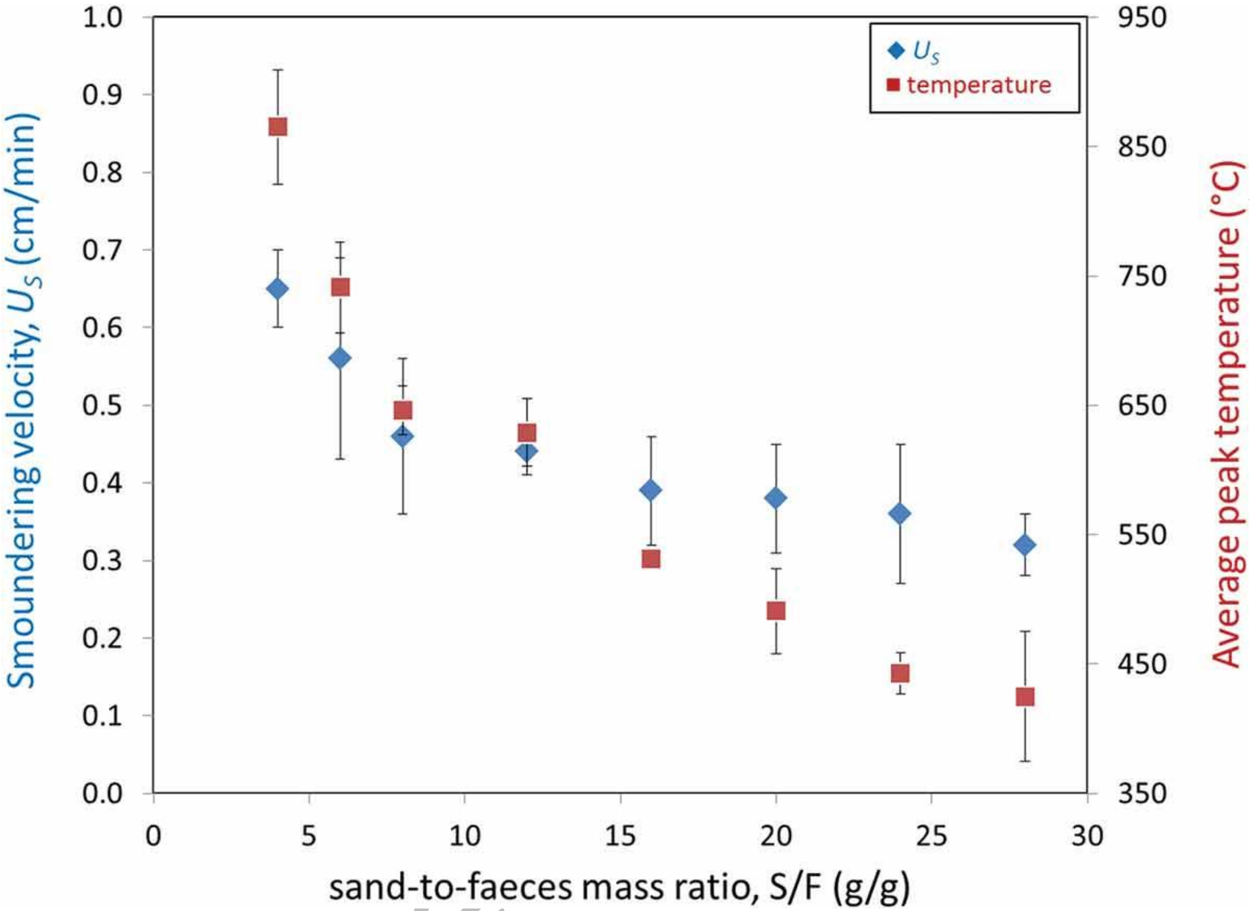

Figure 5. Average peak temperature and smouldering velocity as a function of air Darcy flux.

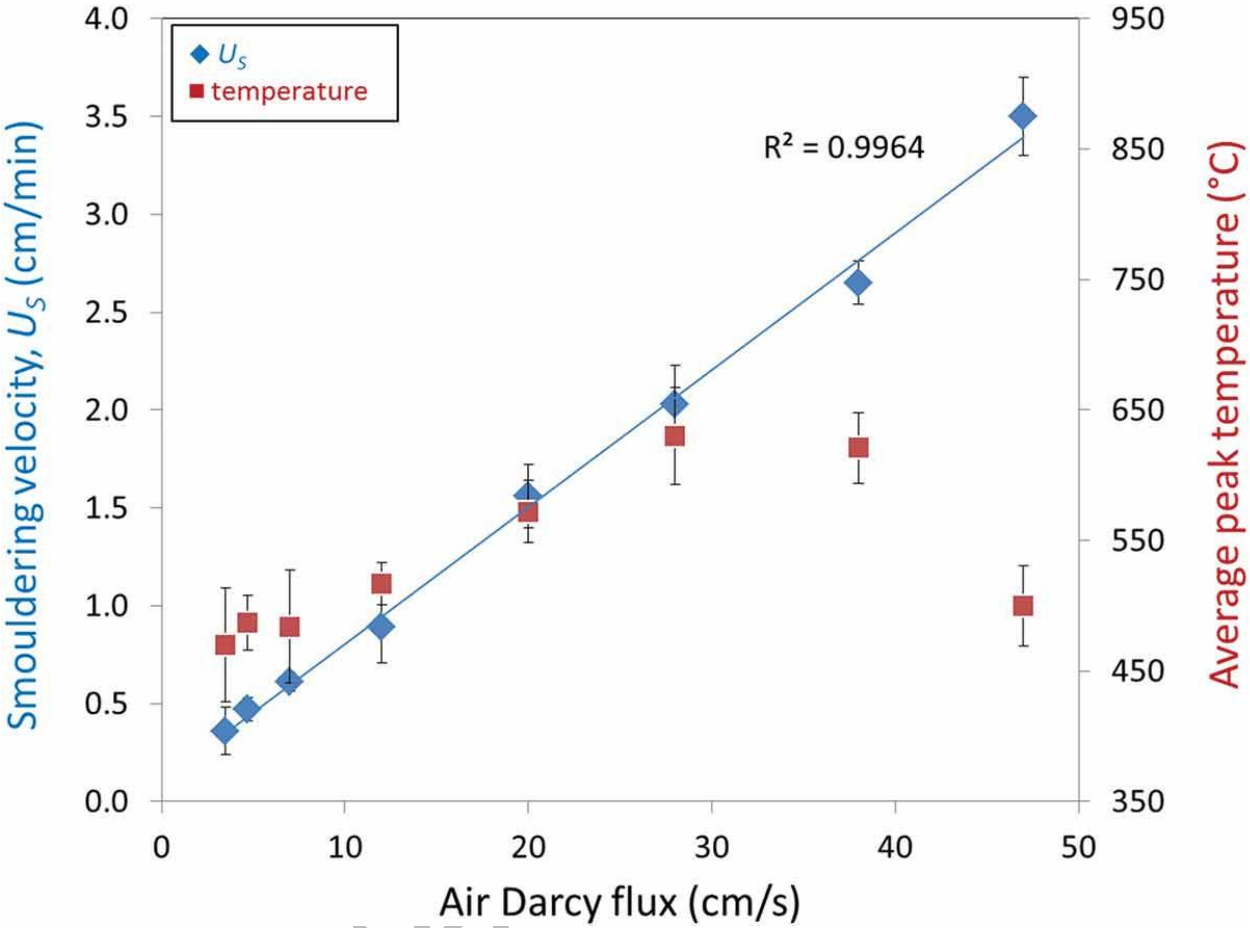

Figure 6. Average peak temperature and smouldering velocity as a function of the average sand particle size.

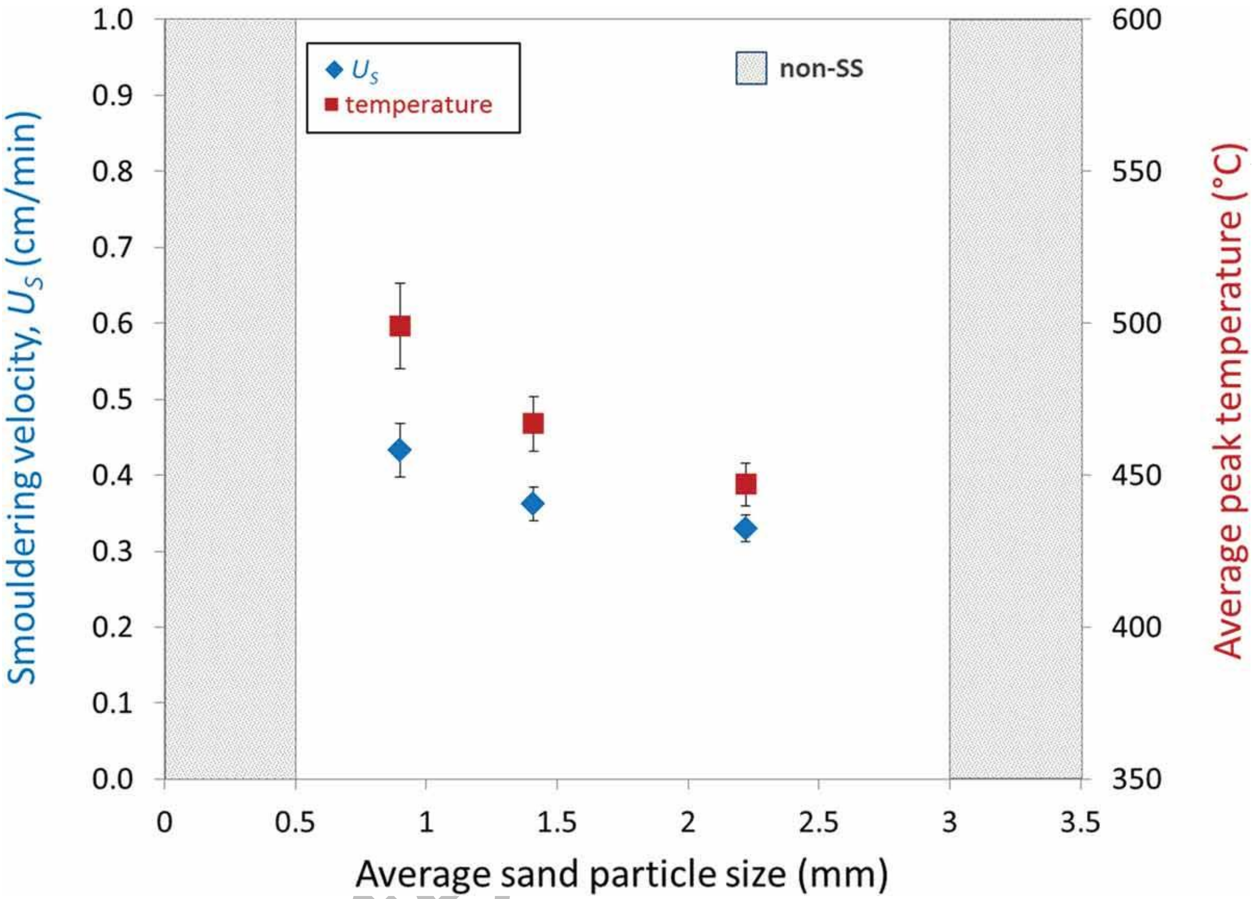

Figure 7. Average peak temperature and smouldering velocity as a function of the ignition temperature.

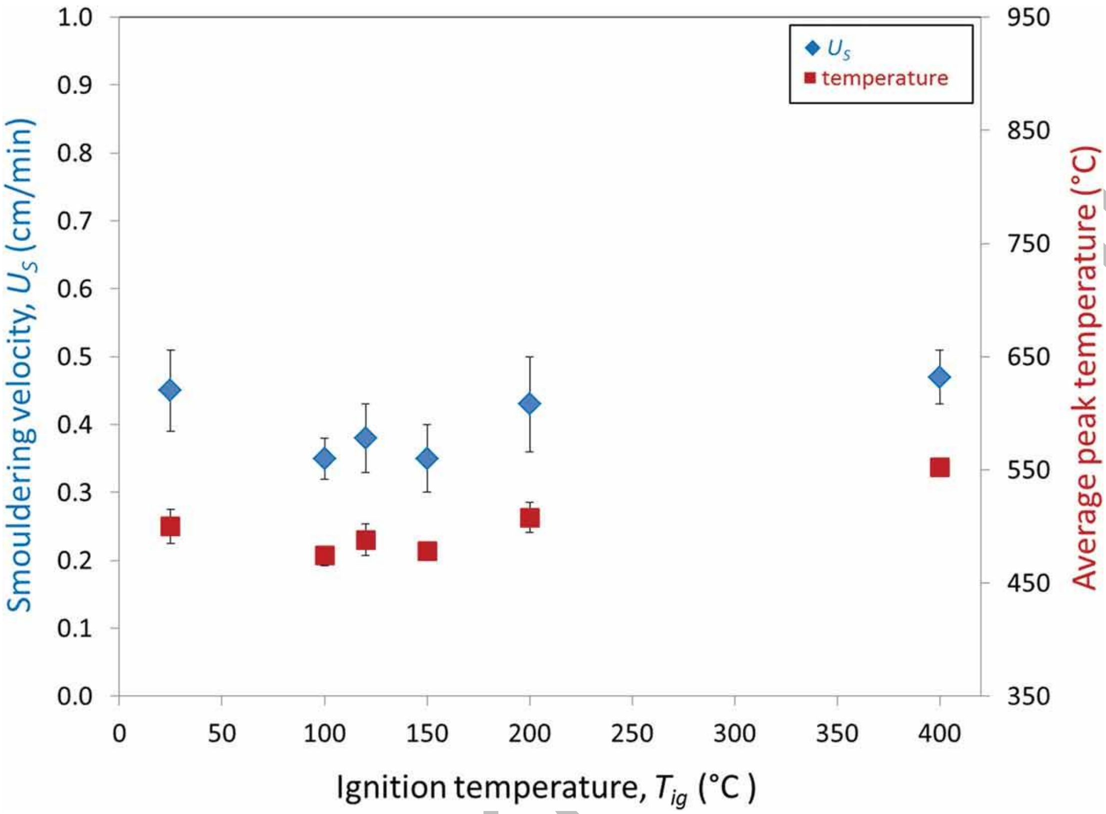

Table 1. Summary of smouldering experiments of faeces mixed with sand.

Variable	Exp.	Sand size (mm)	MC (%)	S/F (g/g)	Air (cm/min)	T_{ig} (°C)
Moisture content	1	0.9	64	24	3.0	250
	2	0.9	67	24	3.0	250
	3	0.9	69	24	3.0	250
	4	0.9	71	24	3.0	250
	5	0.9	72	24	3.0	250
Sand content	6	0.9	50	4	3.5	250
	7	0.9	50	6	3.5	250
	8	0.9	50	8	3.5	250
	9	0.9	50	12	3.5	250

	10	0.9	50	16	3.5	250
	11	0.9	50	20	3.5	250
	12	0.9	50	24	3.5	250
	13	0.9	50	28	3.5	250
Air Darcy flux	14	0.9	50	24	3.5	250
	15	0.9	50	24	4.7	250
	16	0.9	50	24	7.0	250
	17	0.9	50	24	11.7	250
	18	0.9	50	24	20.0	250
	19	0.9	50	24	25.0	250
	20	0.9	50	24	38.0	250

	21	0.9	50	24	46.7	250
Sand grain size	22*	0.3	67	24	7.5	120
	23	0.9	67	24	7.5	120
	24	1.3	67	24	7.5	120
	25	2.2	67	24	7.5	120
	26*	4.5	67	24	7.5	120
Ignition temperature	27	0.9	67	24	7.5	25
	28	0.9	67	24	7.5	100
	29	0.9	67	24	7.5	120
	30	0.9	67	24	7.5	150
	31	0.9	67	24	7.5	200

	32	0.9	67	24	7.5	400

*experiments not-SS

Table 2. Smouldering velocity (U_S) and average peak temperature for two smouldering experiments (three repetitions). Experimental conditions: Experiment A (from Yerman et al., 2015) - 70% MC, 12.5 g/g S/F, air Darcy flux 7.5 cm/s, 0.9 mm sand size and 400 °C T_{ig}. Experiment B - 33% MC, 16 g/g S/F, air Darcy flux 11.7 cm/s, 0.9 mm sand size and 250 °C T_{ig}.

Experiment	A			B		
Repetition	1	2	3	1	2	3
Us (cm/min)	0.22 ± 0.07	0.25 ± 0.03	0.17 ± 0.02	1.26 ± 0.04	1.20 ± 0.02	1.25 ± 0.03
Average temperature (°C)	576 ± 45	529 ± 39	538 ± 46	578 ± 18	615 ± 25	585 ± 16

Table 3. Type and grain size of sand used in the experiments.

Porous medium	Nominal size (mm)	Mean size (mm)
Fine sand	0.1 - 0.5	0.31
Medium sand	0.6 - 1.2	0.90
Coarse sand	0.8 - 1.8	1.41
Coarse sand 2	1.5 - 3.0	2.22
Gravel	3.0 - 6.0	5.50