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Smouldering combustion as a treatment technology for faeces: Exploring the parameter space

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HIGHLIGHTS

- Faeces mixed with sand can be smouldered in a self-sustaining process.
- This process achieves elimination of biological hazards.
- A robust self-sustaining region for different parameters is identified.
- Is promising as the basis for a new, energy efficient waste treatment approach.

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ABSTRACT

The poor management of human excreta in developing countries is among the most prominent global issues due to its negative impact on public health. This work demonstrates for the first time that self-sustaining smouldering of faeces mixed with sand is a feasible alternative to incineration for rapid destruction of waste. Self-sustaining smouldering requires minimal energy input and pre-drying of faeces compared to incineration. This process ensures the elimination of biological hazards via long residence times (>20 min) at high temperatures (>400 °C). Surrogate faeces which exhibits similar energetic, thermal, and mechanical properties to real faeces are used in this study. The parameters controlling the combustion process including moisture content, airflow rate, and sand-to-faeces ratio are mapped to establish the range of conditions where self-sustaining smouldering of faeces can be achieved. Experiments were conducted within the ranges 0–75% for moisture content, 7–108 g/min for airflow rate and 2.75–11.9 g/g for sand-to-faeces (wet basis) ratio. Preliminary validation of the parameter space is done using real dog faeces. In this work, the parameter space defining the range of conditions where self-sustaining smouldering occurs is mapped. Results show successful self-sustaining smouldering of faeces for moisture contents of up to 60%, airflow ranging from 10 to 100 g/min, and wet sand-to-faeces ratio greater than 3.25. This proof-of-concept for a smouldering reactor to treat human solid waste demonstrates that smouldering of faeces could be the basis for a new, energy efficient waste treatment approach.

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1. Introduction

Proper waste management has been identified as one of the global challenges of this century. Incineration and landfilling are the most common methods of waste disposal across the world. Incineration is growing in relative importance [1], being preferred in countries with limited space [2]. Among the most complex waste management processes is the disposal of human excreta. More than 40% of the global population routinely practice open

Abbreviations: DTG, derivative thermogravimetry; MC, moisture content (%); S/F, sand-to-faeces mass ratio (g/g); SS, self-sustaining; TC, thermocouple; TGA, thermogravimetric analysis; T_{peak}, peak temperature recorded in a thermocouple (°C); T_{peak_max}, maximum peak temperature recorded in a thermocouple (°C); U_S, smouldering velocity (cm/min); U_{S_max}, maximum smouldering velocity (cm/min).

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defecation due to lack of adequate sanitation facilities [3]. In developing countries, more than 50% of the urban population have no access to basic sanitation [4]. Poor sanitation is related to many public health problems [5]. Existing approaches to the destruction of human faeces are limited by cost, ineffective sterilization capacity, or practicality [5,6]. Due to the need for rapid destruction and sterilization of the waste, an incineration treatment is often proposed. However, incineration is based on flaming combustion which is associated with high energy losses and continual addition of external fuel. Moreover, the high moisture content (MC) of faeces (75–85%) [7] results in a very low effective calorific value, necessitating substantial pre-drying or the use of supplemental fuel to avoid quenching of the combustion reaction [8,9]. Either of these additional steps makes conventional incineration expensive and energy intensive. Smouldering combustion overcomes these limitations by efficiently transferring the heat generated by the heterogeneous reaction to the unburned fuel, enabling comparable time scales of combustion and heat transfer [10].

To maximise the process efficiency, a one dimensional forward smoulder is used. In forward smouldering, the oxidizer flow and reaction front move in the same direction thereby allowing the heat released by the reaction to be captured by the porous medium and carried forward by the combustion products to preheat the fuel ahead of the front. The energy efficiency of forward smouldering allows for extended quenching limits when compared to the contrasting case of opposed smouldering (in which the airflow is in the opposite direction to the smouldering front propagation) [11]. The reaction rate of smouldering combustion is known to be controlled by the mass flow of oxygen to the smouldering front [11,12].

This paper examines, for the first time, the potential for using smouldering to treat human faeces. This feasibility study is in response to the *Reinvent the Toilet Challenge* launched by the Bill and Melinda Gates Foundation in 2011. The dimensions of the reactor were chosen to accommodate the faeces produced by 10–20 people per day, according to the aims of the foundation. This proof-of-concept for a smouldering reactor to treat human faeces is part of a new integrated, low cost, on-site sanitation system aiming to disinfect human waste within 24 h using minimal resources [13].

1.1. Smouldering combustion

Smouldering combustion is a slow, low-temperature, flameless, oxygen-limited form of combustion driven by the energy released by oxidation of a solid phase fuel [12,14]. It has been studied for a wide range of fuels from a fire safety perspective [15,16], including polyurethane foam [17], biomass [14,18], peat [19], and cotton [20].

Smouldering requires that a fuel be porous as this promotes a high surface area for heat and mass transfer, insulates the reaction front to reduce heat losses, and allows the flow of oxygen to the reaction zone. In the case of liquid or pasty materials (e.g. faeces), smouldering is possible when the fuel is embedded in a porous matrix (e.g. sand). Heat transfer from the reaction to unburned fuel initiates pyrolysis and evaporation before oxidation occurs. Smouldering propagation will occur when the oxidation reaction is sufficiently strong to overcome the heat required for pyrolysis and heat losses. When the reaction is far from its quenching limits, the rate of propagation is directly related to the rate of oxidizer supply to the reaction zone [11]. Close to quenching limits, small perturbations in the fuel characteristics, airflow or heat loses will lead to quenching.

Rein et al. [21] investigated the effect of moisture content, between 46% and 62% (wet base), on the ignition of boreal peat. The critical moisture content for the ignition of this boreal peat was found to be 55%. He [18] also studied the influence of the moisture content and the fuel particle size on the natural downward smouldering of corn stark and other biomass sources. No alterations were observed in the characteristics of the smouldering (temperature, velocity) within the range 0–21% of moisture content. Frandsen [22] showed that the inert porous media and moisture content affect whether sustained smouldering will occur in organic soils. An inorganic content of 81.5% and a moisture content of 33% (wet base) were the ignition limits found. The effect of permeability of the porous media has been studied by Pironi et al. for the smouldering combustion of coal tar [23]. Increasing the grain size was shown to significantly reduce the peak temperature and the rate of propagation up to quenching. Self-sustaining smouldering was not observed using 10 mm gravel in a 15 cm diameter column. That work also examined the influence of water content, where water filled-porosity external to the non-aqueous coal tar fuel resulted in lower peak temperatures and front velocities but did not impede self-sustaining smouldering in the 15 cm tall column. Increased oxygen mass flux has been shown to result in an increase in the smoulder spread rate [17,23–25]. Smouldering temperatures and quenching limits were demonstrated to be a complex function of oxygen supply, convective heat transfer and the thermal properties of the porous medium [17].

1.2. Application of smouldering as a treatment for faeces

The high moisture content of faeces makes this fuel challenging due to its low calorific content (~4 kJ/g (considering moisture content 75%) compared to ~30 kJ/g for coal [26] and to ~20 kJ/g for wood [27]). Little is known about the smouldering characteristics of this fuel. A porous matrix is created with the necessary heat retention and air permeability properties for smouldering combustion by mixing the faeces with sand. Sand is used here because it is a low cost commodity in developing countries and because it has been identified as an effective agent for increasing the porosity of fuels for application to smouldering treatments [24].

To manage the regulatory challenges of working with real faeces and to control the experimental variables, a non-hazardous surrogate faeces is used for the majority of the experiments. Forty-seven experiments are carried out with the surrogate faeces to determine the limits of self-sustaining smouldering across a range of moisture contents, sand to faeces mass ratios (S/F), injected airflow rates, and amount of faeces (packed height). The results include peak temperatures and smouldering velocities as a function of these variables. Eleven experiments with dog faeces are also conducted to confirm consistent results between the surrogate and real faeces. Dog faeces were selected because it contains minimal human pathogens. Overall, this work serves as an initial investigation into the feasibility of applying this approach in a waste treatment system.

2. Experimental procedure

Upwards forward smouldering combustion experiments are done within a purpose-built reactor illustrated in Fig. 1. The column is cylindrical (16 cm inner diameter, 100 cm height), placed over a stainless steel base which houses a spiral-coiled heater (Incoloy-sheathed, 2.2 × 4.2 mm cross-section) and air diffuser. The air diffuser consists of a ring-shaped tube perforated with six pairs of diametrically opposite holes. These components are covered with layers of coarse gravel, fine gravel, and sand to ensure uniform airflow. The heater is embedded beneath the upper surface of the sand layer. The column is then filled with the sand–faeces mixture up to the desired height before a final 2 cm layer of clean sand is placed atop.

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