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Continuous, self-sustaining smouldering destruction of simulated faeces

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ABSTRACT

A new approach for the rapid destruction of human waste using smouldering combustion is presented. Recently, self-sustaining smouldering combustion was shown to destroy the organic component of simulated human solid waste and dog faeces resulting in the sanitization of all pathogens using a batch process (Yermán et al., 2015). Here, a continuous smouldering process is demonstrated for the first time, allowing for a much smaller reactor size and much less energy input per mass of waste treated. The self-sustained smouldering of simulated human faeces mixed with sand is evaluated over long periods (more than 16 h) based on a single ignition. The key process of intermittent self-sustained smouldering, in which the reaction is terminated and restarted by only turning the air off and on, is demonstrated. Experiments examine the influence of two key operator controls: airflow rate and set elevation of the quasi-steady-state smouldering front in a 37 cm high reactor. Quasi-steady-state fuel destruction rates from 93 g/h to 12 g/h were achieved by varying the superficial flow velocity from 7.4 cm/s to 0.11 cm/s, the latter with a velocity approximately an order of magnitude lower than possible for a self-sustaining reaction in an equivalent batch system. Excess energy of up to 140 J/g of sand was recovered from the clean sand produced in each cycle, which could be used to further increase the energy efficiency of this novel waste treatment system.

1. Introduction

A technology is needed that is capable of the rapid and inexpensive destruction of human excreta as a sanitary solution for developing countries [2]. This is due to the adverse effects that human waste has on public health [2,3]. Current treatment methods such as composting and pit latrines are problematic: their long term storage of the waste, combined with poor construction and lack of maintenance results in the leakage of pathogens that contaminate ground and surface waters [3]. The expensive sewage infrastructure and treatment plants common in industrialized countries are infeasible for developing countries.

Incineration and pyrolysis units have been proposed as possible solutions. However, the high moisture content of human faeces, which varies between 65% [4] and 85% [5] wet-basis for a healthy person, reduces its net energy content and therefore requires drying. For instance, the energy content of a faeces sample was measured to be 5.9 kJ/g wet (75.6% moisture content) and 24.3 kJ/g dry [6]. A small scale incinerator tested by Niwagaba et al. [7] concluded that faeces had to be dried to below 10% moisture content and use supplemental fuel for optimal operation. In a pyrolysis unit, the feaces needs to be heated to between 300 °C and 750 °C [8]. Pyrolysis is an endothermic reaction, requiring input energy to drive the reaction, in addition to the energy consumed in drying and heating the fuel. Both incineration and pyrolysis are energy intensive solutions, which increases their operational cost.

Smouldering combustion has the potential to be a low energy, low cost, effective method to destroy faeces. Smouldering is a heterogenous oxidation reaction that takes place on the surface of the fuel. The reaction is limited by the rate of oxygen that can diffuse into the fuel surface [9,10] resulting in low temperatures and slow reaction rates relative to flaming combustion. Smouldering is characterized as self-sustaining when the oxidation reaction generates enough energy, in the form of heat, to overcome heat losses and sustain the propagation of the reaction indefinitely [11].

Smouldering typically occurs in porous materials such as charcoal, peat [12], and polyurethane foam [13]. Organic solids and liquids that exhibit minimal permeability to air will not smoulder. However, they can be susceptible to smouldering when

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commingled with an inert porous material to create a permeable mixture [14]. This was demonstrated in a bench-top batch reactor for coal tar [15], industrial organic liquid contaminants present in soil [14,16] and most recently, for bio-solids waste from wastewater treatment plants [17].

A simplified illustration of the smouldering processes is presented in Fig. 1. The temperature (T) and oxygen profiles (Y_{O_2}) are plotted alongside a depiction of the corresponding regions within the reactor: treated sand zone, smouldering zone, pyrolysis zone, and preheating zone. The smouldering zone consist primarily of smouldering char while the pyrolysis zone corresponds to a complex series of primarily endothermic reactions ahead of the smouldering front. The effective heat transfer between the smouldering reaction and fuel allows for higher quenching limits (i.e., less energy content, higher moisture content) than possible for flaming combustion [18,19].

Forward smouldering as a means to treat human faeces was demonstrated in a batch reactor by Yermán et al. [1]. In that work, smouldering of faeces mixed with sand was shown to destroy all the organic component of the mixture, both with simulated human faeces and dog excreta, while sanitizing all pathogens via long residence times (>20 min) at high temperatures (>400 °C) [1]. The study found self-sustained smouldering can be achieved in a batch reactor for Darcy fluxes (i.e., volume of air per cross sectional area of reactor per time) between 0.6 cm/s and 6.5 cm/s and sand-to-fuel ratios between 2.75:1 g/g and 11.9:1 g/g wet basis. The maximum moisture content that can be smouldered in a batch process was found to be dependent on the fuel pack height: 60–70% for a pack height of 98 cm and 75% for a pack height of 30 cm. Energy production from the exothermic oxidation reaction using high moisture content fuel is one of the main advantages of this process. The recovery of energy from condensable emissions may also be able to enhance the efficiency of this technology [20].

All previous work has used intentional smouldering treatment as a batch process. In the context of designing a toilet in accordance with the Reinvent the Toilet Challenge [2], a continuous process would have numerous benefits. For example, external energy for ignition would be required much less frequently. Also, ther reactor could be much smaller, since storing waste for periodic batch treatment is unnecessary. Furthermore, the ability to continuously vary the destruction rate would allow a continuous system to adjust to variability in usage and loading rates.

The goal of this work is to demonstrate and quantify the performance of the first continuous, self-sustaining smouldering process. The objectives to achieve this goal include (1) demonstrating "intermittent self-sustained smouldering", in which the reaction is terminated and reignited without adding energy, (2) quantifying the metrics of a continuous smouldering reaction and comparing those to a batch system, and (3) quantifying the recoverable heat from the discharged, treated sand. The scale of the experiments in this work at are at the full scale of intended application: a single family toilet. Overall, this work lays the foundation for continuous, low energy solid waste treatment.

2. Experimental method

2.1. Apparatus

The apparatus has a similar layout as the batch reactor used in [1] but is modified to allow the extraction of sand from the bottom. The smouldering reaction occurs in a cylindrical 304 stainless steel reactor 37.2 cm tall with an inner diameter of 6.25 cm and a wall thickness of 0.05 cm. The length of the reactor was insulated with alumina-silicate fiber insulation (Fiberfrax manufactured by Unifrax) housed in a stainless steel jacket with an inner diameter of 16.5 cm. A plug heater, consisting of two 200 W Zesta cartridge heaters (0.64 cm diameter × 5.6 cm length), is inserted 3.5 cm above the bottom of the sand bed. This is the full scale system, designed for the treatment of the waste from a single family.

The reactor is instrumented with nine thermocouples, evenly spaced 2.54 cm apart vertically, starting 6.0 cm above the bottom of the sand bed. The thermocouples (Omega K-type KMQIN-125U-6) are inserted into the reactor horizontally approximately 7 ± 2 mm from the reactor wall. It is acknowledged that most studies have used centerline thermocouples in batch reactors and a comparison between centerline and near-wall temperatures during smouldering is included. The temperature is recorded with an Agilent Technologies 34980A Multifunction Switch-Measure Unit sampling every 2 s. The rate of airflow pushed through the reactor is set using a mass flow controller (Omega FMA5423) with a range of 0–15 standard liters per minute (SLPM).

The carbon monoxide, carbon dioxide, and oxygen concentration of the emissions were measured for select experiments using an ADC MGA3000 Gas Analyzer. The gas was measured in real-time

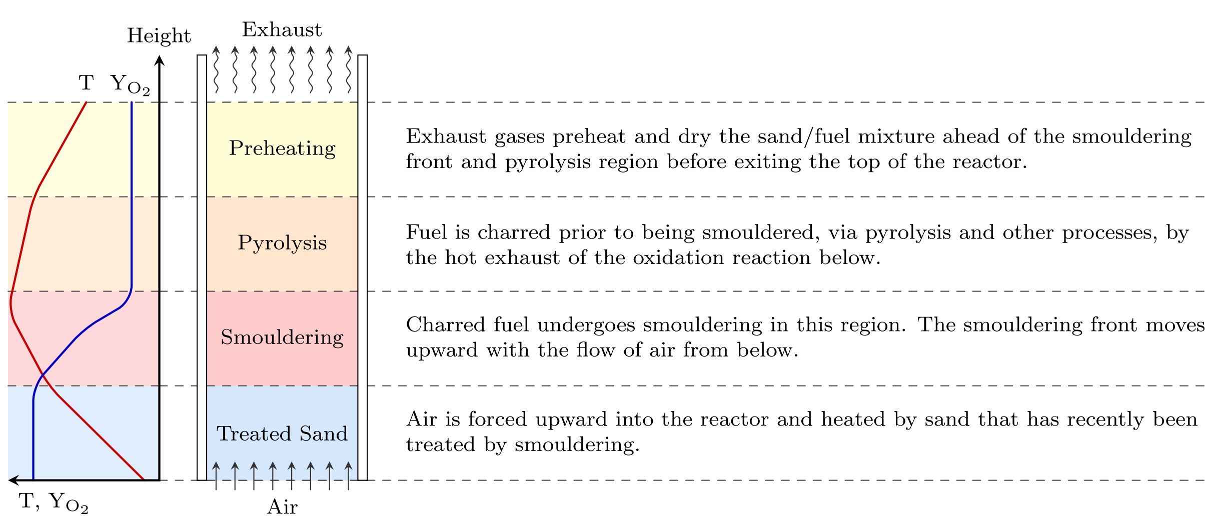

Fig. 1. Illustration of the different processes occurring in the smouldering reactor at steady-state shown alongside a simplified plot of the corresponding temperature (T) and gas stream oxygen concentration (Y_{O_2}) versus reactor height. The temperature profile is of a continuous process and differs from a batch reaction (shown in [20]). The regions are not to scale.