Research Paper

Treatment of fecal matter by smoldering and catalytic oxidation

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ABSTRACT

There is a strong need for transformative sanitation systems in the areas of the world where open defecation habits and/or inadequate sewage treatment methods and facilities exist. This paper describes an innovative thermally efficient solid waste treatment process as a basis for an off-the-grid, non-sewered toilet in order to address this need. Human feces are combusted in a continuous-cyclic manner using two stages of smoldering and catalytic oxidation. It has been shown that thermal coupling of the two stages creates a self-sustained reactor that can combust wet fecal material containing up to 3.2 parts water to 1 part dry matter – equivalent of water content in healthy human feces – without the need for external heating, known as the ultimate challenge in direct combustion of human feces. Furthermore, it has been shown that air flow rate can be reliably used as a controlling mechanism for fecal destruction rate which means the same reactor could be operated for various and varying input rates. The present work demonstrates the potential for manufacturing low-cost, low-energy consuming sanitation systems that are more easily accessible to communities in need of such systems.

Key words | catalytic oxidation, combustion, feces, non-sewered toilet, sanitation, smoldering

ABBREVIATIONS

| FDR | Fecal destruction rate (g/h) |
| HHV | Higher heating value (kJ/g) |
| MDF | Media to dry feces (g/g) |
| MC | Moisture content (%) |
| TC | Thermocouple |
| VOC | Volatile organic compounds |
| WDF | Water to dry feces (g/g) |

INTRODUCTION

Globally, 2.6 billion people do not have adequate access to basic sanitation services, exposing them to risk of diarrheal diseases (WHO UNICEF 2015) that result in 2.5 million preventable deaths a year (Boschi-Pinto et al. 2008; Prüss-Üstün et al. 2008). Even with onsite sanitation facilities, e.g., ventilated pit latrines or connected sewerage systems, inefficient emptying and transport, illegal dumping, leakages in sewerage lines, or ineffective central processing can expose the population to health risks. A household-scale sanitation system in which pathogens are destroyed at source would completely obviate traditional fecal sludge management processes and remove the risk of environmental pathogen contamination and human exposure to health risks downstream.

Previous experimental studies have investigated hydro-thermal carbonization (Danso-Boateng et al. 2013; Afolabi et al. 2017), pyrolysis (Ward et al. 2014; Ilango & Lefebvre 2019), composting (Bundy et al. 2000), chemical disinfection (Tudorache et al. 2011), and incineration (Merali et al. 2005) as potential methods for treating human feces. Each of these methods has its own set of challenges and limitations, particularly with respect to cost, energy consumption, and the need for external heating which is a major challenge in the combustion of human feces. However, the development of more efficient and lower-cost sanitation technologies is of high urgency in order to address the global sanitation crisis.
combustion (Monhol & Martins 2015) and smoldering combustion (Yerman et al. 2015, 2016; Onabanjo et al. 2016; Fabris et al. 2017; Somorin et al. 2017; Jurado et al. 2018) as ways to process human waste. Of the aforementioned methods, smoldering has several advantages. Characterized by low combustion temperature and slow burning rate, compared to flaming combustion, it is well suited for small-scale systems such as household toilets where the steady state fecal destruction rate (FDR) of a continuous process can be as low as 3 g/h of dry fecal mass per person (Tandon & Tandon 1975; Panigrahi et al. 2013).

Before the organic solid can be smoldered, it must lose its water content. Human feces contain a significant amount of water. For example, healthy feces are reported to have about 75% moisture content, while feces associated with diarrhea can contain more than 80% moisture content (Lewis & Heaton 1997). The water quantity in feces can be expressed in terms of percentage moisture content (MC) or water to dry feces (WDF). For example, 75% moisture content is equal to a WDF of 3, as per the equation below:

\[
WDF = \frac{MC}{(100 - MC)}
\]

One method that is especially efficient and convenient for in-situ convective drying and combustion of feces is updraft smoldering in a vertical column. Previous work reported by Yerman et al. (2015) describes a column-based updraft or forward smoldering combustion process that includes a mixture of the feces with a hard, granular, and non-combustible media in order to form a porous packed bed of granular material/feces. The existence of the granular media facilitates oxygen/feces contact by creating an interface through which heat can penetrate and vapors can leave. Examples of such media are sand and zirconium silicate. In previous work, sand was used as the granular media (Yerman et al. 2015, 2016; Fabris et al. 2017). Experiments were conducted using a batch column. The effect of moisture content, air flow rate, and sand-to-feces ratio on smoldering sustainability were investigated to establish the operating window in which self-sustained smoldering of surrogate feces could be achieved. The study showed that self-sustaining smoldering of simulated feces with a WDF of up to 1.5, airflow ranging from 10 to 100 g/min, and sand-to-feces ratio (wet basis) greater than 3.25 was possible. The results were validated using dog feces.

The objective of this present study is to investigate the possibility of continuous smoldering of human feces of WDF 3.2 in our improved system in a self-sustaining fashion meaning that no additional heat or fuel would be needed apart from the initial ignition.

**MATERIALS AND METHODS**

**Fecal matter**

Human stool samples were collected from adult volunteers and transported using Fisherbrand™ Commode Specimen Collection Systems, and frozen until use. The moisture content of feces samples were measured after they were thawed to make sure the freezing and thawing process did not affect the moisture content in such a way that would make the samples non-representative of fresh samples. While freezing and thawing might potentially have other effects on pathogen and microbial activity of human feces, in the context of this study which is smouldering, the only important effect is the feces moisture content that has been verified as representative.

**Surrogate feces**

In the early stages of the process development, as reported by Yerman et al. (2015, 2016), surrogate feces were used to demonstrate the feasibility of smoldering using a surrogate mixture with similar texture and calorific content, but lower water content. Even though the main goal of the present work is to demonstrate processing feasibility of human feces with WDF of 3.2 or higher, the major modifications done to the system warranted starting the tests using surrogate feces in the WDF range previously used as a reference material, and gradually switching to human feces of higher WDF. This gradual change in WDF allowed a better assessment of the expected improvements.

**Media**

As previously discussed in the Introduction, it is necessary to mix feces with non-combustible solid particles for smoldering (Yerman et al. 2015). In previous studies (Yerman et al. 2015, 2016), combustion (Monhol & Martins 2015) and smoldering combustion (Yerman et al. 2015, 2016; Onabanjo et al. 2016; Fabris et al. 2017; Somorin et al. 2017; Jurado et al. 2018) as ways to process human waste. Of the aforementioned methods, smoldering has several advantages. Characterized by low combustion temperature and slow burning rate, compared to flaming combustion, it is well suited for small-scale systems such as household toilets where the steady state fecal destruction rate (FDR) of a continuous process can be as low as 3 g/h of dry fecal mass per person (Tandon & Tandon 1975; Panigrahi et al. 2013).

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\]
et al. 2015, 2016; Fabris et al. 2017), sand was used as the granular media due to its low cost and abundance. However, its vulnerability to mechanical attrition make it unsuitable for continuous smoldering. Two chemically inert granular materials with higher resistance to mechanical attrition than sand, and comparable thermal properties, were identified: zirconium oxide (Zirbeads™116) and zirconium silicate (FOX Industries). In this study, zirconium oxide 1 mm spherical beads were used.

Catalyst

An egg-shell type catalyst composed of 0.5% platinum supported on 2 mm diameter alumina (Al₂O₃) spheres (Alfa Aesar 44796) was used in this study as this is an efficient catalyst for flue gas emissions such as CO and higher hydrocarbons (Shinogi & Kanri 2005).

Combined smoldering/catalytic oxidation reactor

The description of the main reactor sub-modules is given below.

Smoldering reactor

Smoldering takes place in a central vertical column of 75 mm inner diameter and 300 mm height. In manual operating mode, a premixed quantity of thermal media and fuel is fed at the top of the reactor or through a side port near the top.

For ignition, an electric band heater (Zesta Engineering Ltd), set to a maximum wattage of 360 W, wrapped around the bottom of the column (section below the catalyst), is used to heat the unburned fuel mixture until a temperature of 350 °C is reached at thermocouple 1 (TC1). At this point, airflow is introduced, and spontaneous ignition occurs initiating the smoldering process.

As smoldering progresses, the smoldering front propagates upwards in the column. Combustion of pyrolyzed char takes place in the smoldering zone, with peak temperature at the smoldering front typically in the range of 550–700 °C. Below the smoldering zone, the column consists of granular thermal media and ash residues from the smoldered feces.

Smoldering air is provided by a blower that pumps air through a port and the turntable gap at the bottom of the column as well as upwards through the column to provide oxygen to the surface of the fuel in the smoldering zone.

Figure 1 shows details of the reactor geometry and positioning of the thermocouples (TCs). In the present work, TC2 and TC3 are the designated lower and upper bounds of the smoldering front. The volume contained between these two TCs is the smoldering zone.

Turntable

To allow spent thermal media to be removed from the bottom of the column, a turntable is located at a specified distance (3 mm) below the bottom of the reactor column and forms the base of the reactor. When the turntable is rotated, media and residual ash are discharged from the reactor through the gap between the turntable and the bottom of the column.

Continuous-cyclic operation

In a truly continuous operation, smoldered media would be continuously discharged while a mixture of media and feces is either fed continuously to the top of the column, or fed separately and mixed in situ; and ideally, the smoldering front would be at a constant location, undisturbed by the downward flow of fuel mixture and smoldered media. For the experiments reported in this paper, the authors approximate continuous operation in a step-wise cyclical manner.

At the end of a smoldering cycle, and the beginning of a new cycle, a media/fuel mixture of desired WDF and media to dry fuel mass ratio (MDF), pre-mixed ex situ, is fed into the top of the reactor; and an equivalent quantity of smoldered media is discharged from the post-smoldering zone through the turntable. A ‘bed drop’ results from the simultaneous feeding and media discharge, and the smoldering front position is lowered from its position at the end of the previous cycle. As smoldering progresses in the new cycle, the smoldering front moves upwards until it reaches a pre-designated position, air flow is stopped to end the cycle, and the process is repeated for the next cycle.
Catalytic oxidation

Flue gases above the smoldering zone carry the various gaseous species produced during different stages of smoldering towards the top of the column. The gases are then directed via a duct to a catalyst module for further conversion. Auxiliary air is mixed with flue gases before entering the catalyst bed to prevent oxygen deficiency during the catalytic oxidation of CO and volatile organics.

These features were designed specifically to synchronize the catalytic and smoldering processes. Once catalytic conversion begins, exothermic heat release will maintain high temperatures and catalytic activity. In addition, since the optimal temperature range for the catalyst is between 500 °C and 650 °C, in the same approximate range as the temperatures in the smoldering zone, the vertical proximity of the catalyst bed and the smoldering zone helps to keep the catalyst temperature in the optimal range.

Finally, the exothermic enthalpy of reaction released in the catalyst bed results in high flue gas temperatures which are utilized for in-situ drying of the mixture before being transferred to the smoldering zone. This is achieved by directing the flue gases through an annular heat exchanger jacket wrapped around the upper part of the smoldering column. The in-situ drying capacity, enabled by heat recovery from post-catalytic gases, is the key to smoldering fuel with full moisture content without the need for a pre-drying step.

Experimental variables

In the experiments reported in this paper, 60 g of Pt/alumina egg-shell catalyst was placed in the catalyst module. Air flow rates of 3–9 L/min, MDF of 30, surrogate and human feaces of WDF in the range of 1–3.2 were examined. In the ignition phase, surrogate material with WDF of 1 was used. Once the smoldering was well established, and the ignition heater turned off, the WDF of surrogate was increased gradually in 0.25 increments to 2.25, at which point, partially dried human feces with WDF of 2.7 followed by full water content human feces with WDF of 3.2 were
used. The amount of dry matter in surrogate or human feces in each batch is fixed and is 13.5 g in this study.

RESULTS AND DISCUSSION

Characteristics of semi-continuous and post-smoldering catalytic oxidation

Temperature profiles of continuous-cyclic smoldering

Figure 2 shows typical temperature profiles of the new continuous system. The bed height in the reactor is equivalent to seven cycles meaning that seven batches of fuel/media mixture can fit into the reactor. However, by using the turntable to discharge ash and adding fresh fuel mixtures, the system is able to continue well beyond the initial loading of fuel without additional energy input after the initial ignition, and as long as fuel input continues, as can be seen in Figure 2 (top). During the initial ignition phase, the heater is on for about 2.5 hours, after which, it is turned off and the process is allowed to continue by itself. At the end of each individual cycle, there is ‘bed drop’, which means temperature at that particular point suddenly drops, so in Figure 2, the sudden drops of temperature are indicative of the end of each cycle. As the gradual transition from surrogate to human feces occurs, the cycle peak temperatures fall within the same approximate lower and upper bounds, which indicate the smoldering process remains robust as WDF increases to the maximum value of 3.2, as shown in Figure 2 (bottom). At WDF 3.2, 8 consecutive cycles are operated corresponding to treating 454 g of wet human feces.

Reactor design: post-catalytic oxidation and in-situ drying

The reactor used in this study has been designed to facilitate synergy between smoldering and catalytic oxidation processes. Once air flow is initiated and smoldering is ignited, and volatilized gases are produced above the smoldering zone, the catalyst in the catalyst module is already at a high enough temperature to catalyze the oxidation of CO and hydrocarbons in smoldering emission stream. Figure 3 shows the temperature scans in the catalyst bed and the smoldering bed at approximately the same vertical position over three typical cycles. The particular cycles shown in Figure 3 are from the portion of the experiment where surrogate fuel was being used but that does not change the point here because the same synergy was observed when smoldering human feces. Temperatures at TC3 in the smoldering zone increase with time in the early part of the cycle as the smoldering front approaches, but remain largely within the smoldering zone for the rest of the cycle at a nearly constant temperature until air is turned off and media discharge/bed drop is executed.

The temperature in the catalyst bed increases sharply when air is turned on at the start of a cycle and the flow of post-smoldering flue gas is re-initiated, sending reaction substrates to the catalyst module. Catalyst temperatures vary somewhat throughout a cycle, possibly due to non-uniform fuel compositions during the cycle. An upward trend is often seen towards the end of each cycle; a plausible explanation is that as the smoldering front moves upwards, there is less fuel above the front to be pre-dried, thus gas stream flowing to the catalyst is richer in fuel and leaner in water vapor.
When air flow is turned off and the flow of smoldering emissions stops, catalyst temperature also drops as expected. Note that at different times in the cycle, catalyst temperature can be either higher or lower than the smoldering bed temperature, so that heat transfer can be in either direction.

To take advantage of the hot post-catalyst emissions, a heat exchanger jacket was incorporated into the reactor design, wrapped around the smoldering column above the catalyst module. Thermocouples were placed just before, within, after the catalyst bed and after the heat exchanger, just before the emissions are directed towards the exit exhaust. The emissions post-oxidation catalyst are very low in terms of CO and volatile organic compounds (VOC) to levels which are safe and acceptable. However, it should be noted there are other pollutants such as NOx and SOx depending on the diet and operating condition, which need to be treated, but NOx and SOx treatment are beyond the scope of this study.

Effect of air flow rate on reactor performance

Figure 4 (top) shows the peak smoldering temperatures and catalyst temperatures as a function of air flow rate. In this range of air flow rates, increasing flow rate increases the rate of oxygen delivery to char, and hence the rate of reaction in the smoldering zone gives rise to increased peak smoldering temperature. As a result of increasing smoldering temperatures, pyrolysis and drying rates also increase. Catalyst temperature shows an even stronger dependence on air flow rate. With increasing air flow rate, FDR in the smoldering column increases, and the rate at which post-smoldering gaseous emissions flow to the catalyst module increases, giving the catalyst module higher feed rate. When a sufficient quantity of catalyst is present, the higher feed rate translates into a higher rate of heat release over the mass of the catalyst, and hence, higher catalyst temperatures.

Effect of air flow rate on FDR is shown in Figure 4 (bottom); as expected, FDR increases with increasing flow rate. Varying the air flow rate, we have shown good controllability of FDR in the ranges which relate to the daily generation rate of a community-scale toilet and getting close to a household-scale on the lower end. With an average generation rate of 3 g of dry fecal matter per hour per person, as mentioned in the Introduction, the FDR range in the bottom part of Figure 4 corresponds to the generation rate of between 15 and 45 people. This means that simply by changing air flow rate, it is possible to treat waste generated in that range continuously without the need for re-ignition.

CONCLUSIONS

In this study, the operating principle of a novel solid waste treatment process is detailed and results from experiments...
are presented. The previous design was updated in order to address experimental limitations and includes: (1) a turntable to discharge smoldered media and separate residual ash from feces incineration allowing the smoldering to run continuously; (2) post-smoldering catalytic oxidation converting fecal by-products to generate additional heat and mitigate gaseous emissions; and (3) utilization of the post-catalytic oxidation emissions to dry incoming fecal waste in situ.

The strategic placement of the catalyst ensures synergy between smoldering and catalyst where heat from the smoldering zone helps to keep the catalyst temperature in the optimal range (500–650 °C) to oxidize CO and hydrocarbons. The high temperatures of the flue gases as they leave the catalyst are further utilized to pre-heat and dry the fresh fuel mixture.

WDF is a key parameter in smoldering with strong influence on the peak temperature of the reactor. As expected, it was observed that the peak temperature decreased with increasing WDF since additional energy is required to heat the fuel mixture. In the current study, we were able to achieve self-sustaining smoldering with a fuel mixture of WDF 3.2, higher than healthy human feces of WDF 3.0.

This is accomplished due to the combined smoldering and catalyst oxidation processes and there is no need for separate drying equipment. Varying the air flow rate has shown good controllability of FDR (fecal destruction rate) in the ranges which relates to the daily generation rate of a household. This achievement has a significant impact on the energy efficiency of the system where no re-ignition of the smoldering process is required once the system is initially ignited. Results showed that to avoid oxygen deficiency in the catalyst, which reduces catalytic efficiency, flue gases need to be mixed with auxiliary air before entering the catalytic module. In order to achieve a high rate of conversion, the oxygen concentration in the gas mixture fed to the catalyst should not be allowed to fall below stoichiometric demand, plus a given margin to overcome mass transfer resistance, if present.

Overall, the novel system presented in this work was demonstrated to be capable of smoldering healthy human feces in a self-sustainable manner. The authors believe that this is a remarkable accomplishment that paves the way for access to low-cost, low-energy consuming household-scale toilets.

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