



Non-isothermal thermogravimetric kinetic analysis of the thermochemical conversion of human faeces

B. Fidalgo, M. Chilmeran, T. Somorin, A. Sowale, A. Kolios^{*}, A. Parker, L. Williams, M. Collins, E.J. McAdam, S. Tyrrel

School of Water, Energy and Environment, Cranfield University, MK43 0AL, UK

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ABSTRACT

The “Reinvent the Toilet Challenge” set by the Bill & Melinda Gates Foundation aims to bring access to adequate sanitary systems to billions of people. In response to this challenge, on-site sanitation systems are proposed and being developed globally. These systems require in-situ thermal treatment, processes that are not well understood for human faeces (HF). Thermogravimetric analysis has been used to investigate the pyrolysis, gasification and combustion of HF. The results are compared to the thermal behaviour of simulant faeces (SF) and woody biomass (WB), along with the blends of HF and WB. Kinetic analysis was conducted using non-isothermal kinetics model-free methods, and the thermogravimetric data obtained for the combustion of HF, SS and WB. The results show that the devolatilisation of HF requires higher temperatures and rates are slower those of WB. Minimum temperatures of 475 K are required for fuel ignition. HF and SF showed similar thermal behaviour under pyrolysis, but not under combustion conditions. The activation energy for HF is 157.4 kJ/mol, relatively higher than SS and WB. Reaction order for HF is lower ($n = 0.4$) to WB ($n = 0.6$). In-situ treatment of HF in on-site sanitary systems can be designed for slow progressive burn.

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1. Introduction

The Joint Monitoring Programme (JMP) for Water Supply, Sanitation and Hygiene reported that 32% of the global population had no access to basic sanitation services in 2015 [1]. In many developing countries, more than 90% of the faeces generated are not safely disposed, which poses serious health and environmental threats [1]. The “Reinvent the Toilet Challenge” set by Bill & Melinda Gates Foundation aims at the development and deployment of novel sanitary systems without connections to water, sewer and electrical supplies in order to ensure safe, affordable and sustainable sanitation solutions to people worldwide [2]. New concepts of sanitary systems have arisen as response to this challenge. The Nano Membrane Toilet (NMT), which is being developed at Cranfield University, is based on the recognition of human faeces (HF) as a fuel instead of a waste. The NMT includes the in-situ combustion of HF to produce energy for self-sustained operation of the unit [3]. HF is a carbon-based fuel which consists of a mixture

of undigested fat, protein, water, polysaccharide, bacterial biomass, gut secretions, cell shedding and ash [4], and can be converted into energy via gasification and combustion [3,5,6].

In order to efficiently use human faeces as feedstock of combustion units and achieve the advantages that it can bring as a fuel, more information and understanding of the thermochemical characteristics of this material is required. Thermogravimetric analysis (TGA) has been largely employed to investigate the thermal process of coal and biomass fuels, including animal manure and municipal and industrial sludges [7–18], with the objective of assessing the materials as fuel, establishing optimum operating conditions and investigating the kinetics of the process. Most of the published works focus on the co-processing of sludge with coal or biomass, exhibiting that co-combustion of these fuels can be viable from the energetic, economic and environmental point of view. Fewer examples of the thermal behaviour of individual sludge and manure fuels can be found in literature, and most of them are focused on pyrolysis [19–25]. Sanchez et al. [23] investigated the combustion of sewage sludge and animal manure by thermogravimetric analysis, and applied the Ozawa-Flynn-Wall (OFW) model to calculate the activation energy of the process. They concluded that the combustion of these biowastes is complex, changes with

^{*} Corresponding author.

E-mail address: a.kolios@cranfield.ac.uk (A. Kolios).

the degree of conversion, and is characteristic of each material; however, they found similar average activation energy (~140 kJ/mol) and average reaction order (~0.15) for the combustion of both the sludge and the manure. Abbas et al. [24] studied the combustion of dewatered sewage sludge and the kinetics of the process by means of OFW and the Vyazovkin models. They established average activation energy values for combustion (82 and 79 kJ/mol depending on the applied model). The authors also observed that the combustion reaction order varied with conversion and determined an average value of 0.11. Wu et al. [25] reported the combustion of dairy manure to occur in four stages, namely drying, first oxidation zone including the highest weight loss, second oxidation zone, and third oxidation zone related to the combustion of the char residue. The authors applied a kinetic model based on the Arrhenius equation and determined an activation energy value of 83 kJ/mol and reaction order of 5.24 for the first oxidation stage, and values of 56 kJ/mol and 1.25 for the second oxidation stage.

Pyrolysis, gasification and combustion behaviour of human faeces, and associated kinetic studies, have not been reported in literature. As previous work of our research group, Onabanjo et al. [5] carried out an experimental investigation of the combustion of human faeces in a bench-scale downdraft reactor and achieved fuel burn rates of 1.5–2.3 g/min at air flow rates of 10–18 L/min. Kinetic results obtained from sewage sludge and simulant faeces could be useful as initial approach to design systems for human faeces combustion; however, most of the available data refer to the thermal behaviour of blends of these materials with coal or biomass. Further research on the thermochemical behaviour of human faeces is essential in order to design the next-generation of non-sewered sanitary systems with in-situ thermal treatment, such as the NMT.

The aim of this work is to investigate the thermochemical conversion of human faeces by means of thermogravimetric analysis. Three different reaction atmospheres, i.e. N₂, CO₂, and air, were used to study thermal conversion under pyrolysis, gasification and combustion conditions. Samples of simulant faeces, woody biomass, and blends of human faeces and woody biomass were also evaluated for comparison purposes. Non-isothermal kinetics model-free methods are applied for the first time to assess the kinetics of combustion of human faeces. The research provides new data for understanding the thermochemical conversion of human faeces, which is fundamental to design onsite sanitary energy technologies, such as the NMT.

2. Material and methods

Human faeces were collected and stored in a freezer at 188 K (–85 °C) to prevent microbial degradation. The human faeces were collected, stored and manipulated under the approved procedures of the Cranfield University Research Ethics Scheme. Previous to testing, the frozen samples were thawed at room temperature and mixed until a uniform consistency was obtained. The homogenised human faeces sample was dried to a constant weight at 45 °C in a GENLAB Hot Air Oven. The thermal behaviour of HF was compared with those of simulant faeces (SF) and woody biomass (WB). SF was prepared using the recipe described elsewhere [5]. WB was sourced locally. In addition, the thermal behaviour of blends of the HF and WB samples were also analysed; the mixtures consisted of 50, 60, 70 and 80 wt% of HF.

The thermal behaviour of the samples was evaluated through a series of experiments carried out in a Perkin Elmer “Pyris 1” thermogravimetric (TG) analyser in duplicates. Thermal conversion was tested under three reaction atmospheres, i.e. N₂ for pyrolysis, CO₂ for gasification and air for combustion conditions. All tests were performed on 20 ± 0.5 mg of sample and 45 mL/min of gas flow

rate. The temperature was first set at 323 K for 1 min for weight stabilisation, and then constantly heated to a temperature of 1223 K. The sample was kept at the 1223 K for 2 min to ensure complete conversion. In the case of experiments performed with single samples, three heating rates were tested, namely 5, 25 and 50 K/min. All tests with HF and WB blends were performed at a heating rate of 50 K/min.

The mass ratio of the samples is expressed as given by equation (1).

$$R = \frac{m_t}{m_0} \quad (1)$$

where R is the mass ratio, m₀ is the initial mass of the sample, and m_t is the time dependent mass.

HF, SF and WB samples presented different content of ash. The ash content of WB was virtually negligible (0.6 wt%), while those of SF (13.5 wt%) and HF (19.7 wt%) were high. For comparative purpose, the mass ratio of the samples was calculated in dry ash free (daf) basis as shown in equation (2).

$$R' = \frac{m_t - m_{ash}}{m_0 - m_{ash}} \quad (2)$$

where R' is the mass ratio in daf basis and m_{ash} is the mass of ash established as the sample mass at the end of the combustion process.

Tests performed with single samples were labelled as X-Y-Z, where X refers to the type of sample (i.e. X = HF, SF or WB), Y refers to the reaction atmosphere (i.e. Y = N₂, CO₂ or air), and Z refers to the heating rate (i.e. Z = 5, 25 or 50 K/min). The analyses with blends were labelled as xHF-Y-50, where x refers to the percentage of HF in the mixture (i.e. x = 50, 60, 70 or 80) and, as above, Y refers to the reaction atmosphere (i.e. Y = N₂, CO₂ or air), and 50 refers to a heating rate of 50 K/min.

2.1. Determination of combustion kinetics

Non-isothermal kinetics were investigated through model-free methods, which are flexible to allow for changes in mechanism during the course of the reaction [23,27]. The rate of thermal decomposition gas-solid reactions can be described by equation (3) [23].

$$\frac{d\alpha}{dt} = k(T)f(\alpha) \quad (3)$$

$$\alpha = \frac{m_0 - m_t}{m_0 - m_f} \quad (4)$$

where α is the degree of conversion at any time calculated by equation (4), t is time, T is temperature, k(T) is the temperature-dependent kinetic constant, and f(α) is the derivative representation of the reaction model. In equation (4), m_f is the final mass of the sample.

The temperature dependence of the kinetic constant is described by the Arrhenius equation and the heating rate (β = dT/dt) can be inserted in equation (4) resulting into equation (5). This expression describes the rate of combustion reaction as a function of temperature at a constant heating rate.

$$\frac{d\alpha}{dT} = \frac{1}{\beta} A e^{-E_a/RT} f(\alpha) \quad (5)$$

where β is the heating rate, E_a is the activation energy in kJ/mol and A is the pre-exponential factor.

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