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# Conceptual energy and water recovery system for self-sustained nano membrane toilet

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ABSTRACT

With about 2.4 billion people worldwide without access to improved sanitation facilities, there is a strong incentive for development of novel sanitation systems to improve the quality of life and reduce mortality. The Nano Membrane Toilet is expected to provide a unique household-scale system that would produce electricity and recover water from human excrement and urine. This study was undertaken to evaluate the performance of the conceptual energy and water recovery system for the Nano Membrane Toilet designed for a household of ten people and to assess its self-sustainability. A process model of the entire system, including the thermochemical conversion island, a Stirling engine and a water recovery system was developed in Aspen Plus®. The energy and water recovery system for the Nano Membrane Toilet was characterised with the specific net power output of 23.1 Wh/kg$_{settledsolids}$ and water recovery rate of 13.4 dm$^3$/day in the nominal operating mode. Additionally, if no supernatant was processed, the specific net power output was increased to 69.2 Wh/kg$_{settledsolids}$. Such household-scale system would deliver the net power output (1.9–5.8 W). This was found to be enough to charge mobile phones or power clock radios, or provide light for the household using low-voltage LED bulbs.


## 1. Introduction

Although 2.1 billion people have gained access to improved sanitation facilities, which are likely to safely separate human excreta from human contact, since 1990, 2.4 billion people still use unimproved, shared facilities or practice open defecation [1]. It has been estimated that around 18% of urban population and 49% of the rural population still lacks access to the health benefits that improved sanitation facilities can provide [1,2]. This is because the conventional flush toilet, which is widely utilised in the developed countries, is a cost-, resource- and energy-intensive system. A requirement of collection, transportation, treatment and waste disposal processes, which require human resources, chemicals and water, among the others, imposes a considerable financial and environmental burdens on the urban and rural communities [3]. Poor sanitation systems lead to sewage and untreated residuals being released to the environment, which are often discharged directly into seas and rivers, and could infiltrate to the groundwater leading to pollution the surface and ground waters [4–7]. More importantly, open defecation and discharge of untreated residuals impose a significant hazard to human health in the immediate living environment [3,8]. It has been estimated that each year diarrhoea kills 1.4 million people [9] that could have been prevented through safe drinking water and ensuring adequate sanitation and hygiene [10]. For these reasons, revolutionary sanitary solutions enabling cost-efficient, human-safe and environmentally-friendly utilisation of human excreta need to be developed [11].

To improve access to affordable, safe and sustainable sanitation, the Reinvent the Toilet Challenge was established by the Water, Sanitation and Hygiene programme of the Bill & Melinda Gates Foundation. It aims to develop low-cost toilets for treating human excreta and recovering useful resources [2,11,12] without producing hazardous products. Recent studies performed by Onabanjo

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et al. [3], and Monhol and Martins [13] have proven that gasification and combustion are feasible thermochemical conversion processes to utilise the chemical energy of the settled solids from human excreta, which comprises wet faecal matter, regardless of their high moisture content. Moreover, Liu et al. [14] have proposed the self-sustained system for the settled solids from human excreta to power conversion that utilises plasma gasification and solid oxide fuel cells. Such a system was found to have the specific net power output of 194.4–357.3 $Wh/kg_{settledsolids}$, depending on whether the faecal matter was dried or not prior to plasma gasification. Alternatively, Parker [12] proposed a novel toilet concept that utilises a nano membrane for water recovery from supernatant, which is mainly composed of urine, and for energy recovery from settled solids to make the system self-sustainable. The thermodynamic performance of this concept has not been yet evaluated.

Considering the fact that the settled solids from human excreta were proven to be a viable energy source [3,13], this study proposes a conceptual energy and water recovery system for the Nano Membrane Toilet to evaluate the thermodynamic viability of the toilet concept proposed by Parker [12]. The proposed system is designed to process the human excreta from a household of ten people, considering the average input rates of the wet faecal matter and urine of 200 g per capita per day [15,16] and 1.5 $dm^3$ per capita per day [17,18], respectively. Using the equilibrium approach, which is commonly applied for modelling of thermochemical conversion of solid fuels [19–23], and employing the pseudo Stirling engine model in Aspen Plus®, the process performance is evaluated in terms of net power output, specific net power output, and water recovery rate. These parameters are considered as the key performance indicators for the entire system. Finally, the parametric study is performed on the main design parameters of the entire system under power and water priority modes, to analyse the system behaviour and to maximise the process performance.

## 2. Model development

### 2.1. Process description

The energy and water recovery system proposed in this study (Fig. 1) aims at recovering chemical energy from the settled solids from human excreta, which comprises wet faecal matter, and water from supernatant, which is urine, unbound and partially-recovered bound water from wet faecal matter. Although unbound water and urine can be separated from human excreta in the settling tank, the settled solids transferred to the reactor using a mechanical screw conveyor still comprise around 75–80 wt% moisture [12]. A further reduction of the moisture content to the level that is comparable to other kinds of biomass is achieved on drying the settled solids directly against the hot gas leaving the reaction chamber. It is expected that part of the bound water can be recovered during the drying process that is then mixed with the supernatant stream leaving the settling tank. Dried solids are then fed to the reactor that, depending on the amount of air fed to the reactor represented by an equivalence ratio (ER), operates under gasification (ER < 0.5) or combustion (ER ⩾ 0.5) regime [24–28]. Therefore, the chemical energy of the settled solids from human excreta can be converted to either chemical energy of synthetic gas that can be utilised in an internal-combustion engine or thermal energy for recovery in an external-combustion engine. In this study, it is conceptualised that a hot-site of the Stirling engine, which is the external-combustion engine known for quiet operation and ability to utilise even low-grade heat [29], is attached to the reactor wall and the cold-side is cooled with part of air leaving the air fan. It is predicted that such concept has a potential to generate sufficient amount of electricity for the entire system to become self-sustained. However, it needs to be highlighted that the amount of energy recovered by the Stirling engine is not only limited by the desired moisture content and temperature of solids leaving the dryer, it also depends on the amount of supernatant that needs to be preheated to the desired temperature for an optimum water recovery in the membrane.

### 2.2. Model description

The steady-state process model for the conceptual energy and water recovery system for the Nano Membrane Toilet developed in Aspen Plus® comprises two main components – the thermochemical conversion island, and the energy and water recovery island – and assumes an ideal behaviour of gases.

In the thermochemical conversion island, which was successfully validated by Onabanjo et al. [3], solid transport and thermochemical conversion are modelled using solids handling features available in Aspen Plus® [30]. Transport of settled solids is conducted using the screw conveyor. Whereas it can be powered through human endeavour, this study assumes the screw conveyor, which has a conservative specific power requirement of 0.056 $Wh/kg_{settledsolids}$ [31,32], is electrically driven by power generated in the Stirling engine. To accurately account for the composition of the settled solids, these are modelled as a nonconventional component with proximate and ultimate analysis provided in Table 1, and heating value determined from its composition using Dulong's formula.

The drying process is modelled as a stoichiometric reactor, in which the conversion of bound water to unbound water in settled solids is determined from the dryer material balance using the calculator block, with the desired moisture content of dried solids as an input parameter. By considering the flash separator in the dryer model, it is determined whether the amount of energy carried with hot gas entering the dryer is sufficient to remove desired amount of moisture.

Assuming that the residence time is sufficient for the system to reach chemical equilibrium, which is a common assumption in investigating the thermochemical conversion of solid fuels [19–23], a thermochemical conversion of dried solids is modelled using the Gibbs reactor, in which Gibbs free energy is minimised to determine the equilibrium composition of the product gas at given operating conditions. Yet, the Gibbs free energy cannot be calculated for dried solids modelled as a nonconventional component. Therefore, the Gibbs reactor is preceded by the yield reactor that is used to model the biomass decomposition into its constituents, for which the Gibbs free energy can be estimated. Importantly, to account for the heat of biomass decomposition, both reactors are connected with the heat stream. The operating regime of the Gibbs reactor (gasification or combustion) is determined by the amount of air fed via the air fan, which is modelled as a compressor with isentropic and mechanical efficiencies of 90% and 99.8%, respectively [34,35]. The air fan is employed to increase the air pressure by 15 mbar to account for the pressure drop throughout, and thus to reliably estimate the energy requirement of the entire energy and water recovery system.

The energy and water recovery island involves a heat exchanger network, in which the heat exchangers for air and supernatant (Table 1) preheating are modelled as counter-current heat exchangers characterised with a fixed temperature approach and a pressure drop of 5 mbar, the low glass-transition temperature hollow-fibre membrane that recovers water from the supernatant, and the Stirling engine that converts thermal energy to electricity. In the proposed concept, the energy requirement of the membrane stems from the power requirement to increase the pressure of sweep air pressure to overcome the pressure drop in the