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Probabilistic performance assessment of complex energy process systems – The case of a self-sustained sanitation system

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ABSTRACT

A probabilistic modelling approach was developed and applied to investigate the energy and environmental performance of an innovative sanitation system, the "Nano-membrane Toilet" (NMT). The system treats human excreta via an advanced energy and water recovery island with the aim of addressing current and future sanitation demands. Due to the complex design and inherent characteristics of the system's input material, there are a number of stochastic variables which may significantly affect the system's performance. The non-intrusive probabilistic approach adopted in this study combines a finite number of deterministic thermodynamic process simulations with an artificial neural network (ANN) approximation model and Monte Carlo simulations (MCS) to assess the effect of system uncertainties on the predicted performance of the NMT system. The joint probability distributions of the process performance indicators suggest a Stirling Engine (SE) power output in the range of 61.5–73 W with a high confidence interval (CI) of 95%. In addition, there is high probability (with 95% CI) that the NMT system can achieve positive net power output between 15.8 and 35 W. A sensitivity study reveals the system power performance is mostly affected by SE heater temperature. Investigation into the environmental performance of the NMT design, including water recovery and CO_2/NO_x emissions, suggests significant environmental benefits compared to conventional systems. Results of the probabilistic analysis can better inform future improvements on the system design and operational strategy and this probabilistic assessment framework can also be applied to similar complex engineering systems.

1. Introduction

In many developing countries, providing people with access to safe drinking water and hygienic sanitation facility is a key challenge to prevent the spread of infectious diseases. Globally, it is estimated around 2.4 billion people currently have no access to adequate sanitation facilities [1]. The conventional water flush toilet, widely available in the developed countries, is an inefficient use of water resources and requires intensive use of energy [2]. In addition, it requires public infrastructure including water supply, sewer and waste water treatment works, therefore is not feasible for low-income developing regions, including Sub-Saharan Africa. In densely populated urban areas, increasing the coverage of improved sanitation facilities is of particular urgency, due to the potential scale of disease outbreak. Sustainable 'off-grid' decentralised sanitation technologies are widely promoted by many international initiatives [3], as they are more suitable for regions with poor infrastructure. Sanitation systems such as rainwater-flushed-toilets, waterless urinals and composting toilets have been suggested in various studies as potential solutions to reduce or eliminate the use of potable water and improve rural health conditions [3,4]. Despite the availability of such technologies, there remain significant technical and societal barriers which hinder the wide application of these sanitation technologies. Therefore, there are still strong technological and humanitarian incentives for the development of novel sanitation systems to improve the quality of life and disease control.

The 'Reinvent the Toilet Challenge' of the Bill and Melinda Gates Foundation is set to develop affordable, next-generation sanitary systems that can work without connection to external water, energy or sewerage systems [5]. The Nano-membrane toilet (NMT) project developed at Cranfield University provides an example of such an innovative solution for an off-grid, household-scale toilet that is able to treat human waste safely onsite [6]. The NMT unit is designed to operate without external energy and water supply under steady conditions. It integrates a membrane to recover clean water from urine and a

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Nomenclature

φ	neuron output
θ	artificial neural network layer bias
y	artificial neural network output
f	neuron activation function
ER	equivalence ratio
w_i	artificial neural network node weight
u_i	stochastic variable
e_{NO_x}	specific NO_x emissions (in mg NO_x kW h_e^{-1})
e_{CO_2}	specific CO_2 emission (in mg CO_2 kW h_e^{-1})
$\dot{m}_{NO_x}$	rate of NO_x emission (kg s^{-1})
$\dot{m}_{CO_2}$	rate of CO_2 emission (kg s^{-1})
$\dot{W}_{net}$	net power output of the integrated system

compact energy conversion system to treat human faeces thermally. Recent studies confirmed that gasification and combustion are viable thermochemical technologies for the conversion of settled solids from human excreta into chemical or thermal energy [2,7,8]. Thus, the NMT has the potential to achieve self-sustained operation if energy recovery is optimised. Similarly to the development of any novel integrated process, process modelling is essential at the design stage to optimise the NMT system. Previous modelling efforts have focused on using thermodynamic equilibrium models [7], to simulate the thermochemical conversion of human faecal matter and to explore the thermodynamic viability of the NMT concept. Similar thermodynamic models have been applied widely to examine the conversion of various feedstocks including refinery sludge, sewage sludge and manure [9–11]. The traditional approach using deterministic data can reliably predict the system's performance under any specified operating conditions and feedstock characteristics. This provides insights into complex processes and allows the identification of critical parameters and optimum operating conditions [12,13]. A key limitation of such deterministic models is that they do not consider the effect of uncertainties of the input variables that are inherent in real life engineering systems, which are particularly relevant in the context of the NMT system, considering the highly stochastic properties of input variables (e.g. faeces and urine composition). Therefore, performance assessment using the deterministic approach provides an evaluation of the response of the system subject to fixed characteristic input values; however, it does not provide a definitive representation of the actual system's performance that is often subjected to random fluctuations in the external and internal operating conditions [14].

This study presents the probabilistic thermodynamic performance assessment of the energy and water recovery system of the NMT based on an improved thermodynamic model of the NMT system. The system uncertainties arising from the stochastic characteristics of the input variables and their impact on the predicted performance of the NMT system were evaluated using an updated version of the probabilistic performance framework [15,16] as shown in Fig. 1. This probabilistic modelling approach constitutes a non-intrusive formulation that sequentially combines a finite number of deterministic thermodynamic process simulations using artificial neural network (ANN) approximation models and Monte Carlo simulations (MCS) to map the response domain of the system under varying inputs. The outcomes of the analysis can enable a better interpretation of the system performance and support decisions for further optimisation from a design, operation and maintenance perspective. Novelty of this work is on the fact that the developed framework can be further applied in relevant complex engineering systems where uncertainties of inputs can significantly affect their performance and the use of ANNs can allow for confident evaluation of probabilities taking into account non-linear behaviour of performance indicators with respect to these uncertain inputs.

2. Methodology

2.1. Deterministic process & model description

The thermodynamic performance of the energy and water recovery system of the NMT unit is evaluated using a high fidelity deterministic process model, which is a revised version of the model described earlier by the authors [7]. All the processes both in the original and revised schemes were modelled in Aspen Plus simulation software (AspenTech Ltd., UK) using the thermodynamic equilibrium. The conceptual design of the NMT is shown in Fig. 2. Briefly, the urine, unbound water and partially-recovered bound water are first separated from human excreta by physical settlement to yield the supernatant and settled wet solids. The supernatant (primarily urine) is then purified by a hollow-fibre membrane to remove pathogens and odorous chemicals, whilst the settled wet solids are partially-dried in a dryer heated using the hot exhaust gas leaving the combustor, before entering a combustor for energy generation. This combustion process uses an excess of air to complete the conversion of the chemical energy in the settled solids to thermal energy. A SE is attached to the wall of the combustor (hot-end) and recovers thermal energy to generate electricity [17]. Membrane liquid-solid separation SE and the combustor enable the NMT unit to achieve its operational heat and power requirement, therefore maintaining a self-sustained operation.

Previous studies from this research group [2,7] have considered the use of steady-state process modelling to describe the conceptual energy and water recovery systems of the NMT. The models described in these studies consider: (i) the faecal solids and resulting ash to be non-conventional streams, and the gases to have ideal behaviour; (ii) the solid transportation of the settled solids via a conveying and dewatering screw with specific power requirement of 200 J/$kg_{settledsolids}$; (iii) the drying of the settled solids in a stoichiometric reactor coupled to a flash separator which receives the waste heat from the exhaust gas of the combustor; and, (iv) the thermochemical conversion of the partially-dried settled solids in a combustor using Yield and Gibbs minimisation-based reactors. Furthermore, the Pseudo-Stirling engine is considered to be an ideal cycle with an isentropic compressor and expander, and there

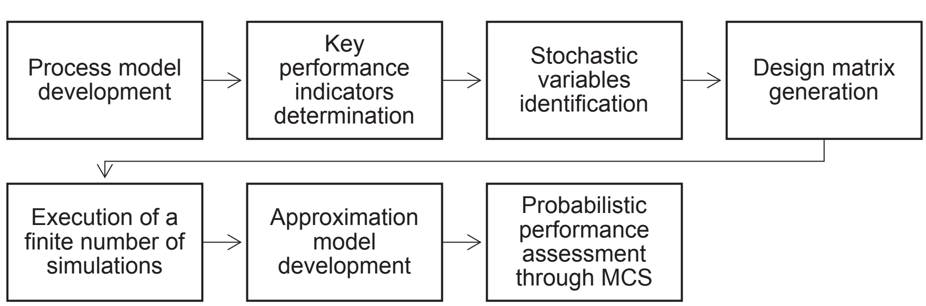

Fig. 1. Overview of the probabilistic performance assessment framework.