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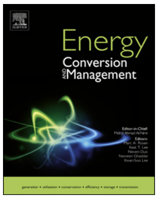

Thermodynamic analysis of a gamma type Stirling engine in an energy recovery system

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ABSTRACT

The demand for better hygiene has increased the need for developing more effective sanitation systems and facilities for the safe disposal of human urine and faeces. Non-Sewered Sanitary systems are considered to be one of the promising alternative solutions to the existing flush toilet system. An example of these systems is the Nano Membrane Toilet (NMT) system being developed at Cranfield University, which targets the safe disposal of human waste while generating power and recovering water. The NMT will generate energy from the conversion of human waste with the use of a micro-combustor; the heat produced will power a Stirling engine connected to a linear alternator to generate electricity. This study presents a numerical investigation of the thermodynamic analysis and operational characteristics of a quasi steady state model of the gamma type Stirling engine integrated into a combustor in the back end of the NMT system. The effects of the working gas, at different temperatures, on the Stirling engine performance are also presented. The results show that with the heater temperature of 390 °C from the heat supply via conduction at 820 W from the flue gas, the Stirling engine generates a daily power output of 27 Wh/h at a frequency of 23.85 Hz.

1. Introduction

Heat recovery and waste utilisation are rapidly advancing fields of research, due to the high priority currently given to energy generation and environmental sustainability. Waste heat from processing plants and the exhaust of engine systems is now typically recovered via an integrated energy system, and materials that would otherwise be considered as waste, are being explored for their energy potential. This is due to the increase in the demand for renewable energy production over the years as a result of increasing population and industrial development. Power generation (electricity) is the most feasible source of energy in the modern world and proves to be a drive for economic and human advancement. The recovery of energy from waste has been a primary target for power generation in recent years [1] and has paved the way for investigations into systems that can generate power from waste, especially for developing countries [2].

In the sanitation industry, the conventional flush toilet systems are undergoing a major design revision because of their extended infrastructure requirements such as sewer systems. Non-sewered technologies, often without or with limited necessity for flush water, are being investigated. Some of these novel toilet systems are described as functioning as thermochemical conversion units, where faeces are thermally treated to produce useful by-products [3]. It has been estimated that about 2.3 billion people in developing countries lack sufficient and suitable means of sanitation. A considerable reduction in mortality rate from outbreaks of infectious diseases in developed and developing countries could be prevented with improved and safer sanitation systems [4]. The Nano Membrane Toilet (NMT) is being developed to treat human waste into clean water and heat without the external supply of water, energy, and sewer. This unit requires the development of new technologies for power generation, and the use of human faecal material as an energy source is one example. The combined benefits of the novel systems embedded in this unit (i.e. membrane technology for urine filtration, and micro-combustor for continuous conversion of human faeces) can improve access to clean water and sanitation around the world, as well as enhance alternative and environmentally-friendly power generation for communities lacking basic amenities [5]. Therefore, heat recovery from combustion-based systems is important, and electrical energy is vital for the functioning of the self-sustaining/off-grid NMT system reliant on pumps and ignition systems.

Conversion of thermal energy to electrical energy in medium-scale commercial environments is mostly associated with gas engines, Rankine engines, microturbines, fuel cells and Stirling engines in a cogeneration system [6]. Heat recovery for power generation in

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Nomenclature

A_d	cross-sectional area of the piston (m^2)
A_p	cross-sectional area of the displacer (m^2)
C_{ap}	specific heat at constant pressure (J/kg K)
C_{av}	specific heat at constant volume (J/kg K)
diss	heat loss due to frictional flow in the heat exchangers (W)
K	Kelvin
k	thermal conductivity (W/m K)
m_d	mass of the displacer (kg)
m_p	mass of the piston (kg)
T_k	temperature of the cooler (K)
T_r	temperature of the regenerator (K)
T_h	temperature of the heater (K)
T_{ck}	temperature of the compression space to cooler (K)
T_{he}	temperature of the heater to expansion space (K)
T_{rh}	temperature of the regenerator to heater (K)
T_{kr}	temperature of the cooler to regenerator (K)
V_b	bounce space volume (m^3)
V_r	volume of the regenerator (m^3)
V_h	volume of the heater (m^3)
V_k	volume of the cooler (m^3)
V_e	volume of the expansion space (m^3)
V_c	volume of the compression space (m^3)
θ	crank angle (degree)
φ	phase angle (degree)
V_{clc}	compression space clearance volume (m^3)
V_{cle}	expansion space clearance volume (m^3)
V_{sd}	piston swept volume (m^3)
V_{sd}	displacer swept volume (m^3)
R	gas constant value
d	derivative
Q	heat transfer rate (W)
Q_{heat}	heat transfer rate in heater (W)
Q_{reg}	heat transfer rate in regenerator (W)
Q_{cool}	heat transfer rate in cooler (W)
Q_{cond}	heat transfer by conduction (W)
A_{fs}	free surface area (m^2)
P_e	pressure in expansion space (MPa)
P_c	pressure in compression space (MPa)
sht	shuttle loss (W)
lir	internal heat conduction loss (W)
Q_{hdiss}	heat dissipation loss due to friction in the heater (W)
Q_{rdiss}	heat dissipation loss due to friction in the regenerator (W)
Q_{kdiss}	heat dissipation loss due to friction in the cooler (W)
h	heat transfer coefficient (W/m^2 K)
Tq	torque (N m)

household-scale applications can be accomplished with the use of an external combustion engine such as a Stirling engine that can function by using the heat generated from a gas stream at high temperature. Stirling engines have been considered for cogeneration systems due to certain features that give them greater advantage over other reciprocating engines, such as low vibration, very low emissions, high efficiency and the ability to utilise different forms of energy [7]. Stirling engines also operate in a closed, regenerative thermodynamic cycle [8] and they have been employed in various applications, such as combined heat and power (CHP) production, solar power generation, heat pumps, nuclear power for electricity generation, and geothermal energy [9]. The performance of the Stirling engine is based on its physical and geometrical features, the type and properties of the working gas, regenerator porosity and efficiency, dead volume, heat exchanger temperature, pressure drop, and heat and shuttle losses. The efficiency of the Stirling engine is usually between 30 and 40% based on operating temperature (working fluid temperature) from 686 °C to 800 °C and operating speed from 33 Hz to 67 Hz [10]. In the case of the NMT unit, the primary aim of the integration of the combustor with the Stirling engine is to utilise the excess heat from the former to power the engine, and convert to electricity by connecting to an alternator. The Stirling engine is considered over other options due to its compatibility with the micro-combustor of the NMT, high specific power and efficiency, and good performance at partial load; also due to features which are particularly advantageous for household applications such as simplicity, long-life cycle, low emission level, and low vibration and noise levels.

The disadvantages of Stirling engines are low compression ratio, working gas leakage and large volume. Certain approaches have been taken to increase the output power of the engines, such as the selection of the working gas, with the use of helium rather than hydrogen at high pressure, and increase in heat transfer surface area and internal heat transfer coefficient. Changes have also been made to the mechanical arrangements, such as the use of free piston Stirling rather than conventional Stirling engines; although the free piston Stirling engine has its own minimal disadvantages in connection with the stability of the mechanical elements, such as the damper and mechanical springs [11].

The application of a biomass energy conversion system using a Stirling engine is more flexible than the conventional biomass energy conversion with gas engines [12]. In addition, there have been recent developments on biofuel powered Stirling engines. The utilisation of bioenergy with the application of Stirling engines has proved to be a promising technology [13]. In Denmark, Carlsen and Bovin [14] developed and tested a 9 kW_e Stirling engine with wood gas as the fuel source and the engine generates about 10 kW and 24% of electric power and efficiency from 11 kW of shaft power. A wood chip fired boiler integrated with a 35 kW_e Stirling engine CHP system was run successfully in Austria [15]. A comparison of the use of the Stirling engine and organic Rankine cycle turbine for electricity generation from poultry waste was carried out by Cotana et al. [16] where the authors showed that the Stirling engine had a better capability of generating higher power output with the conversion of recovered waste heat due to its regenerative thermodynamic cycle. This gives the Stirling a greater advantage over internal combustion engines.

Recent investigations have been undertaken on the numerical and experimental analysis of Stirling engines powered by biomass combustion. An evaluation was carried out by Kuosa et al. [17] on the numerical evaluation of an alpha Stirling engine using the fouling factor to determine the effect of heat exchangers on Stirling engines for CHP application; the analysis considered the brake efficiency, output power and heat recovery to optimise the cleaning interval of the heat transfer surfaces when the cost model is combined with the performance model. Sato et al. [18] conducted a study on the use of a 55 kW_e Stirling engine in a CHP unit powered by wood powder. The combustion and inlet gas temperature were optimised to develop a cleaning process for hot ash, due to the ash fouling that was observed in the heat exchangers of the engine. The study showed that the introduction of a filter system reduced the heat transfer between the burner and Stirling engine, and the power output was affected negatively. Combustion tests were conducted by Nishiyama et al. [13] to analyse the efficiency and quality of wood powder combustion with the integration of a 55 kW_e Stirling engine. The air-to-fuel ratio effect on the output performance of the engine in relation to the hot end was highlighted. An experimental observation was conducted by Thiers et al. [19] on a commercial micro-CHP unit of a Sunmachine GmbH 1.5–3 kW_e alpha type Stirling engine powered by wood pellets with the purpose of developing a numerical model under transient conditions. The specified output performance of the manufacturer could not be achieved as the analysis resulted in high thermal losses, low power output and efficiency. Alfarawi et al. [20]