Applied Energy 102 (2013) 374–385

Contents lists available at SciVerse ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Small scale electricity generation from a portable biomass cookstove: Prototype design and preliminary results

S.M. O'Shaughnessy [a,*], M.J. Deasy [a], C.E. Kinsella [a], J.V. Doyle [b], A.J. Robinson [a,*]

[a] Department of Mechanical & Manufacturing Engineering, Parsons Building, Trinity College, Dublin 2, Ireland
[b] Concern Universal Malawi, 21 Link Road, Namiwawa, P.O. Box 1535, Blantyre, Malawi

HIGHLIGHTS

▶ We have integrated a thermoelectric generator with a cooking stove.
▶ The device has been deployed into a village in rural Malawi for up to 3 months.
▶ The stoves are equipped with temperature and power data logging equipment.
▶ Users have already charged mobile phones, lights and radios from the stove generator.
▶ Data loggers will provide stove usage and power usage data.

ARTICLE INFO

Article history:
Received 20 March 2012
Received in revised form 20 June 2012
Accepted 20 July 2012
Available online 29 August 2012

Keywords:
Biomass
Cookstove
Thermoelectric
Electricity generation
Lighting
Phone charging

ABSTRACT

The World Health Organisation estimates that over 20% of the global population (∼1.4 billion people) lack access to electricity. Furthermore, 40% of the global population (∼2.7 billion people) rely on the traditional use of biomass for cooking (WHO 2011, OEDC/IEA, 2010). This study details the development of a prototype electrical generator for portable stoves commonly in use in the developing world. This generator is capable of delivering small amounts of off-grid electricity. Power is generated using the thermoelectric effect. A single thermoelectric module is utilised to convert a small portion of heat from the stove to electricity. The electricity produced is used to charge a single 3.3 V lithium–iron phosphate battery and drive a low power fan, as well as some other auxiliary features. The airflow produced by the fan is used in conjunction with a commercially available heat pipe heat sink to maintain an adequate temperature difference across the thermoelectric module. From experiments in the laboratory, a maximum TEG power output of 5.9 W has been obtained. On average, 3 W h of energy was stored in a battery during a typical 1 h long burn. Three 1 h long burns produced sufficient energy to fully charge the battery. The performance of the electricity generating cooking stove has subsequently been tested in Malawi using locally sourced fuel and fire stoking methods.

1. Introduction

Over 2 billion people rely on biomass as their main source of domestic energy. In rural Malawi more than 90% of people use biomass for household cooking, heating and lighting [3]. This over reliance on natural resources, unsustainable agricultural practises and population pressures have led to wood scarcity and large scale deforestation with associated negative environmental impacts. Furthermore, women and young children experience substantial smoke exposure when meals are cooked over open fires in the home due to partial combustion of fuel and poor ventilation. Exposure to smoke from traditional cookstoves and open fires is a major threat to health, ranking 10th in the WHO comparative risk assessment for the global burden of disease and responsible for 1.9 million premature deaths (41 million disability adjusted life years) annually [4].

A large proportion (∼1.4 billion) of those people who rely on biomass for cooking also lack access to grid electricity, with 85% of those people living in rural areas [1,2]. For those who can afford it, lighting is derived from a variety of sources, including but not limited to kerosene, diesel, propane, biomass and candles [5]. Technologies that 'burn' to create light can put a significant economic burden on those who use it and it has been estimated that $40 billion is spent on off-grid lighting annually in the developing world [6]. The incongruity is that a disproportionate level of

* Corresponding authors. Tel.: +353 1 896 1061; fax: +353 1 679 5554 (S.M. O'Shaughnessy), tel.: +353 1 896 3919; fax: +353 1 679 5554 (A.J. Robinson).

E-mail addresses: oshaughs@tcd.ie (S.M. O'Shaughnessy), deasym1@tcd.ie (M.J. Deasy), vincent.doyle@concern-universal.org (J.V. Doyle), arobins@tcd.ie (A.J. Robinson).

0306-2619/$ - see front matter
http://dx.doi.org/10.1016/j.apenergy.2012.07.032

Nomenclature

A_p	cross-sectional area of thermoelement (m^2)	T_h	module hot side temperature (K)
I	current (A)	T_c	module cold side temperature (K)
K	thermal conductance (W/K)	ΔT	module temperature difference (K)
L	length of thermoelement (m)	V	voltage (V)
L_c	contact layer thickness (m)	V_{oc}	open circuit voltage (V)
N	number of thermoelements (–)	Z	figure of merit (1/K)
P_{elec}	electrical power (W)	α	Seebeck coefficient (V/K)
P_{max}	maximum electrical power (W)	α_{eff}	effective Seebeck coefficient (V/K)
Q_H	heat delivered to TEG hot side (W)	$\alpha_{p,n}$	Seebeck coefficient of p/n couple (V/K)
Q_C	heat dissipated from TEG cold side (W)	λ	thermal conductivity (W/mK)
R	electrical resistance (Ω)	ρ	electrical resistivity (Ωm)
R_L	load resistance (Ω)	σ	electrical conductivity (S/m)

income is spent on inefficient fuel based technologies that produce very low grade lighting [7]. Furthermore, there are inherent negative health and environmental implications associated with fuel based lighting, such as indoor air quality and carbon dioxide production.

This project has as its technical goal the engineering of a combined efficient low cost cookstove with an integrated electrical generator to power an LED lamp and a mobile phone. The conversion technology is direct heat to electricity using an integrated thermoelectric generator (TEG).

1.1. TEGs and stoves: prior research

Killander and Bass [8] studied the development and testing of a prototype thermoelectric generator used in wood-fed stoves in Northern Sweden. The generator design consisted of two Hi–Z HZ20 modules mounted on a 270 mm × 100 mm aluminium heat collector plate that was placed on the outside of the stove, in a region where the local stove wall temperatures approached 300 °C. The cold side temperature was maintained via an aluminium finned heat exchanger that was cooled by a 12 V, 2.2 W fan mounted above it. To power the fan and also to charge four 6 V lead acid Exide batteries, the output voltage from the TEGs was stepped up to over 13 V by a DC–DC converter, thus providing a reliable 12 V power source. The results showed that during peak feeding times (usually in the morning) the output from the generator was about 10 W, though this would fall to about 4–5 W in the afternoon as the house had heated up. The power generated was sufficient to provide some electric light and provide some TV during the night.

Mastbergen [9] investigated the integration of a thermoelectric generator with a clean cookstove named the EgoFagao. The objective was to deliver 45 W h of power over the course of 1 day, typically consisting of three meal periods. The power was generated from two bismuth telluride Thermonamic (TEP1-12656-0.6) 14.7 W thermoelectric modules in series. Each module was cooled by a variable power 120 mm diameter fan attached to aluminium heat sinks (160 mm × 100 mm × 63.5 mm). This Brazilian-made stove was deployed in Nicaragua, India and Nepal with varying results. Several cultural and technical difficulties were encountered during the field trial. The generator became loose due to thermal cycling, and the batteries failed due to incomplete charging. A second generation device was developed which incorporated improvements to the charging circuit. A life cycle analysis performed by the author highlighted that the maximum TEG temperature could not exceed 280 °C to keep the damage to the module below 20% over 5 years. Mastbergen estimated the total cost of a generator to be $170 in quantities of 1000.

Champier et al. [10,11] investigated the feasibility of integrating a thermoelectric generator to generate 5–10 W of electricity from the waste heat in a multifunction cookstove developed by "Planète Bois" called the "Combustion Latérale Inversée Performante" (CLIP). The energy efficient mud cookstove is a large fixed stove which produces heat for cooking and hot water. The exhaust gases stream was selected as the heat source for the thermoelectric generator. An experimental rig was setup using gases to replicate the temperatures in the stove. The thermoelectric used was a bismuth telluride module from Taihuaxing Co. Ltd. (TEP1-12656-0.8) capable of producing 10.5 W at matched load. Two cooling methods were investigated: forced convective cooling using a fan and natural convection cooling via a water tank. Using four modules, the authors obtained between 1.7 W and 2.3 W per module at a temperature difference of 160 °C and a total of 7 W was generated. Champier et al. made improvements to the generator design in what was called the "TEGBios II" however the device has not yet been incorporated into a real stove to our knowledge.

Several researchers have investigated methods of low-temperature waste heat harvesting using thermoelectric generators [12–14]. However, much of the research into stove generators has been laboratory based, such as studies by Rinalde et al. [15] and Nuwayhid et al. [16,17]. To verify the performance of the generators, the heat source (the fire) is normally replaced by a controllable and constant electrically powered supply. Likewise, the cold side is typically maintained by natural or forced convection methods. Although this procedure allows the evaluation of the generators performance, the test conditions do not replicate those that would occur in the field. Therefore, in an effort to mimic the actual stove conditions, the generator in this study has been integrated into an existing biomass-fed stove. This stove is currently widely used in regions of Malawi.

2. Objectives/scope of work

The overarching objective of the study is to develop a thermoelectric generator system that can be retrofitted onto the chitetezo mbaula cookstove and generate and store enough electricity for evening lighting and daily phone charging.

The specific objectives of the study are to:

(1) Design the appropriate heat collecting and dissipating system to achieve the desired electrical energy storage for a typical cycle of daily meal preparation.
(2) Design a simple circuit that will facilitate battery charge control and DC to 5 V DC conversion.
(3) Test the stove–generator system in a controlled laboratory setting.