Comparative Evaluation of Emissions from Selected Paraffin Lamps and a Paraffin Thermoelectric Generator

David K. Kimemia, Tafadzwa Makonese, and Harold J. Annegarn

Abstract— Paraffin lamps are commonly used as light sources in low-income, off-grid households. Pollutant emissions from these appliances are a potential health hazard and a cause of material soiling by soot deposits. This paper reports on evaluation of emissions of two off-the-shelf paraffin lamps (a standard lantern and a glass lamp) – considered as baseline reference devices – and a prototype paraffin-fuelled thermoelectric generator. The thermoelectric generator is designed to provide a higher intensity and quality of light output than conventional paraffin lamps. This is achieved through LED lamps. In addition, it also has a plug point to charge mobile phones. These devices were fuelled with commercially sourced illuminating paraffin, and tested according to the SeTAR Centre heterogeneous test protocols (HTP). Results show that the thermoelectric generator has 83% reduction in $PM_{2.5}$ (black carbon) emissions per hour of burn (mg/h) compared to the two reference lamps. The CO emissions and CO/CO_2 ratio for the three devices did not show significant differences at the 95% confidence level. The thermoelectric generator has a similar fuel consumption rate to the paraffin glass lamp, while the standard paraffin lantern has a higher burn rate. The thermoelectric generator exhibits lower risks of fires and contact burns since there is no exposed flame. The paraffin thermoelectric generator with LED lamps would therefore be a serious contender as a substitute for polluting paraffin lamps, providing a higher quality of light while reducing black carbon emissions.

***Index Terms* — paraffin (kerosene) lamp; thermoelectric generator; heterogeneous test protocols; off-grid household, black carbon**

1 INTRODUCTION

Energy services for cooking and lighting are a necessity for every household and are important for socioeconomic development. Energy poverty, which refers to lack of access to modern energy services, afflicts many households in developing countries. The energy-poor are reliant on traditional biomass burnt in inefficient stoves for cooking and heating, while liquid fuel appliances are widely used for illumination. Global estimates indicate that about 1.8 billion people lack access to electricity, 620 million of whom live in sub-Saharan Africa [1]. A majority of those without electricity light their space with simple paraffin (kerosene) lamps or candles.

Inefficient solid fuel cookstoves and simple paraffin lamps are sources of household air pollution (HAP) in developing countries [2, 3]. These inefficient fuel combustion appliances divert a significant portion of fuel carbon to products of incomplete combustion that may have greater climate forcing influence than CO_2 and are detrimental to human health [4]. Of these pollutants, carbon monoxide (CO) and particulate matter ($PM_{2.5}$) have the largest impact on human health, while black carbon (BC) has been implicated as a forcing mechanism in global warming [5].

Hitherto, the magnitude and seriousness of particulate pollution emanating from paraffin-fuelled light sources used in poor households was underestimated. Efforts for redressing the household energy challenges concentrated on the development and dissemination of clean cookstoves. However, recent studies have highlighted that even with adoption of clean cookstoves, households are still exposed to significant levels of air pollution from paraffin lamps [6, 7]. It is estimated that simple paraffin lamps, used extensively in low-income households, emit twenty times more PM (mainly black carbon) than previously thought [8]. Paraffin lamps convert about 7–9% of the fuel to PM [8]. The emission of black carbon – a product of incomplete combustion – is a requirement of a paraffin lamp to produce bright yellow light; under optimum combustion conditions, the flame would emit a weak illumination, mainly in the blue wavelengths.

There are various options for mitigating emissions of products of incomplete combustion from paraffin lamps (e.g. the use of LED lights powered by solar energy or paraffin-fuelled thermoelectric generators) [9, 10]. Apart from air pollution reduction, the use of LED lamps would provide a higher quality lighting service and help to improve household safety especially in low-income settlements that are prone to shack fires from candles and paraffin lamps [11, 12, 13]. Paraffin-fuelled thermoelectric generators are proposed as a competitive technology to solar-powered LED lamps/cell phone chargers in locations where paraffin fuels are conveniently sourced. In South Africa, paraffin is a common fuel in low-income settlements where it is sold in neighbourhood *spazas* (informal convenience stores). Promotion of thermoelectric generators in households that use paraffin for cooking and/or lighting would benefit from compatibility advantages.

Although the development of safer and more efficient paraffin stoves has been widely investigated in South Africa, there is a paucity of knowledge on clean

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combustion of paraffin for lighting services. Interest in the paraffin cooking sector has culminated with the homologation of paraffin safety standards [14], however, no standards exist for paraffin lamps. This paper addresses the knowledge gap on domestic lighting services of the energy-poor by presenting laboratory measurements of CO and $PM_{2.5}$ for the two commonest types of paraffin lamps and a prototype thermoelectric generator/LED combination. We compare the fuel consumption and emission rates of the three devices in terms of emissions per unit of energy consumed [mg PM /MJ] and [mg CO/MJ] and draw conclusions based on the results. The experiments were carried out at SeTAR Centre stove-testing laboratory located at the University of Johannesburg.

2 MATERIALS AND TEST PROCEDURES

2.1 Experimental lighting devices

The two paraffin lamps tested in this study are the commonest paraffin wick lamps used in South Africa. The first one is a standard lantern that has a glass shroud and an enclosed chimney (Fig. 1a). The second is a cheaper/inferior lamp that has an open glass chimney (Fig. 1b). In this paper, we refer to the cheaper lamp as a 'glass lamp'.

Fig 1. Image of a) standard paraffin lantern (with red metal frame) and b) glass lamp (with open-glass chimney).

The paraffin-fuelled thermoelectric generator that was tested alongside the paraffin lamps is a pre-production model brand-named iHarvey™ (Fig. 2). The device was supplied to SeTAR Centre by the developer for emission performance evaluations.

2.2 Emission measurement

The following apparatus were used to collect and measure emissions from the lamps and thermoelectric generator:

- An emissions collection hood
- Testo 350 XL™ flue gas analyser
- DustTrak DRX™ particle counter
- Computer
- Electronic mass balance.

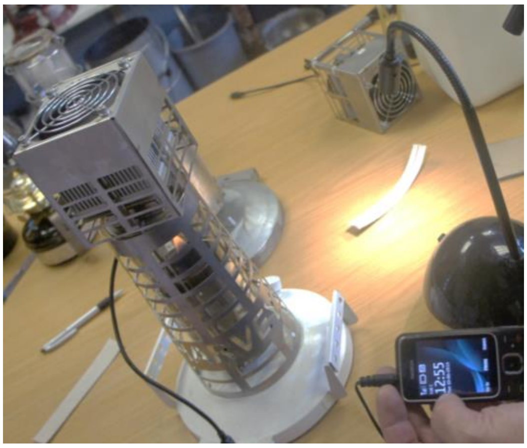

Fig 2. Image of iHarvey thermoelectric generator.

The testing rig is set-up in two adjacent rooms. The first room is set aside for combustion, which happens under an emissions collection hood. The second room houses the gas and particle analysers and data logging equipment (Fig. 3). Combustion products are sampled by two gas probes inserted into the chimney, and then channelled to the flue gas analyser and the particle counter. The test procedure for sampling gaseous and particle emissions is described in detail elsewhere [15].

Fig 3. Flue gas analysers and data capturing equipment set-up at SeTAR stove testing lab.

2.3 Calculation and determination of the emission factors

Based on the chemistry of the burned fuel (raw fuel corrected for remaining materials) the stoichiometric volume of the combustion products was estimated. A gas sample was drawn from the emission stream. As many gases as possible were measured using the Testo™ gas analysers, typically O_2, CO_2, CO, NO, H_2, SO_2 and H_2S. We limit the discussion to determination of CO and $PM_{2.5}$ emission factors.

The concentrations of CO and $PM_{2.5}$ are first corrected for any dilution applied by the equipment, then multiplied by total air demand (λ) to get a total mass emitted. This approach is based on the foreknowledge that any missing fuel has been turned into combustion products of some type. The calculation of λ is made in the following manner:

$$\lambda = 1 + \frac{O_{2\mathrm{meas}} - O_{2\mathrm{oxid}}}{O_{2det} - (O_{2\mathrm{meas}} - O_{2\mathrm{oxid}})} \quad (1)$$

where $O_{2\mathrm{meas}}$ is the measured O_2; $O_{2\mathrm{oxid}}$ is the O_2 required to complete the oxidisation of incompletely burned gases and $O_{2\mathrm{det}}$ is the total O_2 in all detected gases.

The standard reporting metric for carbon monoxide and particulate matter is the mass of pollutant emitted per net Mega-Joule of energy delivered from the chemical conversion of the fuel [mg/MJ]. The heat content of the fuel is determined for each fuel batch through use of a bomb calorimeter. The calculation of the CO and $PM_{2.5}$ emission factors is made in this manner:

$$CO_{EF} = \frac{CO[g]}{H_{NET}[MJ]} \quad (2)$$

$$PM2.5_{EF} = \frac{PM2.5[mg]}{H_{NET}[MJ]} \quad (3)$$

where H_{NET} is the net heat released by the burnt fuel (product of heat content of fuel and the amount of fuel burnt).

The calculation for percentage reduction in emissions between iHarvey and the baseline paraffin lamps was done as per the following equation:

$$\%\,reduction = 100 \cdot \frac{(Hr - Lr)}{Lr} \quad (4)$$

where *Hr* is the iHarvey thermoelectric generator result, and *Lr* is the paraffin lamp result, for the various parameters. A negative result from equation 4 indicates that the iHarvey reduced emissions by the shown margin.

2.4 Test Procedure

Each device was fuelled to the maximum fuel level, weighed and ignited under the hood. The device was left on the mass balance throughout the test to track fuel consumption. Data for the various combustion products and fuel reduction were logged on the computer every 10 seconds. The test duration was 25 minutes from flame ignition to extinction.

A trial run had shown that emissions from the iHarvey reduced to undetectable levels with the thermoelectric generator in place (the generator has a self-powered cooling fan that dilutes and dissipates the emissions from the combustion chamber). Consequently, the unit was tested without the generator piece in place in order to obtain the complete emissions during a burn cycle.

The SeTAR Heterogeneous Testing Protocol (HTP) (downloadable at www.setarstoves.org) was adapted for this suite of tests.

3 RESULTS

3.1 Emissions

Time plots of $PM_{2.5}$ emissions (Fig. 4) shows that about 90% of the iHarvey emissions are produced in the first five minutes after ignition. Thereafter, the emissions remain at an average of 0.01 mg/min. The graph indicates that the paraffin lamps have comparatively higher $PM_{2.5}$ emissions during the burn cycle compared to the thermoelectric generator. The emissions test results are summarised in Table 1.

Since the emissions are not uniform with time, the specific emissions, expressed as [mg/MJ] based on a 25-minute test cycle, are not a constant or representative parameter. As illuminating devices are designed and used to provide a continuous steady output over an extended period, the protocol for stove reporting required modification. We deemed it appropriate to report the emissions over a one-hour equivalent of operation, and in future will conduct the tests over a full 60-minute period, even if the output is steady after the first minutes of the ignition phase. Accordingly, the emission results (CO and $PM_{2.5}$) are extrapolated to equivalent one-hour duration. For both lamps and the iHarvey thermoelectric generator, steady state values were achieved after five minutes. Extrapolation to one hour was achieved using the average emissions from minutes 5 to 25.

In a series of pair-wise comparisons, the t-test at 95% confidence level ($p>0.05$) was used to test the hypothesis that there is no significant statistical difference between the thermoelectric generator, and the paraffin lantern and the paraffin glass lamp respectively. The three appliances exhibited statistically different performance parameters in terms of $PM_{2.5}$ emissions (Table 1). The CO emissions and CO/CO_2 ratio for the three devices showed no significant statistical differences (Table 1). These results, based on the one-hour equivalent burn cycle, infer that the iHarvey paraffin thermoelectric generator has 83% lower $PM_{2.5}$ emissions compared to either of the two paraffin lamps.

3.2 Fuel consumption and illumination

The iHarvey thermoelectric generator showed a similar fuel consumption rate to the paraffin glass lamp, while the paraffin lantern has a higher rate. Manufacturer supplied data indicates that the iHarvey device has a maximum fuel consumption rate of 35 ml/h (28.4 g/h), which compares favourably with the 30 g/h measured in this test.

Other manufacturer supplied data highlights that the iHarvey has a 300 lumen light output, which is five times more intense than the light output of a typical paraffin lantern (Allan Goldberg, personal communication). This implies that the iHarvey provides substantially superior illumination for the same fuel consumption, with lower $PM_{2.5}$ emissions.

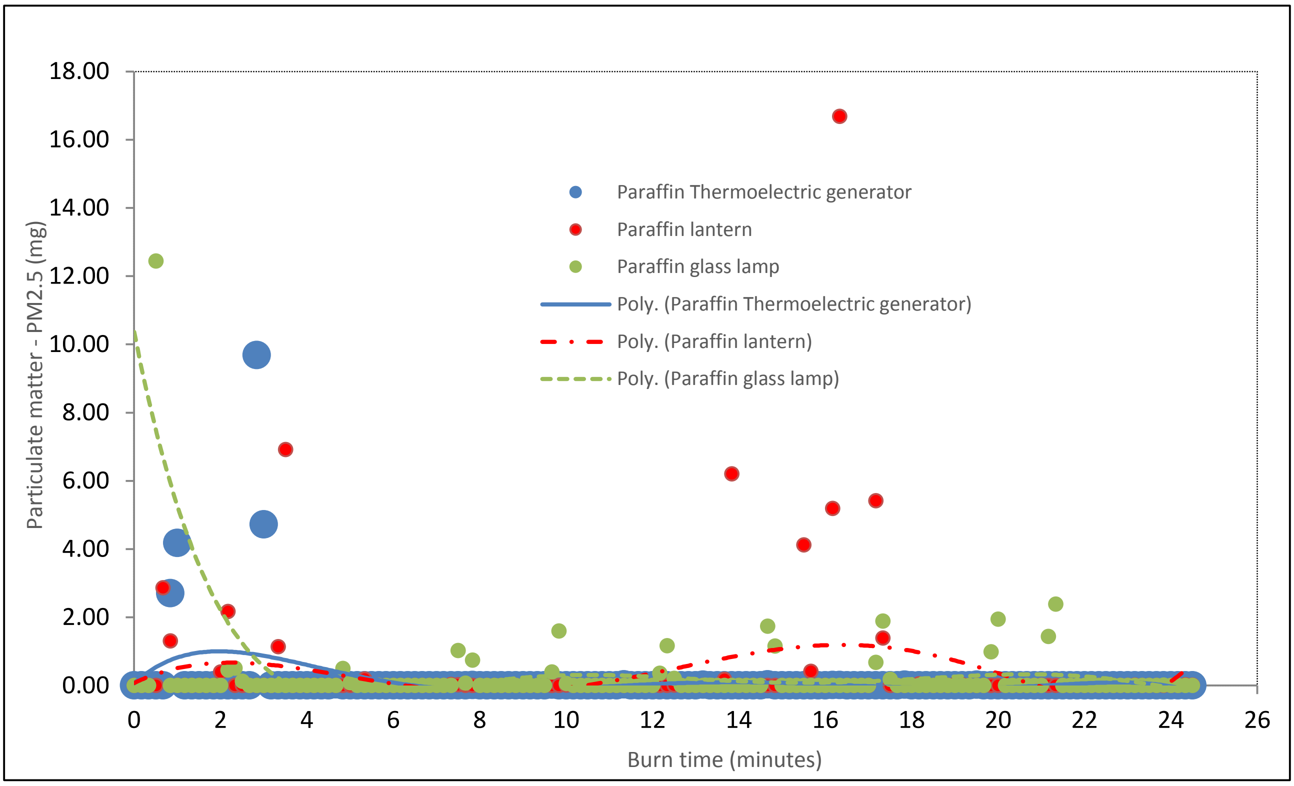

Fig 4. $PM_{2.5}$ emissions profile for the paraffin thermoelectric generator, paraffin lantern and paraffin glass lamp.

Table 1. Pair-wise comparison of fuel consumption, emission factors, emission rates and combustion efficiency between the paraffin thermoelectric generator and two commercial paraffin-fuelled lamps (equivalent 60-minute burn cycle)

Test Device	**Fuel cons. (g/h).**	**CO_{EF} (g/MJ)**	**$PM_{2.5\,EF}$ (mg/MJ)**	**CO (g/h)**	**$PM_{2.5}$ (mg/h)**	**CO/CO_2 (%)**
Paraffin thermoelectric generator	30 ± 3	0.17 ± 0.02	48 ± 0.25	0.18 ± 0.01	21 ± 0.27	0.41 ± 0.02
Paraffin lantern	40 ± 0.58	0.14 ± 0.02	85 ± 0.26	0.16 ± 0.02	127 ± 0.29	0.34 ± 0.04
% reduction	-25%	27%	-44%	13%	-83%	21%
p-value	0.01	0.10	0.00	0.06	0.00	0.09
Sig. at 95% confidence (p<0.05)	Yes	No	Yes	No	Yes	No
Paraffin thermoelectric generator	30 ± 3	0.17 ± 0.02	48 ± 0.25	0.18 ± 0.01	21 ± 0.27	0.41 ± 0.02
Paraffin glass lamp	30 ± 2	0.15 ± 0.01	212 ± 13	0.16 ± 0.01	127 ± 1.0	0.23 ± 0.12
% reduction	0%	16%	-77%	13%	-83%	78%
p-value	1.00	0.21	0.00	0.07	0.00	0.07
Sig. at 95% confidence (p<0.05)	No	No	Yes	No	Yes	No
Paraffin lantern	40 ± 0.58	0.14 ± 0.02	85 ± 0.26	0.16 ± 0.02	127 ± 0.29	0.34 ± 0.04
Paraffin glass lamp	30 ± 2	0.15 ± 0.01	212 ± 13	0.16 ± 0.01	127 ± 1.0	0.23 ± 0.12
% reduction	33%	-6.7%	-60%	0%	0.31%	47%
p-value	0.001	0.27	0.00	0.56	0.32	0.19
Sig. at 95% confidence (p<0.05)	Yes	No	Yes	No	No	No

3.3 Safety

The test results show that the paraffin thermoelectric generator had a CO/CO_2 ratio of 0.4%, which complies with the SABS requirement of maximum 2% for unvented indoor combustion appliances [13]. The iHarvey paraffin thermoelectric generator is thus acceptable for continuous use indoors.

The fuel tank of the paraffin thermoelectric generator did not get hot during the test – one could touch it without danger of blistering (implied that surface temperature was below 40°C), even after 30 minutes of operation. The only part that gets hot is the glass chimney area but this is protected from direct contact by a mesh shield during normal operation. This mesh shield is firmly attached to the frame and surrounds the glass chimney. Hence, there is little chance of the glass fracturing if the device is tipped or dropped, thus reducing risks of accidental fires.

4 DISCUSSION AND CONCLUSION

Household air quality monitoring studies [5] show that particulate matter emissions are still significant in some households that have adopted clean cookstoves. A remaining source of pollutant emissions in such households is attributed to use of paraffin lamps. The paraffin thermoelectric generator with LED lamps would therefore be a serious contender as a substitute for paraffin lamps, providing a higher quality of light while reducing black carbon emissions. Unlike a solar powered device, the iHarvey paraffin powered thermoelectric generator has the ability to produce power on demand at the convenience of the user, irrespective of the time of day or night.

The test results show that the iHarvey thermoelectric generator has a fuel consumption rate that is similar to conventional paraffin lamps, yet it performs significantly better in terms of particulate matter emissions. Compared to the paraffin lantern and paraffin glass lamp, the iHarvey demonstrates 83% reduction in $PM_{2.5}$ emissions rates (mg/h.).

The paraffin thermoelectric generator exhibits lower risks of fires and contact burns since there is no exposed flame. Thus, when used as designed with an LED lamp, iHarvey is a safer option for off-grid households that currently use paraffin lanterns, glass lamps or candles for lighting. The developer demonstrated that the device could generate a light output from an attached LED lamp visibly brighter than the paraffin devices. Manufacturer supplied data indicates that the iHarvey has a total light output of 300 lumen (from three LED lamps), which is equivalent to the light output of five standard paraffin lanterns or thirty candles. Another feature of the iHarvey thermoelectric generator is the existence of a USB connector for powering media or charging mobile electronic devices.

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