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Thermoelectric power generation from biomass cook stoves

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ABSTRACT

The use of biomass cook stoves is widespread in the rural communities of developing countries. It is important to improve the efficiency of these stoves in order to reduce the global warming contribution. An improved biomass fired stove has been developed in our laboratory and a prototype has been built. The combustion chamber is designed to achieve the almost complete combustion of wood thus increasing the efficiency and decreasing indoor air pollution.

An additional development, introduced in this paper, involves the use of a thermoelectric (TE) module in order to generate electricity to power the fan and give light. The air blowing through the stove increases the air/fuel ratio to achieve a complete combustion.

In the first part, the paper presents the results from an experimental benchtest using commercial TE modules (Bismuth Telluride). The evaluation of the conversion efficiency is allowed at various temperature ranges.

Then, the feasibility of adding commercial TE modules to the biomass cook stove prototype is investigated searching the best position of the modules.

Lastly, a TE power generator experimental set up is presented showing that a 6 watts ready to use electrical production is possible with the biomass cook stove.

1. Introduction

In developing countries, rural areas biomass energy accounts for about 90% of the total rural supplies. Biomass combustion meets basic energy needs for cooking and heating in rural households and for heating process in traditional industries. In general, biomass is burnt through open fire stoves. These traditional stoves are characterized by low efficiency which results in inefficient use of scarce fuel-wood supplies [1]. Biomass is a CO_2-neutral renewable source of energy but traditional open fire stoves are known to lead to high emissions of health damaging air pollutants [1,2]. To save wood fuel and spare rural communities from acute respiratory infection (ARI), it is important to replace a traditional open fire stove by an improved one [3,4].

The Non Governmental Organisation "Planète Bois" is developing an energy-efficient mud stove based on traditional stove designs. For zones with unreliable electricity supply, the feasibility of adding a commercial thermoelectric (TE) module to the stove is investigated. Indeed, it is possible to create a TE generator system including the conversion of a part of the wasted heat [5].

Nuwayhid et al. [6] considered the prospect of applying TE modules to rural domestic woodstoves in regions where the electric supply is unreliable and subject to frequent disruption. The generator design work was made using existent high-quality Peltier modules in the power-generating mode. The authors have demonstrated acceptable economic performances [7].

Lertsatitthanakorn [8] investigated the feasibility of adding a commercial TE module made of bismuth-telluride based materials to the stove's side-wall, thereby creating a TE generator system that utilizes a proportion of the stove's waste heat. The results showed that the system generates approximately 2.4 W when the temperature difference is 150 °C. This generated power is enough to run a small radio or a low power incandescent light bulb.

With the use of TE generators, the different functions of the domestic stove can be increased (cooking, water heating, space

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Nomenclature

A	area of TE module (m^2)
C	heat capacity ($J\,kg^{-1}\,K^{-1}$)
k	thermal conductivity ($W\,m^{-1}\,K^{-1}$)
P_{max}	power output at matched load (W)
Po	output power (W)
q	heat flux through one TE module (W)
R_{int}	internal resistance of TE generator (Ω)
R_L	load resistance (Ω)
T_C	cold-side temperature of TE module (°C)
TE	thermoelectric
T_H	hot-side temperature of TE module (°C)
Vo	output voltage of module (V)
Voc	open-circuit voltage of TE generator (V)

Greek symbols

ρ	density ($kg.m^{-3}$)
ΔT	temperature difference (K)
η	module efficiency

heating and electricity supply). Even if the conversion efficiency is low, the electric power is sufficient to supply a small fan to improve the combustion in the stove, charge a battery and light high brightness low power LEDs. The fan forces the air through the stove, leading to higher temperatures and a better air/fuel ratio. This results in a cleaner burning and a more efficient use of fuel. The TE power generation has the advantages of being maintenance free, silent in operation and involving no moving or complex parts.

This paper reports a study conducted in order to investigate the feasibility of using a TE generator in an improved biomass fired stove already developed by "Planète Bois". The experimental set-up is described and the results are presented hereafter. Performances for other conditions (temperature difference, heat exchangers on both sides of the module) can be evaluated with a simple numerical simulation presented below. The best position for the modules is evaluated and finally a TE power generator experimental set up is presented showing that a 6-watts ready to use electrical production is possible with the biomass cook stove.

2. TE power generator benchtest

2.1. General facts about thermoelectricity

The TE effect is the direct conversion of temperature differences to electric voltage and vice versa. For TE power generators, the

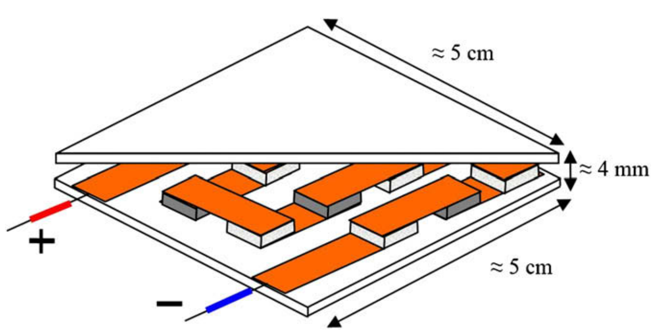

Fig. 1. Structure of a Seebeck cell.

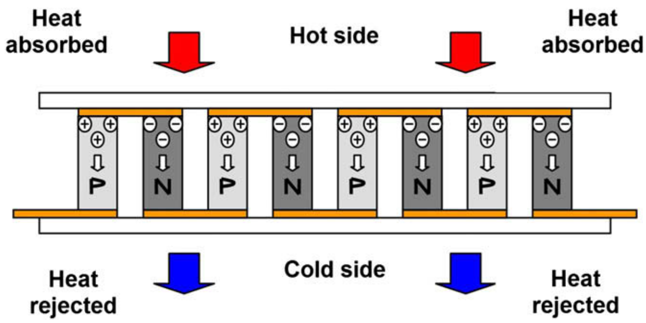

Fig. 2. Working of a Seebeck cell.

effect is that the voltage is created in the presence of a temperature difference between two different semiconductors.

Typical TE modules (also named Seebeck cells) are composed by a set of semiconductor components formed from two different materials. As shown in Figs. 1 and 2, these components are connected thermally in parallel and electrically in series. Two ceramic plates are stuck on each side for electrical insulation.

Semiconductors are divided, depending on the material they are made of, into P-type and N-type components (Fig. 2). When heat flows through the cell, the N-type components are loaded negatively (excess of electrons) and P-type components are loaded positively (default electron), resulting in the formation of an electric flow.

The only couple of materials available on the market, at a reasonable price, for ambient temperature applications, is Bismuth Tellurid (Bi_2TE_3). New materials offering great potential for application, such as clathrates, skutterudites, alloys Heusler, phases of Chevrel and oxides, should soon leave the laboratories [9–11].

2.2. Experimental test system

For our research, we designed and built a TE power generator (see Fig. 3). Bi_2TE_3 modules from Taihuaxing Co. Ltd. are used in the experiment. The specifications of the module are as follows for the hot-side temperature at 230 °C and the cold side at 30 °C:

- Part number TEP1-12656-0.8.
- Size: 56mm × 56 mm.
- Open-circuit voltage: 8.7 V.
- Internal resistance: 1.7 Ω.
- Match load output-power: 10.5 W.

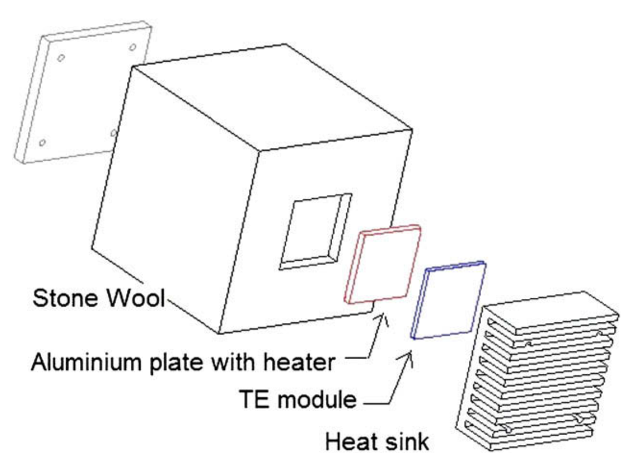

Fig. 3. Experimental TE power generator test system.

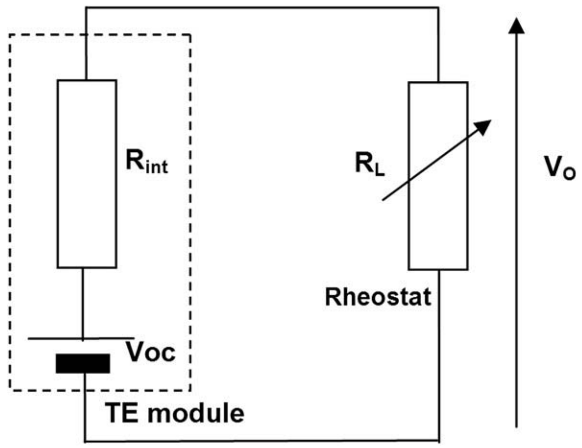

Fig. 4. Electric circuit for measuring the voltage and power output of TE modules.

- Heat flux across the module: about 240 W.

The module is composed of 126 couples.

To supply heat energy to the hot side of TE modules, a thermocoax electric heater SEI 10/50 is used providing a continuous power of about 150 W. An aluminium heat sink with fins was mounted on the cold side of the TE modules. Thermal grease is used to enhance heat transfer between the surfaces. Two different cooling systems are tested to maintain a constant temperature on the cold side [12,13] (an electric air fan or temperature controlled cold water). Best results were obtained with cold water. Temperature measurements were made with type K thermocouple 10/100 mm to avoid heat shunts and were placed in different parts of the modules. The whole device was enclosed in stone wool for insulation.

The temperatures, tension and current were recorded by using an Agilent 34970A Data Logger. The measurement system permits us to obtain a precision of 0.01% for the tension, 0.1% for the current and of 0.5 °C for the temperatures. But, because of the difficulty to measure a surface temperature accurately, the temperature errors are evaluated to 1 °C.

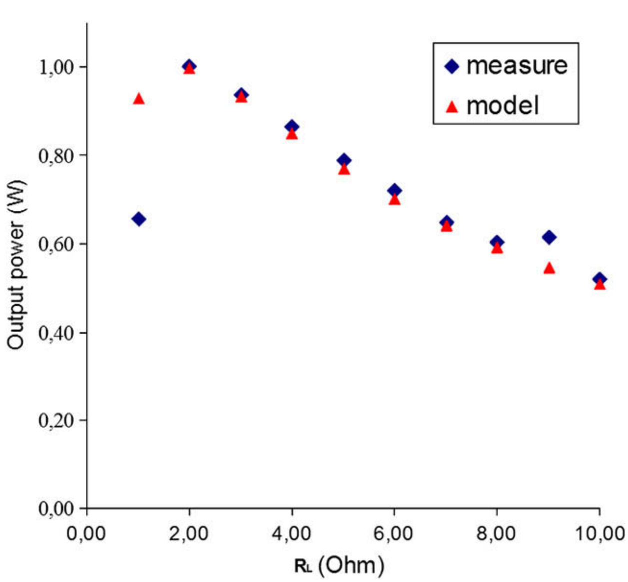

Fig. 5. Output power vs resistance load for a temperature difference of 99 °C, cold side 62 °C, hot side 161 °C (experimental results).

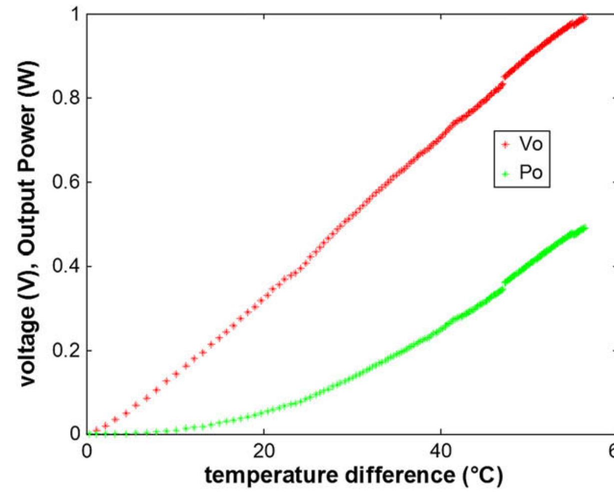

Fig. 6. Voltage and output power function of temperature difference for a load of 2 Ω (experimental results).

The electrical characteristics of the TE modules were tested in steady state and dynamic conditions by using steps of the electric heat power from 0 to 150 W.

A rheostat was connected to the TE modules as a load, and the resistance R_L set at different values in the range 1–10 Ω (Fig. 4). The measured power *P*o that can be produced by one TE module as a function of the electric load R_L is shown in Fig. 5. The temperature difference (ΔT) between the hot side and cold side of the TE module is about 100 °C.

In the same figure, we provided the model base power assuming for the TE generator an internal resistance (R_{int}) of 1.75 Ω and an open-circuit voltage (*V*oc) of 2.65 V for comparison.

The comparison between the experimental results and that of the model permits to validate the experimental procedure.

The variation of the voltage (*V*o) and output power (*P*o) characteristics for an electric load of 2 Ω of the TE module as a function of the temperature difference (ΔT) between the hot side and cold side of the TE module is shown in Fig. 6. Thus, we can verify that the voltage is proportional to ΔT, and the power to ΔT^2.

A fixed resistance (R_L) of 2 Ω is used instead of the matched resistance of 1.75 Ω because it is obvious that being always at the matched output is not realistic in a real working system. However, as explained in [14], knowing the internal resistance makes it easy to determine the maximum output power using $P_{max} = Vo^2/4R_{int}(1+R_{int}/R_L)^2$.

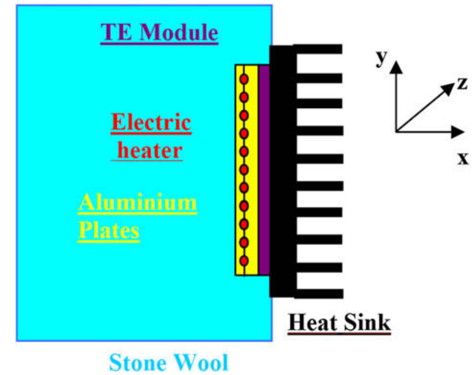

Fig. 7. Model of the TE power generator.

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Table 1
Material properties used for simulation.

	k $W m^{-1} K^{-1}$	C $J kg^{-1} K^{-1}$	ρ $kg m^{-3}$
Stone wool	0.037	40	1.03
Aluminium plate and heat sink	237	904	2700

2.3. Simulation model

Measuring the conversion efficiency of a TE module presents difficulties because it requires an accurate determination of the heat input absorbed at its hot side. We chose a realistic estimate of the heat flux by measuring the temperature difference (ΔT) between the hot side (T_H) and cold side (T_C) of the TE modules and by evaluating its thermal conductivity.

To design and optimize our system, a commercial finite element modelling software package (COMSOL Multiphysics™) was used.

The TE power generator is assumed to be infinite along the direction of the fins (z-axis) and the problem is considered geometrically and thermally symmetric along the x direction. In Fig. 7, the scheme represents a transversal cut of our system.

According to this geometry, we used a 2D simulation with the heat transfer module. The mathematical model for heat transfer by conduction is $\rho C\, \partial T/\partial t - \nabla(k\nabla T) = q$, where T is the temperature, ρ is the density, C is the heat capacity, k is the thermal conductivity, q is a heat source or heat sink, ∇ is the gradient.

The thermophysical properties are presented in Table 1.

The thermocoax electric heater was modelled as a thick plane heat source with the same volume and the same power.

The boundary and initial conditions are reported as follows:

- Convective heat transfer between fins immersed in temperature controlled cold water (Temperature $T_{water} = 35\,°C$ and heat transfer coefficient around 500 $W m^{-2} K^{-1}$)
- Natural convective heat transfer with air (Temperature $T_{air} = 22\,°C$ and heat transfer coefficient around 10 $W m^{-2} K^{-1}$) for the other boundary conditions.

Fig. 8 shows the steady state temperature fields. From these fields, we obtained a temperature profile along x-axis in the centre of the module, between two fins as shown in Fig. 9.

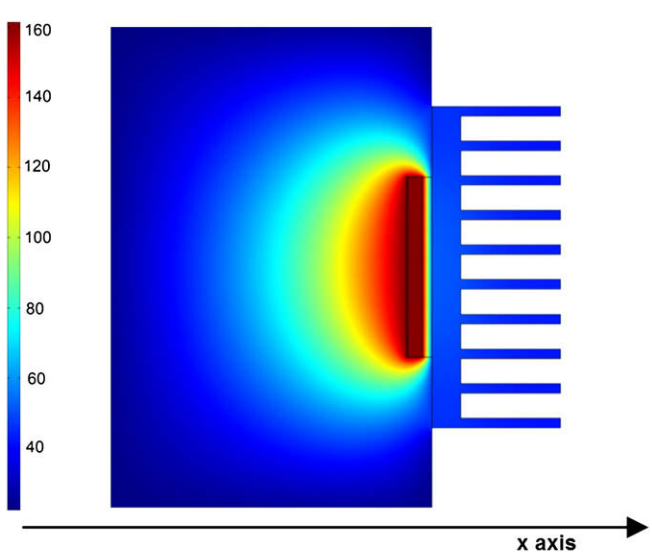

Fig. 8. Steady state temperature fields of the TE power generator (model).

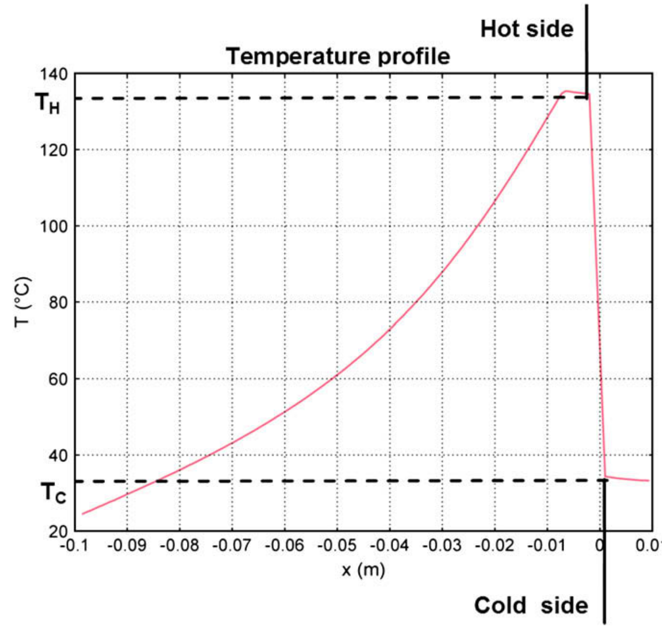

Fig. 9. Steady state temperature profile along the TE power generator (model).

By comparison of the experimental and simulated results, we fitted the thermal conductivity of our TE module to get the right T_H and T_C. The correct value is assumed to be $k = 2.3\ W m^{-1} K^{-1}$. This value concerns the whole TE module including ceramic.

2.4. Results and discussion

As the heat transfer is by conduction only, the heat q through the TE module has been evaluated from the measurement of k and ΔT.

As the output power Po for a load of 2 Ω is known continuously, the efficiency of the module $\eta = Po/q$ can be calculated and plotted versus ΔT (Fig. 10).

We can verify that the efficiency is proportional to ΔT which is reasonable as Po is proportional to ΔT^2 and q to ΔT. For a temperature difference of 60 °C, the efficiency is about 0.6% and the heat flow through the module is around 100 W. In order to achieve a good efficiency we have to get a high ΔT. For a ΔT of 200 °C we can expect an efficiency of about 2%.

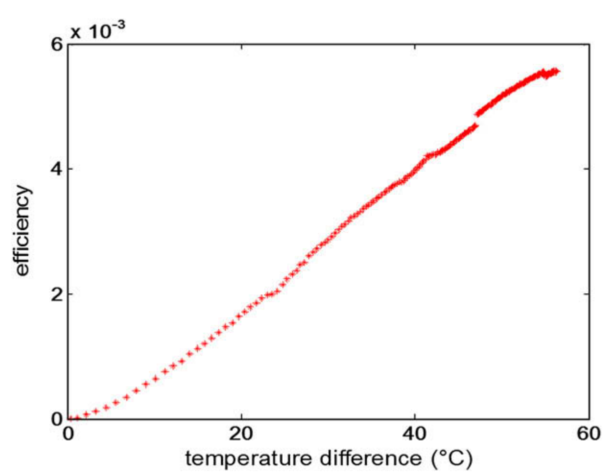

Fig. 10. Efficiency for a load of 2 Ω vs temperature difference (experimental results).

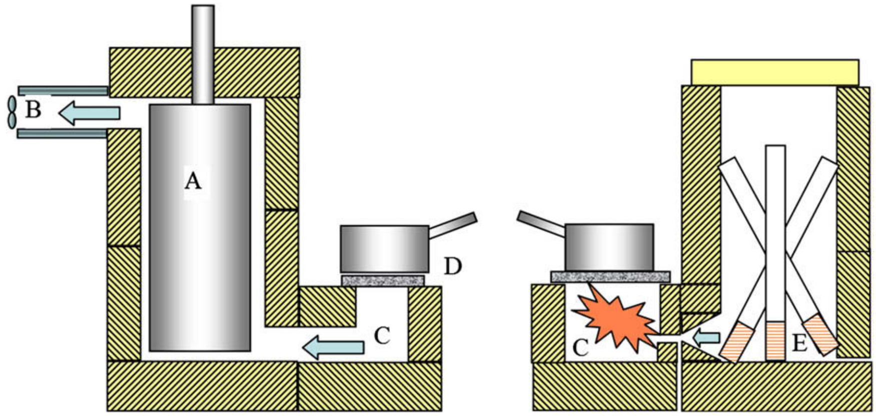

Fig. 11. The two side views of the biomass fired stove, (A) water tank, (B) combustion gas exit and fan, (C) hot incoming combustion gases, (D) cooking plate, and (E) pyrolyzing chamber.

All these results were obtained for a ΔT between 0 °C and 60 °C. To increase the flux, we present further another experimental design using a gas heater in order to obtain higher ΔT around 160 °C.

3. Cook stove as a TE generator

3.1. Biomass cook stove specifications, heat and temperature

An improved biomass fired stove has been developed in our laboratory and a prototype has been built. It uses a small water tank (18 l) as shown in Fig. 11.

The hot incoming combustion gases arrive at the bottom of the water tank chamber and come out at the top.

The first idea was to put the TE module on the tank as water is a good heat sink and does not go over 100 °C.

Considering a typical way of using the stove, an average heat flux along the tank has been evaluated to the value 1.2 W cm^{-2}. This means an average heat flow through one TE module (size: 56 mm × 56 mm) of 37 W.

This heat flux is very low according to the efficiency of TE module and must be improved with an additional heat exchanger as we expect an electric power between 5 and 10 watts.

3.2. Bismuth Telluride TE module property and discussion

The Bi_2TE_3 module can work at a temperature as high as 260 °C continuously and intermittently up to 380 °C heat source without degrading [15].

The cold side of the TE generator cannot go above 165 °C. The construction of the TE generator uses two methods of bonding. The hot side often uses aluminium (melting point 660 °C) to bond the elements while the cold side elements use (SnAg) 3% silver solder rated at 220 °C [16].

It is necessary to make sure that the cold side sink is active which supposes to keep permanently some water in the tank.

There are a few points to take into account to design and locate the TE generator:

- the very low heat flux calculated above,
- the fluctuation of the average temperature between a maximum of about 400 °C and a minimum of around 200 °C depending on the part of the chamber considered,
- the very high temperature reached by the gas at the input.

To increase drastically the heat flux we need to design a combustion gas heat exchanger. The first idea was to put the module halfway up along the tank where the gas temperature is under 300 °C and to collect the heat with a long exchanger along the tank down to the gas input.

This would average the temperature and allow a more reasonable flux but it would increase pressure drop due to heat exchanger fouling. The second idea is to use the big cooking plate as the hot heat exchanger and to use a secondary tank connected to the main tank as cold exchanger.

Due to the irregular feeding rate of wood and to the use of heat for cooking, the gas temperature will not be quite steady and the output voltage will fluctuate a lot. We will have to design the electronic part as well in order to get reasonable electrical energy.

4. TE power generator experimental set up

4.1. First approach

In order to design a benchtest, we took into account the experimental results from a cooking stove built for Morocco by "Planète Bois". The measurements made with this cooking stove for a 10-kW wood consumption showed that about 2.4 kW are used in heating the water and 4.5 kW are used in heating the room. As only a very small part of the heat moving through the TE module is transformed into electricity (efficiency around 2% as explained in part 2.4), two heat fluxes of about 2 kW are available for TE power generator: the flux between the hot gas and the water and the flux between the hot gas and the air. So as to achieve an experimental benchtest with a similar flux, we used a gas heater of 2.2 kW maximum power and put over it an aluminium plate like the cooking plate in the stove or like an exchanger for the water tank.

The TE module was installed on the aluminium plate and two cooling systems were tried again:

– A heat fins exchanger being placed on the cold side with a 10 W air fan.
– A water tank directly put on the cold side of the TE module.

The amount of water contained in the tank applied a pressure on the cell of 10,000 Pa. A weight placed on rods above the fan applied the same pressure on the cell.

The temperature of the cold side was monitored with thermocouples. By comparing the evolution of the temperatures of the two cooling devices, we noted that for equivalent temperatures on the

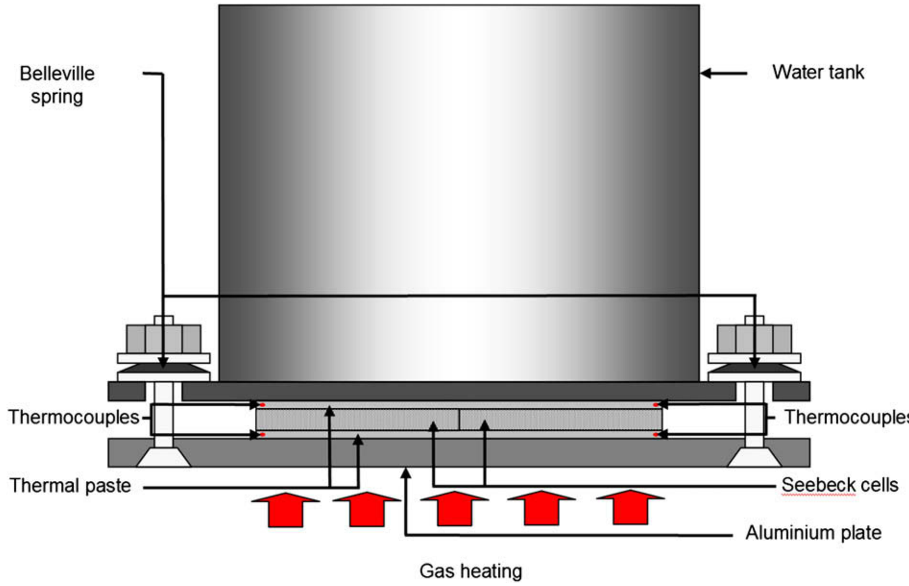

Fig. 12. TE power generator experimental set up.

hot side, different temperatures on the cold side were reached. The cold-side temperature reached 117 °C when the air fan is used whereas it was only 65 °C with the use of water. For this reason and also because it would consume a part of the electricity produced by the TE power generator, the use of the air fan was gave up.

4.2. Thermal part

A new assembly was set up to measure the recoverable power with two, three or four cells electrically connected in different ways. The device, presented in Fig. 12, used a tank of water as the cooling system. This latter was attached to an aluminium plate through threaded rods. The pressure was provided by bolts associated with Belleville springs to avoid breaking the cells. A thermal paste was spread at the interfaces.

We started by using each cell electrically independent (Fig. 13b) to verify their individual performance. The maximum power reached by each module varied between 1.7 W and 2.3 W for a temperature difference between the two sides of 160 °C. Then we tested the whole system with the four modules connected in series as shown on Fig. 13a.

The modules tests in series presented in Fig. 14 show that the power obtained with a temperature difference of 160 °C between the two sides of the cells, which may be considered as the normal working point, is about 7 W.

According to other laboratory experiment [17], it should be possible to get more power from each module by increasing the pressure on the cells. The difficulty is to find a solution which can be used in developing countries and not only in a laboratory. This will reduce the cost of the generator.

4.3. Electrical part

In the cooking stove, electricity is necessary to power the fan as air blowing through the stove increases the air/fuel ratio and so achieves a complete combustion.

At the beginning of the burning, the temperatures are very low and electricity is not available from the TE generator, so it is necessary to charge a battery.

The improved stove eliminates the light produced by the traditional open fire. So it is important to produce some light in the cooking room in a different way.

So the electrical load of our TE modules will be a battery, a fan and LEDs.

As the temperature in the stove changes during the cooking, when people take water or add wood, the output voltage of the TE modules will fluctuate a lot. An electric DC–DC converter is necessary to steady the output voltage. We chose a MAX642 step-up switching regulator which works in the 5 mW to 10 W range with a very good efficiency. We made measurements using

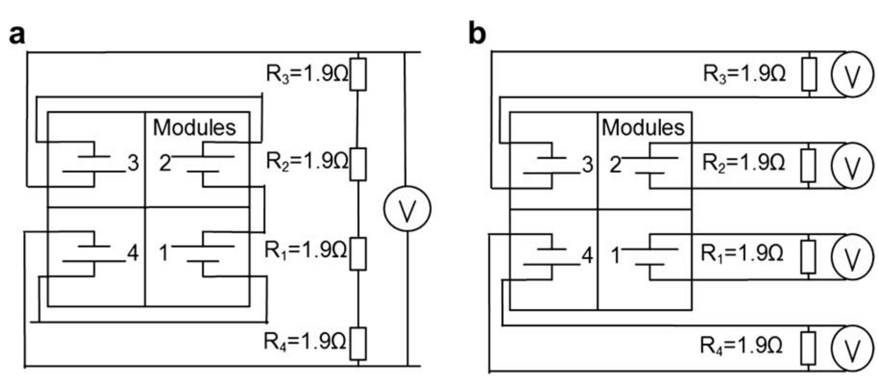

Fig. 13. Electric circuits with a) modules working independently, b) modules connected in series.

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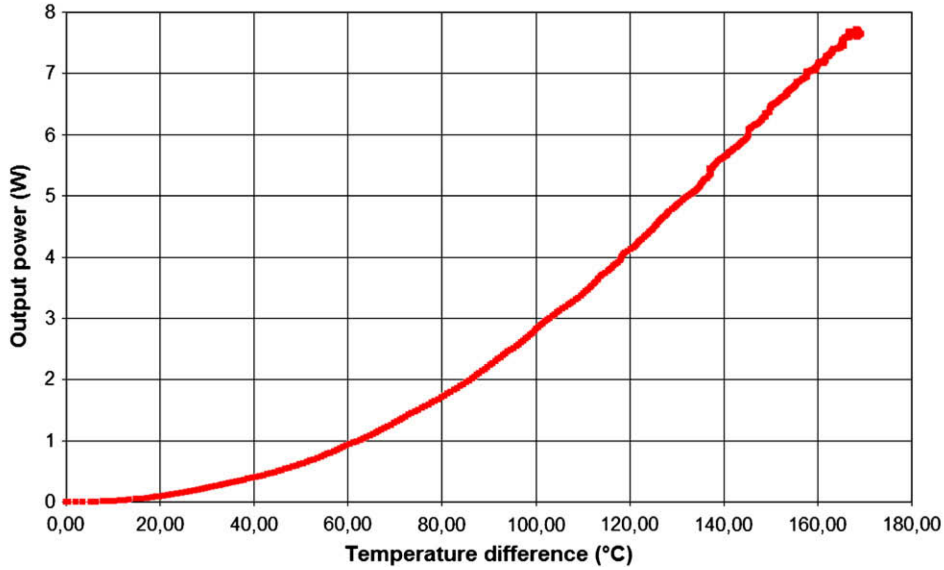

Fig. 14. Output electrical power versus temperature difference for 4 TE modules connected in series (experimental results).

a laboratory power supply with an internal 8 Ω resistance and we got the efficiency over 85% as soon as the power supply produced more than 3 watts.

The Fig. 15 represents the energy balance of our system.

We chose 6 V valve regulated lead acid (VRLA) batteries as they can be used directly in home environment, they are self-contained and safe, they can be stored and used in any orientation and are maintenance free. In a normal use, they are environmentally friendly. They are available at low cost in developing countries.

The expected service life of the standard VRLA battery is typically 5 years when used in floating voltage. For a 6 V battery the floating voltage is about 6.75 V.

The electrical power available for the battery is about 5 W, which implies a charging current of 0.75 A. As the maximum charging current is about 1/5 of the capacity, we chose a 4 Ah battery.

Assuming that the cooking stove will work 2 h twice a day, this means that the energy stored in the battery will be around 20 W h. If we assume that the lights will be on for 10 h per day, which is probably a maximum, we can use 2 W for the LEDs.

4.4. Discussion

This study shows that it is possible to obtain a useful power of about 6 W regulated electrical power with 4 TE modules for the stove.

The cost price has been briefly estimated as follows:

- The price for the electronic part is 31€ for one sample and drops to 15€ for more than 100 samples.
- The price of one TE module for the generator is 75€ and it decreases to 19€ for 10,000 pieces. However, the price of Peltier TE cooling modules of the same size produced in large quantities starts at 16€ for one piece and decreases to 12€ for 100 pieces. As the production of Peltier modules uses the same materials and the same technology except for welding on the hot side, the price should decrease in the years to come to a more reasonable value probably around 25€ for more than 100 samples.

We can estimated the price of our TE generator for a production of at least 100 pieces around 120€ for 6 W. So the cost per watt of our prototype is around 20€.

With an higher pressure on the modules and with a more sophisticated battery charger [18] it is possible either to get more power or to decrease the number of TE modules and then to reduce the cost per watt.

Another way to produce electricity for the fan of the stove is to use solar panels. The photovoltaic cost is around 15€ per watt (based on the average price of 10 watts solar panels supplied with their regulator in France).

The advantages of TE modules are as follows:

– The TE generator does not need extra energy from the stove. It will use the heat flux between the gas and either the water tank or the air, and will only convert a small part (less than 2% percent of this heat flux) into electrical energy.
– The TE generator is incorporated into the cook stove: it requires no electrical link with the outside world, unlike solar panels, or a manipulation of a battery.
– The maintenance is very light: nothing is moving, everything is inside the house, only the battery needs to be changed at the end of its life.
– The generator produces when the stove is on, night and day in fine or rainy weather (monsoon period) unlike solar panels. The battery does not need to be oversized as each use of the stove recharges the battery unlike solar systems where you need to store energy for the cloudy days.

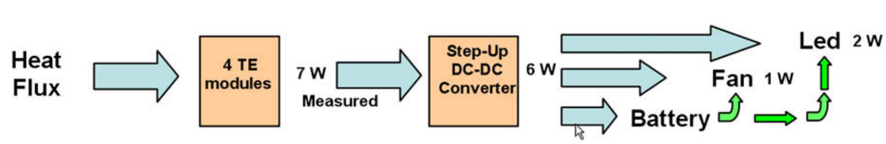

Fig. 15. Energy balance of the TE power generator.

All these advantages show that if for the time being the buying cost of a TE generator is higher than the price of a solar system, the long term cost taking in account the sociological aspect of end users might be comparable.

5. Conclusion

This work describes a part of the design of a clean and energy-efficient biomass stove both to cook and generate electricity for developing countries.

For a simple and low cost application of a rural stove, commercially available modules have been tested. The performance of energy conversion of Bismuth Telluride TE modules has been evaluated experimentally. The best power output of the system depends on the heat transfer through both sides of the module; a particular attention must be paid to the design of the heat exchangers. These results, with the help of a simulation model, are the first step to propose a system with appropriate locations of the modules.

Our study shows that the use of TE modules can be a very convenient way. This would require the importation of the generator module but the exchanger can be manufactured and assembled in a local workshop. The produced electricity will run the fan in the cook stove to increase the combustion efficiency. This will decrease the fuel consumption and the emission level. Extra electricity will be available to power LEDs.

Future work will consist in testing the TE modules into the improved biomass stove.

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