# THERMOELECTRIC TRIGENERATION GAS UNIT FOR REMOTE APPLICATIONS

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***Abstract.*** *Thermoelectric generation by solid state, using semiconductor materials, converts thermal energy to electrical without the need for moving parts. Although the process still produces low energy efficiency, it is characterized by high reliability, extremely low maintenance requirements and long life. Its principle is based on studies performed by Thomas Seebeck in 1800. The current article presents the conception, methodology, assembly, tests and results of trials conducted with a small load TEG unit in a trigeneration system, which meets multiple function requirements for applications in remote locations and nautical vessels. The proposed unit uses a butane gas lantern as the primary energy source for producing light energy and takes advantage of exhaust gas losses to generate DC current and thermal heating. Luminosity is obtained directly from the gas combustion in the lantern. Thermal energy is used to heat water and generate electricity obtained through conversion in a commercial semiconductor module. The unit was installed in a test bench to measure and record performance parameters. The bench also contains systems for fuel gas delivery, water heating and electrical load simulation. The recording of temperature curves was performed with a Field Logger® and a microcomputer using Field Chart® software for data acquisition. Electrical parameters were measured and monitored by high-precision multimeters. A light meter was used to map the luminous incidence in the useful area; other instruments and accessories were also used. A system analysis is presented based on the mass and energy balance. The results obtained were quite satisfactory for the objectives of the investigation.*

***Keywords****: thermoelectric generation, cogeneration, efficiency, energy, combustible gas.*

## 1. INTRODUCTION

Thermoelectricity is characterized by a solid process of thermal to electrical energy (heat) conversion without the need for moving parts, offering high reliability and low maintenance. Its principle is based on studies conducted by Thomas Seebeck in 1800 (Schaevitz et al., 2007).

The first thermoelectric generators were used in the Apollo Space Program at the end of the nineteen sixties, using standard fuel burning, converting heat into electrical power from the thermopile made of multiple thermocouples connected in series/parallel arrangements (Souza, 2006). State of the art thermoelectric generators use P - N semiconductor junctions such as bismuth and tellurium that produce different electrical power when submitted to different temperatures (Santanila, 2005).

Electrical power between 5 and 550 watts can be obtained by a single thermal generation unit. The power configuration supplied by a TEG is similar to that of a battery, in that combinations of multiple TEGs can be made in parallel or in series to meet higher power requirements (Lora and Nascimento, 2004).

TEG generators are widely used in situations demanding high reliability, such as remote sites where there is a need for low maintenance and long useful life or in adverse climatic conditions. Its main applications are cathode protection, automation and data transmission, telecommunication, navigational aids and others (Schroeder, 2004).

TEG systems are currently proposed for electrical energy generation from the residual heat of thermal machines such as automobile engines, wood-burning ovens, heating systems, among other applications (De Araújo, 2005).

The purpose of this study was to develop a gas powered thermoelectric trigeneration (lighting/electrical/thermal) prototype for small low-cost remote applications (Santos, 2007).

## 2. EXPERIMENTAL DETAILS

The experimental apparatus presented in figure 1 is composed of readily available components and materials as described below.

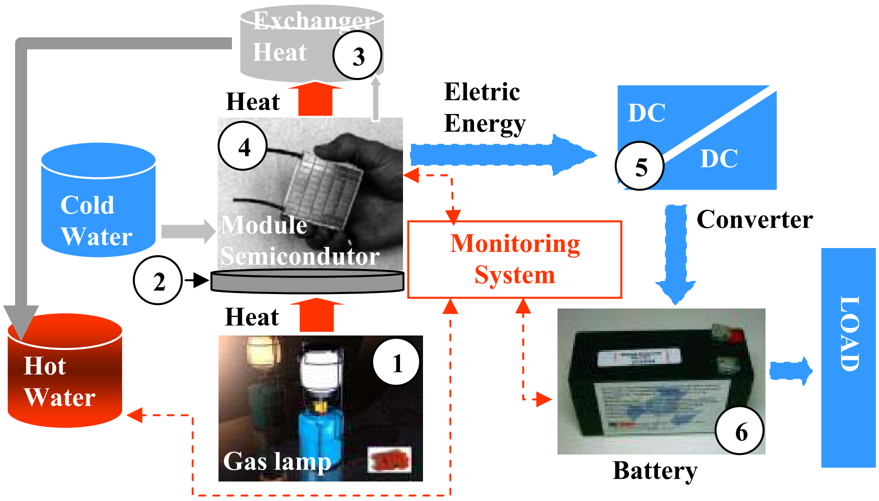

**Figure 1. Proposed TEG unit diagram**

The main component is a gas lantern (1) fed with LPG (liquefied petroleum gas) gas at a regulated pressure of 2 BAR. The system proposes to produce light by the controlled burning of gas that stimulates the irradiation of a mantle made of luminescent material. The hot exhaust gases on the upper part of the lantern are a heat source that warms the surface of the headstock (2), designed to heat the high temperature surface of the thermoelectric module and, by means of a heat exchanger (3) designed to be connected directly to the headstock, produce hot water in a cogeneration system. The DC electrical energy produced in the thermoelectric module (4) and conditioned in the converter (5) is stored in a battery (6) for various applications. The system used instrumentation to measure gas consumption and gas pressure, electrical power of the thermoelectric module, and to monitor and obtain inlet and outlet flow temperatures, among other items.

**Description of System Components:**

**Heat Source –**

The side of the aluminum headstock is in contact with the exhaust gases; **Cold Source** – The heat exchanger cools the cold side of the thermoelectric module and functions as a first stage in the cogeneration system, where the same water flow is used that feeds the heat exchanger of the second cogeneration stage; **Lighting System –** Illumination was obtained from the 500 candle release of light from the lantern mantle; **Semiconductor Module –** Electric light generation from the temperature difference between the heat and cold sources, using the imported HZ-14 tellurium and bismuth-based semiconductor module. This module is capable of producing 14W for a temperature difference of 200°C (Leavitt *et al,* 2003); **Monitoring System and Temperature Acquisition –** A Field Logger® data acquisition system (Novus, 2003) was used to monitor signals sent by type T thermocouples, to obtain temperatures at the different points indicated in Table 1. This system allowed the monitoring and control of the unit and the calculation of the thermal flows involved; **DC/DC Converter Booster –** A DC/DC resonant converter booster will regulate the 12 VDC low consumption battery to provide the increase in electrical power produced with a single HZ-14 module, which has an open-circuit voltage of 3.5VDC for a temperature difference of 250°C. However, it is interesting that that the unit uses an association of modules in series capable of providing 13VDC of electrical power.

The system was installed on a base, as shown in Figure 2. The headstock (heat source) and the copper heat exchanger of the second cogeneration stage were thermally insulated with stone wool and provisionally fixed with silver tape.

The unit was put into operation and gas outflow was adjusted to obtain the best luminosity at a control point. Once the gas (LPG) outflow was set, measurements were taken and temperature data acquisition was performed. After entering steady state operation the voltages and current of the module were measured, as well as ambient luminance, gas consumption and water flow.

Luminance was measured using a luximeter (LX-102, Lutron). The measurements were taken on a horizontal plane in the radius of the circle that passes through the center of the gas lantern, every 0.20m from the source between 0 and 3 m, making a symmetrical vertical scan at each point on the -0.50 to +0.50m range in relation to the horizontal plane considered.

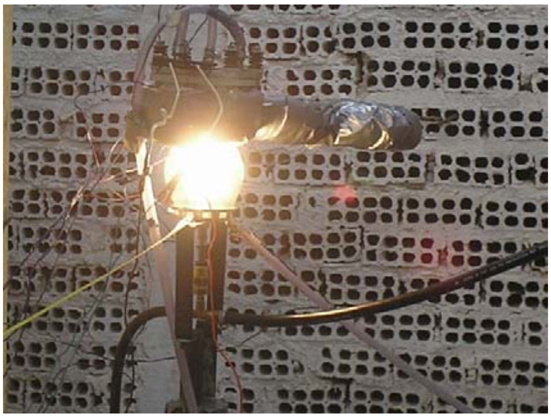

**Figure 2. TEG unit after thermal insulation**

Water outflow was calculated based on the average between the measurements of calibrated volume using a Becker flask and a high-precision chronometer.

**Fuel Power:**

$$F_P = PCI.\dot{m}_g \text{ [W]} \tag{1}$$

Where: PCI = 46,042.24 kJ/kg, the gross calorific power of LPG [kJ/kg] and $\dot{m}_g$ is mass gas outflow of LPG [kg/s]

**Thermoelectric Module Power:**

$$TE_P = U.I \text{ [W]} \tag{2}$$

Where: U is module voltage at 0.765Ω load [V] and I is module current at 0.765Ω load [A]

**Illumination Power:**

$$I_P = (f_i.S)/\eta_t \text{ [W]} \tag{3}$$

Where: $f_i$ is luminance flow [lx or lm/m$^2$]; $S$ is the area of useful cylindrical surface around the light bulb [m$^2$]

$\eta_t$ is the average luminous efficiency of light bulbs in Brazil [ 32.31 lm/W] (Assaf and Pereira, 2003).

**Thermal Power:**

$$T_P = \dot{m}.c.\Delta T \text{ [W]} \tag{4}$$

Where: $\dot{m}$ is mass water outflow [kg/s]; $c$ is the specific heat of the water [4.185kJ/kg] and $\Delta T$ is the difference between input and output temperatures $(t_f - t_i)$ respectively [ºC].

**Energy Balance:**

The global energy balance obtained from the energy conservation equation Eq. (5) allows us to calculate the various losses of the system.

$$F_P = TE_P + I_P + T_P + L_P \text{ [W]} \tag{5}$$

Where: $F_P$ is the power supplied by LPG [W]; $TE_P$ is the useful power produced by the thermoelectric module [W]; $I_P$ is the useful illumination power [W]; $T_P$ is the useful thermal power produced by the first and second stage heat exchangers [W] and $L_p$ represents the various losses incurred across the system [W].

**System Efficiency:**

$$\eta = \frac{TE_P + I_P + T_P}{F_P}$$

## 3. RESULTS AND DISCUSSION

### Outflows:

The gas consumption and water flow obtained to maximum power condition are presented in Table 1.

**Table 1. Gas consumption and water flow measurement on the TEG unit**

| Flows | (kg/s) | Conditions |
|---|---|---|
| LPG Gas consumption ( $\dot{m}_g$ ) | $1.666.10^{-5}$ | Stationary state |
| Water flow ( $\dot{m}$ ) | $1.167.10^{-2}$ | |

### Temperatures:

The temperatures are indicated in Table 2 and temperature transients are presented in Figures 3, 4 e 5. The greatest variation occurred for the heat source temperature (HST) curve, reaching a maximum value of 183 °C. The cold source temperature (CST) had a slight variation between 40 and 50 °C, showing that the heat exchanger designed to cool the cold surface of thermoelectric module was quite satisfactory.

**Table 2. Temperature measurement points on the TEG unit**

| TC | measurement Points | Acronym |
|---|---|---|
| 1 | Cold source temperature | CST |
| 2 | Outlet water flow temperature (1 stage) | OwT1 |
| 3 | Heat source temperature | HST |
| 4 | Inlet air temperature | IaT |
| 5 | Ambient Temperature | AT |
| 6 | Inlet water flow temperature | IwT |
| 7 | Outlet gases temperature | OgT |
| 8 | Outlet water flow temperature (2 stage) | OwT2 |

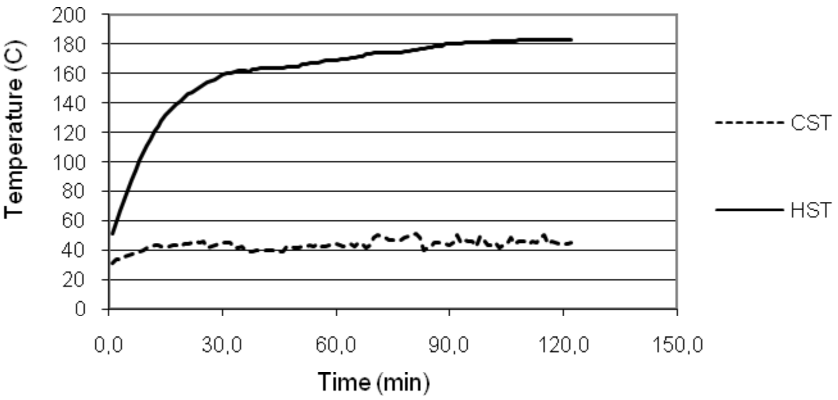

Figure 3. TEG unit temperature graph: Heat and Cold sources temperature

It is showed in figure 3 that the system arrives around 90% of the stationary state temperature, above the hot source surface, in 30 minutes and the stationary state is obtained after 90 minutes of the start.

The heat exchanger of the 1 and 2 stages gets quickly the stationary state and your temperature gradient stay stable along the operation time. This behavior is shown in the figures 4 and 5.

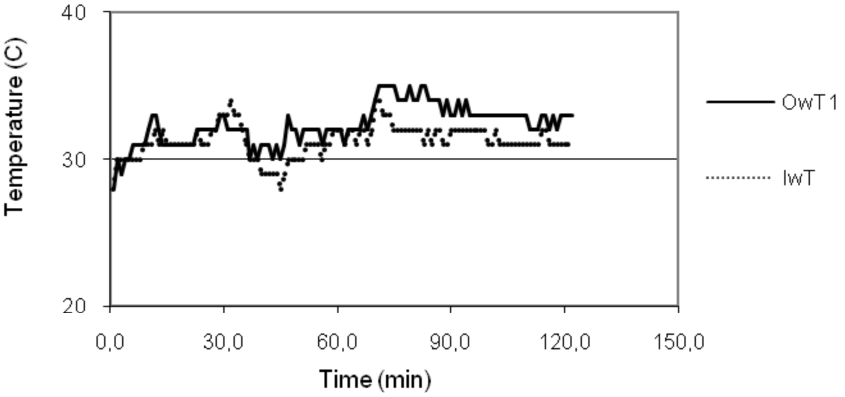

**Figure 4. TEG unit temperature graph: water flow temperature (1 stage)**

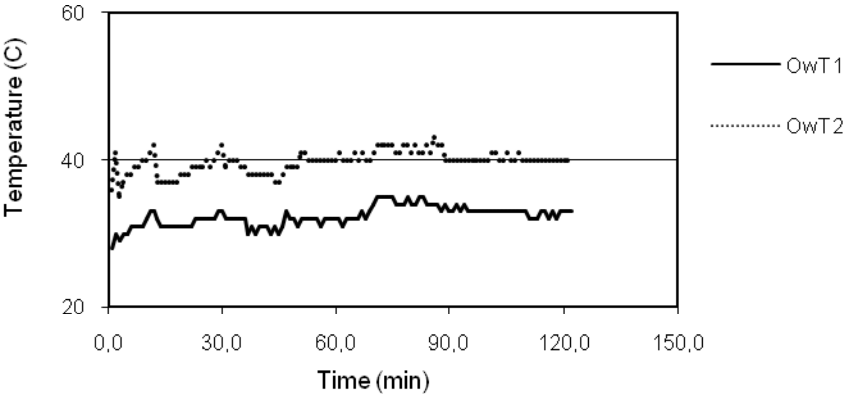

**Figure 5. TEG unit temperature graph: water flow temperature (2 stage)**

**Luminance:**

The values in Table 3 show the profile behavior of the illumination produced by the light bulb. The optimization study of the cylindrical surfaces around a lantern indicates that the greatest power occurs at a radius (r) of 0.4 m around the light bulb, with an illumination power of 8.27 W.

**Table 3. Illumination (Lux) versus distance (m) produced by the gas lantern of the trigeneration TEG unit.**

| Horizontal Distance (m) | Iluminance (lx) | | | | | | |
|---|---|---|---|---|---|---|---|
| | Vertical distance(m) | | | | | | |
| | -0,50 | -0,30 | -0,20 | 0 | 0,20 | 0,30 | 0,50 |
| **0,2** | shade | shade | 200 | 660 | 400 | shade | shade |
| **0,4** | 40 | 70 | 100 | 250 | 215 | 125 | 15 |
| **0,6** | 35 | 57 | 70 | 137 | 115 | 95 | 20 |
| **0,8** | 30 | 40 | 50 | 85 | 80 | 75 | 38 |
| **1** | 30 | 31 | 46 | 60 | 53 | 50 | 36 |
| **1,2** | 30 | 31 | 35 | 45 | 40 | 38 | 32 |
| **1,4** | 24 | 24 | 28 | 35 | 31 | 28 | 26 |
| **1,6** | 21 | 22 | 24 | 29 | 24 | 23 | 22 |
| **1,8** | 17 | 17 | 19 | 24 | 21 | 20 | 18 |
| **2** | 15 | 16 | 17 | 20 | 18 | 17 | 16 |
| **2,2** | 14 | 14 | 15 | 17 | 15 | 14 | 14 |
| **2,4** | 12 | 12 | 12 | 14 | 13 | 13 | 12 |
| **2,6** | 10 | 11 | 11 | 12 | 11 | 11 | 10 |
| **2,8** | 9 | 10 | 10 | 11 | 10 | 10 | 9 |

**Thermoelectric module behavior:**

The HZ-14 thermoelectric module displayed expected behavior (voltage x current) according to information provided by the manufacturer and to the operational conditions of the system, as shown in Figure 6. A maximum power of 5.643 W was obtained (Table 4), a value lower than the maximum power of 14 W expected under ideal fixation, thermal gradient, maximum temperature and insulation conditions. This shows that the system can still be further optimized.

**Table 4. Thermoelectric module performance**

| Principals Results | |
|---|---|
| Open circuit module voltage | 2,456 (V) |
| Module mean voltage (load of 0,202 Ω)* | 1,058 (V) |
| Modulo mean current (load of 0,202 Ω)* | 5,333 (A) |
| Maximum power module (load of 0,202 Ω)* | 5,643 (W) |

* Maximum power conditions

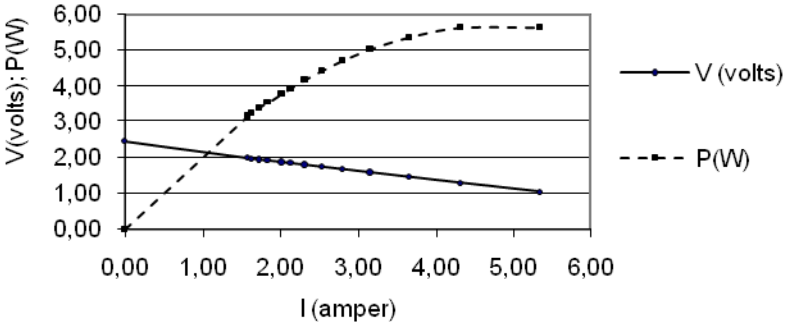

**Figure 6. HZ-14 TEG module performance.**

**Tri-generation unit performance:**

The values in Table 5 show the performance of the prototype. Although illumination efficiency was low and electrical generation was below that expected, the global efficiency of the tri-generation unit was high, owing to power cogeneration using a system of heat exchangers (Cogen, 2003).

**Table 5. Performance of the tri-generation thermoelectric unit prototype**

**(Maximum power condition)**

| Component | Power (W) | Efficiency (%) |
|---|---|---|
| HZ-14 module ($TH_P =$) | 5,64 | 0,74 |
| Gas lantern ($I_P =$) | 8,27 | 1,08 |
| Cogeneration ($T_P =$) | 439,55 | 57,30 |
| Losses ($L_P =$) | 313,60 | 40,88 |
| Σ = | **767,06** | **100** |
| | | |
| Σ trigeneration unit | **453,46** | **59,12** |
| Fuel power ($F_P =$) | 767,06 | |

## 4. CONCLUSION

The system proved to be a good alternative for tri-generation in remote areas, producing total useful energy of 453.46 W with global efficiency of 59.12 %.

The system arrives around 90% of the stationary state temperature, above the hot source surface, in 30 minutes and the stationary state is obtained after 90 minutes.

The HZ-14 thermoelectric module, despite producing only 40.29% of the ideal power (14 W) recommended by the manufacturer, is sufficient to charge a 12 (Volt) and 50 (Amp.hour) battery for 106 hours or feed a 9 W Pl light bulb for 15 h per day.

The cogeneration system can supply 42 liters of water per hour with a temperature gradient of 10°C, which is a valuable advantage in remote locations.

## 5. ACKNOWLEDGEMENTS

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