Experimental study and optimization of thermoelectric-driven autonomous sensors for the chimney of a biomass power plant

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Abstract

This paper develops a thermoelectric generator intended to harness waste heat from the exhaust gas of a boiler in a biomass power plant, and thus generate electric power to operate a flowmeter installed in the chimney, in order to make it autonomous.

The main objective is to conduct an experimental study to optimize a previous design, obtained after a computational work based on a simulation model for thermoelectric generators.

Firstly, several places in the chimney have been considered to host the thermoelectric generator, either inside or outside the chimney power plant. Secondly, the thermoelectric generator was built and tested in order to assess the influence of the cold side heat exchanger on the electric power, flowmeter electric consumption and emission frequency. These tests indicate the best configuration for this heat exchanger that meets the emission requirements for different working conditions of the power plant, either in summer or winter.

The final design is able to transmit information every one second, and requires neither batteries nor electric wires, being a promising application in the field of thermoelectric generation.

Keywords: Thermoelectric generation; waste heat; autonomous sensor; thermal resistance.

1. Introduction

Power generation using waste thermal energy is possible whenever a temperature gap between a hot source and a cold sink is available, at any accessible area in the industry [1]. One of the most promising applications of waste thermal energy is the empowerment of thermoelectrics-based autonomous sensors to form a wireless sensor network. At present, there are some devices that provide monitoring data for security infrastructure (tunnels, bridges, etc) [2] or structure health in aircrafts, wherein the electric power is generated by thermoelectric generators (TEGs), attached to the inner part of the fuselage and to thermal storage devices [3]. Other areas of great interest are the applications for communications, telemetry, etc [4].

In the industry, there are many sources of residual thermal energy. The present study focuses on the case of a biomass power plant, though this application could be easily transferred to other fields.

One of the advantages of this technology is that no batteries are needed (thus avoiding the problems of recycling) low maintenance is required and a long lifetime is expected.

In a previous research [1], we designed computationally a thermoelectric device to operate some sensors in a biomass power plant, and make them autonomous. The main objective of the present paper is to conduct an experimental study to optimize this previous design,

To carry out the experimental tests, a prototype has been built. The study determines the possible locations for the thermoelectric generator in the chimney of biomass power plant, providing the temperature of the heat source. Furthermore, different dissipators are studied to provide the relation between the electric power generated and the thermal resistance of each dissipator. This methodology enables us to determine the most appropriate dissipator for each case.

2. Construction of the test bench

The test bench is shown in Fig.1 and is composed of a thermoelectric generator, the measuring device and the computer. The thermoelectric generator is composed of four modules ENERKIT SC-127-10-15, arranged thermally in parallel and connected electrically in series, each one presents an electric internal resistance of 4 Ω and is composed of 127 pairs. Modules technical and geometric characteristics can be found in [5], type and number of selected modules are based on the results obtained in a previous work [1].

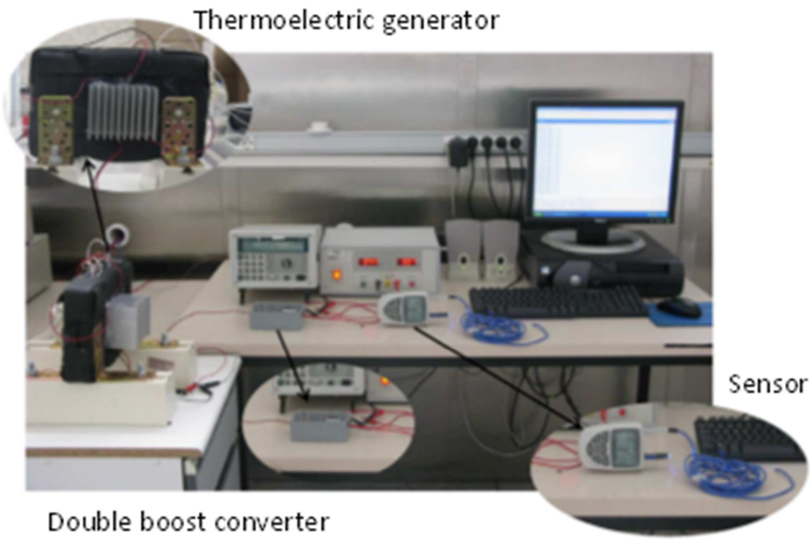

Fig. 1 Test bench of the thermoelectric generator

Other components are: 2 heat-generating electric resistors that simulate the waste heat, a finned dissipator for the cold side of the modules and an insulating cover. Between the modules and the measuring device, an electronic circuit (double-boost converter) is installed, so that the thermoelectric generator always works at the optimal point, amplifying the voltage and reducing the output current [1]. The most sensitive components of the thermoelectric generator are the Peltier modules and electronic components, which will be protected from the outside environment by an aluminum case 100 * 100 * 10 mm.

A previous paper studied the influence of the number of modules and dissipator thermal resistance on the power output, by using a computational model [1]. The current paper sets out to maximize the power output by optimizing of the thermal resistance of the dissipator. Five different dissipators have been tested, as Figure 2 shows. The selected dissipator will provide the electric power required by the measuring apparatus, meeting the corresponding weight and dimensional requirements.

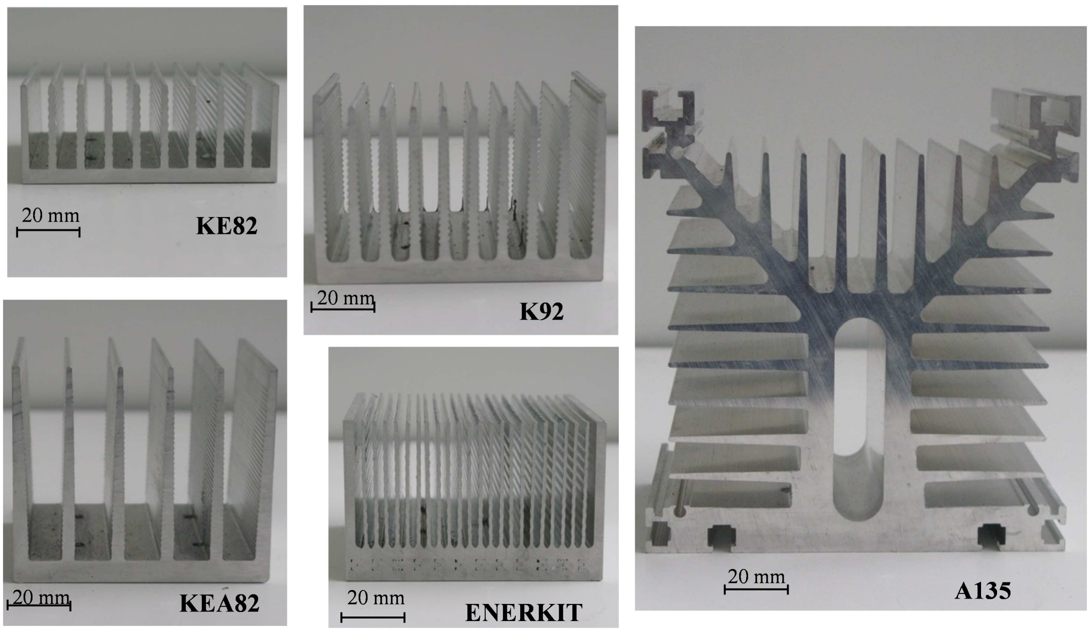

Fig. 2 Dissipators tested

Dissipator KE82 has a base area of 82x82 mm^2, including 10 fins of 32 mm in height and separated 6.9 mm. KE82 presents a base area of 81x81 mm^2, 20 fins of 50 mm in height separated 2 mm. KEA82 has a base area of 82x82 mm^2, 6 fins of 69 mm in height and separated by a distance of 14 mm. K92 has a base area of 92x82 mm^2, contains 10 fins of 60.5 mm in height and separated 8 mm. A135 exhibits a base area of 125x82 mm, it has a height of 135 mm, with numerous fins positioned vertically and horizontally, and a hole in the central part. The mass of each dissipator is shown in Table 1.

Dissipator	m [kg]	Rd [K/W]
KE82	0.22	1.94
ENERKIT	0.81	1.62
KEA82	0.40	1.35
K92	0.48	1.19
A135	1.24	0.76

Table 1 Thermal resistance and mass of the dissipators

3. Assembly of the thermoelectric generator in the chimney of the biomass power plant

The study was conducted for a chimney of a combustion boiler in a biomass power plant in the town of Sangüesa (Spain). The thermoelectric generator will be installed on the chimney outer surface, 25.6 m above the ground. At this spot, the reported smoke temperature is 140 °C on average.

In order to make a more complete study, we study the performance of the prototype under two ambient temperatures, one for the summer and the other for the winter. Spanish Meteorological Agency reports 7ºC of average ambient temperature for the winter and 20 º C for the summer [6].

The original chimney comprises an inner steel cylinder 62.5 mm thick, covered by a 29.5-mm-thick insulator to prevent heat loss. The chimney also includes two more steel layers 8 mm thick, separated 15 mm. Two assemblies for the thermoelectric generator and the chimney are studied.

3.1. *Configuration I*: thermoelectric generator on the outer wall of the chimney

As Fig. 3a shows, the thermoelectric generator is installed on the outside of the chimney, attached to the inner 8-mm-thick layer. Thus, we must install a 15-mm-long heat extender to transfer heat form the chimney to the hot side of the thermoelectric modules.

Given that the smoke temperature is on average 140 °C, the construction data and estimated convection coefficients inside and outside the chimney, the temperature of the inner 8-mm-thick layer reaches 82.7 °C in winter and 87.2 ºC in summer.

3.2. *Configuration II:* thermoelectric generator on the inner wall of the chimney

Figure 3b shows the second configuration. The thermoelectric generator is now in contact with the smoke. Thus, we must install a 116-mm-long heat extender.

The hot face of the modules is at 135.0 ºC in winter and 139.2 °C in summer, so higher temperature gradients in the modules are expected, thus increasing the power generation.

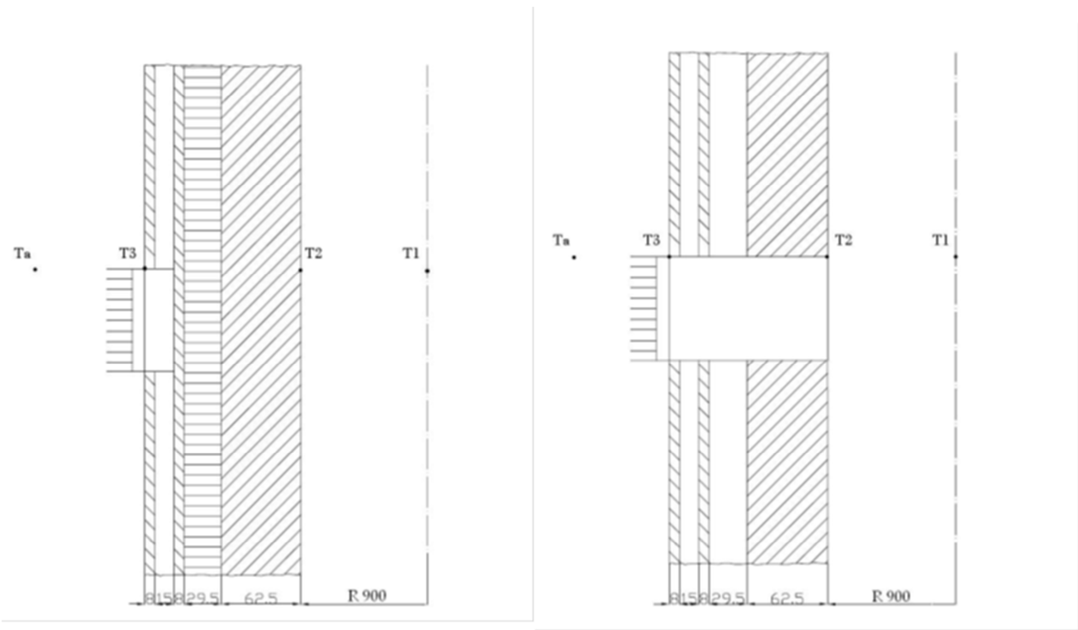

Fig. 3a Configuration I; **Fig. 3b** Configuration II

4. Study of optimum point power for each dissipater

It was selected "*Configuration I*" due to its easier installation. In this section we present the results obtained for each type of dissipator and weather conditions studied. We show as an example the performance of the KE82 dissipator in summer conditions.

The ambient temperature is set at 20 °C in a climatic chamber. Then, the electric resistors generate the necessary heat flow rate so that 87.2 °C are established at the hot face of the thermoelectric modules. This simulates the temperature of the wall of the chimney, as section 3.1 indicates.

In these conditions, 10.7 °C are established between the hot and cold face of the modules. Several tests were performed for different load resistances to obtain the power curve presented by Fig. 4. At the optimal point, the electric power reaches 50,413 mW with 0.863 V of voltage and 58.399 mA of electrical current. The heat flow rate provided by the electric resistors turns out to be 37.6 W (taking into account the heat losses through the insulator), so the efficiency of the thermoelectric generator is 0.1436%.

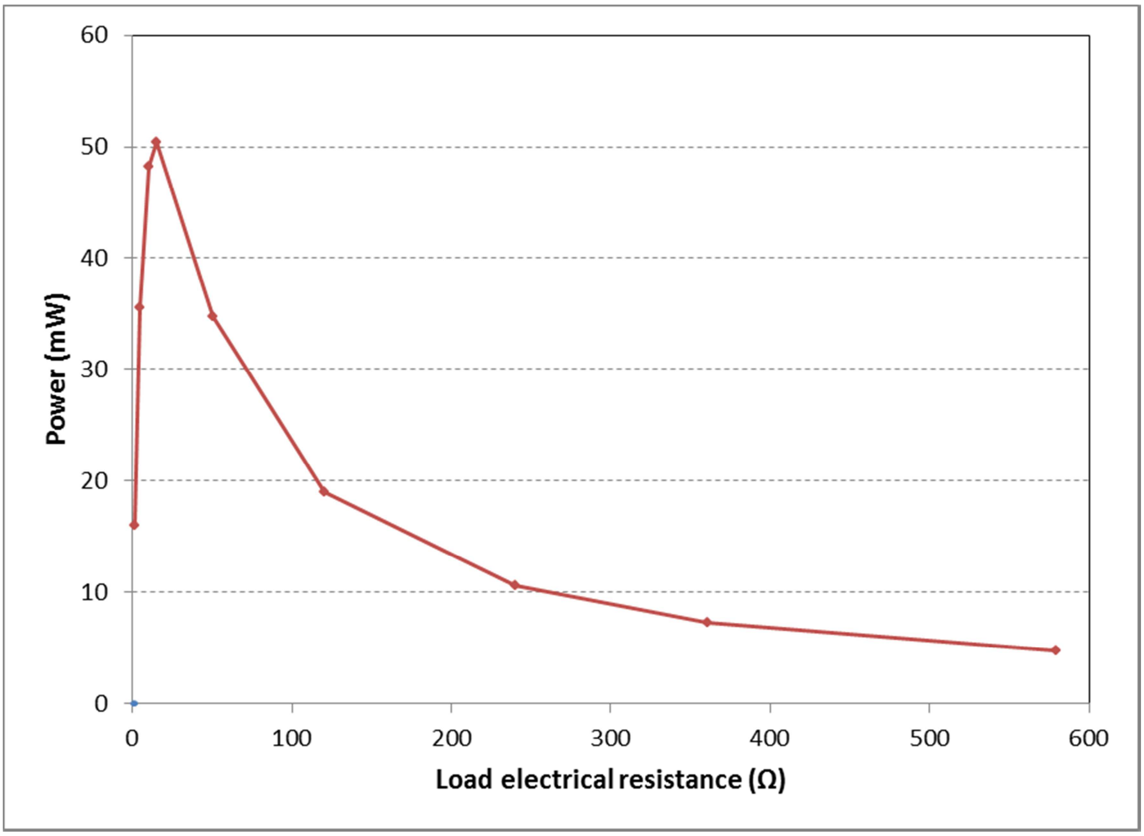

Fig. 4 Power in function of load electrical resistance

At the optimum working point, the TEG produces maximum electric power, which occurs when the load resistance is equal to the internal resistance of the modules. Since in all cases tested the number of modules remains constant, all TEGs reach the optimum point for the same load resistance.

Figure 5 indicates that the generator reaches the maximum power when the load resistance is around 16 Ω. However, the sensors used in the thermal plant have an electric resistance around 600 Ω. The curve shows that at 600 Ω, the electric power would be very low, unfeasible to operate the sensor. This is the reason why the double-boost converter is included [1], so that the TEG works at optimal and the output voltage is amplified.

Table 1 shows the thermal resistance of each dissipator, provided by Eq. (1), since we measure the temperature at the dissipater base (Tb), the ambient temperature (Ta) and the heat flow provided by the heating resistors (Qd).

$$R_{\mathrm{d}} = \frac{T_{\mathrm{b}} - T_{\mathrm{a}}}{Q_{\mathrm{d}}} \qquad (1)$$

We have represented the experimental curve of the optimal maximum power point as a function of the thermal resistance of the dissipator for summer conditions (Fig. 5) and winter conditions (Fig. 6). These experimental curves provide empirical expressions of the generated power, if other dissipators were used.

The choice of the dissipator is crucial, because the thermal generation is directly linked to it. The optimal dissipator for the thermoelectric generator would be the A135, since it leads to a power generation of about 300 mW. However, smaller dissipators involve lower cost and simplify the installation procedure.

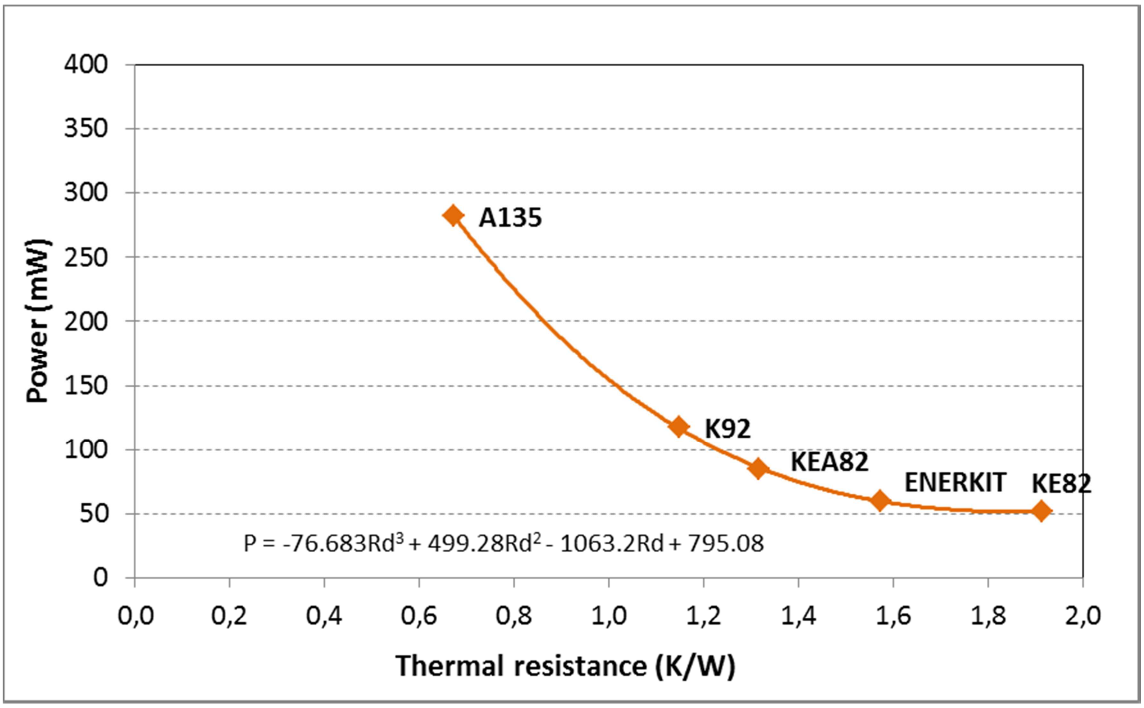

Fig. 5. Power as a function of the thermal resistance of the dissipator. Summer

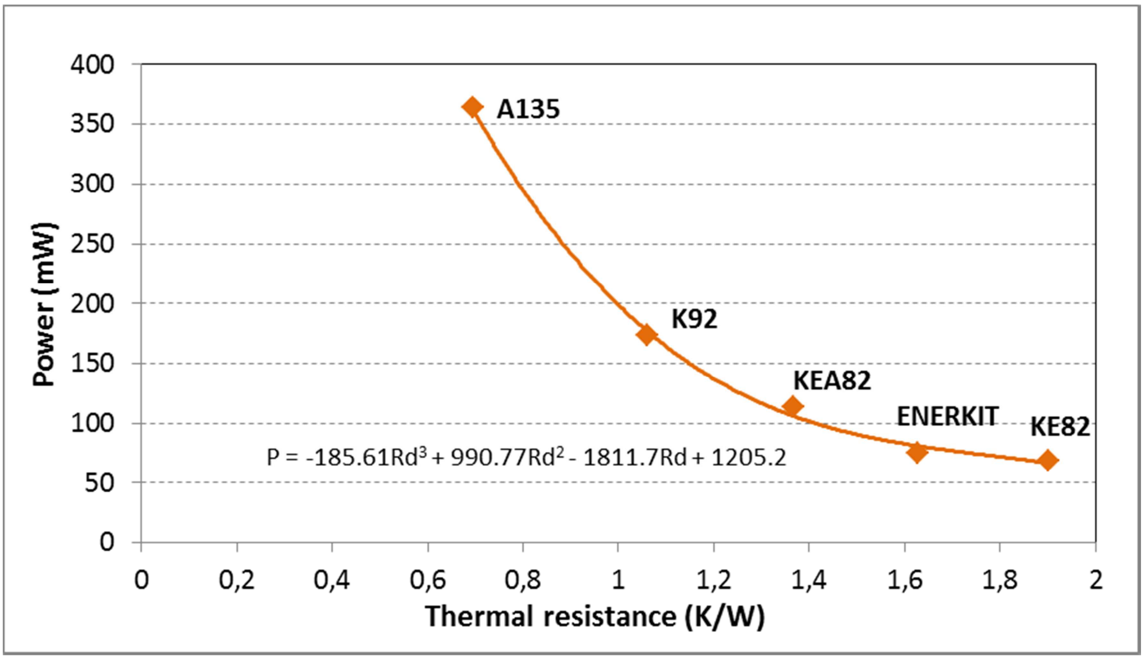

Fig. 6. Power as a function of the thermal resistance of the dissipator. Winter

5. Final design of thermoelectric generating device

The selected measuring apparatus responsible for monitoring the flow of smoke from the chimney of the biomass plant is the Almemo 2450-1/L. This instrument measures only a parameter: temperature, pressure, humidity, flow, etc. In our case, a flow sensor is connected.

In this section we analyze the consumption of the measuring device and the radio frequency transmission system THUW1103 Wireless Data Transmitter. Keep in mind that the autonomous sensor is installed in a chimney at great height, so the data must be transmitted to the control center of the biomass, since it would not be comfortable having to climb the chimney to read the data.

The average power required by the measuring device and the transmitter is 304.68 mW. Thus, among the tested thermoelectric generator, the only one able to supply that amount of power for continuous operation should include the A135 dissipator. The rest do not reach 305 mW, so that the only option would be to work in discontinuous operation. Under these circumstances, the electric power provided by the thermoelectric generator is stored in batteries until the energy stored suffices to energize the measuring apparatus and emit the information.

Regarding the electric power generated, the thermoelectric generator that includes the A135 dissipator is the one that provides the highest power, with 282 mW, for summer weather conditions, and 364 mW in winter. The thermoelectric generator that includes the K92 dissipator is the second one, generating 117 mW in summer and 173 mW in winter. This power is essential in the final design of the model.

Finally, we must also take into account the geometry and shape of the dissipator. We must be aware that the thermoelectric generator is due to be installed at high altitude, in a chimney, so it should not be too heavy (2 kg as Table 1 shows). The dissipator A135, has a height of 135 mm and a base area of 125x925 mm^2, being too much heavy and quite bulky. However, dissipator K92 has a height of 60.5 mm and a base area of 92x92 mm^2, with optimal geometry for the modules used.

Thus, taking into account these aspects, we have decided to install in the thermoelectric generator the dissipator K92, and emit the measure of the flow discontinuously, which seems logical since this parameter is not expected to exhibit large variations within seconds. Therefore, an emitted measure every 3 to 5 minutes provide sufficiently accurate records.

The ratio between the power required by the flow meter (305 mW) and power provided by the thermoelectric generator (173 mW in summer and 117 mW in winter) indicates the time required to store the energy needed to emit one data, which result 1.763 s (in summer) and 2.606 s (in winter).

6. Conclusions

We have studied the possible locations of the thermoelectric generator in the chimney of a power plant, determining the surface temperature for different settings and different seasons of the year.

Generated power curves have been obtained as a function of the thermal resistance of the dissipator. Taking into account geometric and assembly aspects, this methodology allows us to select the optimal dissipator (K92), which leads to electric power generation of 173 mW in winter conditions and 117 mW in summer conditions.

The sensor used for the data transmission system consumes 304.68 mW and cannot be energized continuously. For this reason, we include an electronic system that stores energy, thus allowing discontinuous transmission. The system sends data every 1.763 s in winter and 2.606 s in summer.

Although the study has been applied to the chimney of a biomass power plant, the methodology established and the series of graphs presented are readily transferable to other industries with similar thermal conditions.

Acknowledgments

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Figure captions

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Fig. 2 Dissipators tested

Fig. 3a Configuration I; **Fig. 3b** Configuration II

Fig. 4 Power in function of load electrical resistance

Fig. 5. Power as a function of the thermal resistance of the dissipator. Summer

Fig. 6. Power as a function of the thermal resistance of the dissipator. Winter

Table captions

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