Article

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Development of a Small Thermoelectric Generators Prototype for Energy Harvesting from Low Temperature Waste Heat at Industrial Plant

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A 39-W thermoelectric generator prototype has been realized and then installed in industrial plant for on-line trials. The prototype was developed as an energy harvesting demonstrator using low temperature cooling water waste heat as energy source. The objective of the research program is to measure the actual performances of this kind of device working with industrial water below 90 °C, as hot source, and fresh water at a temperature of about 15 °C, as cold sink. The article shows the first results of the research program. It was verified, under the tested operative conditions, that the produced electric power exceeds the energy required to pump the water from the hot source and cold sink to the thermoelectric generator unit if they are located at a distance not exceeding 50 m and the electric energy conversion efficiency is 0.33%. It was calculated that increasing the distance of the hot source and cold sink to the thermoelectric generator unit to 100 m the produced electric energy equals the energy required for water pumping, while reducing the distance of the hot source and cold sink to zero meters the developed unit produces an electric energy conversion efficiency of 0.61%.

Keywords: Thermoelectric Generator, Thermoelectricity, Energy Harvesting, Waste Heat, Heat Exchanger.

1. INTRODUCTION

In industrial plants an enormous amount of thermal energy is continuously spread out into the environment as a by-product of the main processes. A large part of this energy arises as cooling water at a temperature below 90 °C and low pressure. This low enthalpy energy is normally not recovered and then dissipated into the environment. Moreover, in general, it is required to spend energy to remove it. The best solution, when possible, it is to use such energy for space heating. When this is not possible, another possibility is to transform part of it into electricity. But, in this case, the problem is the low efficiency of a thermal engine working with a temperature gap below 90 °C, which makes the produced electricity very expensive, with respect to the actual market. Therefore, except for particular applications, for example in remote areas where electricity could be very expensive, it seems very difficult to convert low temperature waste heat into electricity in an economically sustainable way.

Several research studies have been carried out to examine the opportunities of waste heat recovery,[1–3] especially for district heating objectives,[4,5] but also dealing with waste heat conversion in electricity for specific industrial sectors.[6–8] In industrial plants, four main conversion processes have been studied: Stirling engines, Organic Rankine Cycle (ORC), Kalina cycle® and Thermoelectric Generators (TEG). Stirling engines shows a very high conversion efficiency factor but also a very high cost of development and maintenance, therefore they were rarely studied at industrial conditions.[9,10] ORC systems have

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been deeply investigated in industry[11,12] and applied at different plants at steel and metal industries,[13–15] cement industry[16,17] and biomass.[18–20] The Kalina cycle® has been also applied for waste heat harvesting in cement industry,[21,22] oil refinery (Chiba plant, Japan), incinerators (Fukuoka plant, Japan), steel works (Kashima plant, Japan),[23] and it was compared with ORC plants performance.[24,25] Waste heat recovery using thermoelectric power generation is still in the experimental phase and under study,[26–29] but some industrial plant test have been carried out in the steel industry,[30,31] cement industry[32] and industrial furnaces.[33]

The present work has focused on the development of a low temperature waste heat recovery device, working as a heat exchanger, which produces, by means of thermoelectric modules, an amount of electricity sufficient to move the cooling/heating fluids and then realizing a cooling system that does not require any consumption of electricity because it is self-produced. The objective of this research is to verify under which constraints these kind of devices could be reasonably applicable and economically sustainable in real plant conditions.

2. EXPERIMENTAL SECTION

2.1. Thermoelectric Generators

A thermoelectric generator (TEG) is a kind of heat engine able to convert directly a heat flux into electricity.[34] A TEG unit is composed by an array of modules able to generate electricity, named thermoelectric modules (TEM), sandwiched between a hot source and a cold sink. Each TEM consists of a number of semiconductor *n*-type and *p*-type thermoelements, electrically connected in series and thermally connected in parallel. When a temperature differential is established between the hot and cold ends of the semiconductor material, a voltage difference is generated between the two faces of each thermoelement and consequently the sum of the voltage can be observed at the extremities of the whole TEM circuit. Therefore, a single TEM can be considered as a voltage generator, and a TEG unit as a battery of voltage generators with a small, but appreciable, electromotive force. Some specific characteristics make TEG units very interesting, in particular they have no mechanical moving parts, are silent and scalable. On the other hand, respect to other heat engines, they have a low heat to electric energy conversion efficiency.

2.2. Experimental Set Up

The device developed in the present work is basically a multi-pass counterflow heat exchanger working also as a thermoelectric generator unit, where the objective is to produce a quantity of electricity that should be at least equal (or more than) the electric power required to move the hot and cold water.

Figure 1 shows the experimental set up. The hot source is obtained tapping demineralized hot water (≈70–85 °C)

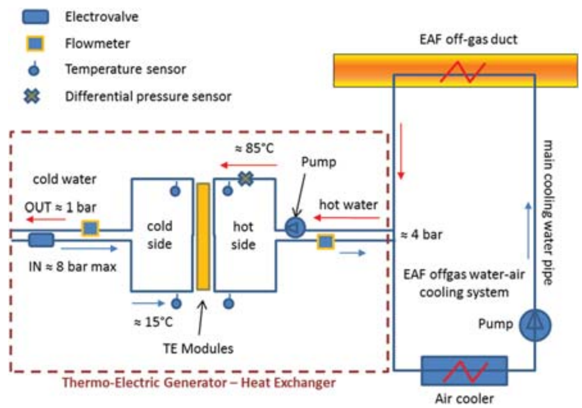

Figure 1. Experimental set up.

from the cooling water circuit of an Electric Arc Furnace (EAF) off-gas duct at Ferriere Nord plant in North of Italy. A pipeline was built to transport the hot water from the main cooling water pipe to the TEG unit site and back into the main pipe. The pressure of the hot water at tapping point and back point has the same value (≈4 bar). The energy required to move the fluid from the main pipe to the TEG unit and back is obtained through the measure of the electric power absorbed by the water pump (LOWARA ecocirc®). The length traversed by the hot water is about 100 metres (to go, and to come back). Hot water flow rate is set by using a pump regulation system.

The cold sink is obtained using fresh water, available at ground level at a temperature of ≈10–15 °C and a pressure of 8 bar supplied by the network. Therefore the energy required to transport the cooling water from the well to the TEG unit cannot be measured, but it is calculated as the same as that required for the hot water, assuming that the hot source and the cold sink have the same distance from the TEG unit. For this part of the circuit an electrovalve is used as a flow rate regulator.

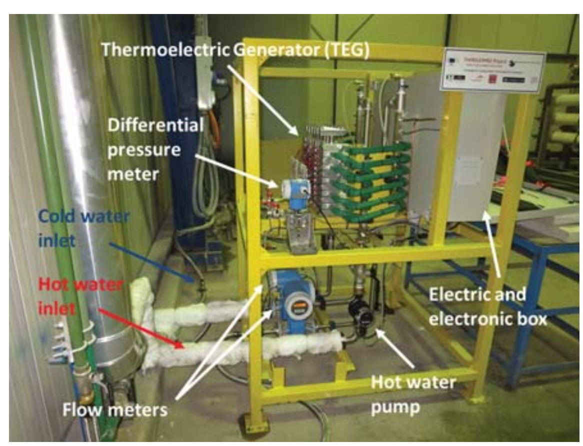

Figure 2. Thermoelectric generator and measuring systems at plant site.

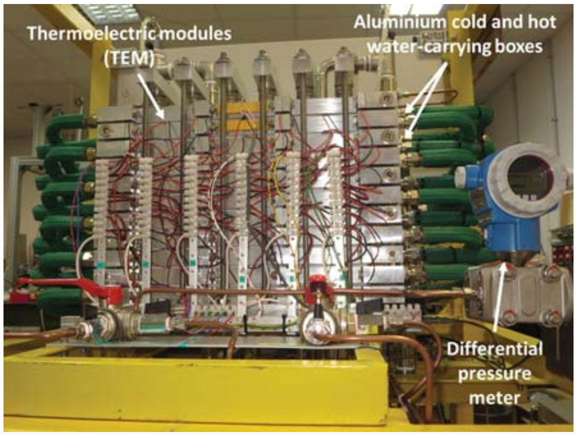

Figure 3. Thermoelectric generator.

Inlet and outlet water temperatures are measured by means of a PT100 sensor (Italcoppie® TRCP1A2C) installed in the water pipes. Flow rates of both the cold and hot water circuit are measured by means of two flow meters (both Endress Hauser Promag 50P). A differential pressure meter is installed to measure the pressure drop through the TEG hot and cold water circuit (Endress Hauser Deltabar S).

Figure 2 shows the TEG unit installed at the plant site. The core of the developed TEG device consists of an array of TEMs (European Thermodynamics model GM250-127-28-10, matched load output power 28.3 W with hot side 250 °C and cold side 30 °C) sandwiched between hot and cold aluminium water-carrying boxes (Fig. 3). The hot and cold water boxes are not in contact with each other, but are in contact only with the TEMs, and traversed back and forth three times by the hot and cold water (multi-pass design). The TEM network is composed of 10 horizontal rows and 6 columns, where each row includes 6 TEMs and each column includes 10 TEMs. The TEMs of each column are electrically connected in series, and not electrically connected with the other columns. Four PT100 sensors measure the external temperature of aluminium water boxes (two at the centre of the device and two on the top).

The electrical power produced by each column of TEMs is transferred to the electric power dissipation unit installed inside the electric box. Each column has its own fixed external resistance load with a total resistance of 3 Ω. This value has been calculated assuming that each module has a matched load resistance of 0.3 Ω (in standard operation conditions). This value was obtained using the module datasheet and from laboratory experiments performed by heating the TEM hot side to 90 °C, and cooling the cold side to 20 °C. Analog I/O modules and a PC are used for pump/electrovalve control, measured data acquisition and data storage. A panel interface was developed, using National Instrument Labview® software, for a fast TEG unit data visualisation and control activities (Fig. 4).

3. RESULTS AND DISCUSSION

The TEG unit was installed in the plant site and then put into operation. The device's performance showed strong variability, as a function of the inlet hot water temperature, which depends on the EAF activity. The hot water temperature trend, at normal operating conditions, ranged from 70 °C to 85 °C, and the cold water between 10 and 11 °C (winter time).

Figure 5 shows the TEG power trend as a function of the inlet hot water temperature at a constant cold water temperature (11 °C), and constant hot and cold water flow rate (1 m^3/h). A strong linear dependence of the TEG power with respect to the hot water temperature has observed, this result is a direct consequence of the similar behaviour shown by the thermoelectric elements.

Hot and cold water flow rates are other important variables affecting the overall TEG performance. In the present work it was decided to focus on the behaviour of the

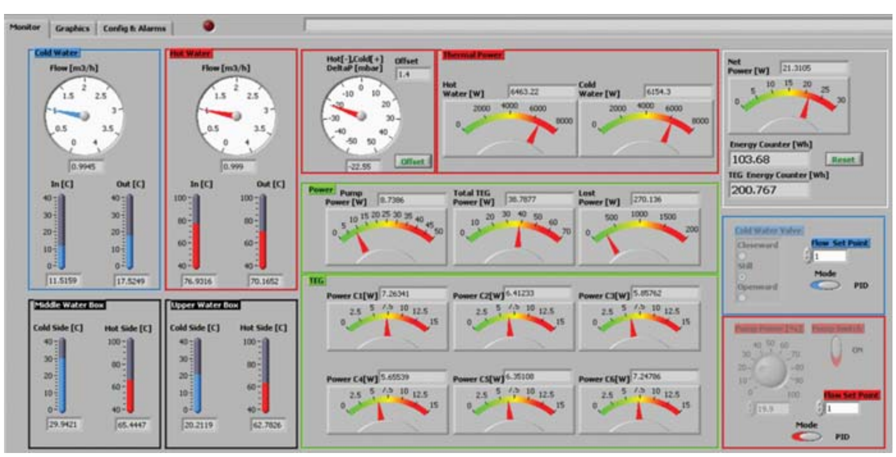

Figure 4. TEG control panel interface.

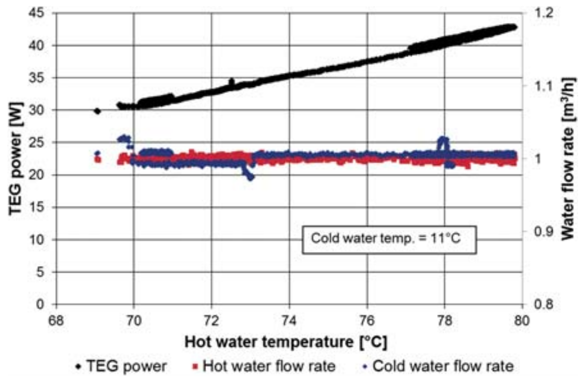

Figure 5. TEG power versus hot water temperature.

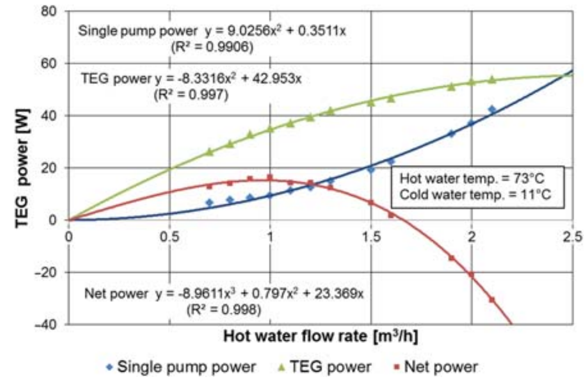

Figure 6. Power production and consumption ($T_{hot} = 73$ °C).

equipment using the same flow rates in the hot and cold circuits. Certainly, it is also possible to investigate situations in which the two flow rates are different, but this requires further study. In any case, it is advisable to perform this type of test under laboratory conditions, because in the plant the water temperature can change substantially over time.

It is important to note that during the design of the TEG unit it is required to select both the pump characteristics and pipe sections, on the basis of the desired flow rates. Consequently the velocity of the fluids have to work in a range between a maximum and a minimum value, depending on the circuit components. In fact, an excessive flow rate leads to an energy lost, due to friction in the pipeline. On the other hand a low flow rate reduces the TEG heat exchange capability and its temperature uniformity, resulting in lower electric conversion performance. Therefore, it is important to design carefully all the components of the system (including the pipeline), to obtain a balance between advantages and disadvantages. In the case of the present device the desired water flow rate was fixed at 1 m^3/h, both for the hot and cold circuit (as a design specification), and as a consequence of this choice, the components of the whole device were selected.

Figures 6 and 7 show measured data obtained during on line trials. The figures show the electric power produced by TEG (green markers) and the simultaneous pump power consumption (blue markers), as a function of the hot water flow rate. For each point on the graph, the cold water flow rate was set to the same value as the hot water flow rate, and under two different inlet hot water temperature conditions (73 °C and 77 °C). These graphs show that both the TEG power production and the pump power consumption have a parabolic dependence with respect to the hot and cold water flow rate (but with a different sign on the x^2 term). Because the device requires two water circuits (hot and cold), the net power has been calculated as the difference between the produced TEG power and the double of the consumed pump power measured on the hot circuit. It can be observed that up to flow rates of 1.6–1.8 m^3/h the system is able to produce net power. At higher values the pumps have a power consumption higher than the TEG power production. Moreover, the maximum net power is obtained at about 1 cubic meter per hour, as required by the design specifications. This confirms the proper overall equipment sizing under the foreseen plant conditions.

The Maximum Power Point (MPP)[35] of each column, i.e., the point at which a column of TEMs delivers the maximum electrical power, was measured modifying manually the external resistance load of each column from 2.5 to 3.5 Ω. These tests showed that the chosen resistance load of 3 Ω, for a single column, sets the system working point close to the MPP for each operational condition. It should be noted that, it is also possible to connect the TEMs in series along the horizontal rows, instead of the columns. As the heat exchanger has a counter-flow configuration, in this case the TEMs should perceive the same temperature difference; this configuration requires further investigation.

Other tests were performed to verify the behaviour of each column. The open circuit voltage, the voltage with the fixed column resistance load (working point) and the current and voltage drop through the digital tester were measured for each TEM of each column. By these values the

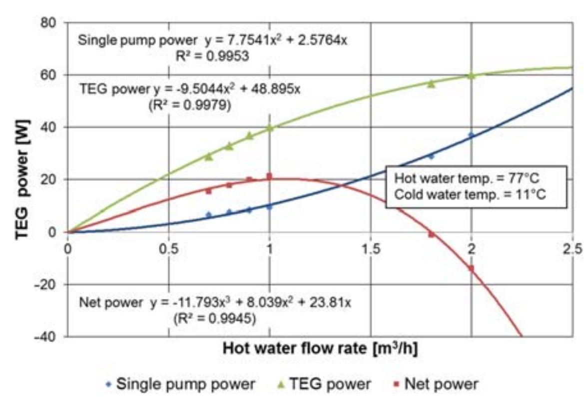

Figure 7. Power production and consumption ($T_{hot} = 77$ °C).

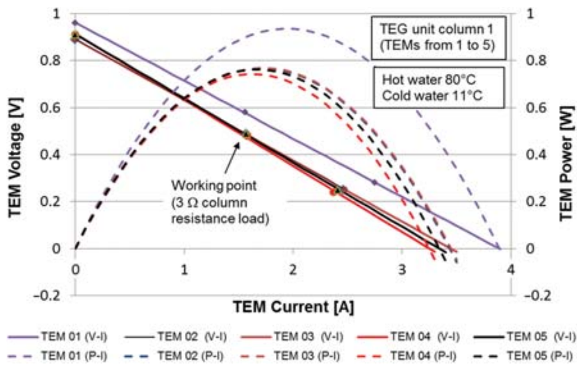

Figure 8. Characteristic curves (V–I) and (P–I) of five TEMs of the first TEG column.

voltage–current (V–I) characteristic curve (linear) and the power–current (P–I) characteristic curve (parabolic) were calculated. Figure 8 shows the two characteristic curves for five TEMs of the first column. Also from these data it is possible to verify that each TEM works very close to its own MPP confirming a good sizing of the selected resistance load.

Table I shows the TEG unit performance at standard conditions. In this state the TEG unit works as an heat exchanger which transfer about 6500 W of thermal energy from the hot source to the cold sink producing about 40 W of electric power.

In Table I the "lost thermal power" is shown, calculated as the difference between the measured power that enters, and the measured power that exits, from the TEG device. The first being the thermal power lost by the hot water crossing the TEG device, and the latter being the sum of the thermal power absorbed by the cold water crossing the TEG device and the produced electricity. This value shows a loss of power mainly caused by pipeline radiation.

Therefore, if considered as an heat engine, the TEG device shows an electric energy conversion efficiency of about 0.61%. This low efficiency is both caused by the actual thermoelectric module efficiency and by the simple counter current design of the thermoelectric generator. In fact, can be observed that the original temperature gap between the hot and cold water of 65.4 °C (=76.9 °C $_{\text{hot source}}$ − 11.5 °C $_{\text{cold sink}}$) drops down, in the real device, to an effective 35.5 °C (=65.4 °C $_{\text{hot source}}$ − 29.9 °C $_{\text{cold sink}}$) between the aluminium water boxes, that is probably a good average values of the real temperature gap received by the thermoelectric modules. In the same conditions, assuming the ZT figure of merit equal to one, the theoretical efficiency is 3.47% and 1.88% respectively.[26] Therefore, in the best case, and by using a better design, i.e., obtained through a reduction of the TEG structural sections, and then reducing the thermal barriers between the thermoelectric modules, it can be expected to double or triple the electric conversion efficiency figure.

In any case, the energy spent to move the hot and cold fluids cannot be neglected in a real device. Assuming the distance of the hot and cold source from the TEG unit of about 50 m, it was measured a pumping power for hot water circulation (both for connection and TEG pipes) of 8.7 W and therefore for both circuits of approximately 17.4 W. As a consequence, the measured actual electric conversion efficiency of the developed TEG unit, under the described working conditions, is about 0.33%. It is also interesting to note that doubling both the source and the sink distance from 50 m to 100 m, doubles approximately

Table I. TEG unit performance at standard operation (measured data).

Variable	Unit	Value	Variable	Unit	Value
Hot water flow rate and cold water flow rate.	[m^3/h]	1	Pressure drop through the TEG hot water circuit.	[mbar]	22.5
Hot water inlet temperature at TEG.	[°C]	76.9	Thermal power lost by hot water crossing the TEG.	[W]	6463
Hot water outlet temperature at TEG.	[°C]	70.1	Thermal power absorbed by cold water crossing the TEG.	[W]	6154
Cold water inlet temperature at TEG.	[°C]	11.5	Electric power produced by the TEG.	[W]	38.8
Cold water outlet temperature at TEG.	[°C]	17.5	TEG electric conversion efficiency (without electric pump power consumption).	[%]	0.6
Aluminium hot water box temperature at TEG central row and central vertical line.	[°C]	65.4	Hot water electric pump power consumption.	[W]	8.7
Aluminium cold water box temperature at TEG central row and central vertical line.	[°C]	29.9	Lost thermal power (mainly radition).	[W]	270.1
Aluminium hot water box temperature at TEG upper row and central vertical line.	[°C]	62.8	Net electric power produced by the TEG (assuming total pump power consumption as double of hot water electric power consumption).	[W]	21.3
Aluminium cold water boc temperature at TEG upper row and central vertical line (external box).	[°C]	20.2	TEG electric conversion efficiency (including electric pumps power consumption).	[%]	0.33

also the pumping power required to move the water into the pipeline. So the TEG unit, in this new situation, produces an amount of electric energy equal to that needed to move the water. So it can be stated that, if the source and the sink are located less than 100 meters away from the TEG unit, it acts as a heat exchanger that requires no energy for its own operation. However, it should be also considered that the use of control instrumentation and power converters causes a further electric consumption, thus reducing the overall efficiency.

4. CONCLUSION

A thermoelectric generator (TEG) unit working at low temperature (<90 °C) has been designed, manufactured and then installed at industrial plant to make long-term test under real conditions.

It was verified that the electric energy produced by the TEG unit is sufficient, and possibly exceeds the electric energy required to transport the fluid as long as they are located at a distance not exceeding 100 m. It was measured that the developed TEG unit works as a thermal engine with an electric energy conversion efficiency of 0.33%, when the distance of the hot source and the cold sink does not exceed 50 metres and water pumping energy is required, or 0.61% when no water pumping energy is required.

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