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A New Low-Cost Water Loop Suitable for BiTe Thermogenerators

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Abstract: This paper presents a new design for a thermogenerator suitable for working on low-temperature (up to 175°C) *BiTe* modules. Its improvement is related to the cooling system that is a low-cost modular device based on domestic hot-water radiators working in a natural-convection loop. Thermal and cost analyses were performed, showing that a competitive 1kW unit could be built (with a specific cost of 21,300 U$D/kW) by optimizing the whole cooling system to work on the new high-temperature (up to 320°C) *BiTe* modules recently launched, while present commercial thermogenerators cost about 60,000 U$D/kW. This novel design has not been claimed in an invention patent application since it is intended for use in the open market worldwide.

Keywords: Thermoelectricity, thermogenerator, innovative prototype, low-cost water loop.

1. INTRODUCTION

At this time there is only a single commercial niche market for thermogenerators related to remote electrical generators in the gas & oil industry. This market is solely served by Global Thermoelectric with its owner-technology, based on high-temperature (560°C) *PbBi* thermoelectric modules and with prices over 60,000 U$D/kW. The use of *PbBi* modules allows Global to design a compact cooling system based on a finned aluminum dissipator that works at 130°C [1]. On the other hand, the use of moderate temperature *BiTe* modules available in the open market (up to 175°C) implies a major challenge to developing a new competitive option regarding this low temperature drop involved. Therefore, the alternative is to develop a new high-performance cooling system with minimal thermal resistance so that it provides a lower temperature on the cold side of the thermopile. This way, both a higher temperature drop on both sides of the thermopile and higher power generated are achieved. Recent studies on BiTe prototypes have proposed the use of vacuum closed loops [2] or fan cooled finned dissipators [3-5] with no significant improvement. Therefore, it is necessary to explore new choices for the cooling system.

This paper presents an innovative cooling system. The innovation relates to the use of hot-water home radiators in order to provide a huge surface of dissipation but keeping the costs low by working in a natural-convection loop built with plastic tubing. This design provides a simple and modular design that can be easily scaled up in order to fit different heating powers.

In a recent work the engineering of the first small (120W) prototype built [6] was presented. This prototype has achieved a reasonable economic performance, having specific costs of 55,000 U$D/kW without performing any sizing optimization process. This paper shows the cost's optimization of the previous prototype, by using the numerical thermal-hydraulic model developed. On the other hand, new *BiTe* Tellurex's modules have been recently launched that can withstand up to 320°C [7]. Here the cooling system is also optimized and a noticeably cheaper generator could be developed.

Although thermoelectricity is an active field for patenting, most patent applications relate to the thermoelectric material itself [8-10] or their electrical arrangements within the thermopile [11, 12] but up today no one claims or has used a cooling system similar to the one proposed here. However, since present commercial thermoelectric modules have very low conversion efficiencies (down to 5%), the thermal power delivered by the cooling system must be twenty times greater than the electrical power generated. So, the optimized design of the cooling system should always be a main concern in order to develop an improved generator, as it is proposed here.

2. PROTOTYPE RESULTS

The prototype was built on sixteen G1-54-0557 Tellurex's modules mounted on two aluminum plates. The cold-side plate is used to support a water heat exchanger within a water plenum. From here the heated water flows upward through the central chimney (a 3-inch diameter and 4m-height steel pipe) exiting through eight hot-water radiators, from where the cold flow goes downward along eight 1-inch-diameter tubes back to the water plenum (see Fig. **1**).

The thermal hydraulic modeling was performed previously. Figure **2** shows the power generated parameterized for different ambient temperatures (T_o) of 0°C, 20°C and 40°C. The maximum generation (obtained for TE hot-side temperature of 175°C) is: 150W, 120W and 90W respectively. Hence is observed the remarkable effect of the actual T_o on the prototype performance. This behavior justifies using a

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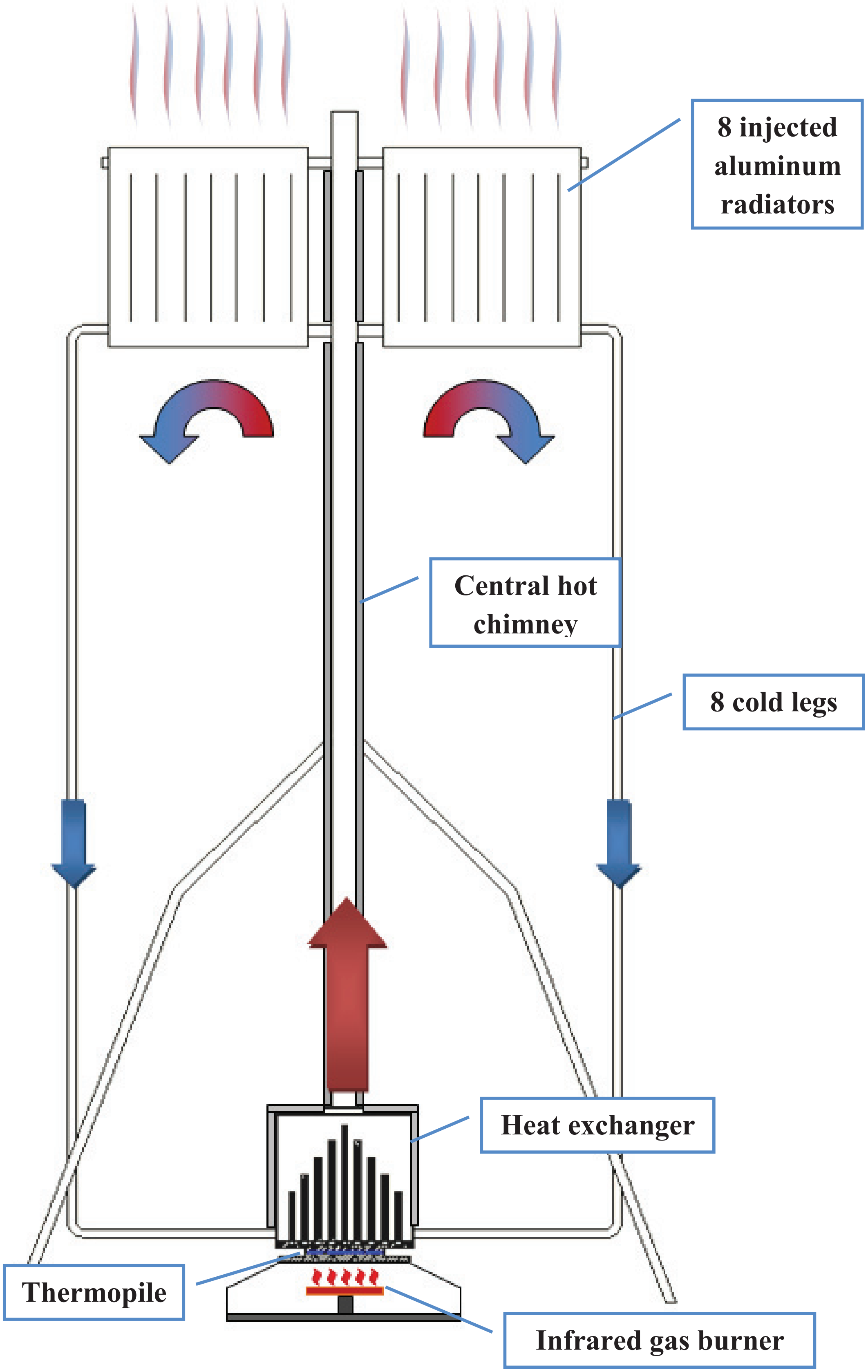

Fig. (1). General scheme of prototype.

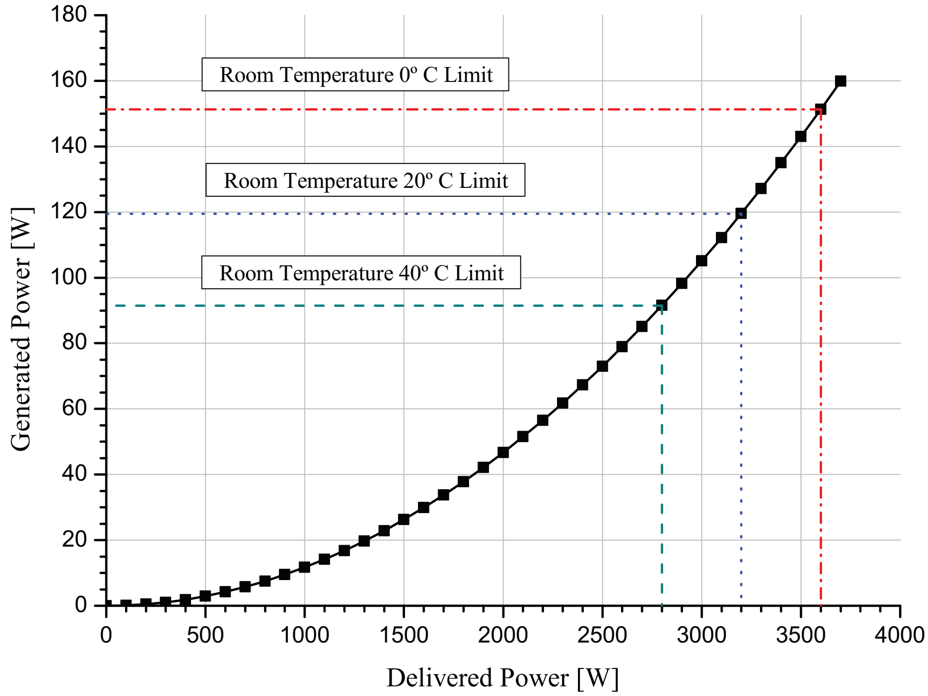

Fig. (2). Power generation curve for prototype.

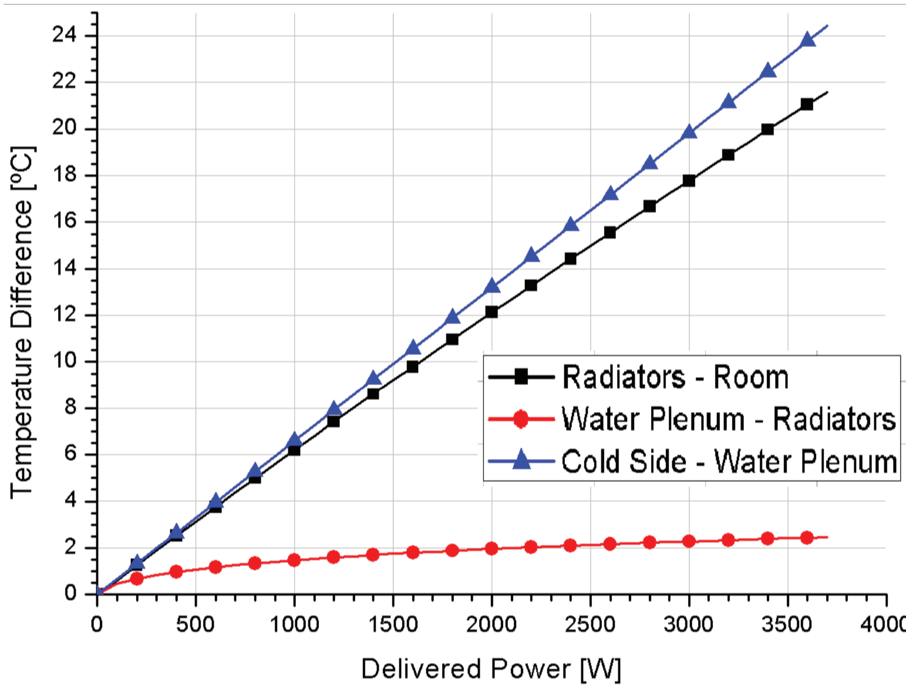

Fig. (3). Different temperature jumps of the cooling system.

microcontroller to regulate the instant burner´s power by means of solenoid valves on gas flow. Figure **3** shows the three temperature jumps of the cooling system that illustrate their thermal resistances: the radiator, the close water loop and the heat exchanger. The main resistance is well balanced between radiators and the heat exchanger, but the loop resistance is oversized implying higher costs.

The cost breakdown for this 120W prototype is shown in Table **1**. Hence is calculated a specific total cost of 55,000 USD/kW. Here we observe that the mechanical components constitute a high percentage (59%) of the total cost. These components have a low exponential factor (about 0.66) for scaling up the power generated and they have a great modularity, thus it is feasible to reduce costs by scaling up the power generated. The water radiators can be easily enlarged by means of adding individual elements and similarly the piping. But the heat exchanger is a special device that must be designed carefully to deliver a given power. Although it is

Table 1. Cost breakdown for the 120W prototype.

Item	cost (U$D)	% total
Water radiators	1,250	19
TE modules	1,200	18
Heat exchanger	1,000	15
Mechanical assembly	750	11
Piping	500	7
Mechanic structure	500	7
Others minor items	----	23
Total	6,700	120W
Total specific cost	55,000 U$D/kW	

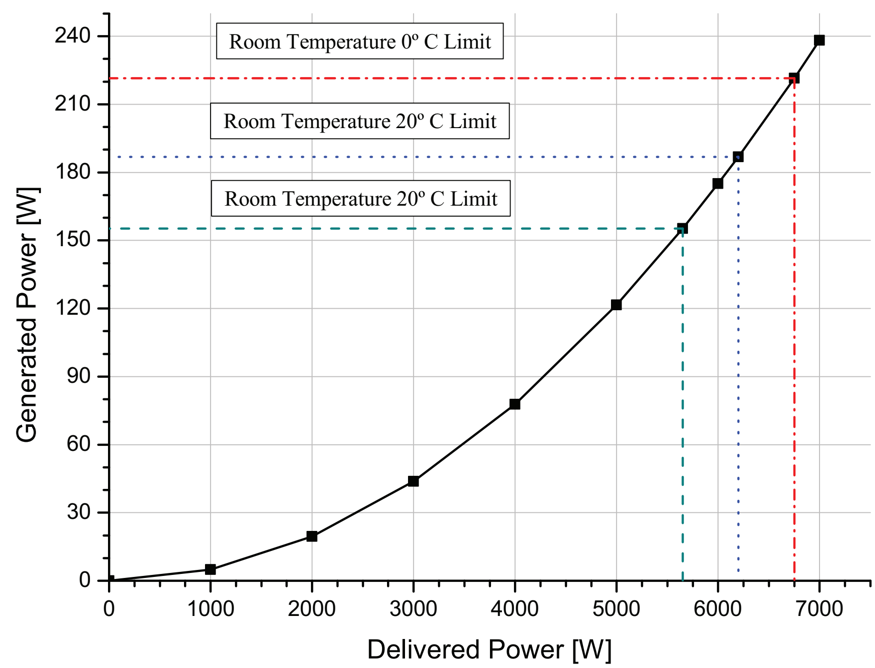

Fig. (4). Power generation estimated for 260°C modules.

possible to use a small unit for dissipating more power than what was previously designed, in this case a higher temperature jump would be obtained, which in turn would cause lower *TE* generation and that implies a higher (U$D/kW) cost. Therefore, the optimization of the thermal-hydraulic design together with cost analysis is a major issue that will be discussed in the next section.

3. THERMOGENERATOR OPTIMIZATION

First we consider the substitution of Tellurex's low-temperature modules previously used (up to 175°C) by Hi-Z's ones that can withstand up 260°C [13]. This change can be simulated in the modeling by setting the right thermal resistance of these modules (0.23°C/W) [14]. Figure **4** shows the noticeable improvement (60%) obtained. Similarly the remarkable improvement obtained with the new high-temperature Tellurex's modules (up to 320°C) that almost triples the original power can be seen in Fig. (**5**).

However, the performance of the cooling system is not optimized for both new TEs studied since the heating power delivery by the heat exchanger is markedly higher than the designed value and so, the temperature jump obtained is noticeably higher, which in turn decreases the TE's temperature jump available and the power generated. It is necessary to redesign the heat exchanger in order to optimize the prototype performance, besides exchanging TE modules.

The optimization of the heat exchanger can be performed according to two design lines:

1) minimizing the temperature jump of the heat exchanger. In this way it is also necessary to minimize the temperature jump of radiators and the hydraulic resistance of the circuit as well. The close loop works on the laminar cooling flow driven by the very low difference of density between the hot central chimney (50°C) and the peripheral cold tubes (30°C), which implies oversizing the whole hydraulic

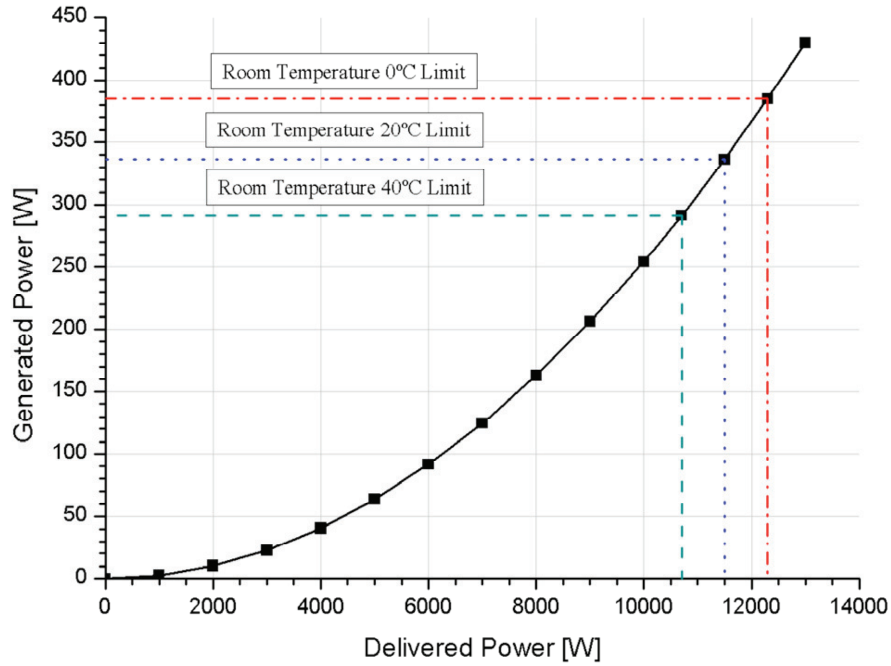

Fig. (5). Power generation estimated for 320°C modules.

Table 2. Comparative cost breakdown for the larger prototype of 500 W (B) vs. the original 120 W (A) one.

Item	Cost A (U$D)	Cost B (U$D)
Water radiators	1,250	3,250
TE modules	1,200	2,000
Heat exchanger	1,000	2,600
Mechanical assembly	750	1,900
Piping	500	1,300
Mechanic structure	500	1,300
Others minor items	1,500	5,300
Total	6,700	17,650
Specific cost (USD/kW)	55,000	35,300

circuit. This design also implies oversizing the set of radiators since it has to work on very low temperatures.

2) using a small heat exchanger working on a boiling two-phase flow. The heat transfer process is noticeably improved (ten times or more) when boiling transfer mechanism occurs. In this case, the temperature on walls of the heat exchanger can practically be set to 110°C and water to 100°C [15]. This way, the central hot chimney working in two-phase together with the peripheral cold lines working in single-phase can create a very large buoyancy force that drives the cooling flow with a minimal temperature jump. So, the piping does not need to be oversized, and the set of radiators working at about 100°C can dissipate heat efficiently.

These two choices of design have advantages and handicaps. The first design needs larger mechanical systems (radiators, heat exchanger and tubing), but since their *TEs* work at a higher temperature jump, they would generate more power at a lower specific cost (U$D/kW). Conversely the second design undoubtedly needs smaller mechanical systems, but their *TEs* work at a lower temperature jump, and therefore they would generate less power. The best choice will be found by studying both the thermal-hydraulic performance and cost.

The first alternative is studied by increasing the size of the heat exchanger proportionally to the heating power delivery (that is, keeping the pitch and diameter of the aluminum bars used as finned dissipators). Thus for example, the 320°C Tellurex's *TEs* needs power four-times greater than what can be delivered by a dissipator double in diameter, for which the same low temperature jump (14°C) is obtained. Similarly the piping diameters must be doubled and the radiator surface must be increased four times. Using a 2/3 exponent for scaling up costs of these components, a noticeable cost reduction (36%) is obtained as shown in Table **2** compared to the original case. Here the cost of new Tellurex modules is also considered, which is markedly lower than

Table 3. Comparative cost breakdown for the new (C) *vs.* original (A) prototype.

Item	Cost C (U$D)	Cost A (U$D)
Water radiators	1,050	1,250
TE modules	2,700	1,200
Heat exchanger	650	1,000
Mechanical assembly	400	750
Piping	275	500
Mechanic structure	275	500
Others minor items	5,300	1,500
Total	10,650	6,700
Specific cost (USD/kW)	21,300	55,000

Fig. (6). Photograph of the 120W prototype.

the original ones (4,000 USD/kW *vs*. 10,000 U$D/kW). In this way, a total specific cost of 35,300 U$D/kW is obtained for the empowered 500W prototype.

The second design is performed by setting the heat exchanger and chimney temperatures at 110°C and 100°C respectively. The chimney flow is a two-phase mixture that carries the given heating power by means of a void fraction (that is, the volumetric fraction of boiling bubbles) to the radiators, where this power is dissipated with an almost nil temperature jump but simultaneously obtaining a one-phase flow in the cold lines. Therefore, the tremendous buoyancy force originated (a thousand-times larger) allows us to put low-diameter tubing in every section (2” in chimney and ¾” in cold lines) reducing the piping costs by 45%.

The radiators high working temperature allows us to reduce dramatically the radiator size. According to the manufacturer’s data the heating power dissipated in each element is given by [14]:

$$P_r = 0.01391\ \Delta T_r^2 + 3.1586\ \Delta T_r \tag{1}$$

Where ΔT_r is the average temperature jump between radiator and ambient, in this case (T_o=20°C) being ΔT_r = 80°C. Hence, the power increase related to the original case (ΔT_r = 20°C) is five-times larger, and therefore the radiator size can be reduced in the same ratio. Conversely, since the *TE* modules must work at a noticeable lower temperature jump (-20%) this effect must be reflected in the power generated by each module. According to the quadratic power law of generation relative to the temperature jump [1, 2] from here the power reduction can be estimated as 36% or conversely, the specific cost of *TEs* can be increased in the same ratio. This cost-breakdown analysis for the new 500W prototype (C) is shown in Table **3** compared with the original (120W) prototype, showed in Fig. (**6**). The final result (21,300 U$D/kW) is noticeably lower than the previous optimization by using the large one-phase cooling system.

4. CONCLUSIONS

This paper presents an innovative design of a cooling system suitable for low-temperature *BiTe* thermoelectric modules that are available in the open market. It is based on low-cost domestic hot-water radiators and plastic tubing in order to build a natural-convection close loop, providing a low-cost and modular option that can easily be scaled up. This way, by using only simple technologies available worldwide but combined in an original manner, this innovative solution becomes a new feasible option for the development of simple and inexpensive thermogenerators. In this sense, the inherent simplicity of thermoelectricity (without moving parts) is a major strength of this technology. At present as we have already pointed out there is only one manufacturer worldwide offering commercial thermogenerators, but this figure could change in the future.

The performance of the whole thermogenerator is noticeably optimized by using new *BiTe* modules of higher temperature (up to 320°C) recently launched in market. So, the economic competitiveness could be noticeably improved, achieving costs of less than half the present commercial prices. This way, an opportunity technology window was created for the developing of new commercial thermogenerators. Moreover, this study has demonstrated the high flexibility of this modular design that can work on either a single-phase or two-phase flow for its cooling system. This design could be easily adapted for future thermopiles that withstand higher temperatures. Following this trend and as the study shows, this technology has an ever more favorable outlook.

5. CURRENT & FUTURE DEVELOPMENTS

Regarding the simplicity of this design, it should have a good chance of success. The first prototype built has been tested only in one-day experiments and no problems were observed. Thus, the next step projected now is to check its durability along one year of continued operation and different seasonal conditions. Although some mechanical issues could be found (for example, regarding the plastic fittings used for small tubes) during this work, these drawbacks do not change the main strengths of our novel design. In that sense, the choice for a natural-convection flow (that is, eliminating the cooling pump) was a decision made regarding the high reliability and free-maintenance objectives.

CONFLICT OF INTEREST

None declared.

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