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Design and Development, via Prototype Testing and Multiphysics Modelling, of a Thermoelectric Generator (TEG) for Integration in Autonomous Gas Heaters

Matteo P. Codecasa[1*], Carlo Fanciulli[1], Roberto Gaddi[2], Francisco Gomez Paz[3] and
Francesca Passaretti[1]

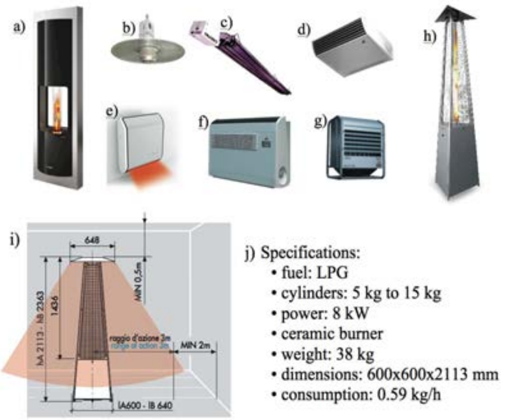
[1] CNR - National Research Council of Italy - IENI Institute - 23900 Lecco - Italy
[2] Italkero S.r.l. - 41122 Modena - Italy
[3] Studio di design Francisco Gomez Paz - 20144 Milano - Italy
*m.codecasa@ieni.cnr.it

Abstract: An autonomous heat-radiating gas heater for commercial outdoor environments has been selected as a test case for implementing cogeneration in autonomous gas heaters and stoves, permitting its installation and operation without the need of a connection to the electrical network. A thermoelectric generator (TEG) was selected for this purpose[1], designed for converting an amount of the produced heat into electrical power for auxiliary (ventilation, battery recharge) or ancillary functions (high efficiency LED illumination). The design approach, the layout and structure of the TEG are discussed, as well as the constraints for its integration in the existing gas heater. Design features and main components are examined: hot side heat collector for capturing heat from the flame; thermoelectric module (TEGM) technology and model selection; natural convection heat radiator at cold side; analysis and optimization of the thermal chain; TEG's assembly and its design as a whole. A prototype has been built and tested, its functional behavior has been modeled through multi-physics numerical simulation[2] to allow for further optimization and extrapolation of the results towards larger and/or more complex designs. A patent application has been issued jointly by the authors, covering the design hereinafter described.

Keywords: energy, cogeneration, gas-combustion, thermoelectric generator, Seebeck, Peltier.

1. Introduction

A wide range of technical solutions based on gas combustion is available for heating of both residential and industrial environment. While in most cases the gas combustion is localized in a central heating unit (the boiler) and the generated heat is transferred to an intermediate fluid (e.g. water) which is circulated through heat radiators located in the rooms of the controlled environment, in some other relevant cases each heat-radiating unit includes the gas combustor and operates autonomously with local feed of gas and electricity. This approach applies more frequently to industrial or commercial environments, where localized heating may be more effective than heating the whole environment and the use of autonomous units is characterized by higher flexibility of design and operation of the plant. For such autonomous gas heaters, a cogenerating TEG may be effectively integrated within the heater[1] and would permit its installation and operation without the need of a connection to the electrical network and it would eventually increase the overall efficiency through the reduction or elimination of any electrical power consumption from the grid for the fan (or pump), for safety, monitoring and control devices and new ancillary functions to be implemented (e.g. illumination).



j) Specifications:
- fuel: LPG
- cylinders: 5 kg to 15 kg
- power: 8 kW
- ceramic burner
- weight: 38 kg
- dimensions: 600x600x2113 mm
- consumption: 0.59 kg/h

Figure 1. Examples from the range of gas heaters by Italkero: a) indoor sealed fireplace; b,c) radiant gas heaters for industrial; d,e) ceiling or wall-mounted heater for indoor residential use; f) compact air conditioning system, including gas heater and cooling compressor; g) wall heater, for use in gyms or industrial; h) umbrella-type heater for outdoor use, model “Falò”; i) schematic representation of the heat distribution around the

“Falò” heater, mainly due to radiation; j) general specification of the “Falò” gas heater, precursor of the “Lightfire” heater design including TEG generator.

The choice of using the direct conversion of heat into electricity through a thermoelectric converter, using the Seebeck effect, is due to the peculiarities of such technology, which allows to design a compact solid-state converter, avoiding thermodynamic cycles and with no moving parts, intrinsically robust and reliable, featuring easy operation and maintenance-free[3],.

The Italian company Italkero develops, manufactures and markets a wide range of gas heating systems for industrial, residential and commercial, interior and exterior. The range includes sealed fireplaces and gas stoves, gas heaters for indoor, gas radiant heaters for industrial and outdoor, and more (see Figure 1 parts a-h). The company started a collaboration with the CNR IENI of Lecco, a research institute with facilities for technological and scientific support for thermoelectrics, aiming to implement the thermoelectric technology as an option for cogeneration in its products lines. The obvious benefit is that a certain amount of electricity, depending on the size and efficiency of the TEG, can be converted on board of the heating devices, directly from the heat generated, and can be appropriately used for:

- allowing the installation of products independently of the electrical network, while still allowing auxiliary or ancillary functions that require electricity (remote control and monitoring, illumination, etc..)
- reducing or cutting down the consumption of electricity from the grid in all heaters equipped with forced ventilation, increasing their energy efficiency
- providing electricity to those products that are without, allowing application of solutions for increasing the thermal performance and energy efficiency (e.g. auxiliary ventilation) or to enable the integration of new ancillary functions (remote control and monitoring, illumination, etc.)

A preliminary study about the line of heating systems, ranging from 5 kW to 25 kW of thermal output, highlighted the following relevant thresholds in relation to the power that could be generated by an integrated TEG:

10 ÷ 30 W → would give the ability to implement ancillary functions such as remote control and monitoring of heaters and/or illumination that comes with high-efficiency LEDs, with no need of connection to network;

30 ÷ 100 W → would supply power to forced ventilation for high yield heat transfer; for present devices with natural convection there's the potential for a great increase of performance (up to 100%) or for a major reduction in size and weight; for devices that already use high-efficiency ventilation, installation versatility would be provided thanks to the independence from network connection;

Above 100 W → if such power comes along with a conversion efficiency of at least 8%, the surplus above 100 W could turn the heating device into a real cogeneration unit, contributing to electricity production in hybrid plants capable to use electricity in the form of direct current at low voltage; there is a clear synergy with photovoltaic technology, having similar requirements and complementary constraints and performances.

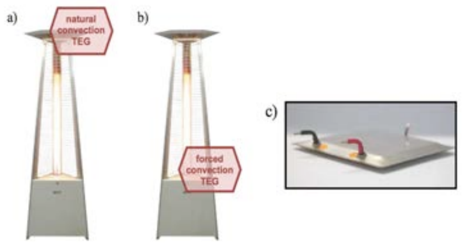
A conversion efficiency ranging from 4% up to the above mentioned 8%, which is achievable with existing materials and state of art thermoelectric modules and assembly solutions, has been identified by Italkero as one of the thresholds for technical and commercial viability of new products implementing thermoelectric cogeneration.

2. Project Development Plan

As a test case for verifying feasibility and impact of the improved design including a device for thermoelectric cogeneration, an heat-radiating gas heater for outdoor commercial environments has been selected. Such type of heaters is completely autonomous because it incorporates a gas cylinder for many hours of operation and a small battery for electronic starter, controller and safety. A new product being redesigned and upgraded, hereinafter named "Lightfire", was the subject of this development. It is based on an existing product, on the market with the name "Falò" (see Figure 1 parts h-j), which is characterized by the fact that the combustion flame is contained in a borosilicate glass and is clearly visible and, therefore, characterizes its aesthetics. Combining special LED-based illumination in the unit is considered a major improvement for the product, both aesthetical and functional. Furthermore, improving the heat transfer to surrounding environment, through forced ventilation of warm air downward, would also be very beneficial since presently such type of radiators have a relatively low efficiency.

Two development steps were scheduled, delivering two prototypes with increasing electrical output and features:

- in the first prototype, the TEG is intended to be located at the top of the heater (Figure 2 part a), above the cover which is set at the end of the borosilicate glass tube; heat sink at the cold side of the TEG exploits natural convection and radiation, for the simplest and most robust design; power requirement is about 10W, suitable to power LED illumination as an ancillary function, as well as to maintain the battery of the starter/controller;
- for the second prototype, the electric power required is about 35W, suitable for powering an auxiliary fan to spread warm air efficiently down and around to the environment; in this case, the TEG is being located at half height of the heater (Figure 2 part b), at the bottom of the borosilicate glass tube and right above the burner; the heat is captured at the base of the flame and transferred through the TEG and a heat sink which eventually may be supported by forced convection, thanks to the fan.



d) Altec-1060 TEGM specifications (referring to conventional *"maximum"* operating conditions: match load, hot side temperature T_h=250°C, temperature gradient DT=220K across the TEGM)

Description	**Value**
Dimensions	40 x 40 x 4,0 mm
Max continuous hot side temperature (short term)	Th_{max} <= 300°C (400°C)
Max continuous cold side temperature (short term)	Tc_{max} <= 100°C (120°C)
Match-load voltage and corresponding current	U_{max} = 4,8 V / I_{max} = 1,7 A
Match-load output electrical power	W_{max} = 8,0 W
Match-load thermal power	Q_{max} = 123 W
Match-load conversion efficiency	η = 6,5 %

Figure 2. Positioning of the TEG in the two prototypes mentioned in the text and options for heat dissipation: a) 10W electrical power TEG at the top of the glass tube containing the flame, heat dissipation in natural convection and radiation, b) 35W system at the base of the glass tube, with forced convection heat dissipation. c) A thermoelectric module for generation (TEGM) from ukranian company Altec (not in scale with other pictures),; d) TEGM specifications

The development activity has covered the definition, integration, sizing and optimization of working prototypes with TEGs, developed with the use of commercial thermoelectric modules (TEGM, see Figure 2 parts c-d). The commercial TEGMs are developed with functional parameters (voltage, current, operating temperature limits, thermal differential, etc.) set in order to simplify their application, with given performance ratings and application notes, and they're optimized for typical operating conditions of generation[4].

3. Design of the Realized Prototype

On left part of Figure 3, see a schematic functional draft of the realized TEG converter prototype, with indication of treated air fluxes; on right part of same figure, a photo sequence of the assembly phases of main TEG's components is shown. Note the insulation pad above the cover, which reaches temperatures over 180°C, to avoid heat radiation which would interfere with heat dissipation by finned heat sinks.

Details about the design of the first prototype realized and tested, featuring special technical solution for critical design issue typical of thermoelectric assemblies[5], are given below:

- the TEG is located at the top of the heater; heat is captured at the end of the glass-tube confining the flame, through an aluminum block fixed axially above the glass-tube; the block is maintained at a high temperature thanks to direct irradiation from the flame and for having the bottom side invested by hot exhaust;
- two TEGMs are applied at opposite sides of the block, onto the lateral (vertical) surface; the chosen TEGMs are the Altec-1060 modules, developed specifically for power generation applications;
- on both sides of TEGM, thermal interface materials are applied: natural graphite sheets, type HiTherm Graftech or similar material, onto hot side; thermal paste or wax phase change materials, type PCM FSF52 of Laird Technologies or similar, onto cold side;
- one independent heat sink is mounted onto each of the two applied TEGMs, exploiting natural convection and radiation; thanks to their extended surface with major fins, they extract heat from the TEGM which are sandwiched between them and the heat capturer;
- the components are held together under strong compression with an elastic assembly of low stiffness, which compresses

and keeps TEGMs in the correct position and under constant pressure, even in the presence of different thermal expansion between the various elements; any thermal bridges, connecting directly the cold sides with the hot heat collector in between, has been avoided;

- the dimensions of the entire TEG are approximately 500 mm diameter by 150 mm height; this volume houses the heat collector, the TEGMs, the finned heat sinks with large surfaces, the overall assembly system, the mounting and electrical connections; the total weight is about 4.5 kg.

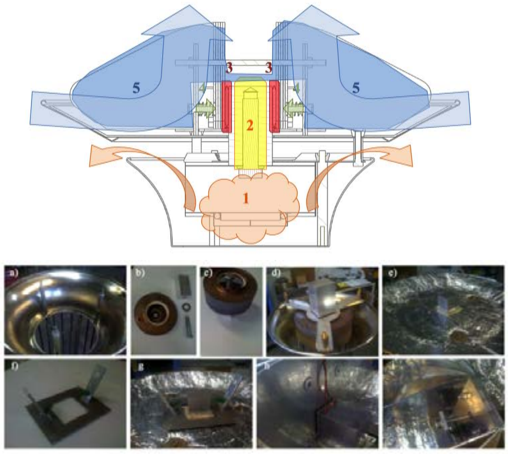


Figure 3. On left side, a schematic section view of the TEG thermoelectric converter with two TEGMs: the top of the glass-tube containing the flame is numbered (1), with the hot exhaust of combustion to be expelled; numbered (2), highlighted yellow, is the aluminum block which captures heat from the top of combustion chamber and directs it towards the TEGMs, which are highlighted red and numbered (3); compression springs of assembly system are numbered (4); natural convection/radiation finned heat sinks are numbered (5), with blue arrows indicating airflow directions. On the right side, the mounting sequence of main components of prototype, integrated at the top in the gas heater "Falò": see in d) and e) the aluminum heat capturer, transferring heat from the flame through the TEGMs; in f) and g), details of the elastic assembly system; in h) one TEGM is compressed between hot aluminum heat capturer and the cold side natural convection/radiation heat sink, the latter more clearly visible in i)

4. Conclusions

The prototype was designed, assembled and tested at a workshop of Italkero, according to specifications provided by the research team of the CNR IENI Lecco. TABLE 1, below, summarizes the average performance measured by operating the heater to the power of 8 kW and noting the actual data found from the TEG: temperature, voltage and current, from which the power output under known load.

TABLE 1. TEG converter measured performance with thermal power set to about 8 kW, working as close as possible to match-load operating conditions for maximum electrical output

Description	Nomeclature	Unit	Value
Number of TEGMs (connected in series)	N	#	2
Hot side heat capturer temperature @ 8kW power	Th	°C	305
Cold side temperature, with T_{env}=15°C	Tc	°C	125
Open circuit voltage of TEG	V_V	V	12,8
Voltage of TEG under electrical load RL=5,5 Ω	V_L	V	6,35
Load-match current	I_L	A	1,23
Electrical power output with electrical load RL	W_{EL}	W	7,81

The functional behavior of the prototype TEG has been modeled through multiphysic numerical simulation, using commercial software of company COMSOL and implementing thermoelectric equations[2,6] representing the interaction of thermal and electrical fields within the TEGMs. The model, validated and tuned with comparison with experimental data given by prototype testing, allows for further optimization and extrapolation of the results towards improved or larger and/or more complex designs.

Italkero and CNR IENI Lecco, jointly, are patent pending the technical solution mentioned in present report.

9. Acknowledgements

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