HIGH-EFFICIENCY THERMOELECTRIC GENERATOR BASED ON HEAT REGENERATION

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1. Introduction

Thermoelectric (TE) energy generation is an attractive method for the direct conversion of thermal energy into electrical energy: TE generators are compact, quiet, stable and very reliable, but they have found few applications because of their low efficiency (typically less than 5%) and high cost . In the last decade lots of efforts have been spent to develop novel TE materials of increased intrinsic conversion efficiency, but also the design of the system architecture plays a fundamental role to control the thermal exchange and to maximize the conversion performances [1]. In particular the effect of heat recovery, the so called "regeneration" or "heat recirculation" [2], is the key to overcome the intrinsic efficiency of TE materials: the heat released at the cold side of TE modules is recovered, according to the limitations imposed by the second principle of thermodynamics, in order to obtain high efficiencies even employing TE materials with ZT≈1 (state-of-the-art materials).

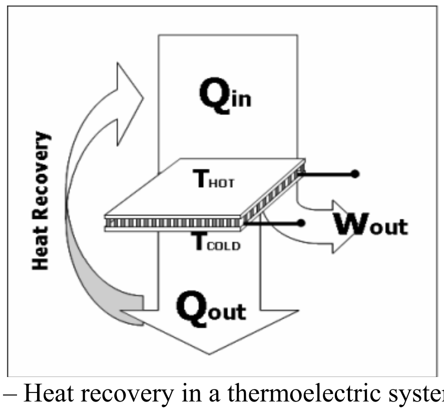

Fig.1 – Heat recovery in a thermoelectric system.

In this paper a TE generator constituted by thermoelectric elements integrated with heat exchangers and with a combustion chamber is presented and analyzed. Theoretical calculations are reported and related architecture is simulated with Fluid-Dynamic simulations (CFD).

2. Efficiency calculation

The system taken into account for efficiency calculation is characterized by a series of TE elements placed in a counter-current exchanger.

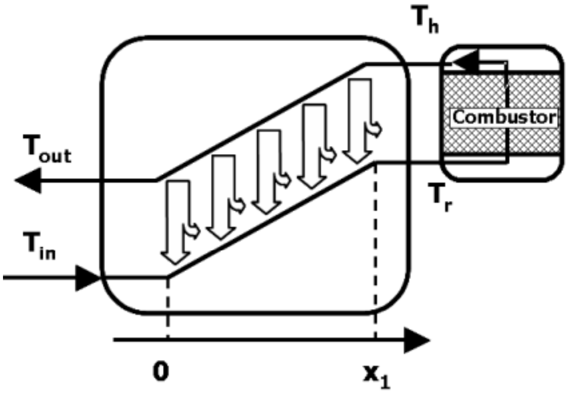

Fig.2 – Schematic representation of the system. On the horizontal axis the *x* position is reported, on the vertical axis a temperature scale is reported.

A mixture of air and fuel at room temperature enters the system (Fig.2), warms up absorbing heat from the cold side of the TE elements, enters a combustion chamber with the regeneration temperature $\mathbf{T_r}$ and, in the combustion chamber, burns reaching the temperature $\mathbf{T_h}$. The burnt gas then exits the combustion chamber and passes through the hot-gas-pipeline counter-current respect to the inlet gas. The burnt gas cools down transferring heat to the hot side of TE elements and exits the system at relatively low temperature. ΔT is the constant temperature difference between the two fluxes and its value depends on the heat exchanger efficiency defined as $\eta_{exc} = \frac{T_h - T_{out}}{T_h - T_{in}}$: better is the exchanger performance, minor is the temperature difference between the flows.

The hypothesis for calculating the theoretical efficiency of such generator are:

- No heat transfer along the pipelines (all the heat is exchanged through the TE elements)
- The temperature increases/decreases linearly with the position *x*
- The temperature profiles of the two fluxes are parallel
- The TE materials figure of merit ZT is considered constant respect to temperature

The overall efficiency is given by the ratio between the electrical output *W* and the enthalpy H_{in} provided by the combustor [3]. For the considered system:

$$W = \int_0^{x_1} Q_h(x)\eta_c(x)\eta_{zt}\,dx \qquad (1)$$

where $Q_h(x)$ is the heat flux through a segment *dx* at the hot side, $\eta_c(x)$ is the Carnot efficiency and $\eta_{ZT} = \left[\frac{\sqrt{1+ZT}-1}{\sqrt{1+ZT}+T_c/T_h}\right]$ is the efficiency linked to the TE materials properties [4];

$$H_{in} = \dot{m} C_p \Delta T \qquad (2)$$

where $\dot{m}$ and C_p are, respectively, the mass flow rate and the specific heat of the convective flux [3].

Starting from equation (1) and (2) it is possible to demonstrate that the system efficiency is given by:

$$\eta_{tot} = \frac{W}{H_{in}} = \eta_{zt} \ln\left(\frac{T_h}{T_{in} + \Delta T}\right) \qquad (3)$$

The chart in Fig.3 plots the values of system efficiency respect to the combustion temperature T_h considering T_{in}=300K, a constant value of heat exchanger efficiency of 0.85 and different mean values of ZT.

It is important to notice that about 19% efficiency can be reached with T_h=800°C for <ZT>=1 imposing a relatively small ΔT (≅115°C) to each TE element.

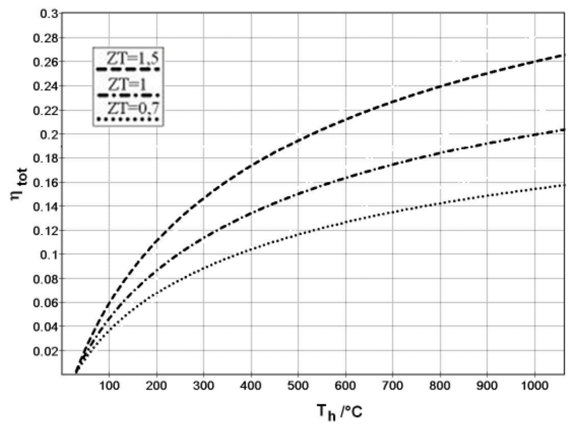

Fig.3 – System efficiency vs T_h

3. The real system and simulations

The system previously described is an ideal one, so now the point is to set up a real system which satisfies the hypothesis made for the efficiency calculation.

In order to inhibit the thermal flux along the pipelines, each conduit is segmented and is made of thermally conductive elements (heat exchangers) separated by thermally insulating elements (Fig.4). Each segment is isothermal (no heat transfer along the pipe) and the temperature profile is characterized by two parallel step-like lines (Fig.5).

In order to obtain an approximately constant ZT value at all the temperatures of the system, different TE materials can be employed in different segments: in particular for each segment the most performing thermoelectric material can be chosen to work at its most suitable temperature. The schematic representation of such a system is given in Fig.4

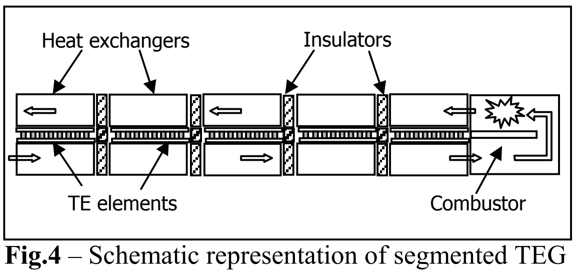

Fig.4 – Schematic representation of segmented TEG

CFD investigations have been carried out to simulate the thermal behavior of the system and evaluate the conversion performances. An example of simulated temperature profile is reported in Fig.5 and confirms the expectations. CFD analysis is integrated with a software which simulates the behavior of TE materials in order to calculate the electrical output.

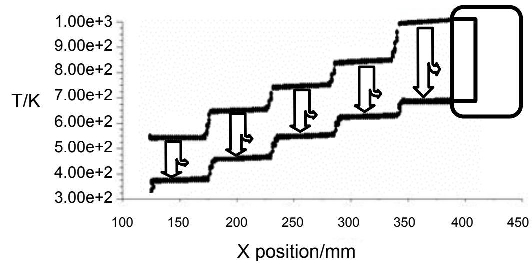

Fig.5 – Simulated temperature profile

As the number of segments increases and the length of each segment decreases, the thermal and electrical performances of the real system approach the ideal system's ones. Fig.6 plots the percentages of theoretical efficiency for different simulated systems with an increased number of segments and decreased length.

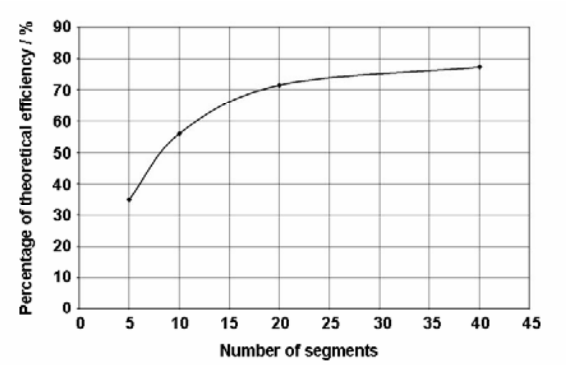

Fig.6 - Percentages of theoretical efficiency for systems with an increased number of segments

Simulated data on a real feasible system, taking into account thermal loses towards the ambient, show that it is possible to reach about 80% of theoretical efficiency with 40 segments.

4. Advantages

The proposed system architecture presents concrete advantages respect to the state-of-the-art solutions for thermoelectric generators.

As a consequence of heat regeneration, the system efficiency overcomes the efficiency of single materials in a compact and versatile system layout.

In each section of the system, different TE materials can be used in order to exploit the best materials for the appropriate temperature range. This permits to maximize the overall system figure of merit as happens in segmented TE materials [5, 6], avoiding the complexity of these latter structures.

Each TE element undergoes a relatively small temperature difference and this brings two important advantages: the thermoelectric materials do not need to show high ZT values for a large range of temperature, they must be performing in a limited interval; materials' thermal and mechanical stability is guarantee by the absence of potentially dangerous elevated temperature gradients.

The system is fully scalable and modular so different layouts can be designed for specific needs (electrical output, power density, size…)

5. Conclusions

The thermodynamic analysis of a thermoelectric generator characterized by a series of TE elements placed in a counter-current exchanger, has brought to a compact and practical equation for efficiency evaluation and has demonstrated that heat recirculation can strongly enhance system performances.

The ideal architecture has been converted into a real system which presents significant advantages and permits to optimize the performance of TE materials. CFD simulation s have been carried out and confirmed the theoretical predictions.

In the last decades the considerable progresses in materials science and nanotechnologies have brought to a great improvement in the figure of merit ZT. If new materials with ZT>2 could be industrially available the described system would compete with most of the present electrical generators for a wide range of applications.

6. References

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