PROJECT PERIODIC REPORT

Publishable summary

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Project acronym: E^2PHEST^2US

Project title: Enhanced Energy Production of Heat and Electricity by a combined Solar Thermionic-Thermoelectric Unit System

Funding Scheme: Collaborative Project

Date of latest version of Annex I against which the assessment will be made: 31/03/2011

Periodic report: **1st** ☐ **2nd** √ **3rd** ☐ **4th** ☐

Period covered: **from** 01/07/2011 **to** 31/12/2012

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Overview

The E^{2}PHEST^{2}US project background addresses the renewable energy exploitation, more specifically solar energy conversion into electrical energy, having the specific purpose of realize and fabricate innovative and scalable components for CSP systems that:

- ✓ efficiently generate at the same time electric energy and heat power;
- ✓ reliably work at high temperatures (700°C÷900°C);
- ✓ recover and exploit heat at intermediate temperature.

An originally designed conversion module (CM) prototype for the production of electric and heat energy has been developed based on direct thermionic and thermoelectric direct converters, thermally combined in series to increase the efficiency with a theoretical thermal-to-electrical efficiency >30%. An innovative hybrid cable, able to carry at the same time high-temperature fluids and electricity has been designed and tested within the project lifetime. The use of advanced new materials enabled the exploitation of thermionic effect at temperatures around 700 °C÷900 °C, enhancing the conversion performance of traditional thermionic systems, which traditionally required higher cathode temperatures (>1300 °C). Nevertheless, it is worth to say that thermionic stage efficiency is independent of anode temperatures up to temperatures <400 °C, where a thermoelectric stage can be added to exploit the thermal range down to room temperature. These complementary properties allowed the development of an integrated system, thus making the best use of thermal energy generated at different temperatures and achieving a better value of total efficiency. The geometrical and operational versatility of the conversion module prototype unit makes it suitable for future use in a wide range of CSP systems (parabolic troughs, solar towers, dish, Fresnel lenses).

A single CM prototype could vary its output ranging from few W up to several kW, owing to its up-scalability (size, technology and manufacture), increased also by the fact that the modules can be arranged in arrays. The small-scale prototype system allowed the evaluation of the performance in comparison with similar systems in terms of output power, production cost, duration and reliability.

All the main activities scheduled in the second period have been performed satisfactorily, with good results. Although a certain delays with the procedures of development and standardization of the solar test platform, STP, have not allowed a sufficient optimization and control of the overall system, in particular the maximum temperature reached at the focal point of the solar platform, and, in consequence, of thermionic process efficiency and overall performance of the system, however, the results obtained show the feasibility of the new concept prototype module proposed. Moreover, several significant technological improvements have been achieved, concerning primarily the advanced materials synthesized together with the innovative technology of preparation of the individual components constituting the CM, in particular, the new encapsulation process under vacuum, obtained with the use of particular gettering compounds.

Main achievements 18-36 months

The main achievements of this last period of work consist mostly of the activity concerning technical design/implementation/automation and specific measurements of efficiency of STP concentrating solar system and of CM (beta and gamma) design, preparation and performances, and finally, related integration in the STP. More specifically, the planned activities implemented in the second period of the Project were:

1. tests of “naked” CM–alfa version at the solar simulator by TAU;
2. building improvements of STP;
3. preparation and installation of the vacuum assisted conversion module (beta version), with relative vacuum pumping system (Fig.1);
4. optimization and automation related to the x,y,z positioning of the module itself and characterization of the main features and outputs on STP (location of the exact focus of the parabola, energy flux measurement at the maximum radiation value in the focus of the parabola, related temperature measurements);

5. design of the vacuum encapsulated CM (gamma version) by CAD method, preparation of the individual parts and final assembly;
6. installation of the encapsulated CM–gamma in the STP;
7. tests of "naked" CM–alfa version at the solar simulator by TAU;
8. output power and electrical current measured with the encapsulated CM–gamma and related analysis.
9. weak points analysis and possible improvements schedule.

The lab tests on naked CM by solar simulator at TAU

The lab test at TAU have been performed on naked CM located into a vacuum chamber, so as to act in the optimal conditions to make the test on the thermionic emission and thermoelectric properties, under controlled conditions of vacuum and concentration of radiant flux, obtained in the solar simulator show in the Fig. 1. The irradiation source was a 4 Kw Xenon lamp. The maximum flux distribution at the focal plane of solar simulator is shown in Fig. 2. Max flux at focal point: ~ 180 W/cm^2; average value ~ 45 W/cm^2.

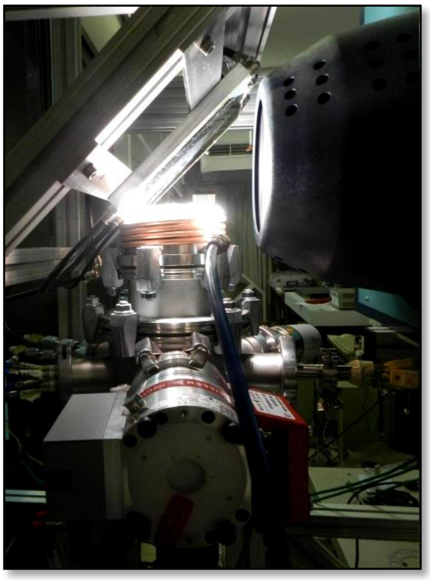

Fig. 1 - The solar simulator at TAU.

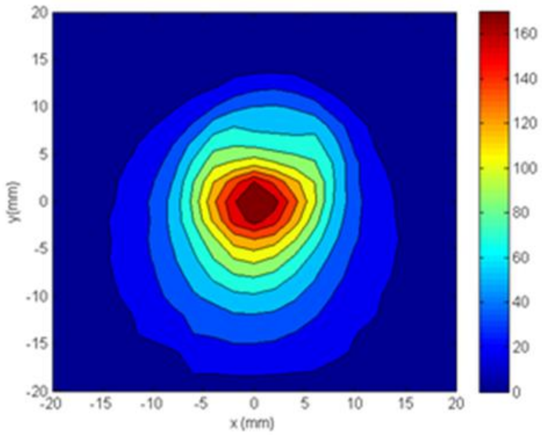

Fig. 2 - Incident flux (W/cm^2) at focal plane.

Installation/integration in the STP of the vacuum assisted conversion module (beta version)

The hardest and longest part turned out to be the adaptation of the conversion module, with its specific allocations in the solar test platform and their compatibility. The CM integration with STP and the total automated control by computer of the whole system was definitely the most complex part of all this last phase of the project.

In Fig. 3 the whole system is shown, resulting from the integration of CM–beta, with the vacuum apparatus and the solar test platform STP, completely computer controlled.

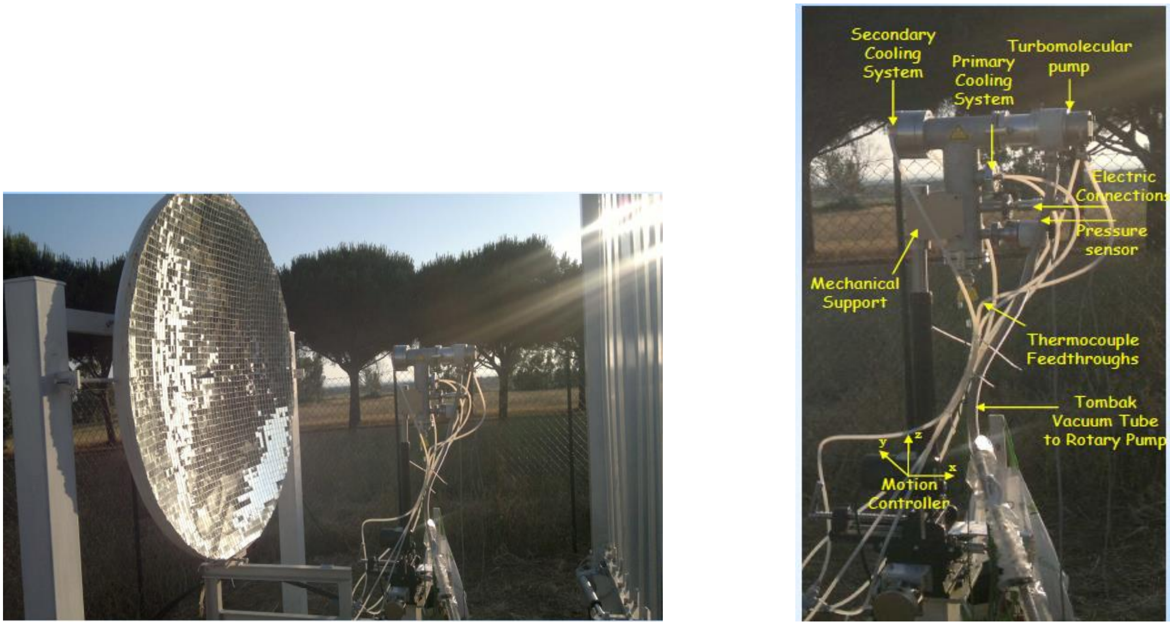

Fig 3. The CM-beta positioned at the focus of the parabola (*left*), the CM with the vacuum pump behind and the x,y,z motor steppers at the basis of the whole apparatus (*right*).

CM vacuum encapsulation (gamma version): fabrication, assembly and integration in STP

The design by Computer Aided Design (CAD) is based on the idea to allocate the CM in a body flange shaped to be compatible with a standard ConFlat® flange, so as the device proves to be compact and very flexible; the module prototype is fasted on top by a commercial fused silica windowed flange. A copper heat sink is designed for quartz window cooling. This configuration allows to minimize optical losses, and to make it in the future commercially more attractive, reducing largely the device dimensions.

Active part of conversion module has been redesigned in order to be less space-consuming (Fig. 4). The thermoelectric module is directly in contact with CM flange on cold side, while hot side is in contact with the collector stage. Ferrule radius has been enlarged to host screws for fastening to the CM.

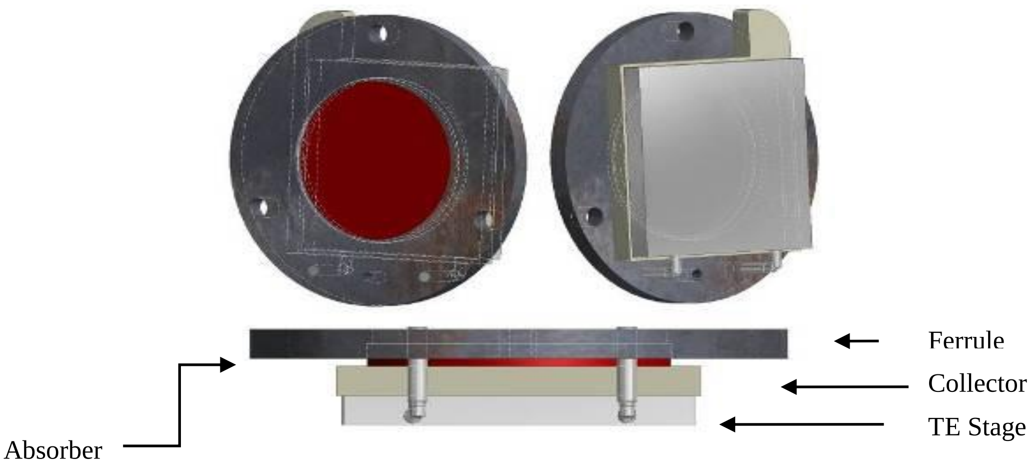

Fig. 4. Conversion module active stage.

- *Fabrication and assembly*

The various components (copper heat sink, transparent windowed flange, stainless DN63CF body flange, molybdenum ferrule, absorber/thermionic emitter, ring-shaped spacer, molybdenum collector, thermoelectric module, getters) have been purchased or directly produced. After an electro-cleaning process, the conversion module body enclosure has been assembled and tested for vacuum operation with a leak detector. The conversion module enclosure keeps a vacuum better than 3×10^{-8} mbar×l/s.

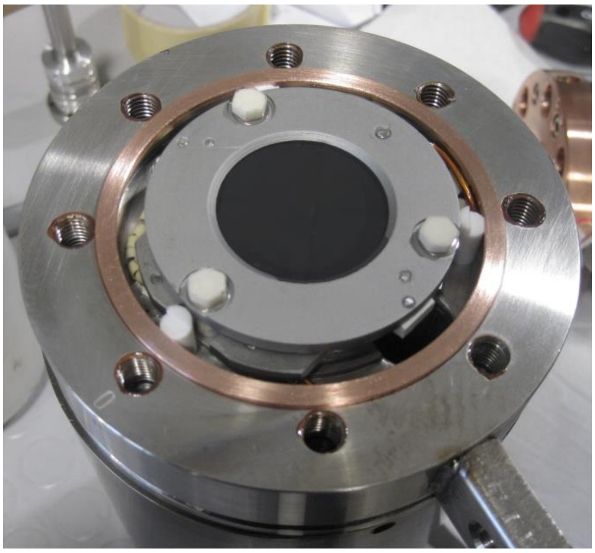

Fig. 5 – Inner part of the encapsulated conversion module.

Electric connections are realized by means of a standard 4-probes vacuum feed-through and cables are connected by suitable pins. Thermocouples for absorber and collector temperatures monitoring are connected to standard thermocouples feed-through and isolated by alumina spacers. Grains are inserted for Macor™ threaded columns mounting. Thermoelectric Module is housed on its seat (Fig. 5).

Collector is placed on the TE module, thermocouple and electric connection are fastened to it. Ring-shaped spacer and absorber are positioned and ferrule is fastened to module. The isolation of electrical connections has been properly tested. A copper non-standard gasket has been developed to fit CM dimensions and internal space needs. In Fig. 6, the assembled encapsulated CM–gamma is presented.

Fig. 6 – Front (left) and rear (right) view of assembled encapsulated Conversion Module

This configuration has been also tested for vacuum operation; the encapsulated conversion module keeps a vacuum higher than 10^{-8} mbar×l/s. A steel stand was finally sealed to the CM (Fig. 7), to mount the module in the STP.

Fig. 7 –Encapsulated Conversion Module.

- *Integration of CM–gamma in STP*

Assembled encapsulated CM has been mounted on STP, ready for conversion operation. Four calorimeters are mounted at an angle of 90° with one another, to control the concentrated solar spot position, respect to the view-port. It is remarkable to notice that vacuum level results stable around 2×10^{-6} mbar. In the following pictures, the encapsulated CM installed at STP is shown (Fig. 9).

Fig. 9– CM-gamma integrated in STP **…at the focal point of the parabola (rear view).**

Electric and Thermal results

From the various measurements both in the solar simulator and on the encapsulated CM, installed at the Solar Test Platform, the values of both power and current obtained are low compared to the optimistic prediction in the DoW. Some experimental issues have affected the testing activities. The CM-alpha within the vacuum system at TAU has suffered of an unexpected high vacuum level under irradiation that limited its performance, although reaching high temperature conditions. On the other hand, CM-gamma and beta showed an optimal vacuum level, but have been unable to be tested at very high temperatures under STP.The strict dependence from vacuum level and emitter temperature are well known in the thermionic process. In any case, space charge and collector work function have been found to be the most important limitations for achieving high performance, especially for the TI stage whose electric output power has been found minimal if compared to the TE stage. Also the TE stage has not provided the same performance measured at a lab level. Conversely, the thermal output works very well, by reaching thermal conversion efficiencies close to 60% and constant as a function of temperature. So some improvements are necessary.

Solutions require further research/optimization of both fundamental and technological type, to achieve substantial improvements of the whole system. It would need to:

- Improve the material properties and related treatments (complex ceramic receiver, surface nano-texturing, diamond quality, doping and H-termination, adhesion, wider difference of work function by cesium treatment of Mo collector surface, minimizing inter-electrode distance, better quality commercial thermoelectric components).
- Strive to reach the maximum obtainable value of vacuum controlling the whole system, in particular the undesired degassing under heating, the optimization of the sealing materials and the getters quality.
- Introduce mechanical spacers to reduce anode-cathode distance, avoiding space charge-effects.
- Cover TE module surfaces with vacuum- and high-temperature-compliant silver conductive paste, optimizing thermal matching of its external surfaces.
- Verify the solar concentrated radiation flux at the STP during the summer season, in order to have a better weather stability and a more reliable statistical analysis, and to improve or substitute some STP components, which are not working optimally.

The project has being carried out by a consortium made up of 7 institutions, among which two SMEs (*) and a large industry (§):

1. Consorzio Roma Ricerche –CRR (Italy)
2. SHAP R&D Srl - SHAP (Italy) *
3. PRYSMIAN Spa - PRYSMIAN (Italy) §
4. Tel Aviv University – TAU (Israel)
5. Consiglio Nazionale delle Ricerche- CNR (Italy)
6. Maya Srl – MAYA (San Marino) *
7. TUBITAK Marmara Research Center- TUBITAK MAM (Turkey)

Project co-ordination and scientific co-ordination are carried out by CRR and CNR, respectively.

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