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XXXIV Cycle

WHP conversion by means of thermomagnetic energy harvester

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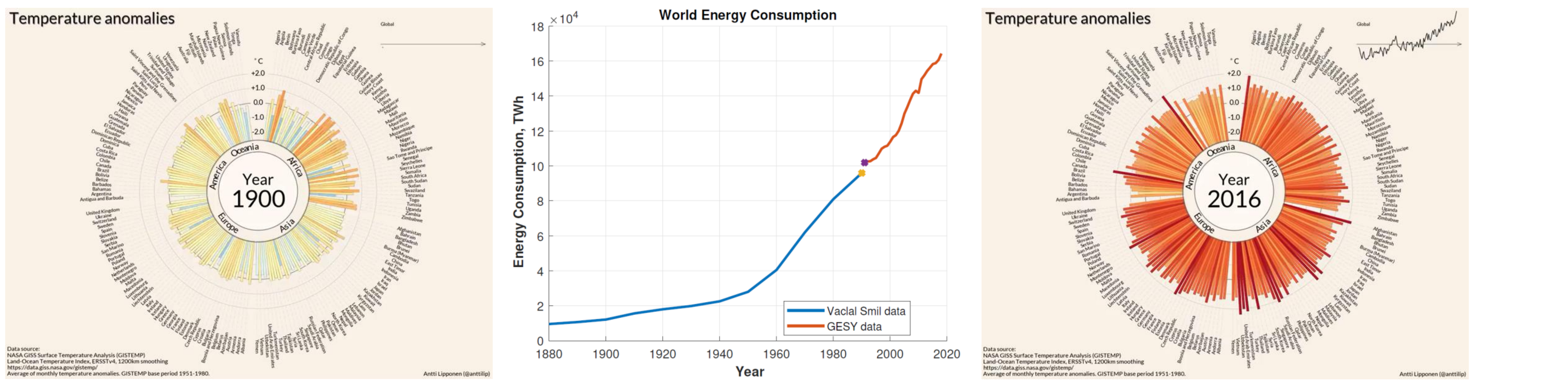
Research context and motivation

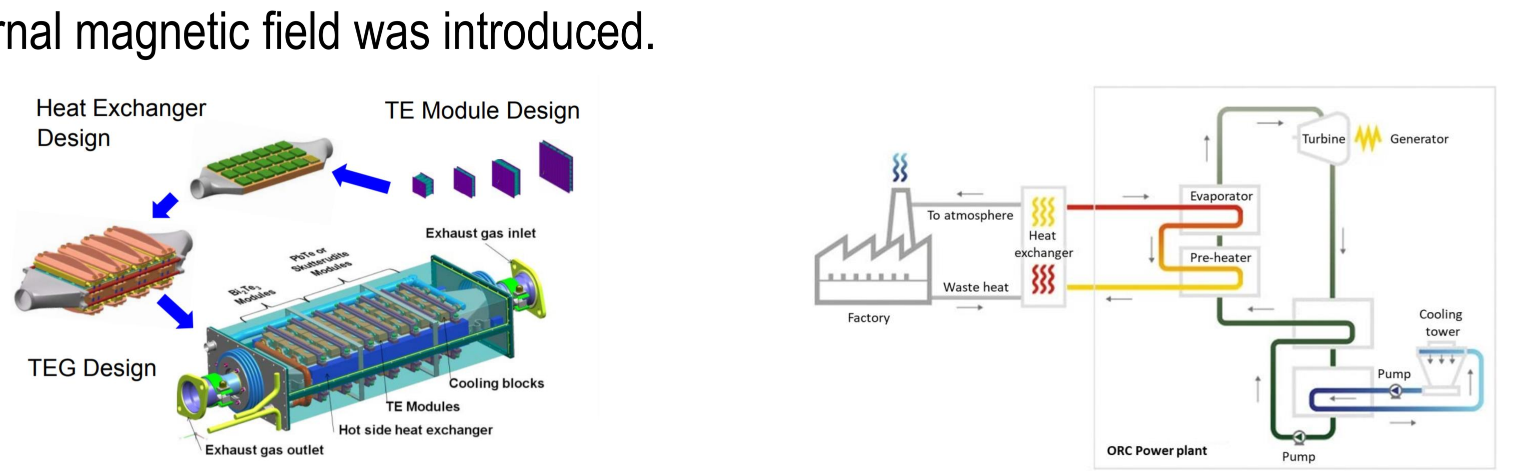
- According to a study made by Vaclav Smil, as shown in the middle figure, the world energy consumption has followed a monotonically increasing trend since the beginning of the first industrial era. Recently, this growth has increased its speed. Energy-related issues including resources location and exploitation, extraction transformation and distribution costs, accessibility and demand, consciousness of utilization, are of paramount importance in this very moment. Consequently, energy consumption, sustainability and environmental impact are now under the spotlight, becoming imperative keywords for the current fundamental and applied research, and represent important directives for the industrial production and investments of large funds in the near future. Energy transformation, at every level of human society, must cope with the non-unitary efficiency of any thermodynamic process and the consequent production of waste heat, playing a crucial role in global warming and CO_2 emissions. A valuable approach to tackle this problem is to capture and reuse the waste heat, providing an attractive opportunity for an emission-free and cost-effective energy resource.



Left: Worldwide averaged temperatures, per countries in 1900; middle: World energy consumption since 1880 until nowadays; right: Worldwide averaged temperatures, per countries in 2016.

Addressed research questions/problems

- In industrial, automotive and aerospace fields, low enthalpy energy harvesting is an important milestones of the environmentally friendly processes of the future, since current coolants with a temperature below 250 °C have their energy content wasted.
- Heat discarded into the environment is one of the largest sources of clean, fuel-free, and inexpensive energy available. Waste Heat Recovery (WHR) and Waste Heat to Power (WHP) are the processes of reusing this heat, to generate mechanical energy or converting it in electricity. A large number of WHR and WHP methods exist: from thermodynamic approaches and exploitation of cross-thermal effects (thermoelectric, thermomagnetic and pyroelectric devices). Normally industrial thermal waste is managed above 250 °C installing large plants, involving moving parts and thermodynamic cycle limits. Furthermore, it's difficult to use the harvested energy, since it's not ready as electricity. Mixed effects enhanced at the nanoscale are, nowadays, less employed but very promising. In particular, magnetocaloric and thermomagnetic machines are very appealing, especially ferrofluid-based devices being simple and emission-free. Ferrofluids (FFs) are colloids, suspensions of magnetic (Fe_3O_4) and not-toxic nanoparticles (NPs) dispersed in a green solvent, whose flow and energy transport processes can be controlled by adjusting the strength and orientation of an external magnetic field. Quite recently, the concept of exploiting temperature variations to drive flows in FFs under an external magnetic field was introduced.



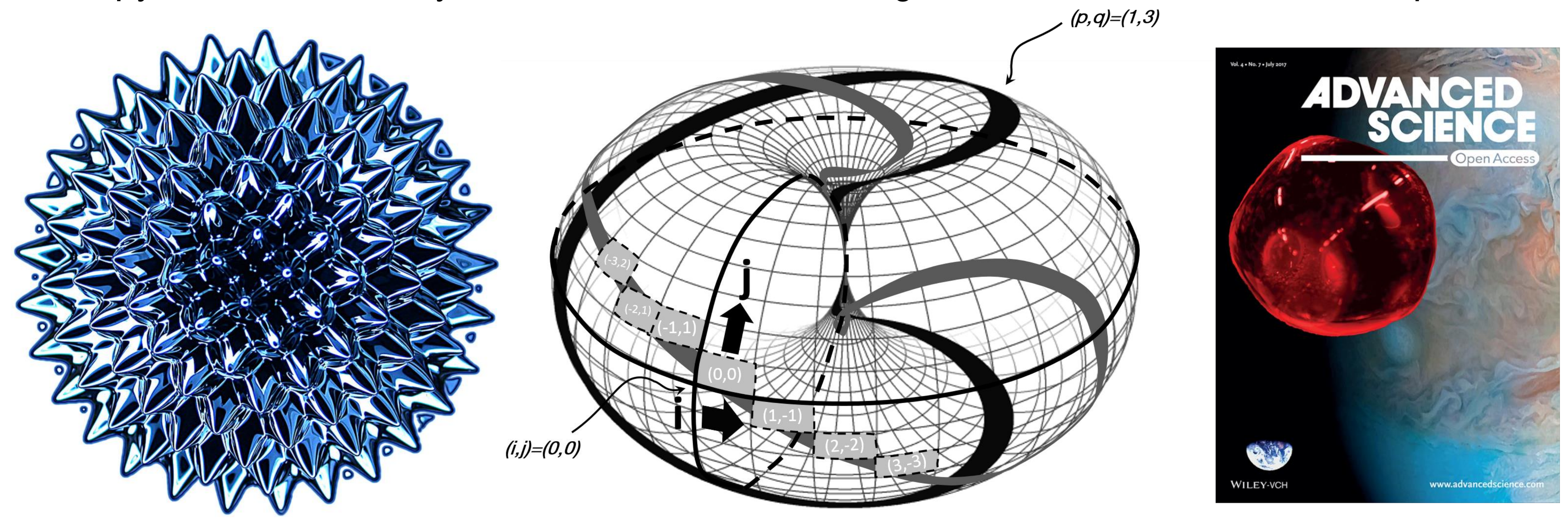
Left: Design of a thermoelectric generator installed on a car; right: Organic Rankine Cycle implemented on an industrial plant.

Submitted and published works

- Chiolerio, A., Garofalo, E., Mattiussi, F., Fortunato, G., Iovieno, M., "*Waste heat to power conversion by means of thermomagnetic hydrodynamic energy harvester*", Nature Energy, Submitted
- Garofalo, E., Bevione, M., Cecchini, L., Mattiussi, F., Chiolerio, A., "*Waste Heat to Power: Technologies, Current Applications and Future Potentials.*", Progress in Energy and Combustion Science, Submitted
- Rajan, K., Garofalo, E., Chiolerio, A., "*Wearable Intrinsically Soft, Stretchable, Flexible Devices for Memories and Computing*", Sensors, vol. 18, no. 367, 2018
- Benedetti, G., Bloise, N., Boi, D., Caruso, F., Civita, A., Corpino, S., Garofalo, E., Governale, G., Mascolo, L., Mazzella, G., Quarata, M., Riccobono, D., Sacchiero, G., Teodonio, D., Vernicari, P., "*Interplanetary CubeSats for Asteroid Exploration: Mission Analysis and Design*", Acta Astronautica, vol. 154, 2019, pp. 238-255
- Ercole, G., Garofalo, E., Lemieux, P., Maglie, M., Pastrone, D., "*N_2O-Cooled Aerospike for a Hybrid Rocket Motor: Nitrous Oxide Characterization and Additive Manufacturing*", 53^{rd} AIAA/SAE/ASEE Joint Propulsion Conference, Atlanta, 2017
- Benedetti, G., Garofalo, E., Mascolo, L., Marino, F., Riccobono, D., "*Opportunity For an End-To-End Mars Flyby Manned Mission by 2022*", 67^{th} International Astronautical Congress, Guadalajara, 2016

Novel contributions

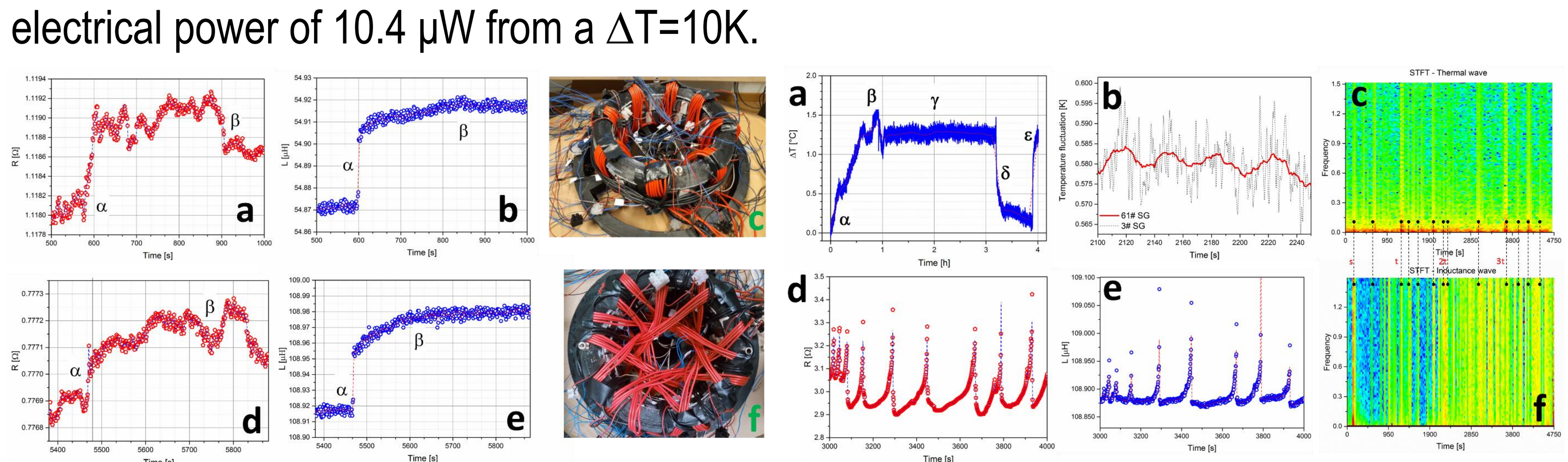
- A ThermOmagnetic hydRODYNAmic energy harvester (TORODYNA) was developed and characterized, an apparatus that belongs to the so called Colloidal EneRgEtic System (CERES) family. The main concept is the stabilization of topological solitons "Hopfions", density waves propagating in the structure, which arise from the movement of the magnetic NPs that, under the exposure to a ΔT and a collinear non-uniform magnetic field, self-organize into clusters from whose movement it is possible to extract electromagnetic energy. TORODYNA is unique since no other technologies are able to convert low enthalpy heat in electricity with a small device having such a low environmental impact.



Left: Scenographic picture of magnetized FF; middle: TORODYNA concept based on Hopfions; right: Reference material: Chiolerio, A., Quadrelli, M., *"Smart Fluid Systems: The Advent of Autonomous Liquid Robotics"*, *10.1002/advs.201700036.*

Adopted methodologies

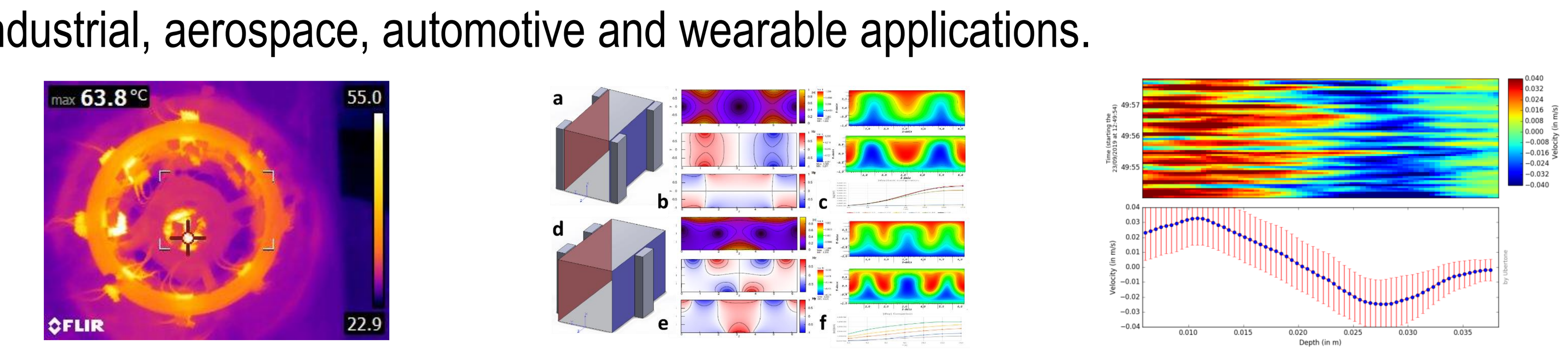
- The lab-scale prototype has a toroidal geometry (from the *tokamak* inertial machines). Peltier modules (controlled by a customized Peltier Array Controller) are used to generate ΔT, while permanent magnets trigger the advection. Thermistors and thermocouples (which data are acquired by a Printed Circuit Boards interfaced with Linux) are installed along the walls and placed in contact with the rotating fluid. To extract the electrical energy, which is measured with an impedance and a pico-amperometer, the structure have been wrapped-up with 2 configurations of coils (poloidal and mixed poloidal/toroidal windings), testing a water-ferrofluid (1.6%) two-phase flow and reaching a maximum extracted electrical power of 10.4 μW from a ΔT=10K.



Left: Effect on the resistance and inductance of the injection of 1 mL FF in water, for both configurations; right: Measured ΔT, R and L during time. By means of Short Time Fourier Transform, fundamental periods have been evidenced.

Future work

- To optimize the 1.0 PLA and 2.0 Pyrex prototypes and then, developing a 3.0 version, employing Ultrasound Velocimetry Profile technique, while comparing experimental results with thermal visualization and CFD simulations. Then, to scale up/down the reactor for industrial, aerospace, automotive and wearable applications.



Left: Top view of the operational TORODYNA with a thermal camera; middle: Simplified simulation models and results; right: results from Ultrasound Velocimetry Profile measurements.

List of attended classes

- 01MKXIY – Sustainable engineering (24/01/2019, 6)
- 01SDJRS – Earth climate and climate change (25/01/2019, 4)
- 01TGSIY – Advanced diagnostics for reactive flows (09/04/2019, 4)
- 01QSKIV – Experimental heat and mass transfer (27/09/2019, 4)
- 01QSLIV – Computational heat and mass transfer (28/09/2019, 4)
- Effective visual communication of science (30/01/2019, 4)
- 02LWHRV – Communication (27/08/2019, 1)
- 01SWPRV – Time management (29/08/2019, 1)