Comparative analysis of a magnetic refrigeration stage in an autonomous cryogenic cooling system

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Introduction:

A 4 Tesla superconducting magnet has been developed by CIEMAT for a compact cyclotron for radioisotope production in the framework of AMIT project (Advanced Molecular Imaging Techniques) in collaboration with other Spanish companies. For the refrigeration of the SC magnets an autonomous cryogenic cooling system (CSS) has been developed in collaboration with CERN.

The CSS is based on a closed loop forced-flow refrigeration configuration, where certain amount of cryogen is cooled down in a commercial cryocooler and it is pumped into the final user application to achieve the desired temperature. This refrigeration equipment has low Carnot efficiencies at low temperatures

Fig. 1. AMIT superconducting cyclotron and the cryogenic supply system (CSS).

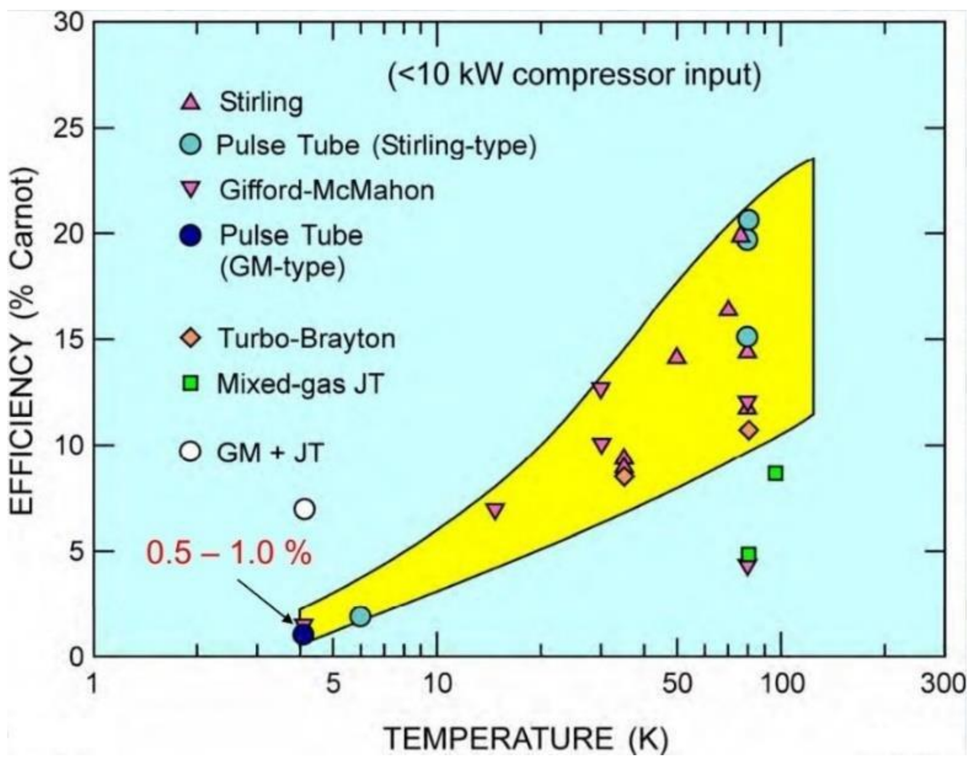

Fig. 2. Carnot cryocooler efficiency as a function of temperature

What is Magnetic Refrigeration?

Magnetic refrigeration is based on the magnetocaloric effect (MCE), which is the reversible temperature change of a magnetic material upon the application or removal of a magnetic field

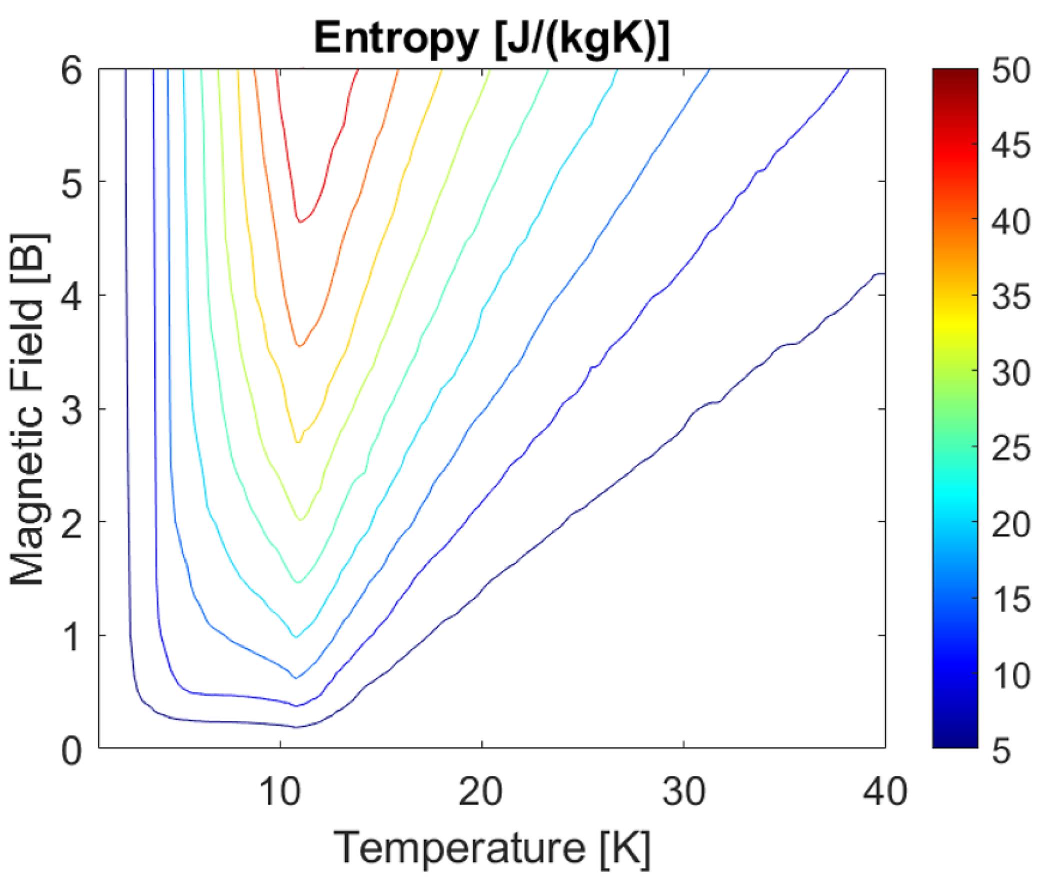

Fig. 3. Entropy of $ErAl_2$ as a function of Temperature [K] and Magnetic Field [B]

Two variables define this effect: the isothermal magnetic entropy change, and the adiabatic temperature change. The adiabatic temperature change is defined as:

$$\Delta T_{ad} = -\mu_0 \int_{H_I}^{H_F} \frac{T}{C_{p,H}} \left(\frac{\partial m}{\partial T}\right)_{p,H} dH$$

The total magnetic entropy change is equal to:

$$\Delta S_M = \mu_0 \int_{H_I}^{H_F} \left(\frac{\partial m}{\partial T}\right)_{p,H} dH$$

Model:

A magnetic refrigeration stage would be included after the 2nd stage of the cryocooler in the CSS. The design of such system will require the study of: the magnetic source, the fluid dynamics and the magnetocaloric material.

A finite difference model has been developed to analyze the thermal and fluid dynamic behavior of such solution where first law and second law equations are iteratively solved.

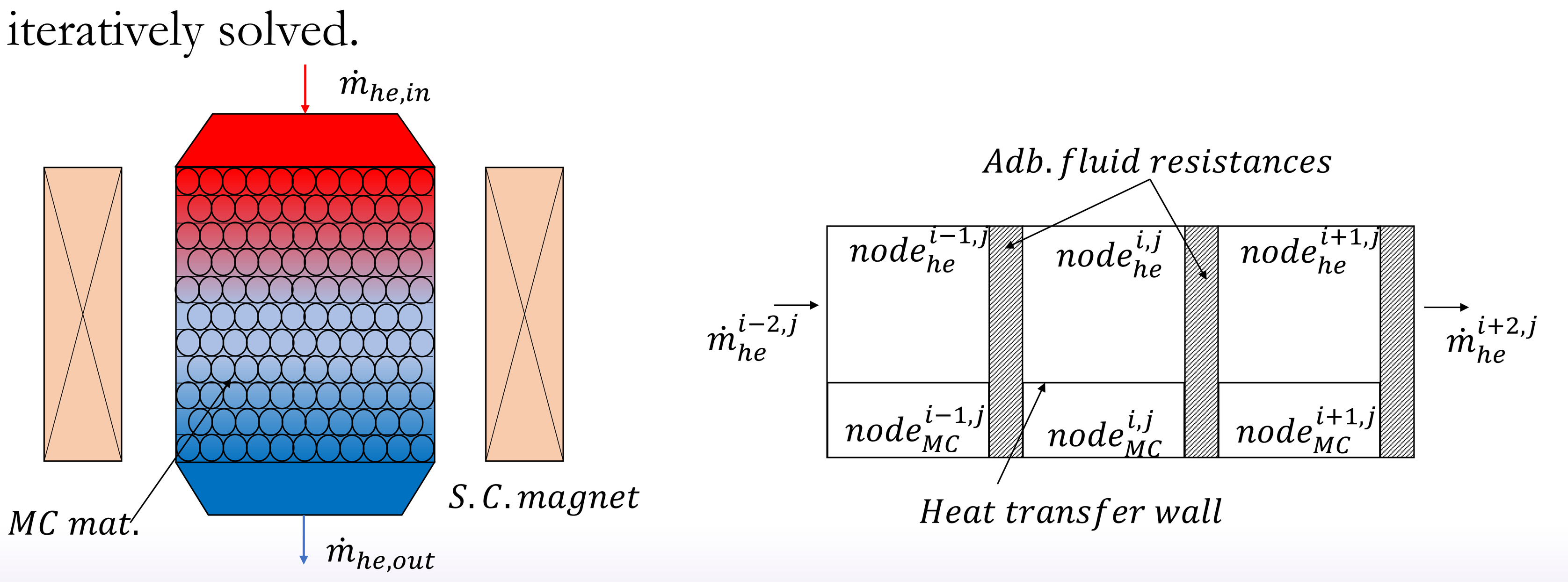

Fig. 4. (a) Schematic of a magnetic refrigeration stage and (b) schematic of a differential regenerator model adopted in the analysis

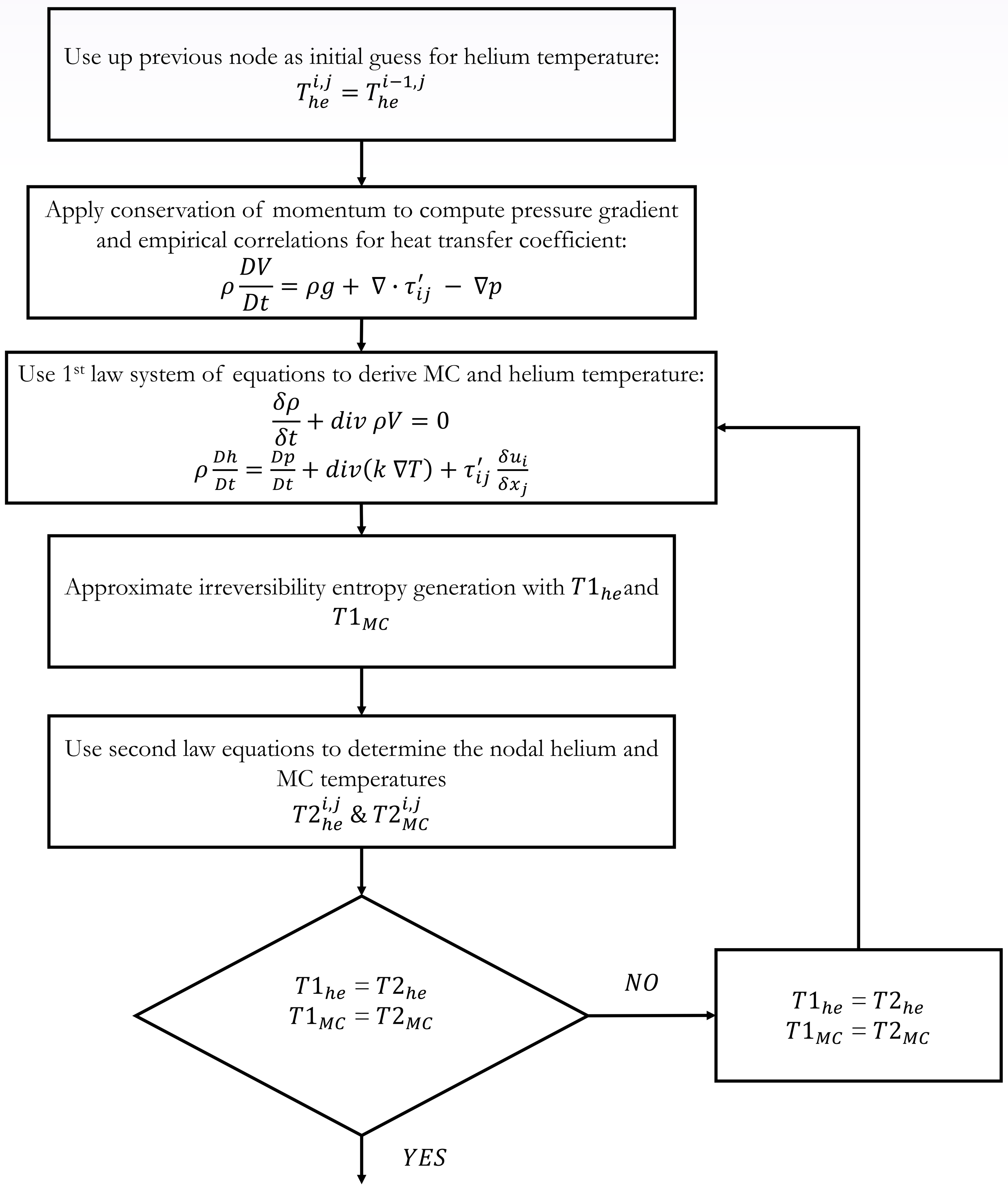

Fig. 5. Flowchart of the simulation procedure

Results:

The magnetic field signal has been optimized to maximized the refrigeration power. In Figure 6, the thermomagnetic cycle undergone by the MC material is shown. An analysis of the optimal MC material as a function of temperature has revealed that GGG would be the material of choice for temperatures lower than 14K, and $ErAl_2$ for higher temperatures.

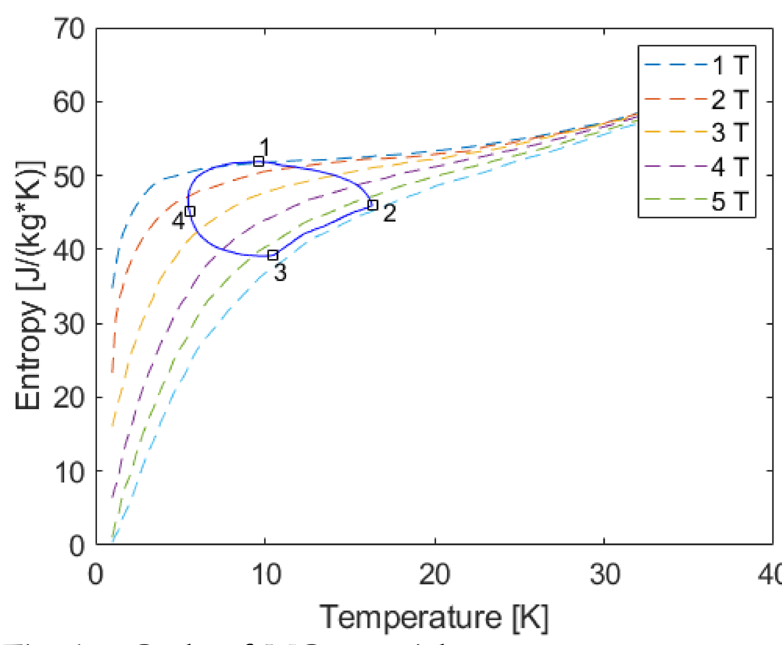

Fig. 6. Cycle of MC material

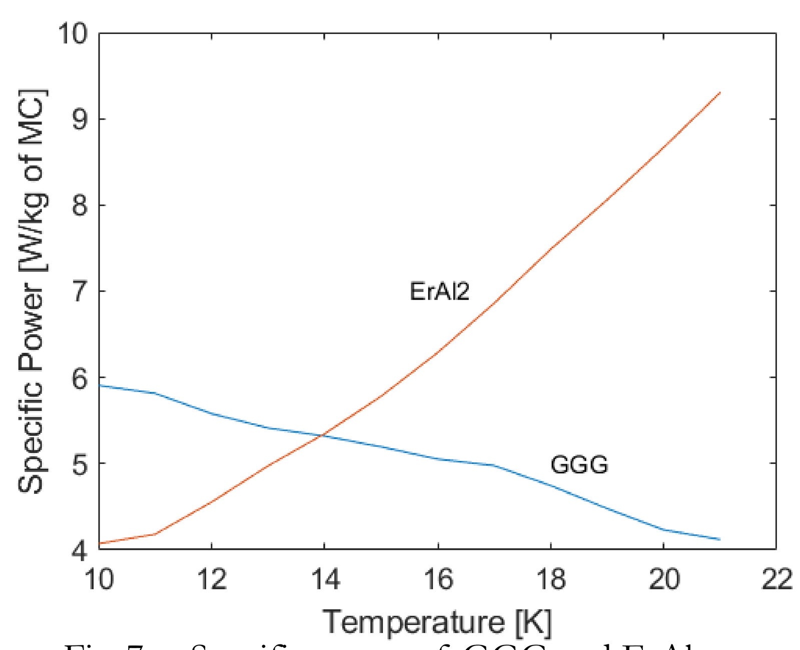

Fig. 7. Specific power of GGG and $ErAl_2$

Conclusion:

A finite difference model of a magnetic refrigeration stage has been developed to analyze and compare the different operational parameters and variables that comprises a magnetic refrigeration stage. The model allows to compare among different MC materials and to optimize the fluid, magnetic and geometric parameters.

Further work is needed in the definition of the magnetic source and hydraulics of the system to completely define the characteristics, cooling power and efficiency of the stage.

Main References:

[1] Radebaugh R. Refrigeration for Superconductors. Proc. IEEE, vol. 92, Institute of Electrical and Electronics Engineers Inc.; 2004, p. 1719–34. https://doi.org/10.1109/JPROC.2004.833678.

[2] Gregory F. Nellis. Magnetically aumented cryogenic refrigeration. University of Wisconsin, 1992.