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Abstract

Abstract: Gifford-McMahon (GM) refrigerator based on gas expansion effect can provide a cooling temperature below 4.2 K, which is widely used to cool superconducting magnets for applications such as magnetic resonance imaging and to provide low temperature environment for condensed matter physics research, etc. Because of the limited specific heat capacity of regenerator materials as well as non-ideal properties of helium at this temperature, the efficiency of GM refrigerator can only reach about 1% of the ideal thermodynamic efficiency. Considering the intrinsic high efficiency of magnetic refrigeration, an integration of both effects may lead to a higher efficiency, which is important for the applications. With the lowest stage regenerator filled with ErNi and TmCuAl, which have both appreciable specific heat and magnetocaloric effect at temperature below 10 K, the hybrid refrigerator has been experimentally proved to reach a higher cooling power than pure GM recently. However, due to the complexity of thermodynamic cycles and fluid dynamics of the hybrid refrigeration system, optimizations based on numeric simulation are necessary to provide a useful guidance for the practical design.

In this paper, a 2D axis-symmetric and transient numerical model of the hybrid refrigerator is established using COMSOL Multiphysics. The model includes a low temperature regenerator filled with Pb and ErNi and an expansion chamber. A local thermal non-equilibrium interface is used to describe the heat transfer between helium and the regenerator material. A periodic heat source is added, which considers the magnetocaloric effect of ErNi generated by a sinusoidal magnetic field up to 1.1 T. Non-ideality of helium gas is considered by using the REFPROP database. Moving meshes is used to simulate the pistons sandwiching the regenerator and the expansion space. With this model, the effect of the timing between gas expansion and magnetic refrigeration is studied and optimized. The corresponding no-load temperature, cooling capacity and efficiency are obtained and compared with the results from pure gas expansion. The results showed that the optimal phase angle (the phase difference between the maximum value of varying magnetic field and the minimum value of varying expansion space volume) is 90°, which was very close to previous experimental results. The cooling power at 4 K increased from 0.13 W with pure gas expansion to 0.27 W with the hybrid scheme, and the efficiency improved by 2.13 times. The successful implementation of the numeric calculation with COMSOL will greatly help to optimize the performance of hybrid refrigerator. Meanwhile, a modification on effective thermal conductivity of porous media in COMSOL is proposed, which is important for a more accurate estimation of the cooling power for such kind of small-scale liquid helium temperature refrigerator.

Figures used in the abstract

Figure 1: No-load temerature as a function of phase angle (the optimal is 90°)