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M3Or4P-07: AC Losses and Surprising Magnet Heating in Reciprocating Active Magnetic Regenerative Refrigerators

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The magnetocaloric effect is a phenomenon where certain materials change temperature when exposed to a change in magnetic field. This adiabatic temperature change in temperature at or below a magnetocaloric material's Curie point can be combined with heat transfer fluid flows to perform refrigeration cycles such as the Active Magnetic Regenerative Refrigeration cycle (AMRR). Detailed analysis of magnetocaloric liquefiers shows it is possible to increase the efficiency (FOM) of small industrial-scale liquefiers (10-30 tonne/day) of liquid cryogens by 50-80% over comparable conventional liquefiers. For several years we have been developing lab-scale prototypes to validate this potential. One device that spans from 100 K to 20 K utilizes a reciprocating dual-regenerator design with three magnetic refrigerants in each regenerator. This assembly is linearly axially moved in and out of a 6.5 T solenoidal superconducting conduction-cooled magnet with two reversing heat transfer fluid flows to execute the four-step AMRR cycle. During this cycle, one of the regenerators executes a heat rejection step while magnetized, and the other absorbs a cold thermal load while demagnetized. Inherent to the AMRR cycle, the magnetization (A/m) of the refrigerants is temperature dependent such that the demagnetized regenerator cools which increases its magnetization while the magnetized regenerator warms which reduces its magnetization as they synchronously move in or out of the field. There is a large magnetic force (toward the high-field region of the magnet) on the magnetic refrigerants as they are moved out of the magnet. Correspondingly the other dual regenerator experiences a slightly smaller magnetic force toward the high field region of the magnet as it moves into the magnet. These opposite attractive forces react against each other, but the net difference in magnetization results in a net force imbalance during the reciprocating movement of the regenerators. The work input required to complete the cycle is the work input for the AMRR cycle. The magnet is put in persistent mode after it is charged to the current required for the desired magnetic field strength H and empty magnet flux density. The magnetic refrigerants also contribute to the magnetic flux density B. In persistent mode the magnet becomes a constant flux device so when there is a change in magnetization inside the bore of the magnet as the regenerators are moved, the free current in the magnet must also increase or decrease to keep the flux constant. The changes in free current in the magnet windings cause flux jumping which causes Joule heating in the Cu stabilizer or AC losses. In earlier prototypes the total mass of the regenerators was about 100 grams. The AC losses in these prototypes were only a few tenths of a Watt so the two-stage 1.5 W @ 4 K GM cryocooler easily kept the magnet at or below ~4.5 K. As we increased the temperature span and cooling power, the regenerators had several layers of refrigerants each with different mass with a total mass of a few kg. During our test runs with the first of these prototypes we found that the heating in the magnet was much larger than due to AC losses causing the coil temperature to rise over 4.8 –5 K in as few as ten refrigeration cycles at 0.25 Hz. This was a puzzle that we solved using COMSOL Multiphysics with the AC/DC module. The detailed drawing of the dual regenerator assembly with all different magnetic properties was used to calculate net magnetic forces between the refrigerant masses and magnetic field during the reciprocating cycle. These results showed the force imbalances were caused by the geometry of the dual regenerator assembly with non-magnetic gaps between refrigerant masses. This paper describes the unexpected mechanisms that caused the excessive heating in the magnet and the results of an innovative experiment we did to validate the COMSOL predictions and convincing show what the caused the magnet heating.

Author: ARCHIPLEY, Corey (Pacific Northwest National Lab (USA))

Co-author: BARCLAY, John (Pacific Northwest National Laboratory (USA))

Presenter: ARCHIPLEY, Corey (Pacific Northwest National Lab (USA))

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