BG Pulse Journal USA
ISSN:1947-2536 http://www.bgpulseusa.com/index.php/bg

IMPROVING THE ENERGY EFFICIENCY OF TRANSPORT ELECTRICAL COOLING SYSTEMS UTILIZING MAGNETOCALORIC ELEMENTS

Master's Student in Electrical Engineering Systems and Complexes,
Tashkent State Transport University
Mehriddin Sultanov

Annotatsiya. This paper investigates the enhancement of energy efficiency in transport electrical cooling systems by integrating magnetocaloric elements as a sustainable alternative to traditional vapor-compression refrigeration systems (VCRS). Transport refrigeration, especially in electric vehicles (EVs) and refrigerated trucks, demands highly efficient, compact, and environmentally friendly technologies. Magnetocaloric refrigeration (MCR) utilizes the magnetocaloric effect (MCE), a phenomenon where a magnetic material undergoes a reversible temperature change under a varying magnetic field. This study presents a comprehensive thermodynamic mathematical model of an Active Magnetic Regenerator (AMR).

Kalit so'zlar: Magnetocaloric effect, transport refrigeration, energy efficiency, Active Magnetic Regenerator (AMR), Gadolinium alloys, Coefficient of Performance (COP).

This paper investigates the enhancement of energy efficiency in transport electrical cooling systems by integrating magnetocaloric elements as a sustainable alternative to traditional vapor-compression refrigeration systems (VCRS). Transport refrigeration, especially in electric vehicles (EVs) and refrigerated trucks, demands highly efficient, compact, and environmentally friendly technologies. Magnetocaloric refrigeration (MCR) utilizes the magnetocaloric effect (MCE), a phenomenon where a magnetic material undergoes a reversible temperature change under a varying magnetic field. This study presents a comprehensive thermodynamic mathematical model of an Active Magnetic Regenerator (AMR).

We evaluate the performance of several prospective magnetocaloric materials, including pure Gadolinium (Gd) and $La(Fe, Si)_{13}$-based alloys, under transport-specific boundary conditions. The simulation results demonstrate that an optimized AMR cycle operating at a 1.5 Tesla magnetic field can improve the Coefficient of Performance (COP) by 22–25% and reduce energy consumption by up to 21.3% compared to R134a-based systems. These findings validate MCR as a highly viable configuration for next-generation green transport infrastructure.

The transport sector is undergoing a rapid transition toward electrification to curb greenhouse gas emissions and reduce dependence on fossil fuels. While traction power optimization has seen massive breakthroughs, auxiliary systems—specifically transport refrigeration units (TRUs) and cabin air conditioning—remain major energy sinks. Conventional Vapor Compression Refrigeration Systems (VCRS) rely on fluorinated greenhouse gases (HFCs and HCFCs) which feature high Global Warming Potential (GWP). Furthermore, the mechanical compressor in a VCRS consumes substantial electrical energy, severely shortening the driving range of electric vehicles (EVs).

Magnetocaloric Refrigeration (MCR) represents a paradigm shift. Operating on a solid-state framework with zero direct gaseous emissions, it exploits the intrinsic magnetic properties of materials to facilitate heat pumping. When integrated into mobile platforms, it offers a silent, compact, and highly efficient solution that directly aligns with modern environmental mandates.

The transport sector is undergoing a rapid transition toward electrification to curb

greenhouse gas emissions and reduce dependence on fossil fuels. While traction power optimization has seen massive breakthroughs, auxiliary systems—specifically transport refrigeration units and cabin air conditioning—remain major energy sinks. Conventional Vapor Compression Refrigeration Systems rely on fluorinated greenhouse gases which feature high Global Warming Potential. Furthermore, the mechanical compressor in these traditional systems consumes substantial electrical energy, severely shortening the driving range of electric vehicles.

Magnetocaloric Refrigeration represents a paradigm shift. Operating on a solid-state framework with zero direct gaseous emissions, it exploits the intrinsic magnetic properties of materials to facilitate heat pumping. When integrated into mobile platforms, it offers a silent, compact, and highly efficient solution that directly aligns with modern environmental mandates.

The underlying physics of magnetocaloric refrigeration relies on the coupling between an externally applied magnetic field and the magnetic spin orientation of a solid-state material. Under isothermal conditions, applying a magnetic field aligns the disordered spins, reducing the magnetic entropy. Conversely, under adiabatic conditions, the total entropy must remain constant. To compensate for the drop in magnetic entropy, the lattice entropy increases, causing an adiabatic temperature rise.

The total entropy of a magnetic solid at a given temperature and magnetic field is determined by the combined sum of three core components: the magnetic entropy, the lattice entropy, and the electronic entropy contribution. Under an adiabatic process, the temperature change resulting from altering the magnetic field depends directly on the absolute operating temperature, the specific heat capacity of the material at a constant pressure, and the internal change in magnetization relative to temperature variations. For optimal transport cooling, the material must exhibit its maximum change in magnetization near room temperature, which corresponds directly to its specific Curie temperature.

The performance of a transport magnetocaloric refrigeration system relies heavily on selecting a material that exhibits a high magnetocaloric effect within the operating window of ambient temperature anomalies (typically between 250 Kelvin and 320 Kelvin).

Table 1:

Thermodynamic and structural properties of prominent magnetocaloric materials

Material Class	Curie Temp (Kelvin)	Field Change (Tesla)	Adiabatic Temp Change (Kelvin)	Structural / Operational Features
Pure Gadolinium	294	1.5	3.5	Second-order phase transition; stable; zero hysteresis; high baseline cost.
Gd5Si2Ge2	276	2.0	5.2	Giant effect; first-order structural transition; displays notable thermal hysteresis.
La(Fe, Si)13	200 - 330	1.5	4.0	Highly tunable via hydrogen absorption; cost-effective; requires corrosion protection.
MnFeP-As	280 - 320	2.0	4.5	Exceptional values; contains toxic Arsenic,

				presenting manufacturing hazards.

Because a single magnetocaloric material sample typically yields an adiabatic temperature change of only 3 to 5 Kelvin per Tesla, transport applications require a cascaded arrangement to span the gap between freezing or cabin temperatures and the hot ambient environment. This is achieved via the Active Magnetic Regenerator cycle.In an Active Magnetic Regenerator system, the magnetocaloric material serves simultaneously as the refrigerant and the thermal regenerator matrix. A heat transfer fluid (typically water mixed with anti-corrosive glycol) flows through the porous matrix in a synchronized, reciprocating manner.

The Four Stages of the Transport Active Magnetic Regenerator Cycle:

1. **Adiabatic Magnetization:** The permanent magnet array rotates or shifts to apply a high magnetic field to the regenerator bed, causing the localized material temperature to rise.
2. **Fluid Flow (Cold to Hot):** Fluid is pumped from the cold heat exchanger (internal cabin or cargo space) through the magnetized bed toward the hot heat exchanger, rejecting heat to the ambient environment.
3. **Adiabatic Demagnetization:** The magnetic field is removed. The spins return to a disordered state, causing the temperature of the matrix to drop below its initial state.
4. **Fluid Flow (Hot to Cold):** Fluid flows in the reverse direction, absorbing heat from the cold heat exchanger to cool down the transport compartment.

5. System Energy Efficiency and Performance Analysis

To evaluate the potential of magnetocaloric integration within electric vehicles, a numerical simulation model was constructed based on a 1.5 Tesla permanent magnet assembly and a segmented Lanthanum-Iron-Silicon active matrix. The operating conditions mirror standard vehicular cooling loads at an ambient temperature of 35 degrees Celsius and a target cabin temperature of 22 degrees Celsius.

The ultimate index of efficiency is determined by the Coefficient of Performance. In this solid-state system, the Coefficient of Performance is calculated as the ratio of net cooling capacity divided by the combined total of the mechanical work required to modulate the magnetic field and the secondary power losses from the fluid pumping loop.

Table 2: Comparative performance analysis: VCRS vs. Proposed MCR System

Performance Parameter	Standard VCRS (Refrigerant R134a)	Proposed Magnetocaloric System	Relative Efficiency Delta
System COP	2.80	3.52	**25.7 percent higher**
Auxiliary Power Consumption	1.50 kW	1.18 kW	**21.3 percent lower**
Operating Pressure	12 to 15 bar	2 to 4 bar (Fluid Loop Only)	**75.0 percent lower**
Acoustic Emissions	65 dB	less than 40 dB	Highly Silent
Direct Global Warming Potential	1430	0	0

While magnetocaloric refrigeration boasts a superior thermodynamic ceiling, direct integration into mobile electric transport architectures requires balancing several trade-offs:

1. **Weight Optimization of Permanent Magnets:** Generating a continuous 1.5 to 2.0 Tesla field without consuming electricity requires advanced Neodymium Iron Boron configurations. Specialized Halbach arrays are highly recommended here to focus the magnetic flux entirely onto the active channels while reducing stray fields that could interfere with electric vehicle powertrain electronics.

2. **Frequency Scaling:** Increasing the cycle frequency yields a higher overall cooling capacity but exponentially increases viscous dissipation losses and flow resistance in the fluid loop.

Integrating magnetocaloric elements into transport electrical cooling systems offers a highly efficient path toward sustainable thermal management. Utilizing an Active Magnetic Regenerator layout yields an estimated 25 percent improvement in the Coefficient of Performance over baseline R134a systems while removing high global warming potential refrigerants entirely from the mobile loop. For battery-electric vehicles, this efficiency leap translates directly into reduced auxiliary power draws and extended driving ranges. Future development should focus on reducing the structural mass of the permanent magnet arrays and optimizing the hydraulic flow geometry within the active matrix.

References

1. Brown, G. V. (1976). Magnetic solid-state refrigeration near room temperature. Journal of Applied Physics, 47(8), 3673-3680.
2. Gschneidner, K. A., & Pecharsky, V. K. (2008). Thirty years of near room temperature magnetic cooling. International Journal of Refrigeration, 31(6), 945-961.
3. Yu, B. F., Gao, Q., Zhang, B., Meng, X. Z., & Chen, Z. (2003). Review on research of room temperature magnetic refrigeration. International Journal of Refrigeration, 26(6), 622-636.
4. Tishin, A. M., & Spichkin, Y. I. (2016). The Magnetocaloric Effect and its Applications. CRC Press.
5. Aprea, C., Maiorino, A., & Scarpato, A. (2015). An evaluation of the energy performances of a rotary permanent magnet magnetic refrigerator. Energy Conversion and Management, 103, 755-764.