A highly reliable cryogenic mixing pump with no mechanical moving parts

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Abstract. This paper presents the design and preliminary test results of a novel cryogenic mixing pump based on magnetocaloric effect. The mixing pump is developed to enable long-term cryogenic propellant storage in space by preventing thermal stratification of cryogens in storage tanks. The mixing pump uses an innovative thermodynamic process to generate fluid jets to promote fluid mixing, eliminating the need for mechanical pumps. Its innovative mechanism uses a solid magnetocaloric material to alternately vaporize and condense the cryogen in the pumping chamber, and thus control the volume of the fluid inside the pumping chamber to produce pumping action. The pump is capable of self-priming and can generate a high-pressure rise. This paper discusses operating mechanism and design consideration of the pump, introduces the configuration of a brassboard cryogenic pump, and presents the preliminary test results of the pump with liquid nitrogen.

1. Introduction
Long-distance spaceflight to the Moon, Mars, and other planets will require refueling in microgravity environments with large quantities of cryogenic propellants to enable missions with massive payloads. Refueling will also extend the service lives of satellites that have consumed nearly all of their orbital maneuvering fuel. Refueling can eliminate many of the systems and spacecraft structural mass required to support and maintain cryogens on the launch pad [1]. Refueling also enables the reuse of infrastructure already in space. These performance benefits will significantly reduce launch costs. However, a key challenge for refueling in space is the fluid management and pressure control of the cryogenic rocket propellant. Parasitic heat leak from the external thermal environment into a cryogenic tank will cause the tank pressure to rise continuously if no active fluid mixing and cooling are applied. In a microgravity environment where natural convection is almost absent, the rate of pressure rise depends not only on the total parasitic heating rate, but also on the parasitic heat flux distribution, heat transfer between the tank fluid and the wall, liquid position in the tank, and the extent of fluid thermal stratification [2]. Fluid stratification can significantly reduce the effective thermal mass of the cryogen and increase the rate of pressure rise. Fluid mixing using fluid jets will minimize thermal stratification and enhance interfacial condensation, and thus enables reliable control of the tank pressure as long as either passive or active cooling power is available to absorb the total parasitic heating. The mixing pump must be energy efficient and very reliable. Reliable operation at cryogenic temperature is a challenge for pumps because no lubricants can be used. Pumping a cryogenic fluid near its saturation temperature can also cause cavitation in pumping chambers and in the diffusion section of hydrodynamic bearings [3].
2. A Highly Reliable, Efficient Magnetocaloric Effect Pump

To meet the challenging requirements for the cryogenic mixing pump, a proof-of-concept Magnetocaloric Effect Pump (MCEP) has been developed and demonstrated. An MCEP utilizes the magnetocaloric effect (MCE) to efficiently generate vapor inside the pumping chamber to force liquid out and then condense vapor to draw liquid in. The vapor generation and condensation processes are accomplished by using a simple, yet very energy-efficient magnetocaloric heat pump that is built into the pumping chamber. The heat pumping effect reduces the MCEP work input to less than a couple of percent of the heat needed for vapor generation and condensation. The operating mechanism of the MCEP is discussed below.

2.1. Magnetocaloric Heat Pump

When a magnetic field is applied adiabatically to a magnetocaloric refrigerant material (MRM), the magnetic moments of the MRM molecules will align with the applied field. As a result, the magnetic entropy decreases. The magnetic entropy is converted to thermal entropy, and the refrigerant heats up. When the field is removed, the magnetic moments become randomly oriented. Thus the MRM magnetic entropy increases and the MRM cools down. The magnetization and demagnetization processes of an MRM are analogous to the compression and expansion processes of a gas. As shown in Figure 1a, the operation of a magnetocaloric heat pump employing a Carnot cycle can be divided into four separate phases: (1) In the adiabatic partial magnetization process (State 1 to 2), the magnetic field is raised to an intermediate level and the MRM is heated up from Tc to Th adiabatically. (2) In the isothermal magnetization process (State 2 to 3), the magnetic field is raised to the maximum intensity while the MRM rejects heat to a heat sink. (3) In the adiabatic partial demagnetization process (State 3 to 4), the magnetic field is reduced to an intermediate level and the refrigerant is cooled down from Th to Tc adiabatically. (4) In the isothermal demagnetization process (State 4 to 1), the magnetic field is reduced to the minimum value while the MRM absorbs heat from its cooling target.

Figure 1. T-S diagram of magnetocaloric heat pump operating with a Carnot cycle, and schematic of a cryogenic-fluid mixing pump driven by magnetocaloric effect.
2.2. Mixing Pump Operation

Figure 1b shows the conceptual design of a mixing pump employing an internal magnetocaloric effect heat pump. A packed bed of MRM and the liquid chamber are enclosed inside the pump’s vacuum insulated housing. A superconducting magnet surrounding the MRM bed section provides the magnetic field to drive the built-in MCE heat pump. The vacuum insulated housing prevents propellant surrounding the pump from directly contacting the fluid inside the pump, which can reduce the fluid temperature swing induced by the MCE heat pump. For applications requiring a unidirectional (DC) fluid flow, a pair of check valves can be used to rectify the flow, similar to those in a conventional piston pump. For propellant mixing applications, a high speed AC fluid jet from the pump could be sufficient to mix the fluid inside the tank to prevent thermal stratification. In that case, the check valves could be completely eliminated and the pump would have no moving parts.

The MRM packed bed is installed inside the pump. Using a packed bed with small beads enhances the heat transfer between the MRM and fluid inside the pump. MRM beads are contained inside hydrophobic porous tubes, and the space between the tubes serves as vapor flow passages. The hydrophobic porous tubes also prevent the liquid inside the pump from directly contacting MRM beads, which can substantially reduce the temperature swing of the MRM. A microgravity-compatible phase separator using a stack of hydrophilic screen sheets allows only liquid to transfer in and out of the pumping chamber, preventing vapor generated inside the pump from flowing out.

Similar to an MCE heat pump, the actual pumping process in an MCEP can be divided into the following four separate major steps: (1) Sensible Heating Step. In this step, the valves are closed and the magnetic field gradually increases, causing the MRM packed bed and surrounding fluid temperature to increase. This continues until the fluid temperature reaches the saturation temperature at the target discharge pressure. (2) Evaporation/Discharge Step. The discharge valve opens and propellant vapor begins to generate on the surface of MRM beads. The magnetic field continues to increase, reaching its peak value, and then gradually decreases near the end of this step. The magnetic field causes the MRM temperature to first rise above the fluid discharge saturation temperature and then drop back to the saturation temperature. (3) Condensing Step. The discharge valve is closed and the magnetic field continues to decrease to introduce cooling in the MRM, allowing vapor inside the pump to condense in the MRM bed and reducing the pressure inside the pumping chamber. This continues until the internal pressure falls below the suction pressure. (4) Condensation/Suction Step. The suction valve is opened and liquid is drawn into the pumping chamber as more vapor inside the pump condenses. In this step, the magnetic field continues to decrease, reaching its minimum value, and then begins to rise, causing the MRM temperature to drop and then rise back to the inlet saturation temperature. At the end of the step, the suction valve closes, completing one pumping cycle.

2.3. Keys to Efficient MCEP Operation

The MCEP work input is proportional to the amount of vapor that needs to be generated and the Coefficient of Performance (i.e., COP, which is the ratio of heating power to work input) of an MCE heat pump. Therefore, preventing vapor from flowing out of the pump is the key to reducing the amount of vapor that needs to be generated for a given liquid flow rate requirement. The COP of an MCE is determined by the amplitude of the MRM temperature swing and the efficiency of the heat pumping process. The MRM temperature swing itself is determined by the required saturation temperature increase ($\Delta T_{sat}$) associated with the desired pump pressure rise, and the temperature difference between the MRM and surrounding fluid during heat transfer processes. When the required saturation temperature swing is small, which is typically the case for this type of application, the temperature difference required for heat transfer between the MRM and the surrounding fluid dictates the maximum temperature span for the magnetocaloric heat pump. Therefore, highly effective heat transfer between the MRM and surrounding fluid is desirable. This can be accomplished by using an MRM packed bed with small beads to achieve a large heat transfer area and a very small hydraulic diameter for high heat transfer coefficient. Among all the heat pump technologies, the MCE heat pump is the simplest and can achieve the highest COP in practice when the temperature span of heat
pumping process is small (i.e., about 1 K). The MCE heat pump technology has been successfully used in Adiabatic Demagnetization Refrigerators (ADRs) to produce very efficient (~ 90% of Carnot) cryogenic cooling for space applications [4]. For a typical mixing pump application, the required pressure rise is only about 1 psi. This pressure rise can be easily achieved by raising the fluid saturation temperature by less than 0.25 K. With an appropriate MRM material, this temperature swing can be easily achieved with a 1 T magnetic field. For a hydrogen mixing pump, candidate MRM materials include HoNi2 and DyNi2, while for a liquid oxygen pump, Gd5Si0.5Ge3.5 is one of the ideal materials [5].

3. LN2 Mixing Pump Demonstrator Configuration
To demonstrate the operation of an MCEP, a laboratory demonstrator was designed, built, and tested. Because of the challenging safety issues with testing liquid hydrogen and oxygen, the pump demonstrator was designed and characterized with liquid nitrogen. The demonstrator used a gravity-assisted phase separator to prevent vapor from flowing out. The design of a gravity-insensitive LN2 MCEP has been developed and its operation had been demonstrated in a separate effort. The following section discusses the configuration of the gravity-assisted LN2 MCEP.

3.1. Mixing Pump Demonstrator Configuration
The demonstrator pumping chamber configuration is similar to the conceptual design shown in Figure 1b. The MRM cartridge in the pump chamber consists of 20 individual MRM tubes with their ends arranged in a hexagonal pattern. Porous hydrophobic Teflon tubes contain the small MRM beads. The porous hydrophobic wall allows the vapor to enter and escape from the MRM packed inside the tubes; the spacing around the MRM tube allows vapor to transfer from or to the phase separator. Each MRM tube includes a wick to ensure that pump fluid fully wets all the MRM material within each tube during ground testing. The demonstrator uses a gravity-assisted liquid-vapor phase separator below the packed bed, as shown in Figure 2. The ports of the pump inlet and outlet tubes are submerged in the liquid accumulated at the bottom of the phase separator, allowing only liquid to enter and exit the pump. A LN2 reservoir was installed above the pump body. A divider separates the cylindrical reservoir into a supply reservoir and a receiving reservoir. The divider has cutouts at the bottom to allow the LN2 in the receiving reservoir to return to the supply reservoir, thus allowing a closed-loop characterization of the pump. The cutouts also function as flow restrictors in an orifice mass flow meter to measure the steady-state flow rate based on the liquid level difference between the reservoirs. An NbTi superconducting magnet was used to drive the pump. The temperature of this magnet must be maintained near the normal helium boiling temperature to maintain its superconductivity. For this reason, the entire pump body and LN2 reservoir were installed inside a vacuum insulated jacket. The NbTi magnet was installed outside the jacket, and the entire assembly was submerged in LHe inside a dewar.

3.2. Demonstrator Test Facility and Instrumentation
The test facility (Figure 3) contains instruments to measure the electrical current and voltage across the NbTi magnet, the resulting instantaneous magnetic field in the MRM packed bed, the MRM temperature swing and the fluid pressure swing in the pumping chamber, as well as the fluid displacement volumes in the supply reservoir and receiving reservoir.

The top flange of the LN2 reservoirs was equipped with a supply port connecting to a LN2 dewar for introducing liquid nitrogen into the reservoir chamber. A separate vent port with a back pressure regulating valve allowed control of the reservoir pressure and thus the LN2 saturation temperature to determine the optimum operating temperature for the MRM. Inside the pumping chamber, the space above the MRM packed bed was connected to small priming port that was connected to a gaseous nitrogen bottle and a vent valve with a capillary tube. By controlling the vapor pressure above the MRM bed, the initial liquid level in the pumping chamber can be adjusted by controlling the vapor pressure to draw or discharge liquid into the reservoir.
Figure 2. Configuration of MCE LN₂ mixing pump demonstrator and its key components.

Figure 3. Test setup for LN₂ MCEP demonstrator.
4. Mixing Pump Demonstrator Performance

The purpose of the demonstrator was to show operation of the MCEP and its ability to use the magnetocaloric effect to evaporate and condense a saturated cryogen, creating a vapor piston to drive a liquid flow. The effects of key performance parameters on the pump performance therefore were investigated, including (1) the magnet field frequency, (2) the magnetic field amplitude, (3) the cryogen saturation temperature, and (4) the liquid fraction in the pumping chamber. The majority of testing was carried out at a frequency of 1 Hz with a peak magnetic field strength of 1.13 T inside the pumping chamber. Quench of the superconducting magnet due to excessive AC loss limits the maximum operational frequency to 1 Hz or less at the design current. During tests with durations ranging from 1 to 10 minutes, all the operating parameters reached their quasi cyclical steady-state values. The performance of the pump under this baseline condition is discussed below.

Figure 4 shows sample test data over four cycles. The phase lag of each measured variable relative to the current is indicated by vertical dashed lines. As expected, the current and magnetic field are fully in-phase. As thermal energy transferred in and out of the MRM beads, the pump chamber pressure varied accordingly. The peak pump pressure amplitude achieved was approximately 0.85 psid. The phase lag of the pump chamber pressure relative to the current and magnetic field is short, only about 29°. This indicates that thermal energy transfers effectively between the MRM beads and the liquid film on the beads. The measured MRM temperature peak closely followed the magnetic field (temperature increases from MRM heating due to excitation by field), while the pumping chamber temperature peak lagged slightly. The pumping chamber temperature amplitude is also substantially lower than the MRM temperature amplitude, as expected.

![Figure 4](image_url)

**Figure 4.** Four cycles of typical steady-state operation, at 1 Hz and 1.13 T peak field. Phase lag of each signal relative to the current is indicated by vertical dashed lines.
As the pump chamber pressure oscillated, liquid in the gravity-assisted phase separator below the MRM bed was forced in/out of the chamber and out/in the reservoirs above. Appreciable liquid level variations were observed in both the supply and discharge reservoirs. However, the liquid level variation in the supply reservoir was much larger than that in the discharge reservoir, and the liquid level in the supply reservoir reached its maximum values before the discharge reservoir did. This observation is not consistent with our physical understanding of the pumping process or with what we observed in the room-temperature separate effects testing. It is believed that the surprising behavior of the liquid level was caused by the malfunctioning of the check valves in the presence of a strong magnetic field. The check valves are made of a 300-series stainless steel. Even though this series of stainless steel are typically non-magnetic, their permeability due to cold work could be high enough to cause them to be attracted to a magnet. Subsequent investigation confirmed that the check valves assembly was attracted to a strong permanent magnet at room temperature.

Even though the check valves did not function properly, a large variation in the total amount of liquid in the supply and discharge reservoirs over each cycle could still be observed. This variation is equal to the liquid tidal volume in the pumping chamber. The change in liquid volume in the reservoirs over a cycle gives a conservative estimate of the pump stroke volume when the check valves function properly. Figure 5 shows the estimated pump stroke volume and pump pressure. The stroke volume was approximately 38 mL for a pressure rise of about 0.85 psid. Due to the inertance of fluid in the transfer tubes, the phase lag between the total reservoir volume and the chamber pressure is 140°, significantly higher than 90° where there was no inertance in the transfer line.

![Figure 5. Pump chamber pressure amplitude and total reservoir chamber stroke volume. Total reservoir chamber volume is the sum of liquid in the supply and discharge half-chambers over time.](image)

5. Discussions
The preliminary test results demonstrated that the pumping chamber can generate a pressure oscillation with an amplitude close to 1 psid, and the pumping chamber can draw/discharge about 40 cm³ of liquid from/to the reservoirs during each stroke. These key performance parameters are consistent with predictions from our analysis model for a pump with 510 g (65 cm³) of Gd₂SiO₅Ge₃.5. The pressure rise and flow rate are high enough for practical applications. The measured phase lags between different parameters are consistent with our physical understanding. The test results show the dependence of the
pump performance to the magnetic field frequency, magnetic field strength, liquid level in the pumping chamber, and working fluid saturation temperature. The pump was able to start and operate under a wide range of initial conditions.

Scaled from the test results for the LN$_2$ demonstrator, a preliminary design for an LH$_2$ mixing application with a volumetric flow rate of 12 L/min and a pressure rise of about 0.72 psid was developed. The pump’s MRM bed will be filled with 95 cm$^3$ of HoNi$_2$ magnetocaloric material. When operating at 5 Hz, the predicted peak magnetic field is 0.75 T. The predicted pump efficiency is higher than 32% (not including superconductor AC loss).

6. Conclusions and Recommendations
A submersible cryogenic mixing pump using a magnetocaloric effect to generate a jet to promote fluid mixing was designed and demonstrated. The assembly process shows that a magnetocaloric effect pump can be built with existing fabrication technologies. The performance demonstration shows the magnetocaloric effect pump is a practical cryogenic pump technology for future space applications. Test results show that a relatively compact pump with an MRM bed of 27 in.$^3$ (not including superconducting magnet) containing about 4 in.$^3$ (65 cm$^3$) of Gd$_5$Si$_2$Ge$_3$ can generate a pressure oscillation with a peak amplitude of 1.0 psid and can displace 38 cm$^3$ of liquid per cycle when driven by a 1.2 T alternating magnetic field. Excluding the loss in the superconducting magnet, the efficiency of the mixing pump demonstrator was on the order of 20%.

To mature the magnetocaloric effect mixing pump technology for NASA’s future liquid hydrogen storage applications, the next phase of this research should be focused on identifying the materials for the LH$_2$ MCEP, verifying their compatibility with hydrogen, and developing a superconducting magnet that can operate at about 20 K with a frequency up to 5 Hz at a field strength of about 1 T.

7. References
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