IEEE Grant Application Address Climate Change:

Components for next-generation magnetocaloric heating, air conditioning, and water heating

Team Name: NexGen Heat Pumping Solutions

Section Name: IEEE Richmond Section

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Project Description:

1. Background & Problem Statement

Heat pumps have the potential to reduce carbon emissions in the US from heating, ventilation, air conditioning (HVAC) by 142 million metric tons per year and cut energy use for building heating and cooling by a factor of 2-3 [1]. Traditional heat pumps couple a conventional compressor with a water tank, and rely on refrigerants with high global warming potential (GWP), and contribute to greenhouse gas emissions [2]. To meet US emissions goals, a shift to more efficient technologies that use low or zero GWP refrigerants is necessary. *Against this backdrop, magnetic heat pumping (MHP) is a solid-state, zero-GWP technology that promises to be up to 30% more energy efficient than conventional vapor compression technologies, eliminates refrigerant leaks, and enables widespread electrification of buildings [3].*

MHP relies on driving phase changes in magnetocaloric materials (MCM) near their Curie temperatures in response to magnetic fields, resulting in entropy (and temperature) shifts. This effect can be harnessed through an active magnetic regenerator (AMR) cycle with the Brayton cycle [4,5] shown in four steps (Fig. 1). In addition to AMRs, MHPs consist of magnetic field sources – typically in the form of a spinning permanent magnet array, fluid flow circuits including flow control valves, and heat exchangers [4]. Many MHP systems have demonstrated the power and efficiency needed for cooling [6] and heating [7,8,9], however, they suffer from large size and weight for a given heating/cooling power, i.e., low power density, which translates into costs too high for commercial adoption. Another challenge of MHP is achieving large temperature spans necessary for heating or cooling. In order to achieve high MHP power density while also reaching large temperature spans with good efficiencies, our proposed project will focus on improving AMRs, permanent magnet arrays, and device operation.

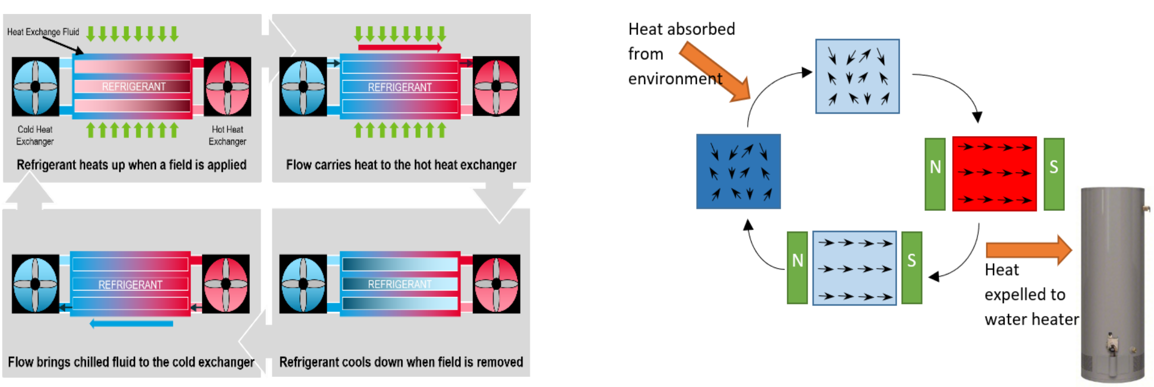

Figure 1. Four-step Brayton cycle of applying field and flowing heat transfer fluid (left). Schematic of how heat is transferred to the MHPWH (right). Red is hot, dark blue is cold, light blue is cool.

High temperature spans have been modeled and demonstrated using AMRs composed of layered MCMs [10]. *Recent work conducted by researchers at VCU in close collaboration with Ames Laboratory, focused on increasing MHP power density* by increasing operating frequencies – which directly increases power density, optimizing operating conditions to improve efficiency [11], and developing compact permanent magnet arrays to minimize MHP size and weight [12]. Results from this work promise high power density (HPD) MHPs using gadolinium packed particle beds with the same or better cooling and heating power density as off-the-shelf compressors up to ~500 W at temperature lift of 10°C [13].

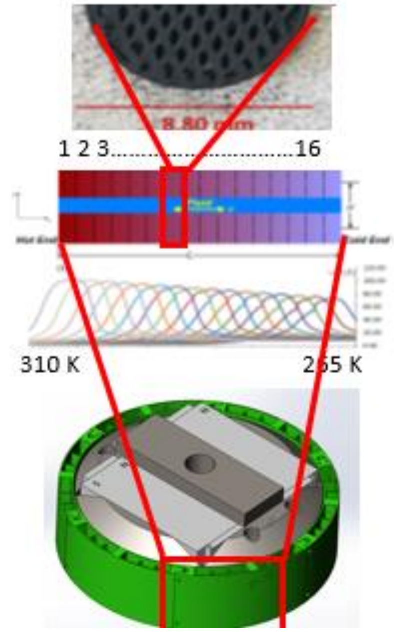

Figure 2. Additively manufactured AMR structure [18], 16-layer AMR [12], Heat pump design with 12 AMR beds (green) and compact magnetic circuit (gray).

While packed particle bed AMRs are simple to manufacture and have demonstrated the highest reported AMR power density [8], maintaining high efficiency is difficult due to large pressure drops from tortuous flow paths. Parallel plate AMRs can achieve smaller pressure drops [14] and enhance magnetization when oriented correctly [15], however, in order to achieve similar heat transfer properties as packed particle beds, plates need to be very thin and accurately spaced [16], which is difficult to manufacture. Microchannel and lattice AMRs show promise for improved MHP performance with lower pumping power, leading to higher system efficiency.[14,17] However, efforts to build microchannel and lattice AMR geometries using additive manufacturing (AM) have met with varying degrees of success [17,18,19,20] with feature sizes larger than desired and rough surface finishes. Recent efforts by the Advanced Magnetic Materials Processing Lab at VCU using direct ink writing additive manufacturing technologies showed good control over microchannel geometry [21]; however, post-processing steps had a detrimental impact on MC properties of select candidate materials systems due to carbon in binders - an outstanding issue that needs to be addressed going forward.

To this end, funds are sought to support an undergraduate project at Virginia Commonwealth University to develop MHP components for HVAC/WH applications using a magnetic-field-assisted Fused Deposition Modelling (FDM) metal 3D printing scheme. The undergraduate project will be conducted in the Advanced Magnetic Materials Processing Laboratory (AM^2P) at Virginia Commonwealth University (VCU) under the auspices of the Vertically Integrated Projects (VIP) program. Under the supervision of Dr. Radhika Barua, two graduate students (Vaibhav Sharma and Anthony Duong) will serve as mentors for the undergraduate students working in the proposed project

2. Research Plan

FDM uses a melt extrusion method wherein a feedstock material is pulled through a hot nozzle at around 200-300℃ and extruded layer by layer in a pre-determined path on a build platform to form a 3D object. It is worthwhile to note that with such low nozzle temperatures, this technology is mainly limited to several low melting-point polymers [22]. Metals melt at temperatures well above 1000℃ and is facilitated by precursor FDM filaments comprising of polymer composites with fine metal/alloy powder dispersed within the material. With minimal modifications to a FDM machine (hardened steel/ jewel tip nozzle, a filament warmer in the extruder etc.), any desktop FDM printer can be used to print a metal part, including printers as cheap as the $200 Creality Ender 3. *Unfortunately, metal/alloy-polymer composite filaments for facile fabrication of magnetic components are not commercially available. Therefore, no attempt has been made towards producing caloric regenerators FDM 3D printing technology to date.*

In the proposed project, students will fabricate precursor filament feedstock materials comprising of magnetocaloric powders and the biodegradable polymer PBSA (Polybutylene succinate-co-adipate) using a home-built Lynman filament extruder chamber, Figure 3. As starting steps, the framework of the filament extruder has already been assembled by the VIP students in the AM^2P research group, Figure 3. Additional funds are sought to modify the extruder to upgrade hardware (nozzles, 3D printed polymer casing, screw assembly etc.) to increase temperature operation of extruder to enable the fabrication of filaments with high magnetic particle loading (greater than 75 volume %). To enable homogenous alignment of the magnetic particles along the length of the composite filament, it is desirable to install a Halbach magnet array around the nozzle of the extruder.

Figure 3. The customized Lyman extruder currently assembled in Dr. Barua's lab at VCU is an open-source machine designed to turn polymer pellets into cheap filament for 3D printing.

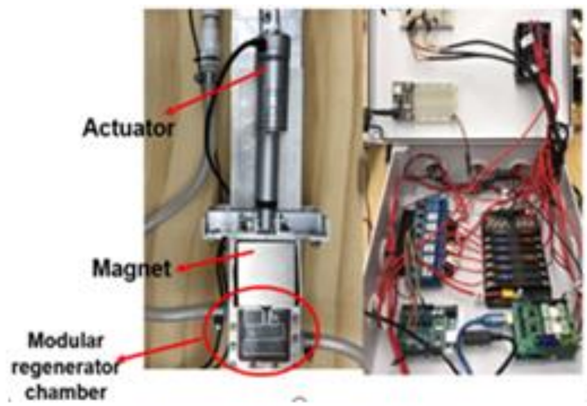

Figure 4. Magnetic Heat Pumping test rig with regenerator chamber for validation of system performance of the proposed 3D printed AMR heat exchange structures.

Proof-of-concept demonstration efforts will be centered on fabricating spatially designed microchanneled AMR structures (~250 µm dia) using magnetic nanoparticles of nominal composition, $La_{0.6}Ca_{0.4}MnO_3$. Detailed characterization of the 3D printed test coupons will be achieved using a variety of structural and compositional probes (including x-ray diffraction, scanning electron microscopy, and computed tomography) as well as response probes (thermal imaging, magnetometry, mechanical testing etc.) – all conducted at VCU's Nanomaterial Core Characterization Facility. Magnetic regenerators with down-selected compositions and geometries will be 3D printed, and its system performance (namely, cooling efficiency and heat transfer characteristics) will be assessed using a custom-designed patented home-built magnetocaloric cooling device prototype, Fig 4.

3. Measurable Project Outcomes

The proposed innovative magnetic heat pump technology uses a solid-state refrigerant combined with water-based heat transfer fluid for a zero-GWP technology that can potentially be as much as 30% more energy efficient than conventional vapor compression technologies. Additional benefits of MHP include 120V plug-in operation and quiet operating conditions– an important feature as noise due to the compressor is a "quality of life" issue in existing vapor-compression heat pumping technologies. *The target Coefficient of Performance ($COP_{cooling}$) for the proposed 3D-printed regenerators is 10. This value is substantially higher than that of a standard 4 ton 21 SEER residential vapor-compression heat pump available today ($COP_{cooling}$~ 6.9 [23]).* In line with IEEE's commitment to workforce development, the project will also complement related undergraduate research projects currently being conducted in the AM^2P research groups under the auspices of the Vertically Integrated Projects (VIP) Program, a transformative research initiative engages undergraduate students in faculty-lead multidisciplinary projects.

4. ***Expected Costs (Budget Allotted: $ 1000)***
   - Ruby Tipped Nozzle and Steel Hardened gears for Lyman extruder upgrade: $ 200
   - Ender 5 Plus 3D Printer with Sprite Extruder Pro Kit (for 3D printing casing with heat-resistant polymers, mainly PEEK): $ 700
   - Heat-resistant Sm-Co permanent magnets for Halbach array assembly: $ 100

5. ***References:***

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I endorse this project and agree that the IEEE Richmond Section will be responsible for the financial management of the funds, including responsibility for tracking, receipts and reporting as required by IEEE Finance. Any approved funds that have not been expended by March 1, 2024 will be returned to IEEE Region 3 no later than December 31, 2024.

Allen J. Jones

Allen Jones
IEEE Richmond Section Chair