Midterm Report

Title: Components for next-generation caloric heating, air conditioning, and water heating

Team Name: NexGen Heat Pumping Solutions

Section Name: IEEE Richmond Section

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1. Problem Statement

Heat pumps can potentially 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.[1] To meet US emissions goals, shifting 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 up to 30% more energy efficiency than conventional vapor compression technologies, eliminates refrigerant leaks, and enables widespread electrification of buildings.*[1]

In response to magnetic fields, MHP relies on driving phase changes in magnetocaloric materials (MCM) near their Curie temperatures, resulting in entropy (and temperature) shifts.[2] For maximal system efficiency, the MCM in an MHP must be shaped as a micro-channeled heat exchanger – a challenging task due to the inherent brittleness of the working materials.[3] Recent efforts by the Advanced Magnetic Materials Processing Lab at VCU using direct ink writing additive manufacturing technologies showed good control over microchannel geometry[4]; 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. As an alternative, *this project is focused on developing MHP components using a **magnetic-field-assisted Fused Deposition Modelling (FDM) metal 3D printing scheme**.*

2. Underlying Challenge of the Project

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.[5] 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 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 to produce caloric regenerators with FDM 3D printing technology.*

In the proposed project, the 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, Fig 1. The Lyman extruder is one of the few designs for those trying to make 3D filament for FDM printers. However, it has been primarily tailored, according to the creator Hugh Lyman in a comment he made in a Thingiverse.com thread for his project, for ABS plastic.[6] It falls short in the extrusion of PBSA filament, where we believe the inconsistent temperature gradient across the cross-sectional area of the material within the barrel hinders the production of high-quality PBSA filament.

According to an article by Phillip Keane,[7] the thermal conductivity of ABS (0.25 W/(m*K))is almost twice that of PBSA (0.13 W/(m*K). In the current Lyman extruder design, the heat distribution across the cross-section within the barrel is uneven; for ABS plastic, this is acceptable because the existing system works for this material. However, the poorer thermal conductivity of PBSA and the resulting larger thermal gradient cause the PBSA to melt unevenly, leading to either an unmelted center that causes blockage of the nozzle or a higher applied temperature that allows the heat to propagate to the center but results in PBSA material at the periphery that is much higher than the melting point of the PBSA and flows out of the nozzle with too little viscosity to be pulled into a filament. This challenge limits the production of high-quality PBSA with embedded magnetic materials.

Introducing magnetic materials into the extruded plastic presents an additional challenge: heightened abrasion concerns within the extruder barrel. As ferromagnetic particles are introduced into the plastic matrix, they not only alter its properties but also become abrasive agents. This will cause wear within the barrel of the extruder that will need to be mitigated with either more frequent component replacement or modification of the barrel and its ancillary components to resist this additional abrasion. Failure to adapt for the abrasion wear could cause premature failure of the components, poor consistency in diameter of or additive dispersion within the material extrusion, or inclusion of the worn away barrel material in the PBSA plastic, potentially leading to manufacturing problems in downstream processes.

3. Proposed Modifications to the Lyman Extruder

Our proposed modifications center around these key improvements:

- **Barrel Length Extension:** By extending the barrel length, we aim to provide the PBSA with a more extended heat exposure and at least three gradually increasing heating zones that will give the heat sufficient time to propagate to the center of the barrel, allowing the material within it to reach a consistent, near-melting temperature throughout its cross-sectional area near the end of its volume. This extension provides ample time for the PBSA to become molten with a consistent viscosity allowing for the desired filament production.
- **Additional Heaters:** To maintain a precise and consistently increasing temperature profile along the extended barrel, we plan to incorporate multiple additional heaters strategically placed to facilitate uniform heating. This approach ensures that the PBSA reaches the desired molten state by the dime it reaches the nozzle, reducing the chances of viscosity-related issues during extrusion.
- **Lining of the Barrel and Heat Zone Components:** To mitigate the abrasion concerns within the barrel when extruding PBSA plastic with embedded magnetic materials, the barrels will be evaluated with coatings on the inside layer. These coatings will consist of chrome plating, nickel plating and possibly Physical Vapor Deposition (PVD) of Diamond-Like Carbon (DLC), Titanium Nitride (TiN) or Zirconium Nitride (ZrN). Each process is known within the tooling industry to provide excellent wear resistance[3].

4. Conclusion

In conclusion, the proposed modifications to the Lyman extruder will address the challenges of producing PBSA plastic filament infused with magnetic materials. By extending the barrel length, incorporating additional heaters, and optimizing the extrusion process, we aim to achieve a more consistent temperature profile within the barrel's cross-section. This, in turn, is expected to mitigate issues of viscosity variation and enhance the overall extrusion performance for PBSA. This can potentially improve the capabilities of producing PBSA with embedded magnetic materials with varying properties and concentrations, which can drive innovation in 3D printing and other applications.

References

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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.

2. 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^{2}P research groups under the auspices of the Vertically Integrated Projects (VIP) Program, a transformative research initiative engages undergraduate students in faculty-lead multidisciplinary projects.

3. 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

4. References:

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