December Report

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

Team Name: NexGen Heat Pumping Solutions

Section Name: IEEE Richmond Section

Contact person: Radhika Barua (IEEE # 94243812)

IEEE Student Member associated with the Project: Anthony Duong (IEEE #98851458)

Undergraduate Students: Thomas Pierce, Kamau Bey, Micaiah Akyeampong, Vincent Mazzochette

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, postprocessing 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.

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.

3, Experimental Methods

In the proposed project, the students will fabricate precursor filament feedstock materials comprising magnetocaloric powders and biodegradable using a home-built Lyman filament extruder chamber. To obtain consistently repeatable results for analysis, the modified Lyman Extruder was assembled (Figure 1) to have complete control over the working parameters of the extrusion process. This means when in “automatic mode,” the extrusion process can sustain filament production without the assistance of the individual. Experimentation was to begin by first controlling the parameters of the components separately from the control box. The Auger screw, puller, and spooling system were initially controlled to vary speeds and reaction time. Subsequently, the diameter sensor was assembled and integrated with the puller. The diameter sensor was calibrated using a calibration tool. In manually controlling these working components, the team sought to extrude single batches of filament at a time and monitor the extrusion process, managing the speeds and responsiveness of the working systems.

4.2.1 Set-Up and Instrumentation

The Components of the Lyman Extruder include the following:

- Hopper: Container where raw plastic pellets or other pelletized materials are loaded. It feeds the material into the extrusion system
- Auger Screw: An extrusion screw that transports material into the barrel via rotation and some pressure. Critical for material’s transformation from solid to molten state.
- Heating system: One or more heating bands positioned along the extrusion barrel. It melts the plastic (or other material) into a molten state ready for extrusion.
- Barrel: The barrel is a metal tube through which the plastic material travels.
- Cooling System: After the plastic is extruded, a fan is employed to rapidly cool and solidify the filament.
- Diameter sensor: Light sensor that reads the incoming light from a supplied Light Emitting Diode (LED) and the associated shadow pattern formed by the filament as it passes between them. It produces a min/max and average diameter values during the extrusion process.
- Spooling System: Once the filament is extruded and cooled, it needs to be wound onto a spool for storage and later use in 3D printing. This spooler is a motor powered system that spools the filament while simultaneously winding the filament back and forth along the spool through gear-driven motion powered by the spool’s rotation.

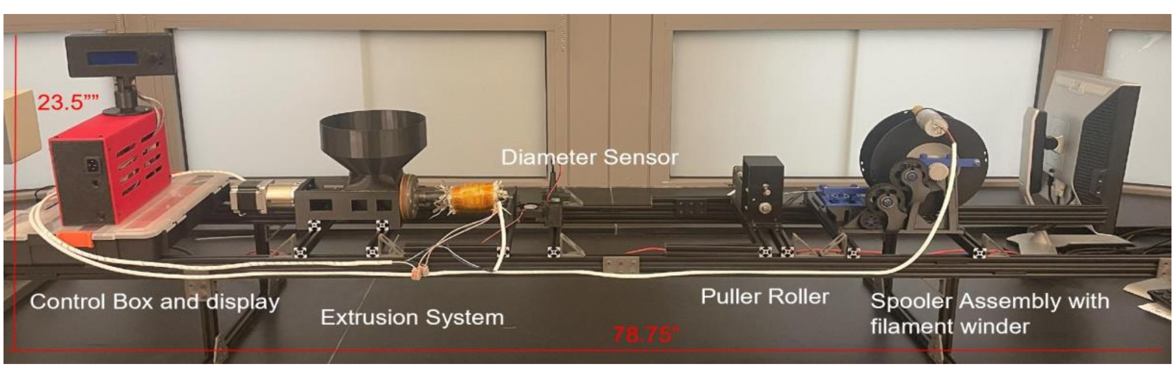

Figure 1. Physical Prototype Extruder. The team envisions a fully mounted extruder system that allows independent adjustments in the X, Y, and Z axes for optimal precision and versatility.

The setup and Instrumentation for the extruder testing are as follows:

- Material loading: load the pelleted material into the hopper.
- Power: Power on the extruder and allow the barrel and nozzle to heat up (heat soak).
- Temperature settings: Set the temperature controls to the desired temperature to melt and mix the material.
- Adjust necessary puller or auger speeds desired for extrusion
- Begin the extrusion process.
- Spooling: Attach the extruded filament exiting the puller to the spool wheel and turn on the motor to rotate it.

4.2.2 Testing Procedure and Measurements

The testing procedures for the extruder are similar to the initial setup of the system. When performing tests with new material or material mixes, the team developed percent compositions of clear and colored pellets by weight. Once these steps were complete the extrusion was paused and the filament was cut at the nozzle leaving enough filament to pull molten behind it for future test cycles. Testing worksheets (Figures 4-5 and 12-22) were used to document the progress of each extrusion and identify roadblocks or challenges to remedy for better efficiency. The test cycle procedure utilized by the team is as follows:

- Measure raw virgin material and colorant by weight & add to extruder hopper.
- Power on the extruder .
- Set the extruder to manual mode initially and set target temperature ● Let extruder heat soak for at least 10 mins.
- Begin the extrusion process.
- Grab molten material once it emerges from the nozzle and pull it through the diameter sensor to the puller.
- Allow the extruder to produce filament until a desired diameter or uniformity is reached.
- Cut the beginning filament to exclude it from the spooling process.
- Attached usable filament to spool through the spool system tube via tape or hole in the spool wheel.
- Turn on the spool motor and rest on the spool wheel. ● Switch extruder to automatic.
- Allow the extruder to adjust itself based on diameter sensor readings.
- Monitor filament production and measure with caliper to ensure filament diameter.
- Track any erroneous change in diameter, surface roughness, viscosity, or color noticed during the extrusion process and mark the time of change.
- Derive implementation for improvement (if applicable during current testing), and make the appropriate changes via the control box if necessary or applicable.

4.3Validation Process

The main method to confirm the design's success will be using the produced filament successfully in a 3D printing test environment. In addition to the aforementioned constraint verifications outlined, the team will test the final filament products to manufacture common benchmark 3D print models. These types of tests ensure the filament's quality and consistency and confirm the filament's overall compatibility with the 3D printers used in Virginia Commonwealth University's research lab. The team will work with the graduate and undergraduate student researchers in the lab to create a feedback loop about the produced filament's overall success for the research lab's needs. Given the team can produce a successful result, additional mechanical and magnetic testing can be performed to quantify the results. This type of testing may include:

- **Tensile Testing [9]:** this type of mechanical test involves subjecting the samples to uniaxial tensile loads until failure. It will allow the team to measure parameters such as ultimate tensile strength (UTS), elastic modulus, and elongation at break. Additionally, this type of test allows the PLA print specimen to be compared to the standard mechanical properties of bulk PLA material to ensure consistency.
- **Flexural Testing:** a mechanical test to evaluate the bending strength and modulus of the printed samples through flexural stresses. This kind of testing provides insight into the material's ability to withstand bending forces.
- **Magnetic Permeability Testing:** a measure of how well the material responds to an applied magnetic field. These tests use equipment such as a permeameter to provide a qualitative measure of the PLA specimen's magnetic permeability.
- **Hysteresis Testing:** an analysis of the magnetic hysteresis loop. This kind of analysis provides information about the material's magnetic behavior under varying magnetic fields.
- **Magnetic Susceptibility Measurements:** a magnetic susceptibility meter can be used to measure the material's response to an applied magnetic field and assess its magnetic properties.
- **Magnetic Flux Density Measurements:** a Gauss meter is used to quantify the magnetic flux density within and around the 3D-printed samples.

Tensile experimentation, while outside this project's primary scope, aims to identify more intrinsic characteristics like yield strength and plastic deformation. The information obtained from this kind of testing assists engineers and manufacturers in design applications that inform the user of the failure limits and yield strengths of the material. This also gives knowledge to the 3D printable capabilities the filaments will have once printed if used for structural or engineering purposes. The contribution to the 3D printing landscape is immeasurable as components can be replicated or produced comparable to their existing counterparts.. As filament producers (extruders) are designed, the goal is to achieve uniform diameters with little deviation. Depending on the material used and the development of raw, virgin material, the diameter, and mechanical properties can be designed with a single spool of filament.

5. Concept Generation

In the generation for processing raw material into filament, three primary options were considered. The first option (Figure 6) involves utilizing a "Screw Auger" motion, employing an auger-style drill bit turned in reverse to move the raw material through the extruder barrel. This design is straightforward, cost-effective, and allows for precise control of material movement.

The second (Figure 7) option explores a "Piston Pump" motion, where a reciprocating piston pump facilitates material flow through the barrel. This design offers a balance between complexity and efficiency, incorporating a one-way valve to negate the reciprocating motion within the material. Lastly, the third option (Figure 8) involves a "Vane Pump" motion, utilizing a vane pump similar to those found in air compressors or superchargers. This design, while potentially providing high torque, is likely to be the most expensive due to the inclusion of a high ratio gear reduction gearbox. Each option presents unique advantages and considerations, offering a spectrum of choices for processing raw materials into filament with varying degrees of complexity, cost, and precision.

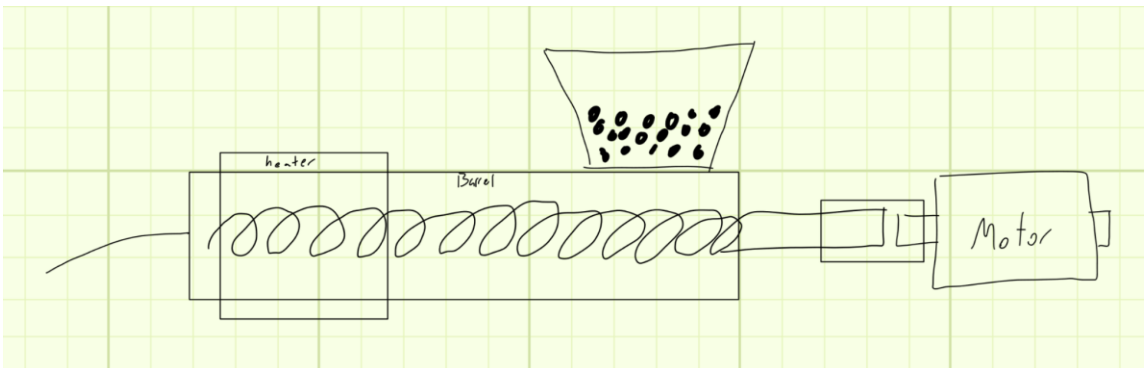

Figure 2. Design Concept A. “Screw Auger” motion. The raw material is moved through the extruder barrel by a screw auger i.e. an auger style drill bit turned in reverse. This is sized to be a close fit to the size of the barrel such that the pellet material is forced forward with the motion of the screw. The power comes from an electric motor coupled to the screw, possibly with a gear reduction. This sketch was drawn by Vincent Mazzochette on September 27th 2023.

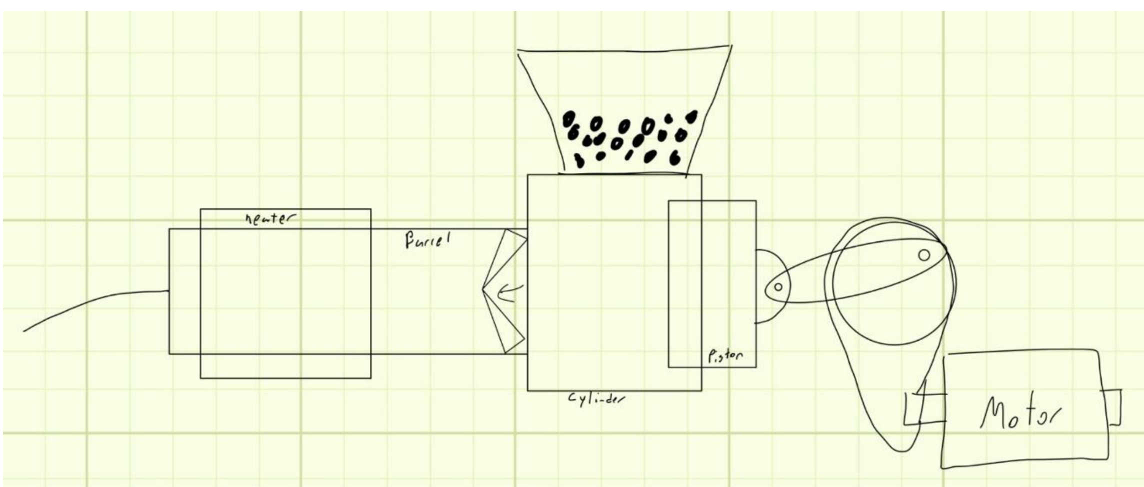

Figure 3. Design Concept B. “Piston Pump” motion. The raw material is moved through the extruder barrel by a reciprocating piston pump. The reciprocal motion of the pump is negated within the material by way of a one way valve within the barrel. The power comes from an electric motor coupled to the piston by way of a set of pulleys and a crank rocker. This sketch was drawn by Vincent Mazzochette on September 27th 2023.

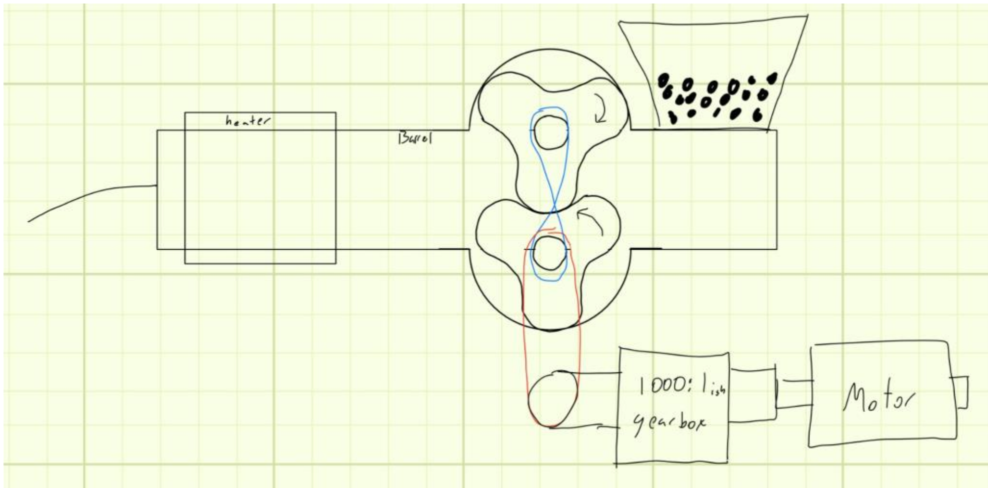

Figure 4. Design Concept C. “Vane Pump” motion. The raw material is moved through the extruder barrel by a vane pump, similar to that of an air compressor or supercharger. The power comes from an electric motor coupled to the piston by way of a set of pulleys and a high ratio gear reduction gearbox providing very low RPM but high torque to the pump. This sketch was drawn by Vincent Mazzochette on September 27th 2023.

7. Preliminary Results

In thermodynamic terms, extruding PLA presents a unique challenge for the Lyman extruder due to its thermal properties. According to an article by Phillip Keane2, the thermal conductivity of ABS is almost twice that of PLA (0.13 W/(m*K) for PLA vs. 0.25 W/(m*K) for ABS. In the current Lyman extruder design, the heat distribution across the cross section within the barrel is uneven, for ABS plastic this is apparently acceptable because the existing system works for this material. However the poorer thermal conductivity of PLA and the resulting larger thermal gradient cause the PLA to melt unevenly leading to either an unmelted center that causes blockage of the nozzle or alternatively, a higher applied temperature that allows the heat to propagate to the center, but results in PLA material at the periphery that is much higher than the melting point of the PLA and flows out of the nozzle with too little viscosity to be pulled into a filament. This challenge limits the production of high-quality PLA 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 being included in the PLA plastic, potentially leading to manufacturing problems in downstream processes.

The Lyman extruder has proven effective for ABS plastic in the 3D printing industry, but PLA filament extrusion has had its limitations. Inconsistent temperature distribution across the material cross-section in the barrel impedes the production of high-quality PLA filament, hindering its potential for various applications. This project has seen the opposite. The testing worksheets

(Figures 4 and 12) show ABS filament extrusion testing inconsistent with temperature distribution and uneven melting temperatures during the extrusion process. The use of sourced ABS pellets in the test cycles shown did not yield the expected results. Preliminary analysis suggests that the ABS pellets may not have been adequately dried or that ambient conditions in the lab might have impacted their performance. As far as preliminary testing is considered, the modified Lyman extruder did operate as expected, without full monitoring and controlling components such as the diameter sensor or puller.

The irregularities observed during extrusion, including diameter variations (measured with a caliper) could be attributed to moisture absorption by the ABS pellets. The second test for ABS included an extrusion to act as a "purge" to test our primary agent in future testing, PLA. In future iterations, it is crucial to ensure proper drying of materials and control ambient conditions to enhance the reliability of the extrusion process. This underlines the importance of material preparation in achieving consistent and high-quality filament production. Further investigations and adjustments to material handling procedures will be implemented in subsequent test cycles to address this issue and optimize the overall extrusion process.

In the course of our extensive PLA testing, we have achieved significant progress and optimization in the extrusion process, particularly with a 4% mix of blue color pellets, Figure 5. An anonymous mix of blue pellets was tested for diameter sensor consistency, as well as various combinations of 2 and 3%. 4% mix pellets proved itself most consistent for diameter sensor readings, color saturation, and overall mixing while the material was in its molten stages. Through meticulous adjustments to parameters such as temperature, puller speed, and derivative settings, we successfully mitigated issues related to filament clotting, inconsistent diameter, and the presence of undesirable chunks in the extruded material. This was due to derivative adjustments to the temperature's integral PID controller to eliminate erroneous temperature oscillations during extrusion in test cycle. The puller's derivative was adjusted as well to increase its response time according to the recorded filament diameter read after the extruder's nozzle. Notably, our commitment to continuous improvement is evidenced by the refinement of our spooling system, where the redesign of the spooler arm has eliminated slipping issues and provided consistent filament extrusion. This was done to reduce the external tension on the system once the cooled filament was attached to the spinning spool system. Implementing additional mesh filters, a new nozzle, and the careful calibration of temperature parameters has further enhanced the quality of our PLA extrusion.

Given the significance of the preliminary results, the next steps in the design implementation process should involve careful consideration of design modifications. Our proposed modifications are centered around these key improvements:

- **Barrel Length Extension:** By extending the barrel length, we aim to provide the PLA 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 PLA 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 PLA

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 PLA 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 of these processes is known within the tooling industry to provide excellent wear resistance3.
- **Second Diameter Sensor**: The second diameter sensor aligns with the iterative improvement process by enabling more examination of filament characteristics. This data can be instrumental in refining temperature control algorithms, optimizing the extrusion process, and ensuring consistent filament quality. This dual sensor setup would contribute to a richer dataset, capturing minute variations in diameter and logging inconsistencies for relevance.

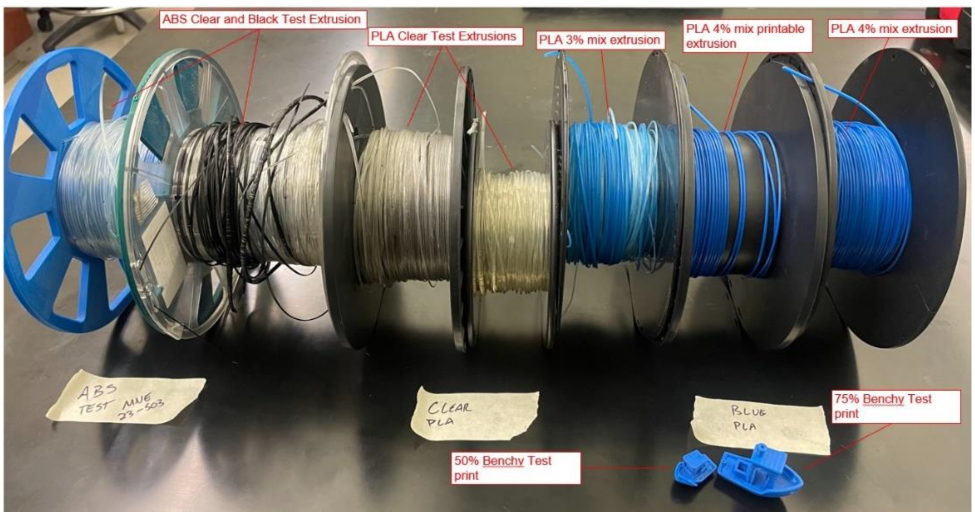

Figure 9. Testing spools fabricated using the modified Lyman Extruder

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