Vacuum Flasks Designed for Cold Supply Chains with Additive Manufacturing

Introduction

Cold supply chains are temperature regulated supply chains and can be separated into active and passive categories. Active cold chains require a regular energy supply to control temperature while passive cold chains rely on insulation. One of the greatest limitations of active cold chain technology is in its consumption of energy. As demand for refrigerated goods continues to increase due to population growth, the lack of reliable electrical grid infrastructure in areas like Sub-Saharan Africa or South Asia disrupts the use of active cooling technology. This makes the development of more insular containers for passive cold chains a pursuit of interest for those involved in the supply chain industry. The most important applications of these containers would be in the transport of high-value perishable goods such as medicine or vaccines.

The nature of vacuum flask technology makes it a strong contender for utilization in passively cooled cold chain transport. The vacuum created between two metal walls allows for greater thermal insulation by preventing heat conduction or convection to a greater extent than typical styrofoam boxes used for insulation.

Targeted Problem

Problems facing the adoption of vacuum flasks in cold chain transport are heavy design costs and the lack of precedent in usage for smaller scale transport.Additive manufacturing offers a potential route for prototyping more efficient and effective containers for passive cold chain transport. In this proposal, we suggest the use of powder bed fusion and fused deposition modeling in order to produce vacuum flask containers as proof of concept for development in insulated products.

An Additively Manufactured Vacuum Flask

Design Overview

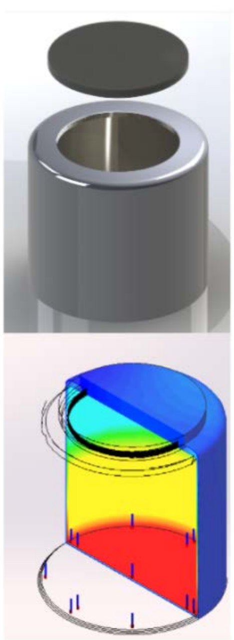

Figure 1.1 and 1.2. CAD File and Thermal Transfer Visualization

The vacuum flask presented here was designed to insulate temperature sensitive goods efficiently. The design of the flask had the following constraints: use additive manufacturing for the shaping process, fit within a build volume of 350x350x400 mm, have relatively high stiffness to prevent significant deflection when transporting, and have a relatively high yield strength in order to prevent plastic deformation under significant load.

While designing the vacuum flask, there were a couple of objectives which needed to be optimized: the flask needed to maximise the time to equilibration of temperatures and minimize the cost of production. In order to serve a functional role in transporting temperature sensitive goods, it is necessary to consider the diffusivity and conductivity of heat through the walls of the container. With this in mind, creating an objective focused on maximizing the time it takes to reach thermal equilibrium would allow the flask to be better suited for long transportation periods. In order to accomplish this design challenge the following free variables were identified: choice of material, choice of shape and area of flask, and a limited selection of shaping processes.

The use of additive manufacturing (AM), as opposed to traditional methods, gives this design a few practical advantages. Additive manufacturing allows manufacturers to have an economical batch size in the single digits and because of this AM works well for rapid prototyping. Customization is another inherent advantage of additive manufacturing. This advantage is derived from the minimal need of physical alterations to production hardware when design changes are needed. Finally, specialized machines designed for large scale production can be circumvented when in the design process which could lead to smaller capital investment needed when considering a new product/project.

For the specifications of the proof of concept product the total volume is 1881 cubic centimeters. This volume is also the volume of the additively manufactured portion of the design, as the whole product is additively manufactured. The product will be either manufactured through powder bed fusion of fused deposition modeling. The total mass of the product will be 14.769 kg, the majority of which comes from the steel of the flask body.

Additive Manufacturing Elements of Design

Materials Integrated into Design

Material Property	Property Range
Thermal Conductivity	6 - 423 W/ m.∘C
Thermal Expansion Coefficient	8.27e-6 - 2.06e-5 strain/∘C
Young's Modulus	6.89e4 - 2.2e5 MPa
Yield Strength	50 - 1.14e3 MPa
Price	.74 - 4.23e4 USD/kg
Maximum Service Temperature	76.9 - 1.04e3 ∘C
Minimum Service Temperature	(-273) - (-3.15) ∘C
Specific Heat Capacity	125 - 545 J/kg.∘C

Figure 2.1 Range of material properties of available metals for additive manufacturing

Metal Forming Process	Usable Materials
Electron Beam Melting	- Medium carbon steel - Commercially pure Titanium - Titanium alloys
Selective Laser Melting	- Silver - Gold - Stainless steel
Selective Laser Sintering, Metals and Ceramics	- Copper - Brass - Nickel - Low carbon steel - Bronze - High carbon steel - Stainless steel - Nickel-based superalloys - Nickel=chromium alloys

Figure 2.2 Materials categorized by additive manufacturing techniques

Due to the broad scope of the proposal, there is a broad range of materials and material properties that need to be considered when applying additive manufacturing to vacuum flasks. As seen above, there are general ranges for material properties which might be important to the design of the product. In Figure 2, a list of the possible materials categorized by the processes which can shape them is provided. In the case of a proof of concept, electron beam melting was chosen for reasons discussed below. This process narrowed the available materials to one of 3 possible contenders, from which medium carbon steel was chosen due to its properties being optimized for vacuum flask development and relatively low cost. A steel was also chosen as case examples of steels being used for vacuum flasks exist within the commercial market.

Fabrication Processes

The use of powder bed fusion processes, specifically electron beam melting, is beneficial over other methods due to its relatively low cost, wide selection of materials, and efficiency. The powder bed family of processes and their respective capital costs and production rates are labeled in figure below. The cost is lower in comparison to other methods of production, due to not requiring molds which optimize single unit production. For this specific project, electron beam melting was chosen due to its efficiency and compatibility with medium carbon steel. Though selective laser melting and sintering are also relatively low in cost, both are not effective when compared to electron beam melting. The entirety of the product will be made using electron beam melting except for the lid, which will be printed using FDM.

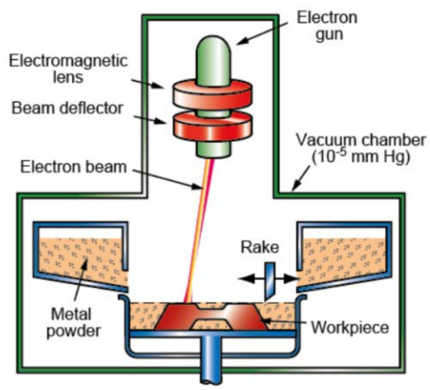

Figure 3. Electron Beam Melting Diagram

Logistics of Integration

Integrating additive manufacturing into existing infrastructural systems would entail joining traditional methodology with those proposed in this report. It should be noted that the rapid prototyping of vacuum flasks is not meant to replace scalable production solutions, but to augment an organization's ability to test and iterate products cost-effectively and with greater control.The traditional method and a potential AM methods of producing a commercial vacuum flask are compared in Figure 4.1. The figure provides an image of how additive manufacturing might be able to produce vacuum flasks. The additive manufacturing method would ideally have similarities to this process in order to provide a good comparison to traditional methods.

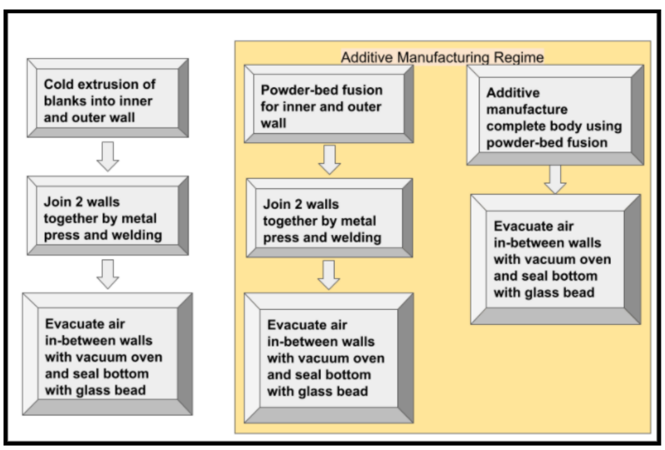

Figure 4.1 Flow chart for vacuum flask manufacturing with cold extrusion and additive manufacturing

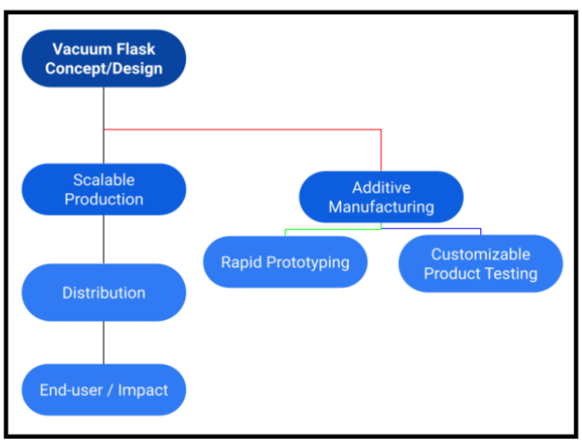

Figure 4.2 Flow chart for integrating additive manufacturing in the design and distribution of product

Design and AM Analysis

Costs and Benefits Associated With Additive Manufacturing

Additive manufacturing reduces the barrier for design by getting rid of the need for purchasing traditional manufacturing processes to begin prototyping. It also allows for greater, less costly market integration of vacuum flasks for cold chain production. Due to its nature, additive manufacturing reduces waste when compared to typical machining manufacturing. This can reduce the amount of material needed for purchase by up to 15x[1]. Additive manufacturing would reduce the cost per unit as opposed to manufacturing with machining. While this comparison becomes less significant as scaling increases, this excels in small-scale prototyping.

Social Implications of Design

This design can aid in effectively transporting perishable goods, which has been of notable significance during the pandemic. The extended ability to maintain passive temperature control is advantageous for ensuring secure transportation. For instance, many medical goods require careful temperature control prior to utilization, which becomes a significant barrier to administering holistic healthcare to infrastructurally underdeveloped areas with regards to electricity. In sub-Saharan Africa, it was reported that "only 28% of health care facilities, on average, had reliable electricity"[2]. The United Nations found that approximately 1.6 million individuals died in Africa in 2015 of preventable diseases, largely due to the inaccessibility of vital, life-saving vaccines and medications[3]. According to Toby Peters, a professor in cold economy at the University of Birmingham, "The last mile is the biggest challenge", when discussing vaccine distribution in remote areas in Africa[4]. With the ability to maintain low temperatures for extended periods of time with minimal electricity, vulnerable communities can have easier access to medicine.

Environmental Implications of Design

Refrigerated transports occupy 1-2% of the world's CO_2 emissions. In a study comparing different distribution operations of perishable food, the method that was not temperature controlled showed up to a 30% reduction in average energy consumption in comparison with its temperature controlled counterparts. The coefficient of performance for transport refrigeration systems is around .5 at -20 celsius while ambient temperatures have a coefficient of 1.5-1.75. By reducing the need to use temperature controlled transports, our design can reduce CO2 emissions and energy consumption[5].

References

1. Ammer, R., Rüde, U., Markl, M., Jüchter, V., & Körner, C. (2014). Validation experiments for LBM simulations of electron beam melting. International Journal of Modern Physics C, 25(12), 1441009. https://doi.org/10.1142/s0129183114410095

2. Adair-Rohani, H., Zukor, K., Bonjour, S., Wilburn, S., Kuesel, A. C., Hebert, R., & Fletcher, E. R. (2013). Limited electricity access in health facilities of sub-Saharan Africa: a systematic review of data on electricity access, sources, and reliability. Global health, science and practice, 1(2), 249–261. https://doi.org/10.9745/GHSP-D-13-00037

3. United Nations. Dying from lack of medicines | Africa Renewal. United Nations. https://www.un.org/africarenewal/magazine/december-2016-march-2017/dying-lack-medicines.

4. Lewis, N. (2021, January 15). Solar tech could help distribute Covid vaccines in Africa. CNN. https://edition.cnn.com/2021/01/14/africa/africa-covid-vaccine-cold-chain-spc-intl/index.html.

5. Adekomaya, O., Jamiru, T., Sadiku, R., & Huan, Z. (2016). Sustaining the shelf life of fresh food in cold chain – A burden on the environment. Alexandria Engineering Journal, 55(2), 1359–1365. https://doi.org/10.1016/j.aej.2016.03.024

6. Woolman, J & Mottram, RA, "The Mechanical and Physical Properties of the British Standard En Steels", Pergamon Press, Oxford (1966)

7. Kalpakjian S. and Schmid, S.R. (2003)," Manufacturing Processes for Engineering Materials", 4th Edition, Prentice Hall, Pearson Education, Inc. Upper Saddle River, NJ 07458, USA. ISBN 0-13-040871-9.

$$T_{b'} = T_c + \frac{T_{surr}\Delta S}{c_p}$$

Where

- T_{surr} is the temperature of the surrounding air
- ΔS is the change in specific entropy of stainless steel
- c_p is the specific heat capacity of stainless steel
- T_c is the temperature of the liquid contained within the flask
- $T_{b'}$ is the temperature of the outside surface of the vacuum flask's inner wall

Tsurr = 294 K (room temp)
DeltaS =
Cp = .5k
Tc = 253 K

$$Q'_0 = A_{in}\varepsilon_{ss}\sigma\left(\left(T_c + \frac{T_{surr}\Delta S}{c_p}\right)^4 - T_{surr}^4\right)$$

Where

- Q'_0 is the rate of heat transfer by radiation through the vacuum portion of the flask
- A_{in} is the surface area of the outside of the inner wall of the flask
- ε_{ss} is the emissivity of stainless steel
- σ is the Stefan–Boltzmann constant

Ain = .178 m^2 (approximate)
Ess = .07 (polished steel)
Stefan- Boltzman = 5.67 *10^-8

$$\begin{aligned} Q'_{lid} &= Q'_{cond} + Q'_{conv} + Q'_{rad} \\ &= kA_{lid}\left(\frac{T_b - T_{surr}}{\Delta x}\right) + hA_{lid}\left(T_b - T_{surr}\right) + A_{lid}\varepsilon_{pp}\sigma\left(\left(T_c + \frac{T_{surr}\Delta S_{pp}}{c_p^{pp}}\right)^4 - T_{surr}^4\right) \end{aligned}$$

Where

- k is the thermal conductivity of air
- h is the convective heat transfer coefficient of free air
- ε_{pp} is the emissivity of polypropylene
- A_{lid} is the outer surface area of the lid
- c_p^{pp} is the specific heat capacity of polypropylene
- ΔS_{pp} is the specific entropy of polypropylene
- Δx is the distance over which conduction across the temperature gradient takes place

Now we have an expression for the total rate of heat loss, which is the sum of the rate of heat loss through the walls of the vacuum flask and the rate of heat loss

$$Q'_{total} = Q'_{out} + Q'_{lid}$$

K = 25.93 mW/mK at 1 bara

H = 12.12 W/m^2C
Epp = .92
Alid =
Cppp =