ENERGY STORAGE IN AUTO-INJECTORS

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ABSTRACT

The specific potential energy of energy storage media is a crucial property when considering a power source for portable devices. Several methods of energy storage are evaluated in this whitepaper using a First Principles modeling approach. Two-phase Liquid vapor equilibrium (LVE) systems are of particular interest due to their near-constant vapor pressure, potential for compact storage, and low storage pressures.

The energy stored by a two-phase system is highly dependent on the temperature of the system and offers a modest amount of energy per unit mass of propellant vaporized, and exceptional energy density. Compressed gases offer high specific energy, but low energy density.
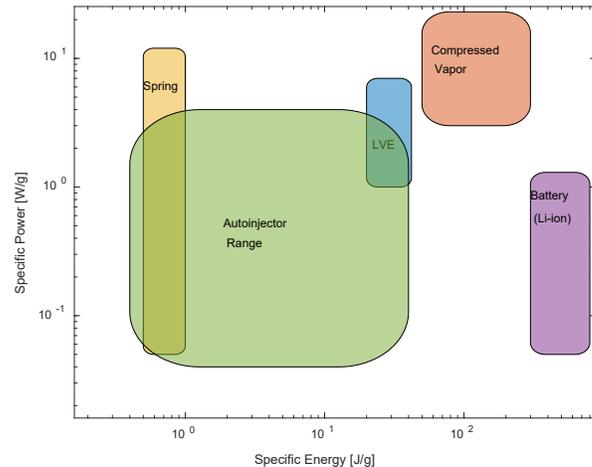

Figure 1 - Energy Storage Media Specific Energy versus Specific Power. Energy is assumed to be delivered in 8s.

INTRODUCTION

Portable devices such as autoinjectors require stored energy to function. Lightweight storage media that can provide relatively large amounts of energy on a unit volume and unit mass basis are extremely desirable. Different methods of energy storage can be compared based on their specific energy (energy/mass) and their energy density (energy/volume). Specific power and power density can be quantified as the rate at which this energy can be delivered. Figure 1 compares the specific energy and specific power available in several energy storage media. For this analysis, we are concerned with rates of energy delivery which are relevant to portable autoinjectors – the delivery of ~0.1-10 Joules for a 1 mL delivery in ~8 seconds (approximately 0.01 to 1 watt) dependent on fluid viscosity and hypodermic needle gauge. If we allocate 250mg to energy storage media the bounded range is approximately as shown. The upper limit and lower limits of specific power are constrained by syringe and other component robustness as well as market requirements such as patient pain/comfort arising from the speed of the injection and the maximum acceptable time for the injection. The lower limit of specific energy is constrained by system work requirements and the upper limit by system storage space and cost.

One particularly interesting class of energy storage media are liquid vapor equilibrium (LVE) propellants. LVE systems have two phases, gaseous and liquid, in a state of thermodynamic equilibrium. So long as liquid remains in the system, the pressure is dependent only on temperature. Such propellants can provide a near constant pressure source. This paper will present a general model for the available energy per unit mass of two-phase propellant and compare the specific energy and energy density to other storage methods.

BACKGROUND

For a thermodynamic two-phase system to exist in liquid vapor equilibrium, the molar free energy of each phase must be equal. This means that the rate of exchange from liquid phase to vapor phase is the same as vapor phase to liquid phase. The state variables of a particular two-phase system (pressure, specific volume, and enthalpy of each phase) are dependent on the temperature of the system. Additionally, as matter changes phase in response to a change in volume or

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temperature, the system may liberate or absorb thermal energy. This is the latent heat of vaporization or condensation and can be mathematically described as the difference in enthalpy between the liquid and vapor phase at a given temperature.

TWO-PHASE SYSTEM THERMODYNAMIC MODEL

GENERAL MODEL

We propose a general model to calculate the specific energy (denoted e with units of J/g) of a two-phase system under various thermodynamic conditions. The system model consists of media inside of a control volume in a frictionless piston-cylinder, which is thermally insulated except for a single thermal resistance R_{th} between the system and an ambient heat sink. The piston can be used to change the volume of the cylinder, and the pressure, temperature, and quality of the system change over time in response. We assume that the temperature of the system inside of the control volume is homogeneous.

Figure 2 - Model Two-Phase system

Consider the rate form of the first law of thermodynamics for the system:
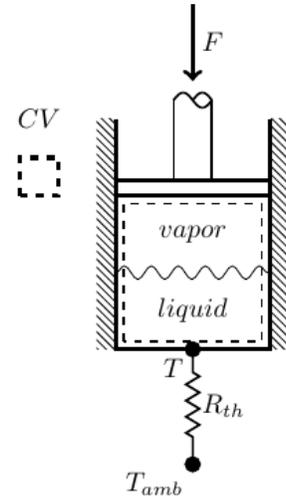
$$\dot{U} = \dot{Q} - \dot{W} \tag{1}$$

where the rate of change of internal energy is defined in terms of system mass m and isobaric heat capacity c_P:

$$\dot{U} = m c_P \dot{T} \tag{2}$$

The thermal energy rate caused by phase change and heat transfer with the ambient heat sink is defined in terms of specific enthalpy h and rate of conversion to vapor phase $\dot{m}_g$:

$$\dot{Q} = \left(h_g - h_f\right)\dot{m}_g + \frac{T - T_{amb}}{R_{th}} \tag{3}$$

And the pneumatic work output of the system is defined:

$$\dot{W} = P\dot{V} \tag{4}$$

Substituting equations (2), (3), and (4) into equation (1) and substituting $\dot{m}_g = \frac{\dot{V}}{v_g - v_f}$:

$$\dot{T} = \frac{1}{m c_p}\left[\frac{\left(h_g - h_f\right)}{\left(v_g - v_f\right)}\dot{V} - \frac{T - T_{amb}}{R_{th}} - P\dot{V}\right] \tag{5}$$

Equation (5) is the ordinary differential equation for a two-phase system. This ODE is non-linear as many of the thermodynamic properties are functions of temperature. Note that the subscripts g and f refer to the vapor and liquid phase, respectively. In order to determine the evolution of temperature, pressure, and quality of a given system, we integrate this ODE over time with prescribed initial conditions, rate of volumetric expansion, and thermal resistance.

ENERGY DENSITY COMPARISON

In this section we will evaluate the specific energy and energy densities of other common energy storage methods and compare them to our previously discussed two-phase systems.

METALLIC SPRING

In the case of a metallic spring, material is deformed or deflected and stores strain energy. Assume the average stress in a metallic spring is half of its yield stress σ_u. The strain energy per unit volume of material is given as:

$$U_s = \frac{1}{2}\sigma_u \varepsilon \tag{6}$$

Substituting Hooke's law and dividing each side by density yields the specific energy of a spring system:

$$e = \frac{\sigma_u{}^2}{2E\rho} \tag{7}$$

The energy storage per unit mass of a metallic spring is a function of the spring's material properties. With Equation (7), we can approximate the specific energy storage of a spring made from music wire, a very common material for springs, as 0.76 J/g. By multiplying the specific energy by the music wire density, and accounting for the volume over which material in a spring may be distributed, we can approximate the energy density as 1.0 J/mL. In general, the energy available from a spring will depend on the strain in the spring and will not be constant over the period of energy release (though some nearly constant-force springs can be contrived). Note also that certain spring geometries have higher specific energy: for example, a square wire torsion spring puts more material at maximum stress than a round wire torsion spring, allowing the former to store more energy before exceeding the material yield stress.

ISOTHERMAL COMPRESSED GAS

Another common medium for energy storage is compressed gas. For an isothermal process, the work done by the gas can be calculated by integrating the pneumatic work by substituting the ideal gas law into the pneumatic work equation. After integration from the initial to final system volumes:

$$e = R_{specific} T \ln\left(\frac{V_f}{V_0}\right) \tag{9}$$

where $R_{specific}$ is the ideal gas constant divided by its molar mass. Equation (9) states that the amount of work per unit mass we can extract from a compressed gas is only a function of the initial and final volumes of the gas, its temperature, and its molar mass. For example, equation (9) can be used to evaluate the specific stored energy of Argon gas at different temperatures (Figure 3) and expansion ratios. Compressed gas systems have potential for high energy storage per unit mass at high compression ratios $\frac{V_f}{V_0}$. One disadvantage to compressed gas systems is that the pressure drops as the working volume expands. The energy density of compressed gases is often quite low since most gases have low density at low compression ratios. For example, Argon stored at 20 °C and 10MPa has a density of 0.16 g/mL giving it an energy density of 23J/mL.
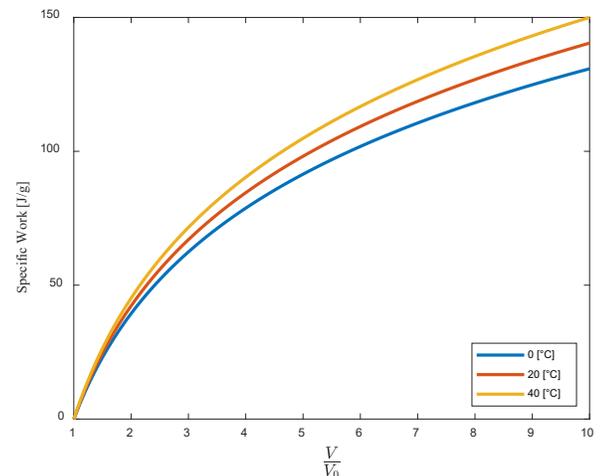

Figure 3 - Specific Work of Compressed Argon Gas

TWO-PHASE SYSTEM

Two-phase systems are interesting due to their ability to provide constant pressure. To compare the specific energy available in a two-phase system we will use our General model to simulate an expansion of the control volume in Figure 2, under the conditions given to the right. Thermodynamic properties of the propellant were interpolated from a thermodynamic reference sheet [1].

Parameter	Value
Propellant Mass [g]	0.5
Initial Temperature [°C]	20
Initial Volume [mL]	1
Volume Expansion Rate [mL/s]	1

The output for our General model shown in Figure 4 gives the system temperature over time for the adiabatic and isothermal limits, as well as three intermediate cases.

For systems with large R_{th}, the temperature of the system drops because the conversion from liquid to vapor phase requires thermal energy which is "donated" by the propellant. We next examine the specific energy available in a two-phase system under a range of thermodynamic conditions. The results plotted in Figure 5 show that for large R_{th}, the specific work approaches the adiabatic limit and for small
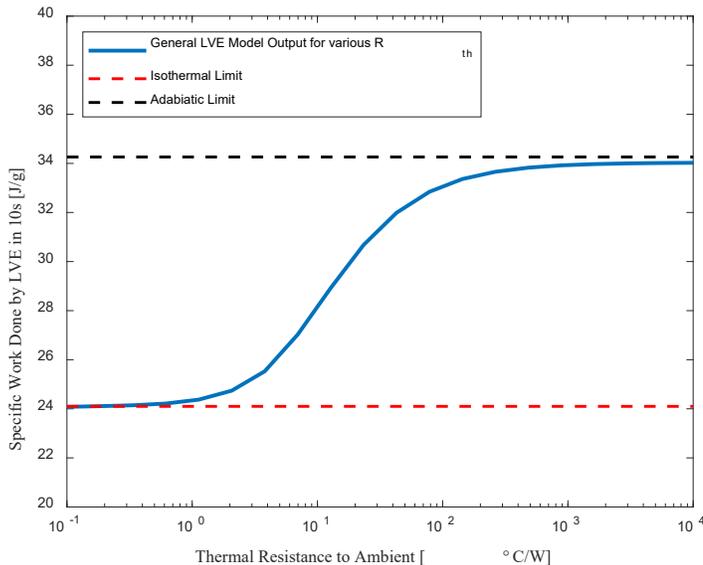

Figure 4 - Propellant Temperature as a function of time for different thermal resistances.

Figure 5 - Specific energy available in two-phase system

R_{th}, the system approaches the isothermal limit. The specific energy is computed by normalizing the PV work discharged from the system by the mass of fluid which is converted to vapor over the course of the actuation. Because systems with small R_{th} absorb thermal energy from the environment readily, a larger mass of liquid is converted to vapor, reducing the specific energy of the system. Since two phase systems store energy in a dense liquid phase, they are more energy dense than compressed gases.

LITHIUM-ION BATTERY

Electrochemical batteries have high specific energy storage. For the sake of comparison, we will consider data on Panasonic NCR18650B Lithium-Ion battery [2]. This battery claims a specific energy of 875 J/g, and an energy density of 2430 J/mL both of which are much larger than the previously discussed energy storage methods. Batteries however cannot typically rapidly discharge their energy contents, giving them a relatively low specific power.
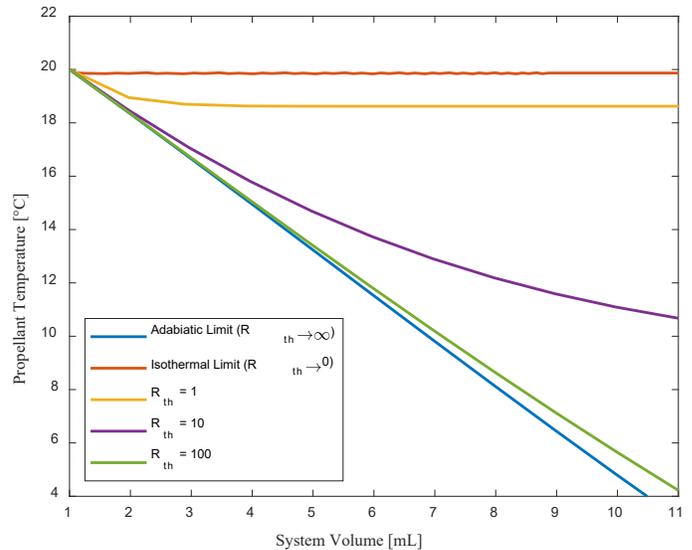
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COMPARISON OF ENERGY STORAGE MEDIA

The table below summarizes the specific energies discussed previously. The specific power p can be calculated by dividing the specific energy e by the time over which it is released. The energy release time may be different depending on the application.

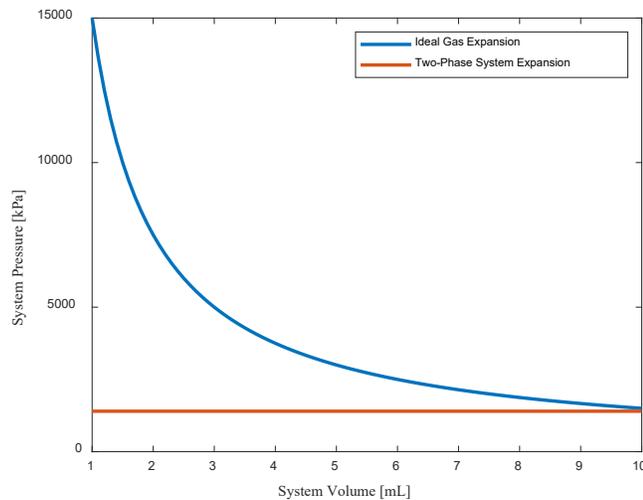| Storage Media	e [J/g]	p [W/g]	e_v [J/mL]	p_v [W/mL]
Metallic Spring, Music Wire	0.7	0.09	1	0.1
Panasonic NCR18650B	800	0.5^1	2400	2
Compressed Argon, 10MPa, 20 °C	140	20	23	2.9
Two-phase R410a, 20 °C	34	4	14	0.5
Two-phase CO_2, 20 °C	42	5	56	7

Figure 6 - Ideal Gas Expansion Compared to Two-phase (R410a) System Expansion. Argon is allowed to make a 10:1 expansion.

A simple example is a drug delivery device in which fluid is expelled from a syringe preferably in approximately 8 seconds, and this is the basis for the power calculations to the left.

CONCLUSIONS

After considering several energy storage methods we can draw several useful conclusions. Lithium-ion batteries are by far the most energy-dense storage medium commercially available and are typically found in consumer or medical devices. Metal springs are relatively inefficient in terms of specific potential energy but are inexpensive when compared to other options of energy storage. Note also that there are no fundamental limits to the time of release of the energy so theoretically springs may have very high-power density, however they may be challenging to use because they may define certain characteristics such as length. Compressed gases offer much higher specific energy than two-phase systems, whereas two-phase systems are more energy dense because they can store energy in a denser liquid phase.

In a hypothetical delivery device, a compressed gas system requires storage at a significantly higher pressure than a nearly constant-pressure two-phase system. Figure 6 compares pressure during the expansion of a compressed gas system and a two-phase LVE system where final pressure is defined to be equal. Clearly the compressed gas system releases more energy during the expansion of the system than the two-phase system.

However, selecting an energy storage media for any device involves considering design tradeoffs, and the high storage pressure of a single-phase system creates additional design constraints not captured in the table above. These include canister mass that scales linearly with storage pressure, larger forces required to pierce or otherwise access the energy stored in the canister, safety and fabrication challenges associated with high-pressure systems, and contending with diminishing power output as the canister is discharged. Conversely, for two-phase systems managing the 'dead volume' of the system is critical to avoid vaporizing propellant without doing pneumatic work. Two-phase systems provide constant pressure as the system expands, so long as thermal resistance to ambient is managed, and low storage pressures.

REFERENCES

[1] "Thermodynamic Properties of DuPont Suva R410A Refrigerant," DuPont, 2004.
[2] "Panasonic NCR18650B Spec Sheet," Panasonic, 2012.