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Liquid nitrogen energy storage unit

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ABSTRACT

An energy storage unit is a device able to store thermal energy with a limited temperature drift. After precooling such unit with a cryocooler it can be used as a temporary cold source if the cryocooler is stopped or as a thermal buffer to attenuate temperature fluctuations due to heat bursts. In this article, after a brief study of the possible solutions for such devices, we show that a low temperature cell filled with liquid nitrogen and coupled to a room temperature expansion volume offers the most compact and light solution in the temperature range 60–80 K. For instance, a low temperature cell as small as 23 cm^3 allows the storage of 3.7 kJ between 76 K and 81 K. Experimental results were obtained varying the expansion volume size, the filling pressure and the temperature range. These results agree with our simple model based on thermodynamical properties of nitrogen. A cell filled with porous material was tested to confine the liquid in the cell independently of the gravity. This material enhances the thermal exchange for high liquid filling ratio whereas below ≈16% a solution must be found to improve the heat exchange coefficient between the fluid and the cell walls. Our calculations are extended to the 80–120 K temperature range for nitrogen and argon in order to clarify the various parameters to take into account for an energy storage unit dimensioning.

1. Introduction

Because temperatures below 100 K are needed in many technologies and for fundamental and applied research at low temperature, the cryocoolers have been intensively developed and improved for 30 years [1,2]. Their reliability is presently so high that they permit low temperature infrastructures in remote locations avoiding the heavy logistic of cryogenic fluid transportation and/or the periodic refilling of cryostat: only electrical power is needed. They are also used for cooling very sensitive detectors in space for earth observation or in astronomy missions, or in health sciences for SQUID detection [3]. However, most of these cryocoolers, as Stirling or Pulse Tubes, are based on compression–expansion cycles of helium and the pressure oscillations lead to vibrations which are undesirable for very fine measurements. Despite the efforts made to reduce this inconvenient, no compact and light solution is nowadays available for these types of cryocoolers and this limits their use for the cooling of highly sensitive sensors. One solution to this issue is to stop the cryocooler [3–5] (or just drastically decrease its frequency in order to avoid the mechanical/electrical stresses due to repeated starts and stops) during the measurements phase. To allow long periods of measurements in such conditions, a temporary cold source is necessary to maintain the sensors at low temperature after this stopping. In this case, the experimental set-up schematized in Fig. 1a can be very useful. A device able to store thermal energy without large temperature drift (Energy Storage Unit – ESU) is coupled to the cryocooler cold finger through a thermal switch: during the first phase (precooling phase), the ESU is cooled down with the thermal switch in its high conductance state (ON state). After this first phase, the switch is toggled to its low conductance state (OFF state) and the cryocooler can be turned off. During this second phase (called hereafter as the ‘‘ESU mode’’), thanks to the large thermal inertia of the ESU, the power dissipated by the sensors is absorbed without rapid temperature increase. The role of the heat switch is to prevent a high additional heat load coming from the warming cold finger due to the cryocooler stopping. Let us mention that this system allows also a constant temperature platform for the sensors if this one is thermally coupled to the ESU through a heat leak and controlled at a temperature higher than the ESU one [4,5]. Moreover, an ESU directly coupled to the cold finger can also be used as a cooling power booster [6] as described in Fig. 1b: in case of sudden heat bursts, the thermal energy is mainly absorbed by this device, limiting the temperature increase of the cold finger and turning unnecessary the utilization of overpowered cryocoolers

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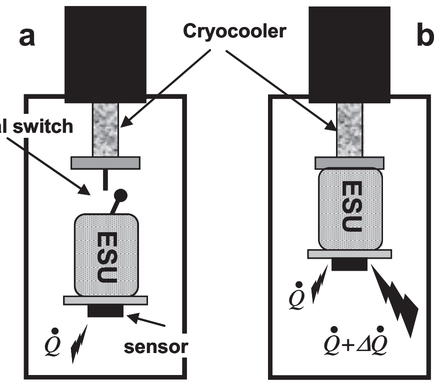

Fig. 1. Schema for integration of an energy storage unit (ESU) in a cryocooler for "vibrationless configuration" (a) or cooling power booster (b).

(then heavier and more power consuming) to compensate these transitory and short events.

Such an ESU can be very convenient if they can be easily integrated in (small) cryocoolers: for such purpose, their volume at low temperature must be as small as possible. They also have to be as light as possible, not only for space application but also for minimizing the mechanical supports and therefore the heat leaks coming through.

In the next section of this article, the mass and the volume of an energy storage unit, working around 80 K, using the sensible heat of solid materials or the triple point of cryogenic fluids are evaluated to show that none of these ways provides a compact or a light solution. In Section 3, a much more compact solution is proposed using the latent heat of nitrogen vaporization ("Liquid ESU"). The experimental set-up and the modus operandi of such a device are described. In Section 4, the results of the experimental tests are shown and discussed. The extension of ESU for temperature up to 120 K is briefly discussed in Section 5.

2. Solid state and triple point energy storage units: mass and volume estimation

2.1. Solid state energy storage units

The simplest way to limit the temperature drift of a cryogenic platform upon heat release is by coupling it to a solid piece of high heat capacity and, in order to minimize the mass and/or the volume, a material with high massic and volumic specific heat must be chosen. Moreover, to fully benefit from the heat capacity, the thermal time constant must be short to avoid superheating (hot-spots) where the heat is delivered: metals are recommended. However, at low temperature (let say, $T < 20$ K), the lattice specific heat becomes quite low and a solution is to use the huge specific heat anomalies associated to the paramagnetic–magnetic phase transition of localized spins: for instance, materials with this type of magnetic anomalies are widely used in the low temperature part of the cryocooler regenerators to increase their heat capacity [7]. At high temperature, all the metals have more or less the same *molar* specific heat (Dulong and Petit law) then a high *massic* specific heat is obtained for light metallic elements. In the 60–100 K temperature range, despite the differences in the Debye temperatures, this feature globally remains: in Table 1, the mass, volume and thermal diffusion time of a spherical energy storage unit able to store 1800 J (e.g. 1 W during 30 min.) between 75 K and 80 K are computed for various materials. This table, not pretending to be an extensive study, indicates the order of magnitude of mass and volume needed to store such an energy using common solid materials. Three criteria were used to select the materials:

(i) ESU mass inferior to 2 kg.
(ii) Volume smaller than 0.5 L.
(iii) Internal thermal time constant shorter than 30 s.

From the mass point of view, the best material is the lithium (lightest metal) but it leads to a rather high volume. A second problem with lithium is its dangerous nature: a passivation process must be found (surface treatment or alloying). Sodium and magnesium present the same problems but magnesium-based alloys could be a solution. If the volume is a more important criterion than the mass (for ground applications for instance), copper seems to be the best solution. Moreover, this material with its very high thermal diffusivity is specially adapted to absorb short but intense heat bursts. Aluminum is a good compromise between mass and volume. In this selection process, the plastic-like/synthetic materials were discarded due to their poor thermal diffusivity despite their large massic specific heat. As an example, Table 1 indicates the thermal properties of nylon that would present a good feature in respect to weight (comparable to magnesium). Other materials with more adequate properties may exist but this table gives the orders of magnitude: to store 1800 J between 75 K and 80 K the minimum mass would be ≈0.25 kg (≈0.45 L of lithium) and the minimum volume is around 0.2 L (≈1.7 kg of copper). Such heavy or voluminous ESU is somewhat incompatible and/or disproportional with the small cryocoolers available nowadays and a more compact and lighter alternative to solid-state ESU should be found.

2.2. Triple point energy storage units

Thermal energy can also be stored by using the latent heat associated to Liquid–Gas (LG), Solid–Gas (SG) or Solid–Liquid (SL) phase transitions of cryogens. Moreover, working at the triple point, the energy can be stored at constant temperature: this elegant solution was studied a few years ago mainly using nitrogen [3,6,8] and more recently using hydrogen [9]. In the 60–80 K range considered in this article, both triple points of N_2 and Ar could be chosen and some of their properties are listed in Table 2. For a constant volume cell working at the triple point, the solid melts during

Table 1
Thermal and geometric characteristics of solid state ESU storing 1800 J between 75 K and 80 K using selected materials (see text).

Material	Density (kg/m^3)	Specific heat (80 K) (J/(kg K))	Thermal conductivity (80 K) (W/(K m))	Mass (kg)	Volume (L)	Diameter (cm)	Internal thermal time constant (s)
Lithium	534	1526	141	0.24	0.44	9.4	13
Sodium	971	928	126	0.39	0.40	9.1	15
Magnesium	1740	543	196	0.66	0.38	9.0	10
Aluminum	2713	357	118	1.01	0.37	8.9	16
Brass	8802	209	101	1.72	0.20	7.2	24
Copper	8960	205	530	1.76	0.20	7.2	4
Indium	7330	193	94	1.87	0.25	7.9	23
Nylon	1140	680	0.22	0.53	0.46	9.6	8100