Applied Thermal Engineering 95 (2016) 178–185

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Research Paper

Liquid–gas cryogenic energy storage units operating at constant temperature

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HIGHLIGHTS

- A closed system that absorbs heat at constant temperature is described.
- It consists of a cryogenic cell connected to an expansion volume at room temperature.
- The heat storage is obtained by liquid evaporation at constant pressure.
- A low temperature cell of 36 cm^3 was able to store 3.6 kJ at 81 K.
- The performance of this type of device is discussed as a function of temperature.

ARTICLE INFO

Article history:
Received 5 August 2015
Accepted 16 November 2015
Available online 25 November 2015

Keywords:
Cryocooler
Low temperature devices
Energy storage
Latent heat
Space cryogenics

ABSTRACT

The cryogenic energy storage unit described in this article is a device that is able to absorb heat at constant temperature and that provides some significant advantages over the cryogenic storage units working at the triple point. It consists in a low temperature cell coupled to a relatively large expansion volume at room temperature. The heat is absorbed thanks to liquid evaporation, rendering this device able to operate at any temperature along the saturation curve, which is an advantage in respect to the triple point devices. Moreover the large latent heat of evaporation allows a compact low temperature cell. During the period where the heat is absorbed, the constant temperature is obtained by an ON–OFF pressure control using the expansion volume as a vacuum ballast. This concept was tested using nitrogen as working fluid, a 38 cm^3 low temperature cell and expansion volumes of 5.7 L and 24 L. Because some possible applications of such devices need their integration in the thermal bus of satellites, the low temperature cell was turned gravity independent by filling it with ceramic foam to retain the liquid by capillary effect. This experimental setup was tested at various temperatures in the 64–81 K range, and as much as 3.5 kJ stored with a thermal stability of around 0.1 K was obtained. A disadvantage of such an Energy Storage Unit is the relatively large room temperature volume: its size is discussed as a function of both the controlled temperature and the working gas.

1. Introduction

A cryogenic Energy Storage Unit (ESU) is a closed system able to store thermal energy at low temperature without significant temperature drift [1]. It can be coupled to the cold finger of a cryocooler in two different ways [2]: by being directly coupled to the cold finger or by using a heat switch. In the first way (Fig. 1, “booster mode”), the cooling power of the cryocooler is increased temporarily and the temperature fluctuations due to sudden heat bursts or to the periodic operations of highly dissipating sensors in satellites can be damped, avoiding an oversizing of the cryocooler leading to an increase of weight and electrical power consumption. If coupled to the cold finger through a thermal heat switch (Fig. 1, “Vibration-free configuration”), it provides a temporary cold source after stopping the cryocooler: such a configuration can be used when very sensitive measurements at low temperature must be taken in an environment free of mechanical vibrations and electromagnetic noise [3–5].

In this last configuration, the ESU must be first cooled down with the heat switch in its highly conducting state (ON state), and then toggled to its OFF state (highly resistive state): from this point on, the cryocooler can be stopped and the heat dissipated by the

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http://dx.doi.org/10.1016/j.applthermaleng.2015.11.059
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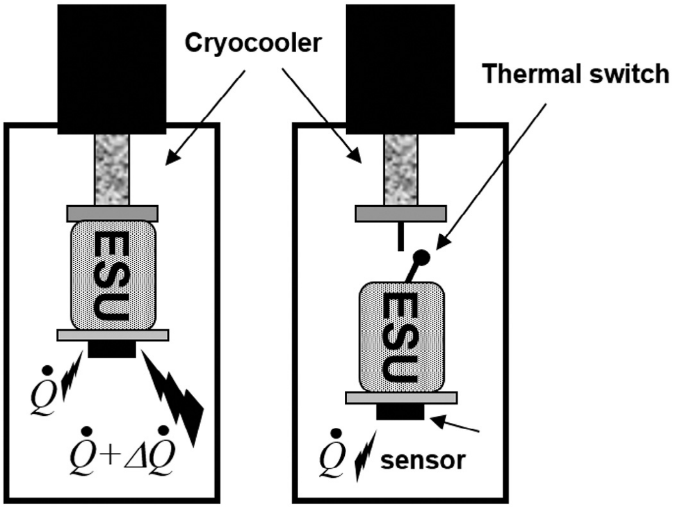

Fig. 1. Schema of the Power Booster Mode (left) and Vibration-free (right) configurations for ESU integration in a cryocooler (from Reference [2]).

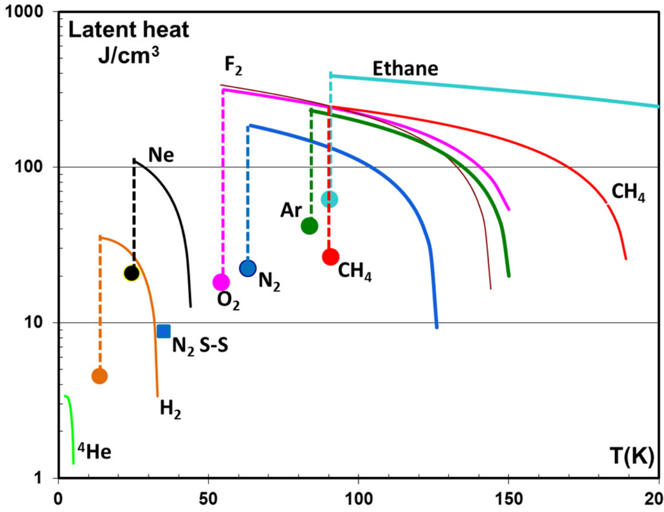

Fig. 2. Latent heat of cryogenics fluids with triple point below 100 K. Full circles indicate the solid–liquid latent heat at the triple point; the solid lines indicate the liquid–gas latent heat between the triple point and the critical point. The squared symbol indicates the latent heat of the Solid–Solid transition (α-γ) at the triple point solid–solid–gas of nitrogen.

measurements will be absorbed/stored by the ESU (this phase will be referred henceforth as the *ESU-mode*) leading to a null or limited temperature drift depending on the ESU systems. As a matter of fact, various solutions were already used to store thermal energy at low temperature. The most natural and elegant one is to use a pure substance at its triple point: as far as the three phases coexist, the heat dissipation is absorbed naturally at constant temperature and constant pressure by the latent heat of the solid–liquid transformation. Such a smart solution has been extensively studied [1,3,6] and already tested in space [7]. Another way, the most simple, uses as storage medium the high specific heat of some materials to store energy thanks to a (reduced) temperature increase [4,5,8–10]. A third way takes advantage of the large latent heat associated to the liquid–gas phase transition, the heat dissipation being absorbed by liquid evaporation along the saturation curve [2]. However, in this case, to allow recycling, the system must be closed. Hence, the gas formation leads to a pressure increase and, consequently, to a temperature increase during the ESU mode. Depending on the requirements, one or others of these solutions can be adopted but may present some significant drawbacks. In this article, we present a fourth solution also based on the liquid–gas transformation but storing energy at constant temperature. In the next section, this solution is compared to the triple point solution with a special focus in space applications and its implementation is described. Using nitrogen as the working fluid and the vibration-free configuration of the ESU, tests in the 67–81 K temperature range and with various initial thermodynamic parameters are analyzed in section 3. Section 4 is devoted to the extrapolation of such devices for other temperature ranges and to the use of other cryogenic fluids.

2. Energy storage unit at constant temperature: liquid–gas versus triple point

2.1. Latent heat and temperature range

If a constant temperature operation is mandatory during the ESU-mode, a natural choice would be a cell working at the Triple Point of a pure substance (TP-ESU): as far as the three phases – solid, liquid and gas – coexist, the temperature is, in principle, strictly constant. In such an ESU, the working fluid is first allowed to solidify (almost totally) and, during the ESU-mode, the heat absorption leads to the melting of the solid at constant temperature. However, if the system is closed (allowing regeneration without external gas feeding), this melting is spontaneously accompanied by a (exothermic) condensation of a small part of the existing gas to maintain the pressure constant: despite this effect, the energy absorbed during this isothermal melting is given with a very good approximation by the solid–liquid latent heat. The volumetric latent heat of melting at the triple point and of liquefaction along the saturation line [11] are plotted in Fig. 2 for various cryogens.

Although this kind of TP-ESU provides an elegant solution to obtain a stable temperature without any electronic or mechanical control, it presents some disadvantages:

i) Below 100 K, only a few triple points are available. Then, if the temperature at which the ESU must work does not correspond exactly to one of those, a triple point at lower temperature must be chosen and a platform, thermally coupled to the TP-ESU, must be controlled at the desired temperature by heating it and using some electronic control. In this case, the main advantage of the TP-ESU (a temperature stable without any artificial control) disappears, and, moreover, part of the stored energy is spent only to heat the platform.

ii) If the TP-ESU consists of a simple closed cell at low temperature (called as *Single Volume solution* in Reference [1]) and 100% filled with liquid at the end of the ESU-mode, its pressure at room temperature will be prohibitively high (≈2800 bars for nitrogen, for instance [2]). To work with more reasonable pressures in the whole system at room temperature (≈100 bars, for example), a solution is to significantly decrease the liquid filling ratio by increasing the volume of the cold cell. In any case, rendering such pressurized reservoirs safe leads to thick walls, which in turn lead to a significant cell mass. As an example, the minimum mass for a TP-ESU built in aluminum, able to store 1800 J at 63 K using nitrogen and 84 K using argon, was calculated as ≈500 g and ≈300 g respectively in Reference [2] and would need a volume of about 0.6 L (N_2) and 0.4 L (Ar). Another solution to avoid high pressure is to connect the low temperature cell to a large expansion volume at room temperature (referred as *Double Volume solution* in Reference [1]) that stores the gas at a relatively low pressure when the whole system is at room