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40 K Liquid Neon Energy Storage Unit

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Abstract

A thermal Energy Storage Unit (ESU) could be used to attenuate inherent temperature fluctuations of a cold finger, either from a cryocooler working or due to suddenly incoming heat bursts. An ESU directly coupled to the cold source acts as a thermal buffer temporarily increasing its cooling capacity and providing a better thermal stability of the cold finger ("Power Booster mode"). The energy storage units presented here use an enthalpy reservoir based on the high latent heat of the liquid-vapour transition of neon in the temperature range 38 - 44 K to store up to 900 J, and that uses a 6 liters expansion volume at room temperature in order to work as a closed system. Experimental results in the power booster mode are described: in this case, the liquid neon cell was directly coupled to the cold finger of the working cryocooler, its volume ($\approx$12 cm^3) allowing it to store 450 J at around 40 K. 10 W heat bursts were applied, leading to liquid evaporation, with quite reduced temperature changes. The liquid neon reservoir can also work as a temporary cold source to be used after stopping the cryocooler, allowing for a vibration-free environment. In this case the enthalpy reservoir implemented ($\approx$24 cm^3) was linked to the cryocooler cold finger through a gas-gap heat switch for thermal coupling/decoupling of the cold finger. We show that, by controlling the enthalpy reservoir's pressure, 900 J can be stored at a constant temperature of 40 K as in a triple-point ESU.

Keywords: Thermal Storage; Liquid Neon; Heat Switch; Temperature Stabilization.

1. Introduction

The development of very long wavelength infrared devices for space observation missions, earth observation and military applications has increased the demand for reliable cryocoolers that work below 50 K. Such devices

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(Quantum-well Infrared photodetector – QWIP[1], for instance) require stable temperatures as low as 40 K in order to work properly. In addition to the stable temperature requirement, the QWIPs are sensitive to mechanical vibrations.

Some low vibration Stirling type pulse tube cryocoolers[2,3,4] were developed to operate at this temperature range. It is the case of the “Large Pulse Tube Cooler”(LPTC) developed by CEA/INAC/SBT and Air Liquide[2] that comes as an alternative to the Stirling coolers. The operational temperature range of this cooler is 40 – 60 K and its cooling power is around 1 W at 40 K.

Even with pulse tube coolers, without moving parts at low temperature, some vibrations are induced either by the compressor and the pressure oscillations inherent to its operation, which could be incompatible with very high precision measurements. One way to stop/reduce these vibrations is to stop the cryocooler, or to decrease its frequency, avoiding the mechanical stresses due to repeated starts and stops[5]. This procedure leads to a fast temperature drift of the cooler temperature that results in a short time of measurements in a vibration-free environment. To slow down this fast temperature rise, the sensitive sensors could be connected to an energy storage unit (ESU) that will act as a temporary cold source in a vibration-free environment. The idea is to couple this high-enthalpy reservoir (ESU) to the cold finger through a thermal heat switch, which is responsible for the thermal coupling or decoupling of the ESU from the cold source. During the sensor operation, the heat switch isolates the temporary could source (ESU) from the fast temperature drift occurring when the cryocooler is stopped.

High specific heat materials can be good candidates for thermal energy storage units and render the system very simple. It is the case of the developed ESUs using lead[6] that work at 11-20 K and Gd_2O_2S[7] at 3-6 K. Around the 40 K range, erbium based alloys (1.3 J cm^{-3} K^{-1}) could be a solution but the liquid-to-vapor transition of neon presents itself as a much more compact solution due to its high latent heat (50 J cm^{-3}). Hence, an ESU using this fluid was tested which stores up to 1000 J at 40 K in a 20 cm^3 cell ($\approx$ 20 g of Ne) leading to a very small volume at low temperature. A liquid nitrogen ESU was already developed by our group to store up to 3600 J in the 80 K range[8].

2. **Energy storage unit system description**

Fig. 1 depicts the experimental setup of the liquid neon ESU. This closed system consists of a low-temperature cell, the energy storage unit itself, linked to a volume at room temperature (RT) that stores the evaporated neon. The low-temperature cell is connected to the cold finger of the cryocooler through a gas-gap heat switch, which allows to thermally decouple the cell from the fast temperature increase of the cold finger when the cryocooler is stopped.

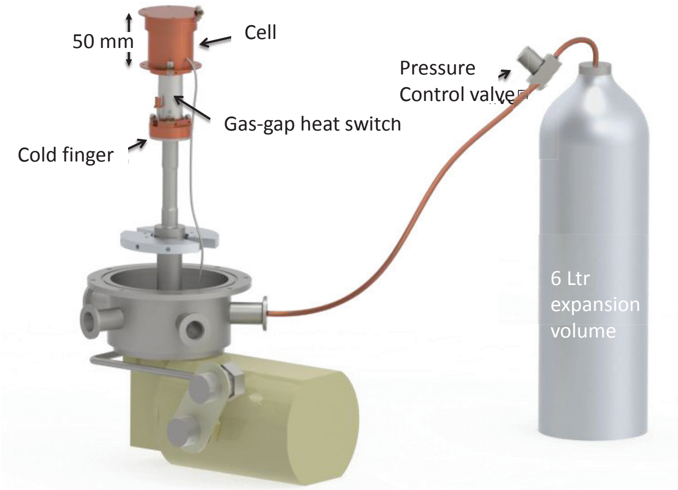

Fig 1 (a): Liquid neon Energy Storage Unit experimental setup. The pressure control valve is used to operate the ESU at constant temperature.

To turn this system gravity insensitive, a porous material is used to retain the liquid phase inside the low-temperature cell: a filter paper with 10 µm of average porous size was chosen for this purpose.

Using the configuration depicted in Fig. 1, the ESU could operate in two different modes: the temperature drift mode and the temperature controlled mode. These two operational modes are summarized in Fig. 2. In the ESU temperature drift mode the low-temperature cell is permanently open to the expansion volume, the pressure in the RT volume and the low temperature cell are then always the same. This whole system is closed at a certain Ne pressure (≈ 15.6 bars for the shown results) and a total cycle is divided in 2 phases:

1) For the cool down, the cryocooler is ON and the heat switch is in the state of high conductance (ON). The low temperature cell is cooled down until achieving neon's saturation temperature. Neon starts to condense inside the low temperature cell. The cooling process will continue until it reaches some minimum temperature, condensing more fluid while reducing its pressure. In general, the initial filling pressure is calculated in order to obtain a cell completely full of liquid at this minimum temperature. The switch is toggled to the OFF state in order to decouple the ESU from the cold finger. At this stage, the ESU mode is ready to start.
2) This second phase starts by turning OFF the cryocooler and the sensitive sensors become able to operate in a vibration-free environment. Their dissipated power is absorbed by the liquid neon, which results in its evaporation while the gas expands to the room temperature volume, avoiding a rapid pressure increase (the larger the volume the slower the temperature increase). This slow pressure drift along the saturation line, results in a slow temperature increase. The ESU mode stops when the liquid ends. The applied power has no more latent heat to absorb it, and so the temperature rises faster. A recycling cooling process (phase 1) is needed in order to "re-charge" the ESU and re-enable its operation.

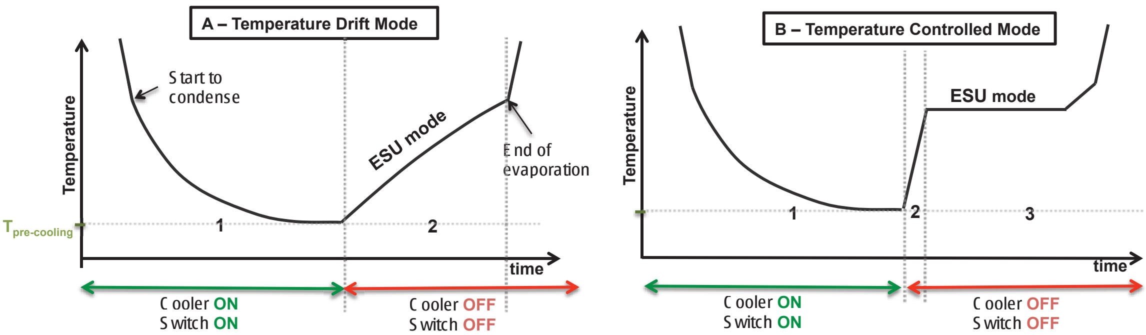

Fig. 2. Two different ESU operational modes. Left: Temperature drift mode. Right: Temperature controlled mode

As previously mentioned, this ESU operates upon the saturation conditions of neon. This means that an evaporation process at constant temperature can be obtained by controlling the pressure of the low temperature cell. Using this concept it is possible to use the ESU at constant temperature, like in a triple point transition. The higher latent heat of the liquid-vapour transition in comparison with the triple point transition turns the "Liquid ESU" smaller and lighter than the "triple point ESU"[9].

A pressure control valve is placed between the low temperature cell and the room temperature expansion volume (Fig. 1) in order to control the temperature of the cell. This pressure control is only possible while the pressure in the low temperature cell is higher than the one in the expansion volume pressure. A summary of this operational mode is shown in Fig. 2 (right), which is divided in 3 phases:

1) With the pressure control valve open, the cell is cooled down and neon starts to condense. The condensation proceeds down to the minimum temperature (just like in the temperature drift mode). During this process the overall system pressure decreases. At the end of this phase the switch is toggled to the OFF state.

2) At this point, the pressure control valve is closed; the low temperature cell is heated up to the setpoint temperature. During this process, with the two volumes isolated from each other, the pressure in the cell increases due to the temperature increase, while the pressure in the expansion volume remains constant and lower than that of the cell: the expansion volume will act as a "vacuum source" enabling the control of the pressure in the cell. The ESU mode can start.
3) A constant temperature phase is available. The pressure control valve actuates in order to maintain a constant pressure in the cell during the liquid evaporation due to the sensor's dissipated heat. The ESU mode ends when the pressure between the two sides of the control valve is equalized: the valve can no longer control the pressure. Some liquid may remain in the cell and the temperature increase starts just slowly. When no more liquid exists, a recycling cooling process (phase 1) is needed in order to "re-charge" the ESU and re-enable its operation.

For applications where a high cooling capacity is required for a short period of time, the liquid ESU concept also can be used. An ESU directly coupled to the cold source acts as a thermal buffer, temporarily increasing its cooling capacity, making the use of oversized cryocoolers for sporadic heat bursts unnecessary. This concept, called here the "ESU booster mode"[9], also attenuates the temperature fluctuation inherent to the working cryocooler or due to the sudden heat bursts. Some experiments were performed in the three operational modes and are presented and discussed in the next section.

3. Experimental Results

A 35 cm^3 copper cell is connected to the cold finger of the cryocooler through a gas-gap heat switch[7], as shown in Fig. 1. This cell is connected to a 6 liters expansion volume at room temperature through a capillary tube. The pressure control valve for the ESU temperature control mode is placed in this capillary tube at room temperature. Fig. 3 presents a typical run of the temperature drift mode. The system filling pressure of 15.6 bars of neon determines T = 40.1 K as the final temperature of this drift mode. The initial temperature (T = 37.7 K) corresponds to a cell full of liquid. A constant heat power of 1 W was applied during the ESU mode.

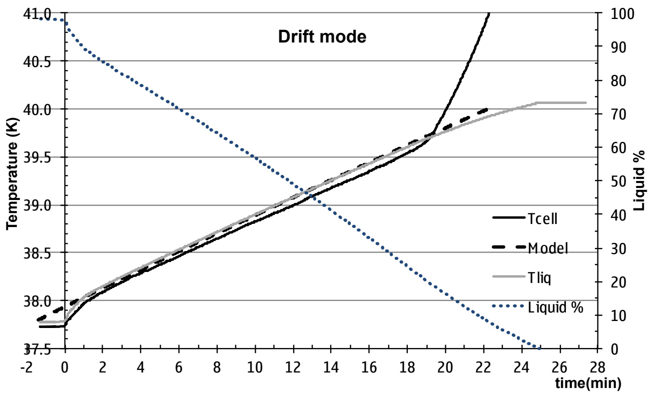

Fig. 3. Experimental results running in the temperature drift mode. The system filling pressure is 15.6 bars and the heat power applied was 1 W.

The temperature of the liquid/vapor (grey line) is given by the pressure measurement in the saturation curve. The liquid volumetric percentage in the cell during the ESU mode (dotted line) is calculated using the total volume of the system, the filling pressure and the pressure/temperature of the liquid as measured.

During ≈ 18 min the ESU actuates as a thermal buffer attenuating the cell's temperature increase. During this period the own-code simulated results (dashed line) match very well the cell's temperature. The thermal split between the cell temperature and the liquid temperature when the liquid amount is ≈ 20 % of the cell's total volume is associated to the liquid that remains trapped inside the small pores of the porous material. Despite this amount (≈ 20 %) of inaccessible liquid, a total of 1080 J were stored in this process with a temperature drift of 2 K only.

A typical temperature controlled run is plotted in Fig. 4. The same system was charged with 15.6 bars of neon and a pressure control valve was used to control the cell pressure. The ESU pressure and the expansion volume pressure (valve upstream and downstream pressures) during the ESU operation are plotted at the top of Fig. 4.

After the cooling process (t = 0) the overall system pressure is ≈ 11 bars (T ≈ 38 K). At this point the pressure control valve was closed and the cell was heated up to the control temperature (T = 40 K) causing an increase in the ESU pressure (black line). The switch is toggled to the OFF state. Once the cell is at 40 K the ESU is ready to operate and a heat load of 1 W was applied to the cell. The pressure control is well observed in the pressure plot by constant ESU pressure while the expansion volume pressure increases, resulting from the evaporation of the liquid neon. This control results in small oscillations in the cell temperature, which are lower than 100 mK. The ESU mode stops when the both pressures equalize. In this case, the same temperature split between the cell and liquid temperature was observed when the remaining liquid amount was ≈ 20 % of the total.

With the ESU thermally decoupled from the cold source, the ESU absorbed a heat load of 1 W during 15 min, with a temp stability up to 100 mK. The total stored energy in this test was ≈ 900 J.

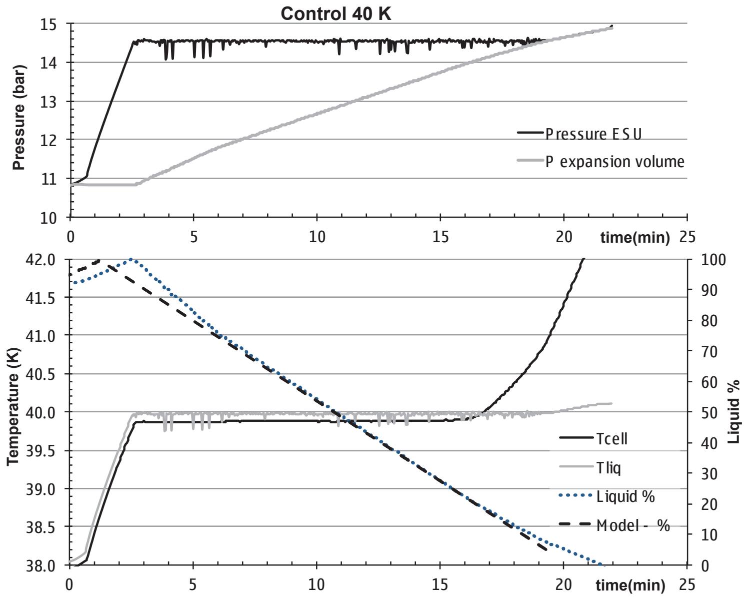

Fig. 4. Experimental test of the temperature controlled mode at 40 K: the first plot shows the pressures in each side of the valve; in the second plot are the ESU temperatures during the test. The filling pressure was 15.6 bars and the heat load applied 1 W.

A smaller low-temperature cell (≈ 12 cm^3) was developed to test the ESU booster mode concept. The stabilization of a cold source with inherent temperature fluctuations or incoming heat bursts is the objective of this concept. This cell is directly coupled to the cryocooler's cold finger and it is connected to the 6 L expansion volume. In this test, the cryocooler with ≈ 4.5 W of cooling power at 40 K is kept in operation. In the test showed in Fig. 5 a heat load of 9 W (t ≈ 0.5 min) was applied to the cell. During ≈ 2 minutes the ESU absorbs this applied heat load power without a large temperature increase (a temperature drift of 1 K). Note that during these ≈ 2 minutes the cooling capacity of the cryocooler was doubled.

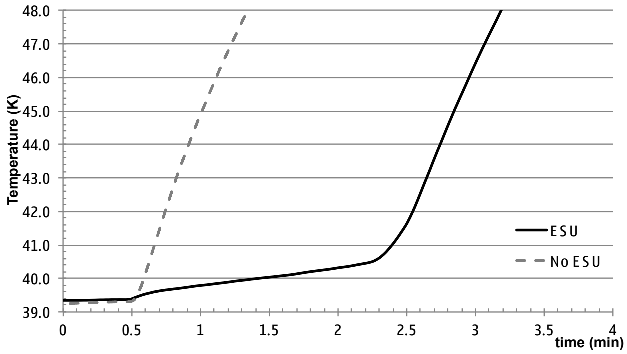

Fig. 5. Experimental test of the ESU booster mode using a heat load of 9 W. The same experiment is performed without the use of the ESU. The cooling power of the cryocooler at 40 K is around 4.5 W.

The benefits of the integration of an ESU in a cryocooler when subjected to an extra heat load of 4.5 W is well understood when compared with the test where no ESU was used. An increase of 10 K in 1 minute was the result of the test while 9 W were applied without the presence of the ESU.

4. Conclusion

The latent heat of the liquid-vapor transition of neon was used to obtain a vibrationless temporary cold source and a stabilizer for the cryocooler cold finger in the 40 K range. Using a small low temperature volume of 35 cm^3, which was thermally decoupled from the cold source, a heat load of 1 W was applied during 18 min with a temperature drift of 2 K. Using a valve to control the pressure, 900 J were stored at a constant temperature as in a triple point transition.

Using an ESU directly coupled to the cold finger (“booster mode”) doubled its cooling capacity during 2 minutes. This concept turns unnecessary the use of oversized cryocoolers in applications were a high cooling capacity is only required for short events.

More operational tests results about this liquid neon ESU will be published elsewhere.

Acknowledgements

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