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Comparison of mechanical cryocoolers versus stored cryogens for balloon-borne observations

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ABSTRACT

This study examines the relative mass required in the use of stored cryogens and mechanical cryocoolers, for cooling of detectors and optics in stratospheric-balloon—borne observatories. Lofted mass per unit heat removed from a cryogenic instrument is calculated, as a function of temperature, for three cooling approaches: (a) the use of stored cryogens; (b) use of an acoustic-Stirling ("pulse tube") mechanical cryocooler powered by electric storage batteries; and (c) the same cryocooler with solar-electric energy collection partially or fully replacing storage batteries. For the latter case, the mission duration at which the systems masses are equal is also found. Principal conclusions are (1) stored cryogens can provide cooling for lower mass than storage-battery—operated cryocoolers over most of the temperature range considered, but the difference is not large; (2) solar-conversion systems can be the lower-mass option at higher temperature, but the mission duration for equal mass increases rapidly below ~30 K.

1. Introduction

Recent interest in performing astronomy observations from earth-stratosphere balloon platforms has led to consideration of the tradeoffs between using mechanical cryocoolers versus stored cryogens, for cooling the detectors and optics. Cooling requirements vary widely, from greater than 100 K to below 6 K; duration can be from 1 day to months; and observations include day-only and night-only. Lofted mass can constrain the altitude achievable by the balloon-borne instrument, while power is typically less important than for space missions, and cooling-system hardware cost is relatively unimportant. This study finds relationships between various operational conditions, such as the detector temperature and mission duration, in terms of mass of the cryogenic system per amount of heat removed from the instrument, and as a function of the cold instrument temperature.

2. Cooling available per unit mass of a stored-cryogen system

Heat can be removed from, for example, an optical detector by warming a stored cryogen such as liquid helium. In the simplest case the detector is immersed in or surrounded by the liquid cryogen, in which case the lowest temperature is limited by the pressure-dependent boiling point of the cryogen, and the cooling power is just the latent heat times rate of evaporation. Increased cooling power is available at higher temperature, by utilizing the increase in enthalpy of the warming gas. For this study the cryogens considered were those elements with normal boiling points below 100 K: helium (He), hydrogen in the temperature-dependent equilibrium ortho–para ratio (e-H2), neon (Ne), nitrogen (N2), argon (Ar), and oxygen (O2). As a practical matter neon is unlikely to be used due to its scarcity and cost; it is included for completeness. Knowing the latent heat, the enthalpy required to raise the gas temperature from the boiling to final cooling temperature, the cryogen density, and the mass of the required container, the amount of cooling available per unit mass of the entire system can be calculated.

The total heat removable by evaporating and warming a given mass of a cryogenic liquid, from the normal boiling point, T_sv, to a final temperature, T_cool, is given by

$$H(T) = [H(T\_cool) - H(T\_sv)] + Lv(P\_sv), \qquad (1)$$

where $P\_sv = 1$ atm and $H(T)$ is enthalpy per unit mass of cryogen. Multiple stages of heat interception can be employed if desired.

Numerical values for the latent heat and enthalpy were taken from the GasPak [1] gas properties database. In calculating the enthalpy available from warming the gas to its final temperature, the pressure was assumed constant at 1 atmosphere. Efficiency of the heat exchange with the gas was assumed to be 100%, which is not overly difficult to approach under these conditions. While the temperature of the liquid cryogen can be reduced somewhat by maintaining the cryogen at the ambient pressure at float

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altitude (~700 Pa at ~36 km float altitude), the reduced pressure makes it difficult to effectively transfer heat to the gas; thus we restrict the discussion to cryogens at one atmosphere vapor pressure.

The liquid cryogen is contained in a vessel, typically a vacuum-insulated dewar, which contributes to the mass of the stored-cryogen system. We have taken values for the CryoFab [2] line of storage dewars as typical: the data are available through the company website. The dewar mass and capacity for liquid hydrogen dewars was used for neon. Container mass per stored cryogen mass is reasonably constant for quantities larger than 200 l; since this study was particularly interested in the results for long-duration flights, these values were used. We note that whatever piping, heat exchangers, etc., is required, is not considered part of the storage system, but rather as part of the instrument.

For flights of several days or longer duration, the rate of evaporation of cryogen due to parasitic heat load in the dewar can be important. For the larger capacity dewars, this rate is typically a percent or so per day, although this might be reduced somewhat if colder ambient conditions exist at float altitude. The parasitic heat load evaporates liquid, thereby reducing the amount of latent heat available, however the evaporated gas remains able to absorb heat on warming. Including this, Eq. (1) is modified to

$$H(T) = [H(T\_cool) - H(T\_sv)] + Lv(P\_sv) * (1 - \mathrm{NER} * \mathrm{duration}), \tag{2}$$

where NER = normal evaporation rate (taken to be 1% of total capacity per day), and duration is the time, in days, over which cooling is required. The magnitude of the parasitic effect will be discussed in Section 5.

Fig. 1 shows the data for total mass per stored cryogen mass and for normal evaporation rate. Table 1 shows the values of total mass per cryogen mass selected for the calculations.

3. Cooling with a mechanical cryocooler powered solely by batteries

An alternative to cooling with cryogens is to store electrical energy in batteries which are carried as part of the balloon payload, and to pump heat from the instrument as needed, using a mechanical cryocooler. In this case the relevant comparison is the amount of heat which can be extracted from the instrument per unit mass of the storage batteries; like the stored thermal energy in the cryogen, the stored electrical energy is fixed at launch. Efficiency of conversion of electrical energy into pumped heat is a function of temperature; applying the appropriate factor yields the heat pumped per unit mass of batteries.

Table 1
Total mass/cryogen mass ratio (kg/kg) used in calculating enthalpy per lofted mass.

H2	He	Ne	N2	O2	Ar
10.6	4.8	1.6	1.6	1.4	1.4

The mass of the storage batteries is the dominant contributor to mass for this case. The Columbia Scientific Ballooning Facility (CSBF [3]) provides information on the mass and energy storage of the batteries supplied to ballooning missions they support. The value for the median-sized large battery system was used here: 766 kJ/kg (213 W-h/kg).

We use the correlation of cryocooler COP (Coefficient of Performance, or electrical energy input per unit heat pumped) found by Olson et al. [4] for acoustic-Stirling ("pulse-tube") mechanical coolers:

$$\mathrm{COP} = 1 + (T\_reject/T\_cool)^2, \tag{3}$$

where *T_reject* is the temperature at which the mechanical cryocooler rejects heat and *T_cool* is the temperature to which the instrument is cooled. An efficiency of 0.85 for the cryocooler drive electronics was assumed. The heat pumped per unit mass of battery storage is then

$$Q\_battery = (766\ \mathrm{kJ/kg}) * 0.85/\mathrm{COP}. \tag{4}$$

Mass of the cryocooler and drive electronics was not included in the total mass calculation; instead, as in the case of cryogen-gas plumbing, it was considered as part of the instrument. For acoustic-Stirling–type cryocoolers this mass is typically fairly small, ~10 kg or less. In pumping heat, the energy dissipated (and pumped) by the cryocooler must be rejected. The ambient air, at temperature of ~240 K, does not provide good thermal transport due to the low pressure; however, radiation away from sun- or earth-facing directions is effective. This can add complexity to the overall system, but we do not address that issue here other than to say that the additional mass is likely less than that for the cryocooler, is specific to the instrument design, and is thus not considered.

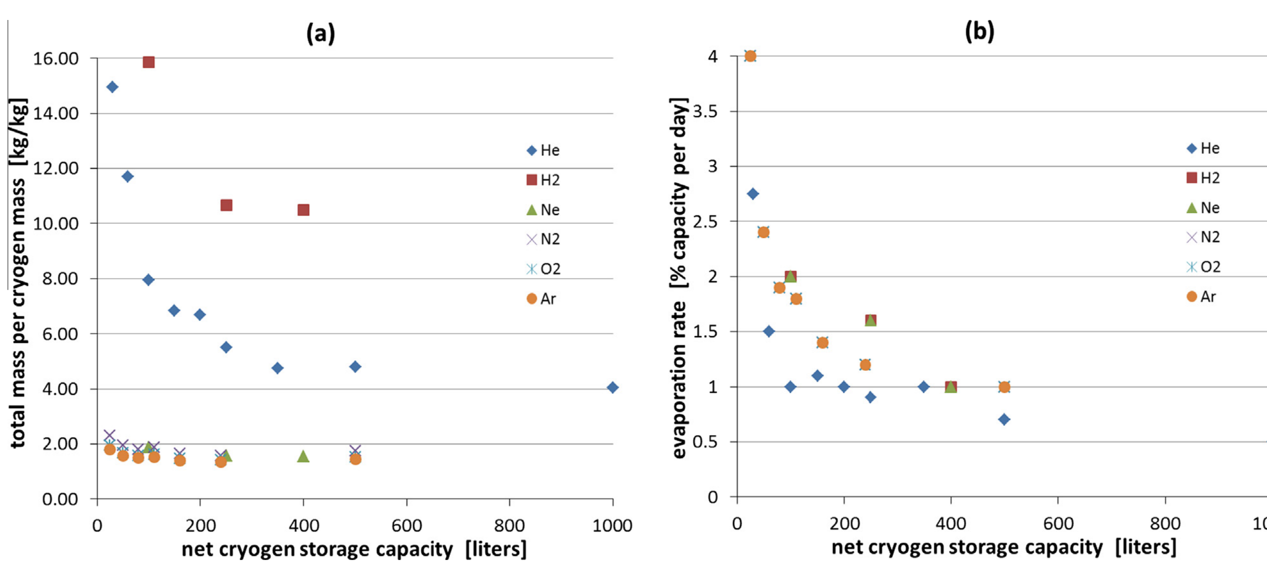

Fig. 1. (a) Total mass of cryogen plus storage vessel per unit mass of cryogen, for six cryogens, as a function of storage vessel volume. (b) Normal evaporation rate for the same dewars, in units of percent capacity per day.