Distributed Cooling Techniques for Cryogenic Boil-Off Reduction Systems

J. R. Feller[1], L. J. Salerno[1], A. Kashani[2], J. R. Maddocks[2], B. P. M. Helvensteijn[2], G. F. Nellis[3], and Y. B. Gianchandani[4]

[1]NASA Ames Research Center, Moffett Field, CA 94035
[2]Atlas Scientific, San Jose, CA 95120
[3]University of Wisconsin-Madison, Madison, WI 53706
[4]University of Michigan-Ann Arbor, Ann Arbor, MI 48109

ABSTRACT

Zero boil-off (ZBO) or reduced boil-off (RBO) systems that involve active cooling of large cryogenic propellant tanks may be required for future space exploration missions. For liquid oxygen or methane, such systems could be implemented using existing high technology readiness level (TRL) cryocoolers. For liquid hydrogen temperatures (~ 20 K) no coolers exist. In order to partially circumvent this technology gap, the concept of broad area cooling (BAC) has been developed, whereby a low mass thermal radiation shield could be maintained at a temperature around 100 K by steady circulation of cold pressurized gas through a network of narrow tubes. Using this method, it is possible to all but eliminate the radiative heat leak to 20 K . The heat transfer capabilities of BAC networks are described. In addition, novel components (namely, a cold helium circulator and a piezoelectrically actuated micro-valve) are proposed that could improve the efficiency and enhance the capabilities of BAC systems.

INTRODUCTION

This work is motivated by NASA's recurring interest in enabling technologies for long-term storage of cryogenic propellants. Depending on the mission requirements, reduced boil-off (RBO) or zero boil-off (ZBO) storage will likely require the use of advanced passive thermal control techniques, such as high performance multilayer insulation (MLI). But in many cases (for example, multi-month loiters in low earth orbit) integration of active cooling components might also be necessary, or at least advantageous. For active RBO or ZBO preservation of liquid oxygen (LO_2) or liquid methane (LCH_4), this does not present a serious problem, at least conceptually, as flight-like pulse tube cryocoolers, operating at cold head temperatures of 90 K and above, and with sufficient cooling capacities (tens of watts), are available.

Direct cooling of LH_2 tanks is not a feasible option because a high capacity 20 K cryocooler technology is presently, and for the foreseeable future will remain at a low readiness level. Simple calculations indicate that, along with effective MLI, an actively cooled thermal radiation shield,

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maintained at ~ 100 K, is capable of nearly eliminating the radiative heat leak to 20 K. Heat is intercepted and removed at the shield temperature using *existing* cryocooler technology. Preliminary studies examined conductively cooled shields integrated directly with one or more discrete cold heads. In order to achieve a reasonable temperature uniformity, high thermal conduction rates are required. The fact is that such a shield would be prohibitively massive.

The mass of the thermal shield can be greatly reduced if distributed cooling techniques are employed. Of the techniques that have been considered, the most promising is the broad area cooling (BAC) scheme. A BAC system consists of a network of tubing (diameter ~ 1 mm), thermally bonded to a low-mass shield structure, through which cold, pressurized helium (~ 1 to 2 MPa) is circulated. The heat absorbed by the helium stream is removed at a remotely located cold head. The resulting pressure drop across the network is manageable using existing flight-like gas circulators. A BAC shield can in principle be of low mass. With moderate flow rates, a temperature uniformity on the order of a few degrees may be achieved with a ~ 1 mil thick metal foil shield.

HEAT TRANSFER IN THE BAC NETWORK

A schematic diagram of a basic BAC circulation loop is pictured in Figure 1. In this case, the gas circulator is warm; it is partially isolated from the cold section of the loop by a recuperator (depicted as a counter-flow heat exchanger). Heat is removed from the circuit via a heat exchanger that is directly integrated with a single discrete cold head. The BAC network would typically consist of a number of identical parallel cooling lines, distributed uniformly over the shield surface. As discussed in a previous paper[1], the relations describing the temperature rise ΔT and pressure drop ΔP between the network inlet and outlet in terms of the mass flow rate $\dot{m}$ (kg/s) and the $\dot{Q}$ total heat load (W) are simple and intuitive, provided certain conditions are met, as they usually are in most applications of interest. For a single cooling line of length L,

$$\dot{Q} = \dot{q}_\lambda L = mc_p \Delta T \tag{1}$$

where $\dot{q}_\lambda$ (W/m) is the (assumed constant) heat load per unit length, and c_p is the mass-specific heat of the gas. Usually, ΔT is treated as a design parameter (*i.e.*, it is the maximum allowable temperature rise). In that case, Eq. (1) states that the required mass flow rate is directly proportional to the total heat load. The pressure drop is given by

$$\Delta P = -\frac{1}{2}\frac{L}{D} f \rho u^2 = -\frac{8L}{\pi^2 D^5}\frac{f}{\rho_{av}} m^2 \tag{2}$$

where ρ is the gas density, ρ_{av} the average density between inlet and outlet, u is the gas velocity, f is the appropriate friction factor, and D is the tube inner diameter.

The heat transfer effectiveness of a BAC cooling line has been investigated experimentally using a distributed cooling test fixture at NASA Ames Research Center. The test section consisted simply of an aluminum plate bonded with a low-temperature epoxy to a short length of stainless

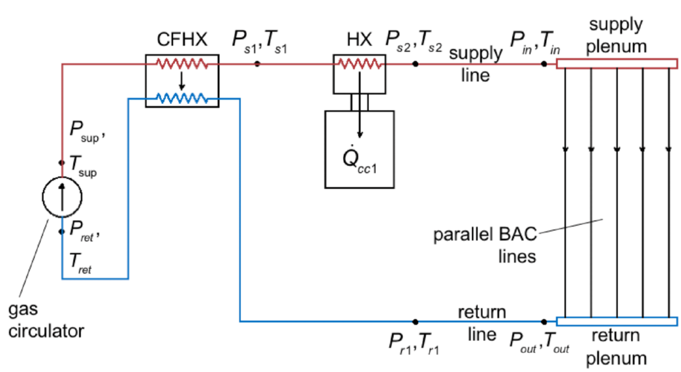

Figure 1. Schematic of a typical circulation loop interfaced with a BAC network. The warm gas circulator is thermally isolated from the cold section of the loop by a recuperator, here shown as a counter-flow heat exchanger.

steel tubing, through which cold (~ 80 K) pressurized helium gas flows. The temperature drop between the plate and the gas stream and the temperature rise between inlet and outlet were measured as functions of the total heat load on the plate. The total thermal resistance between the plate and the gas stream is deduced and compared with the theoretical prediction. Using the *NTU* (number of transfer units) description of heat exchange from an isothermal wall to a steady gas flow, the heat transfer effectiveness ratio is

$$\eta = 1 - \exp\left(-NTU\right) = 1 - \exp\left(-L / R_\lambda c_p m\right) \tag{3}$$

where R_λ (m·K/W) is the unit line resistance. This is plotted vs. the mass flow rate in Fig. 2. The condition $L >> D$ is not satisfied, so the effectiveness is enhanced over the long-tube limit due to end effects. However, the measured R_λ can be used to infer the value of h for long BAC lines, which is the lower curve in Fig. 2 . In Fig. 3 η is plotted vs. L, for mass flow rates of 5, 20, and 35 mg/s. This figure illustrates why the BAC concept works: A simple short tube thermally bonded to a surface constitutes a poor heat exchanger. But a sufficiently long tube, drawing modest quantities of heat per unit length, which by Eq. (1) equates to a low required flow rate, can be quite effective.

OTHER SYSTEM COMPONENTS

As stated in the introduction, high capacity 90 K pulse tube refrigerators are available at high technology readiness level (TRL > 7). Likewise, high TRL flight-like gas circulators (compressors) exist and are used in reverse-Brayton and other recuperative-cycle cryocoolers. One attractive circulator option is to employ a small linear pressure wave generator (which is efficient and reliable) in conjunction with a flow rectifier. The rectifier consists of two opposed check valves, acting as flow diodes, and two small buffer volumes, acting as acoustic compliances. This is the fluid-dynamic analog of the electrical ac-to-dc full-wave rectifier.

The recuperator also has a high TRL component. It typically carries a substantial mass penalty. Ideally, it should be as effective as possible. Any ineffectiveness will translate into an extra heat load on the cold head, with attendant increases in cryocooler mass and power requirements. On the other hand, the recuperator mass necessarily increases dramatically as its effectiveness is pushed toward 100 percent. The recuperator therefore represents a difficult design trade.

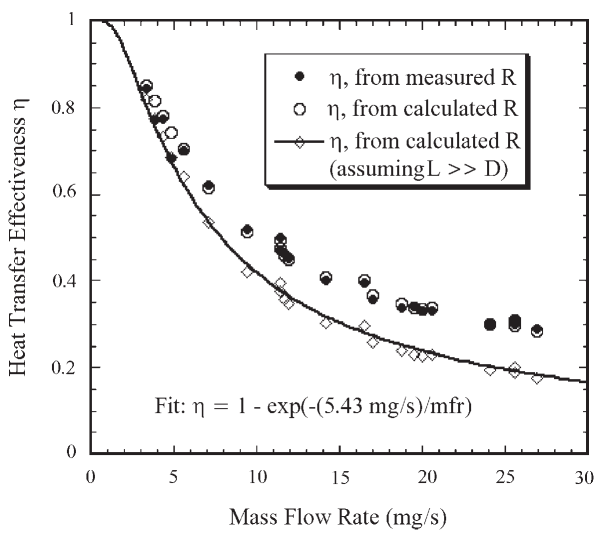

Figure 2. Heat transfer effectiveness of the BAC test article. Solid circles: Effectiveness given by Eq. (3) with the measured thermal resistance between the plate and the gas stream. Open circles: With thermal resistance calculated from thermal fluid model (and temperature-dependent fluid properties). Diamonds: $L >> D$ limit, with calculated thermal resistance.

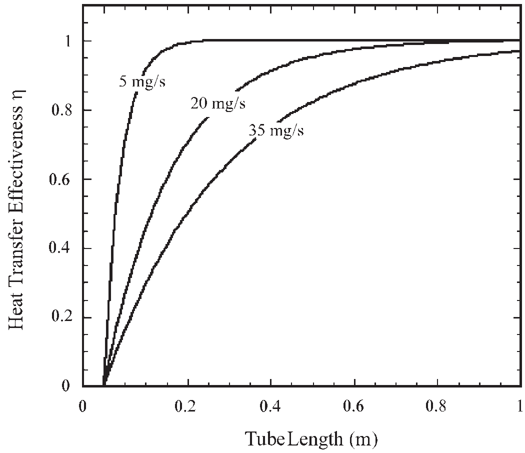

Figure 3. BAC heat transfer effectiveness vs. tube length (long-tube limit, using the measured thermal resistance between the plate and the gas stream).

Of course, the function of the recuperator is to thermally isolate the warm circulator from the cold flow loop. It would therefore be preferable to employ a cold circulator. A very promising candidate is the hybrid pulse tube / circulator (Fig. 4). The cold head is tapped into and a relatively small oscillating flow is diverted to a cold rectifying interface. The warm compressor is thermally isolated from the cold circulation loop by the regenerative heat exchanger, instead of the much more massive recuperator. Moreover, there is no need for the cold head heat exchanger, as shown in Fig. 1, nor for a second compressor to drive the circulation. In the entire cooler / circulator unit there are only four moving parts: two flexured pistons (dual opposed) in the linear compressor, and two check valves. The check valves must be capable of operating reliably at cryogenic temperatures. Such systems, including reliable cryogenic check valves, have been developed and are used routinely at the University of Wisconsin-Madison.[2] Alternatively, an independent cold circulator, as in Fig. 5, could be employed. In this case a warm linear compressor, again isolated from the circulation loop by a regenerator, drives only the cold rectifier, while heat is rejected from the circuit by a

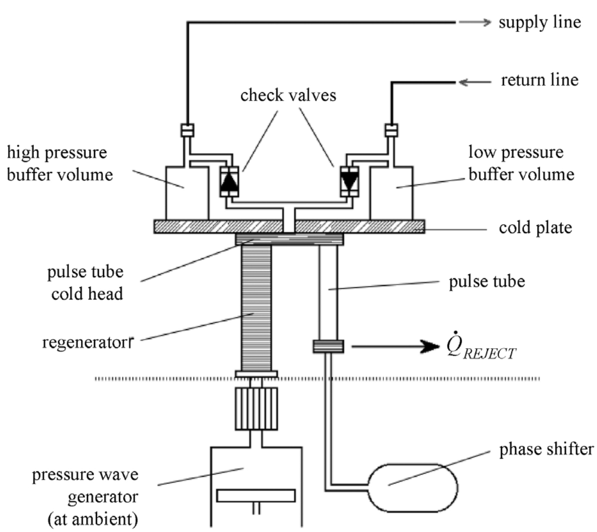

Figure 4. Hybrid pulse tube refrigerator / circulator. The warm linear compressor, thermally isolated from the cold circulation loop by the regenerator, drives both the pulse tube cooler and the cold flow rectifier.

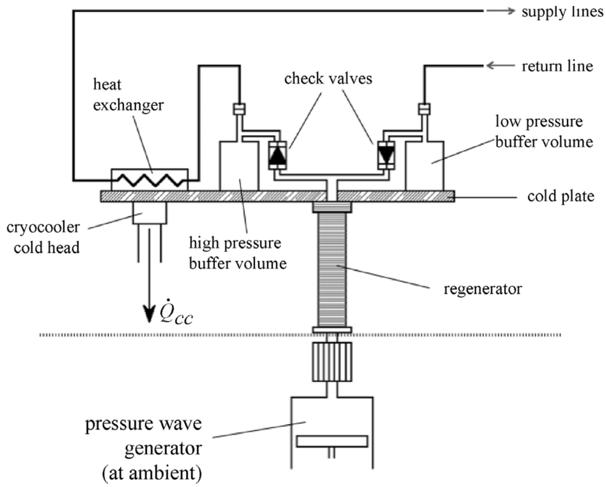

Figure 5. Independent cryocooler and gas circulator. The cryocooler cold head is interfaced with the circulation loop via a heat exchanger. The circulator's warm compressor is isolated from the loop by a regenerator; it drives only the cold flow rectifier. A small pulse tube could also be incorporated to remove the heat leak due to the regenerator's ineffectiveness.

closed pulse tube refrigerator as in Fig. 1. A phase shifter (not shown) at the cold plate would be used to ensure an optimum phase difference between the pressure wave and the oscillating flow in the regenerator. A small pulse tube could also easily be introduced to take up the heat introduced due to the regenerator's ineffectiveness. This configuration might be preferable to the hybrid, as it would allow independent variation of cooling power and flow rate, thus perhaps providing a higher degree of system control.

Finally, the stability and versatility of a BAC network would be enhanced by incorporating within each branch an active flow control valve. To this end, a piezoelectrically actuated MEMS-patterned micro-valve has been developed in a collaborative effort among researchers at the University of Michigan-Ann Arbor, the University of Wisconsin-Madison, Atlas Scientific, and Ames Research Center[3]. Several prototypes have been produced and tested. The micro-valve has the following highly desirable characteristics: Reasonably high flow rates with acceptable pressure drop, very fast response time; very fine throttling control, operable down to 20 K, negligible power dissipation, and a very small package (about the size of a sugar cube).

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