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STUDY OF PROPELLANT PRESERVATION USING A RE-LIQUEFIER SYSTEM

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Abstract: *For long time orbital and interplanetary missions, a fundamental problem is to preserve propellants in liquid state. The research works has shown that for missions longer than few months, a cooler and associated control, power and heat rejection systems results in a lower total systems weight. There are two alternatives active cooling systems to prevent boil off propellant. First is closed cycle coolers to balance the parasitic loads on the propellant and the second is re-liquefier. This paper presents an analysis of re-liquefier system, which uses the propellant vapor as working fluid.*

Keywords: *cryorefrigerator, re-liquefier, liquid propellant.*

1. INTRODUCTION

There are two possibilities to preserve propellant in liquid phase for long time orbital and interplanetary missions. To preserve the propellant a cooling system is necessary. This cooler can prevent the boil off of the propellant. One alternative is a closed cooling system to balance the parasitic heat loads. Like closed cooler we can consider Stirling, Brayton and Puls Tube cryocoolers. These coolers use a gas refrigerant that is not the same as the stored propellant. The second alternative is is to use the vapor from the storage tank as the refrigerant. This vapor is re-liquefied by the cooler and put back into the tank.

This may eliminate the need for a mixer in the propellant tank, may reduce the effect of leaks in the cooler and may allow a more graceful way to accommodate cooler failure. However, the re-liquefier is unlikely to be operating at its optimal operating point and will require some means of controlling contamination.

2. EMBEDDED COOLER WITH HEAT EXCHANGER

For better understanding of the problem, in figure 1 a conceptual Brayton closed cycle is presented. This cycle can be any recuperative cycle, because these kinds of coolers easy can become re-liquefiers.

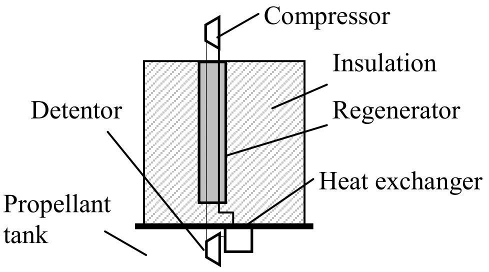


Fig.1. Closed cycle cryocooler

The cryocooler is sized to balance the tank heat load, so boil off is prevented.
The coefficient of performance of the cryocooler is:

$$COP = \eta\left(\frac{T_c}{T_h - T_c}\right) \qquad (1)$$

where:
T_c - temperature of the cold expander;

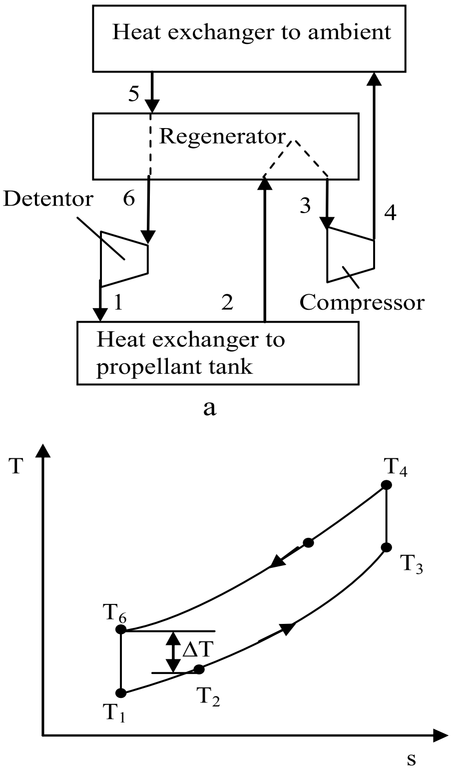
T_h - temperature of the compressor;

$\left(\frac{T_c}{T_h - T_c}\right)$ - Carnot efficiency;

$\eta < 1$ - coefficient which contains all the losses.

If this cryocooler has been optimized, η has the maximum value. The cryocooler described in figure 1 will be considered a reference system. Any changes of the structure system will be reflected in η value.

In figure 2 a schematic drawing and T-s diagram for a reverse Brayton cycle are presented.



a

b

Fig. 2. Schematic layout (a) and T-s diagram (b) of Reverse Brayton Cycle

In real conditions, gradients temperature exist between the cryocooler and its load and between cryocooler and heat rejection system The cryocooler must operate over a bigger temperature range than given by nominal heat rejection and load temperatures. The hot end of the cryocooler will be ΔT_h above T_h and the cold end will be ΔT_c below T_c. These temperature gradients reduce the efficiency to

$$COP = \eta' \left(\frac{T_c}{T_h - T_c}\right) \tag{2}$$

where

$$\eta' \approx \eta \left[1 - \left(\Delta T_h + \Delta T_c \frac{T_h}{T_c}\right)\left(\frac{1}{T_h - T_c}\right)\right]$$

We assume that $\Delta T_h << T_h$, $\Delta T_c << T_c$ and η of the cryocooler is the same to first order. In practical situations, as the cryocooler is larger the efficiency is higher.

The temperature drop at the cold end of cryocooler has a larger effect on the efficiency than the same drop at the cold end.

3. EMBEDDED COOLER WITH PUMP MIXER

The cryocooler presented in figure 1 is connected to the propellant tank by a simple heat exchanger and it will work in good conditions for ground applications. The heat exchanger is placed in the ullage of the propellant tank and it can easily to re-liquefy the vapor. In space, stratification of the stagnant liquid and vapor in absence of buoyancy driven mixing can be significant. Stratification can be eliminated by using a pump, called pump mixer, to circulate the fluid. In figure 3 is presented a mixer that has integrated with the heat exchanger.

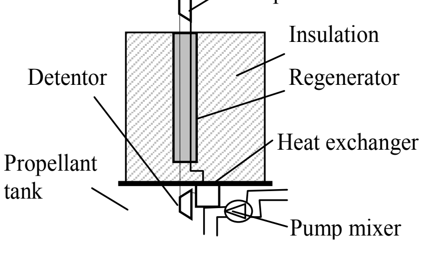


Fig. 3. Closed cycle cryocooler with a pump mixer integrated with the heat exchanger

A liquid acquisition device is needed to ensure that high quality liquid is fed to the pump mixer. Another device (such as a spray bar) is needed to ensure that flow mixes all of liquid in the tank.

In this situation, the coupled mixers with heat exchanger can maintain the tank temperature at constant value. The pump mixer dissipates power that must be removed by the cryocooler.

The heat flux that must be removed will be:

$$\Phi_c = \Phi_p + \Phi_m \qquad (3)$$

where:

- Φ_c is total cooling power of the cryocooler;
- Φ_p is the heat flow leak;
- Φ_m is the power dissipated by the pump mixer

In that situation the cryocooler power is bigger by Φ_c / Φ_p.

We can consider the pump mixer and cryocooler as a single unit having an efficiency η''.

$$\eta'' = \eta \frac{\Phi_p}{\Phi_c} = \eta\left(1 - \frac{\Phi_m}{\Phi_c}\right) \qquad (4)$$

is the efficiency compared to a cryocooler without pump mixer.

4. RE-LIQUEFIER USING PROPELLANT AS REFRIGERANT

Instead the use of pump mixer, there is the possibility to directly inject the cold refrigerant into the tank. The vapor propellant from the tank return to the cryocooler to be circulated and re-liquefied. In figure 4 a re-liquefier is presented. It requires the same working fluid as is stored in the tank.

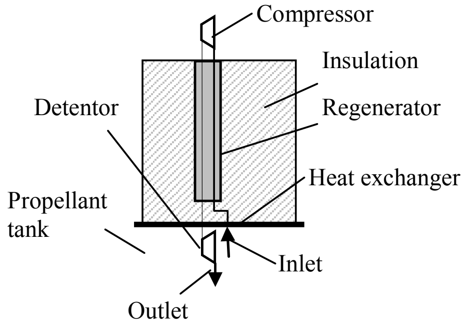


Fig.4. Open cycle cryocooler working as re-liquefier

This re-liquefier presents two important advantages:

- the pump mixer is eliminated. the mixing flow is supplied by the compressor.
- because low pressure in return circuit, this can be used as a vent line in case of compressor failure. In that situation the additional vent line is eliminated, reducing the heat leak on the tank. Using return line like an emergency vent line also intercept the parasitic heat leak that the nonfunctioning cryocooler components on the tank.

Both advantages reduce the heat that must be removed from the tank by cryocooler.

By eliminating the pump mixer, the efficiency of the liquefier is:

$$\eta''' \approx \eta\left(1 + \frac{\Phi_m}{\Phi_c}\right) \qquad (5)$$

This relation can be generalized to show the effect of any reduction of heat flow, Φ_r, into the tank:

$$\eta''' \approx \eta\left(1 + \frac{\Phi_r}{\Phi_c}\right) \qquad (6)$$

There are some disadvantages in case of use re-liquefier. The cryocooler must use vapor propellant as working fluid, with return pressure at tank pressure value and with two-phase fluid in the expander. An unbalanced enthalpy flow in the cryocooler heat exchanger results because cold end two-phase regime operating conditions. This reduces the efficiency of the cryocooler:

$$\eta'''' \approx \eta\left(1-\frac{\dot{m}\Delta h}{\Phi_c}\right) \tag{7}$$

where $\dot{m}$ is the mass flow through the cryocooler and Δh is the enthalpy change of the two phase flows. If the tank temperature and pressure change in time due to orbital conditions or tank operations, then the operating pressure of the cryocooler also changes. This is not an efficient operating condition.

Another disadvantage is the contamination of working fluid. Condensable gases and other solids in the propellant can block the flow passages in the cryocooler, damage the compressor and expander and reduce the effectiveness of heat exchangers. This contamination can be removed with extensive filtration, but in this situation a pressure drop will appear in filters. This pressure drop will lead to pressure ratio and power requirement of the compressor increase. If the pressure ratio of the compressor is increased from p to $p+\Delta p$ and the efficiency compressor is not changed, then:

$$\eta''''' \approx \eta\left(1-\frac{\Delta p}{p}\right) \tag{8}$$

The mass flow rate in the cooler is expected to be significantly lower than mass flow rate from the pump mixer. This will reduces the effectiveness of the mixing

The design details must balances the cooling system efficiency against the risk of contamination causing system degradation or failure.

5. RE-LIQUEFIER USING PROPELLANT AS REFRIGERANT WITH THERMODYNAMIC VENT SYSTEM

This concept was introduced for liquid hydrogen applications. One problem with the re-liquefier with thermodynamic vent system, presented in figure 3, is ensuring that only vapor is returned to the cooler. Liquid flowing in the inlet line can cause flashing. This results in potentially damaging pressure spikes. On the ground, one can ensure there is vapor at the inlet by placing the inlet in ullage tank. In space, some device is the thermodynamic vent system TVS.

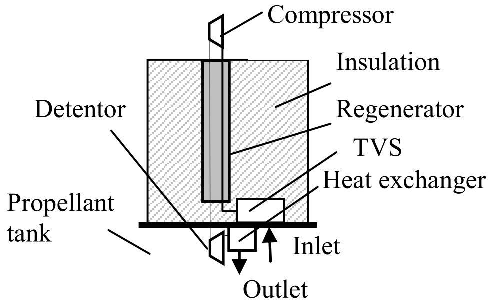


Fig. 5. Open cycle re-liquefier with thermodynamic vent system

This system, presented in figure 5, consist of a recirculation pump, a Joule-Thomson (J-T) expansion/shutoff valve, and a parallel flow concentric tube heat exchanger/spray-bar apparatus. The pump extracts liquid propellant from the tank and flows it through the heat exchanger. The fluid re-enters the tank through orifices in the spray bar that expel the fluid radially into the tank. This results in propellant destratification and ullage condensation through mixing. When pressure control within the tank cannot be maintained through mixing alone (bulk liquid is saturated at the ullage pressure), a small amount of fluid extracted from the recirculation flow is passed through the J-T valve where it is expanded to a lower pressure and temperature. The subcooled two-phase fluid mixture is then passed through the heat exchanger, which extracts heat from the recirculation flow, and subsequently is vented overboard.

6. CONCLUSIONS

To prevent boil off of the propellant two types cryocooler are presented. For a closed cryocooler, a different working fluid is used. If the system contains a pump mixer, this device circulates cooled propellant through the tank. This system presents the advantages in efficiency and the possibility to test the cooler before integration in propellant tank.

The second type is a re-liquefier , the propellant being the working fluid. In that situation, additional cooling is provided by a thermodynamic vent. This system is simplier to integrate and provide an emergency vent way that intercepts the parasitic heat of the cooler.

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