Two-Stage Refrigeration for Subcooling Liquid Hydrogen and Oxygen as Densified Propellants

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ABSTRACT

The thermodynamic design on two-stage refrigeration cycles is performed as one of several feasibility studies for the densified propellant technologies funded by the NASA Glenn Research Center. The refrigeration is required to increase the density of liquid oxygen and liquid hydrogen by subcooling to 65 K and 15 K, respectively, and to reduce the gross lift-off weight of a launch vehicle by up to 20%. The objective of this study is to seek the most efficient and economic two-stage refrigeration cycle, which satisfies the specific cooling requirements at the two temperature levels so that both densified propellants can be supplied simultaneously on a scheduled launch countdown. Recuperative cycles such as Claude and reverse Brayton refrigeration can be modified for subcooling liquid oxygen and liquid hydrogen in a manner commonly used for large capacity flows at lower temperatures. It is proposed to use a hybrid or cascade cycle, combining recuperative heat exchangers, expander and Joule-Thomson (J-T) valve at 65 K and 15 K. A variety of two-stage cycles derived from J-T, reverse Brayton and Claude cycles are examined in this paper. The essential features and characteristics of selected hybrid two-stage cycles are reported through a rigorous thermodynamic analysis. Among the examined cycles, the two-stage reverse Brayton helium refrigeration system shows a very suitable possibility for cryogenic propellant densification technology.

INTRODUCTION

Since 2002, the Florida Solar Energy Center has conducted intensive research and development on cryogenic propellant densification technologies funded by NASA Glenn Research Center through the NASA Hydrogen Research at Florida Universities Program. By use of cryogenic propellants densification technologies, the single-stage-to-orbit (SSTO) and the reusable launch vehicles (RLV) become more attractive because of the reduced vehicle mass. The 8 ~ 10% denser cryogenic propellants at temperatures lower than those of the normal boiling point (NBP) can reduce the gross lift-off weight (GLOW) of a launch vehicle by up to 20% or increased payload capability.[1]

As an initial investigation, several promising densification systems were investigated based on various launch scenarios, and a rigorous thermodynamic analysis using real propellant properties was performed to suggest the most feasible and reliable system for the launch vehicle application.[2] It turned out from the investigation that a combination of a thermodynamic venting system (TVS) and a Claude refrigerator for each propellant showed promise of being a highly efficient system from a thermodynamic point of view, but the system becomes rather complicated. The TVS system or subatmospheric boiling bath heat exchanger technology requires an additional gas compressor to densify NBP cryogenic propellants by lowering the vapor pressure. Furthermore, this technology requires two independent densification systems for liquid oxygen and liquid hydrogen, even though they may be suitable for large cooling power requirements.

In this paper, it is suggested for thermodynamic efficiency and economic practice that a two-stage refrigeration cycle be used to satisfy the specific cooling requirements at the two densification temperatures. The two-stage refrigeration cycle provides specific cooling powers at the two temperatures so that both densified propellants can be supplied simultaneously on a scheduled launch countdown. This technology is achievable by employing recuperative cycles such as the reverse Brayton and the Claude refrigeration cycle, which are commonly used for large capacity applications at lower temperatures. By designing a hybrid or cascade cycle with recuperative heat exchangers, expander, and Joule-Thomson valve, it is possible for us to provide the specific cooling requirements at specific densification temperatures at the same time. To verify the feasibility and characteristics of this new concept, rigorous thermodynamic analyses have been performed for a variety of two-stage cycles using combinations of J-T, reverse Brayton and Claude cycles.

IDEAL (REVERSIBLE) CYCLES

For the case where two cooling temperatures and their cooling capacities are given, we can classify possible refrigeration systems into three main categories as shown in Fig. 1. Figure 1(a) shows a 'Two single-stage coolers' system. Two separate cooling systems with two input powers provide the required cooling capacities at each cooling temperature. As the densification temperatures, 65K and 15K are selected for oxygen and hydrogen, respectively. Fig. 1(b) shows a 'One two-stage cooler' system that provides two independent cooling powers at two cooling temperatures and requires one input power. Also, the 'cascade cooler system' in Fig. 1(c) can be considered as one of the candidates for the two cooling temperatures and two cooling powers application. For ideal reversible refrigeration cycles, however, the minimum required input power should be the same for the three cases. By combining the energy and entropy balances, the minimum required work input for the three cases in Fig. 1 can be expressed as Eq. (1).

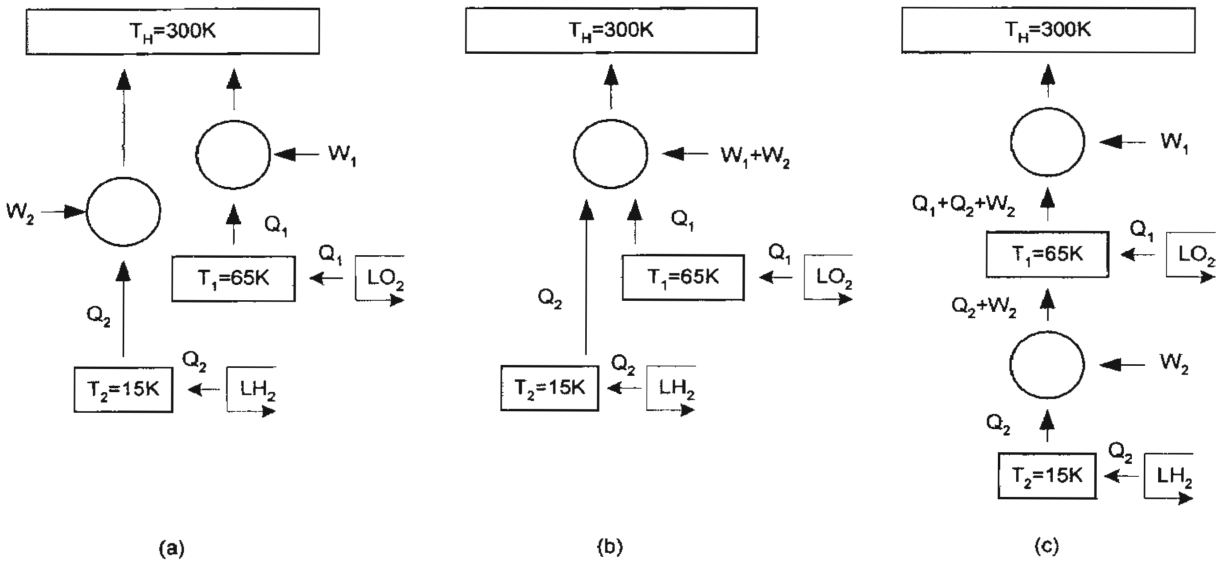


Figure 1. Ideal reversible cycles operating at two cooling temperatures; (a) two single-stage cooler system, (b) one two-stage cooler system, (c) cascade cooler system.

$$
\begin{aligned}
W_{A\,or\,B} &= W_1 + W_2 = Q_1\left(\frac{T_H}{T_1}-1\right)+Q_2\left(\frac{T_H}{T_2}-1\right)\\
W_C &= W_1 + W_2 = (Q_1+Q_2+W_2)\left(\frac{T_H}{T_1}-1\right)+Q_2\left(\frac{T_1}{T_2}-1\right)\\
&= Q_1\left(\frac{T_H}{T_1}-1\right)+Q_2\left(\frac{T_H}{T_1}-1\right)+Q_2\left(\frac{T_1}{T_2}-1\right)\left[\left(\frac{T_H}{T_1}-1\right)+1\right]\\
&= Q_1\left(\frac{T_H}{T_1}-1\right)+Q_2\left(\frac{T_H}{T_2}-1\right)
\end{aligned}
\tag{1}
$$

This implies that when we construct ideal cycles, any variation of system configuration does not affect the thermodynamic performances unless operating temperatures and cooling requirements are changed. In reality, however, there must be differences among them since their performances depend on thermodynamic and mechanical efficiencies of system components. For instance, system (a) and (c) in Fig. 1 have at least two work input components which is, in general, compressors. The requirement of two compressors to run the system may result in a more complicated, more expensive, less reliable, and less efficient system. On the other hand, system (b) in Fig. 1 can be operated by only one compressor, so that it has an inherent simplicity in system constitution. Furthermore, it can be a versatile system to provide various cooling powers at each cooling stage by controlling system design parameters such as work input, and cooling-power distribution ratios. Therefore, the choice of the appropriate refrigeration system and optimal operating condition based on both thermodynamic and practical considerations should be made at the design stage.

TWO-STAGE COOLERS

Figure 2 schematically shows a few simplified variations of the two-stage refrigeration cycle. Figure 2(a) depicts a two-stage reverse Brayton helium cycle. Two expanders are located at each densification stage to densify cryogenic propellants. The gas temperatures at the exits of the 1st and the 2nd expander are required to be low enough to densify saturated cryogenic propellants. Since helium is maintained in a gaseous state at the exit of the 2nd (lower temperature) expander, a dry expander can be used. The helium gas temperatures at the expander exits and the required cooling powers at each stage can be controlled by varying the mass flow fraction at the inlet of the first expander, the total mass flow rate in the compressor, and the compressor discharge pressure. Figure 2(b) shows another two-stage cooling cycle, a combination of reverse Brayton and Claude cycles with a J-T expansion valve. Even if a Claude cycle is self explanatory that it uses an expander in the 1st stage and a J-T expansion valve in the 2nd stage, this configuration is referred to as a two-stage reverse Brayton-Claude cycle in this paper because of the additional densification heat exchanger at the exit of the 1st stage expander. Since the isenthalpic process in the J-T expansion valve is a major source of irreversibility, a lower system efficiency is expected and a higher operating pressure is required. For hydrogen as a working fluid, we expect a benefit of obtaining subcooled liquid hydrogen at the exit of the J-T valve to enhance heat transfer in densifying saturated liquid hydrogen. Figures 2(c) and 2(d) depict more complicated combinations of reverse Brayton, J-T and Claude systems as references. These hybrid systems consist of both an expander at the liquid oxygen stage and a J-T expansion valve at the liquid hydrogen stage; this gives two independent helium or hydrogen cycles to take advantage of each system component. However, the system configurations tend to be complicated and maintenance issues can be evolved. Therefore, the two configurations in

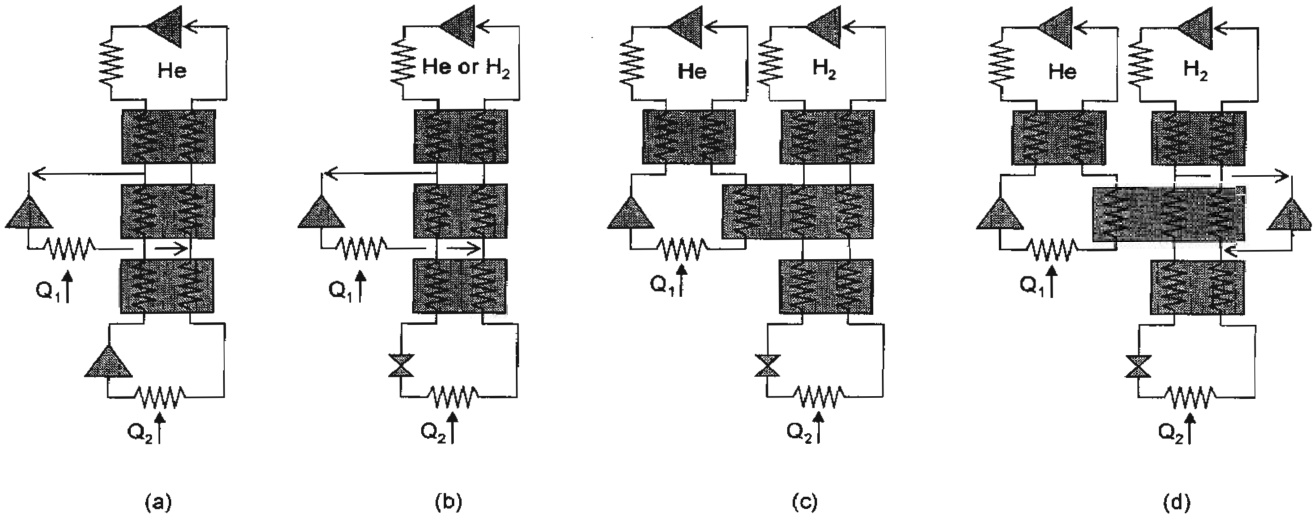


Figure 2. Two-stage cooler variations; (a) two-stage reverse Brayton helium cycle, (b) reverse Brayton-Claude helium/hydrogen cycle, (c) combination of reverse Brayton helium and J-T hydrogen cycle, (d) combination of reverse Brayton helium and Claude hydrogen cycle.

Figs. 2(a) and 2(b) are chosen in this paper to explore the possibility of using two-stage coolers to provide the required cooling powers at the required densification temperatures.

Two-Stage Reverse Brayton Helium Cycle

Based on the preliminary investigation on the required cooling power for various launch scenarios[2], the cooling powers that are required to densify 1 kg/s of liquid hydrogen and 6 kg/s of liquid oxygen are fixed in the rest of thermodynamic analysis. These flow rates depend on cooling the propellants before the start of the loading process. If the densification occurs during vehicle load, the rates become much higher. The corresponding cooling powers are 48 kW at 15 K and 268 kW at 65 K, respectively. In this analysis, discharge and suction pressures of the compressors are set to 2020 kPa and 101 kPa, respectively. The mass flow fraction at the inlet of the 1st expander, y, is defined as follows:

$$y \equiv \frac{\dot{m}_{\text{1st expander}}}{\dot{m}_{compressor}} \qquad (2)$$

Figure 3 shows results of the thermodynamic cycle analysis for the two-stage reverse Brayton helium cycle. In this analysis, computerized real properties of helium are used.[3] Figures 3(a) and 3(b) show the required total mass flow rates of system and mass flow fractions at the inlet of the 1st expander as functions of densification stage temperatures. To obtain 65K and 15K of cold helium gas after the expanders at the densification stages, the system requires about 1.2 kg/s of total mass flowrate in the compressor and the mass flow fraction should be slightly over 50% of the total mass flow rate from Fig. 3(a) and (b). Figures 3(c) and 3(d) show the same results from a different angle of view. By changing the total mass flow rate of the system and the mass flow fraction, it is possible to get various densification temperatures at each stage for a fixed compressor discharge pressure. For a given total mass flow rate, the liquid oxygen densification temperature decreases as the mass flow fraction increases, since the mass flow rate expanded in the 1st expander increases for a fixed cooling power. However, the liquid hydrogen densification temperature has a minimum value, because the liquid hydrogen densification temperature is affected by the liquid oxygen densification temperature and mass flow rate at the 2nd stage at a fixed cooling power. In this analysis, the Figure of Merit (FOM: %Carnot) is calculated to be 0.54.

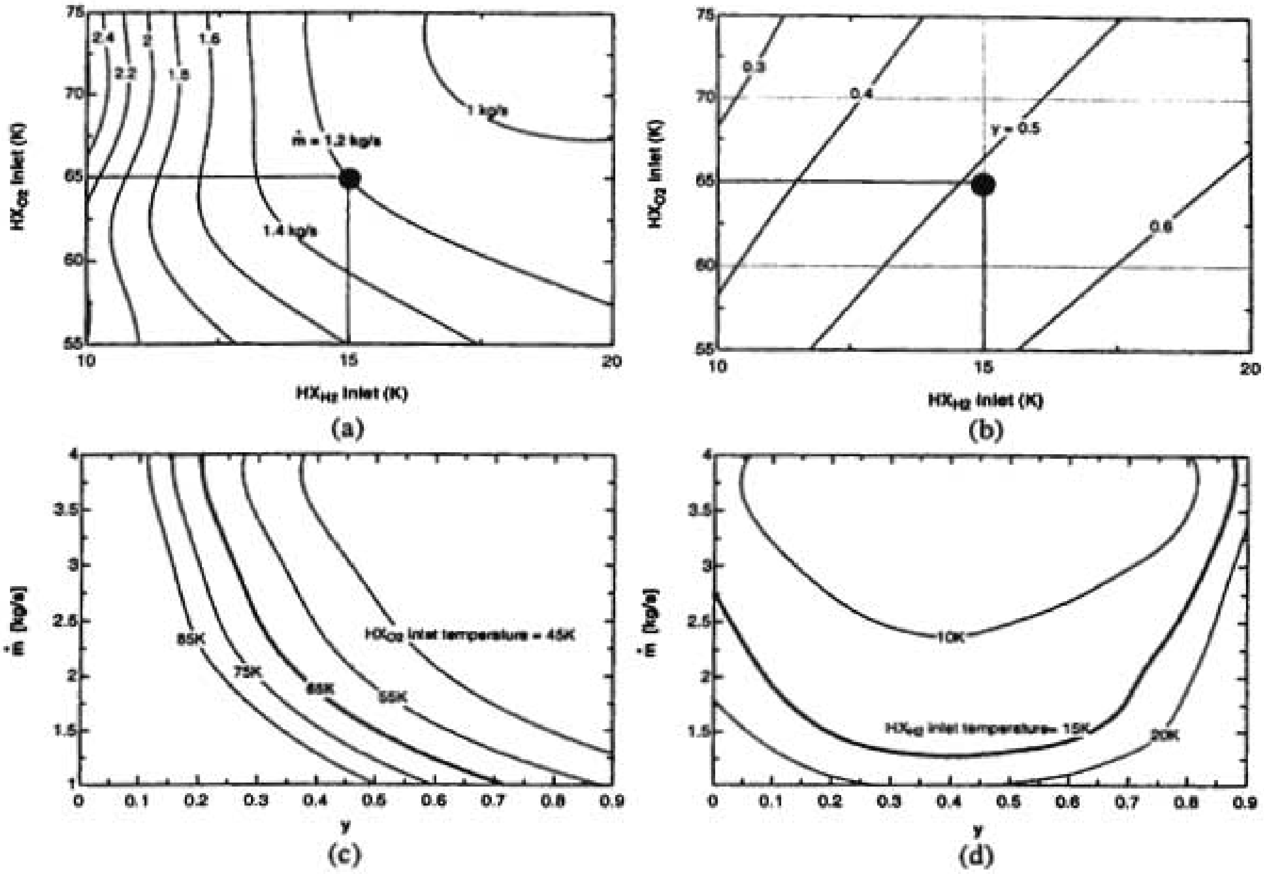


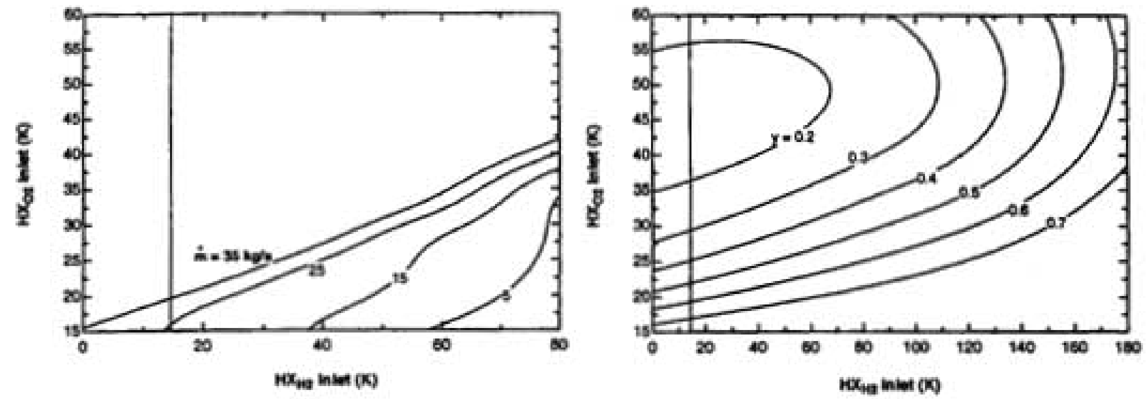
Figure 3. Selected analysis results of two-stage reverse Brayton helium cycle ($P_{discharge}$=2020 kPa, $P_{suction}$=101 kPa, heat exchanger effectiveness = 0.95, expander efficiency = 0.8)

Two-Stage Reverse Brayton-Claude Helium Cycle

The same analysis was performed for the two-stage reverse Brayton-Claude helium cycle, and the results are shown in Fig. 4. Since this cycle includes a J-T expansion valve, the calculated total mass flow rates of the system to satisfy the required cooling power at a given densification temperature are much higher than those of the two-stage reverse Brayton helium cycle for the same discharge pressure. In addition, available densification temperature ranges, in particular, for liquid oxygen are too low; thus, oxygen may be frozen or frosted in the heat exchanger. The same analyses were performed for higher and lower compressor discharge pressures, total mass flow rates, and mass flow fractions. In spite of intensive efforts to obtain better densification temperature ranges and operating conditions, this configuration seems to be inappropriate for this specific propellant densifier application.

Two-Stage Reverse Brayton-Claude Hydrogen Cycle

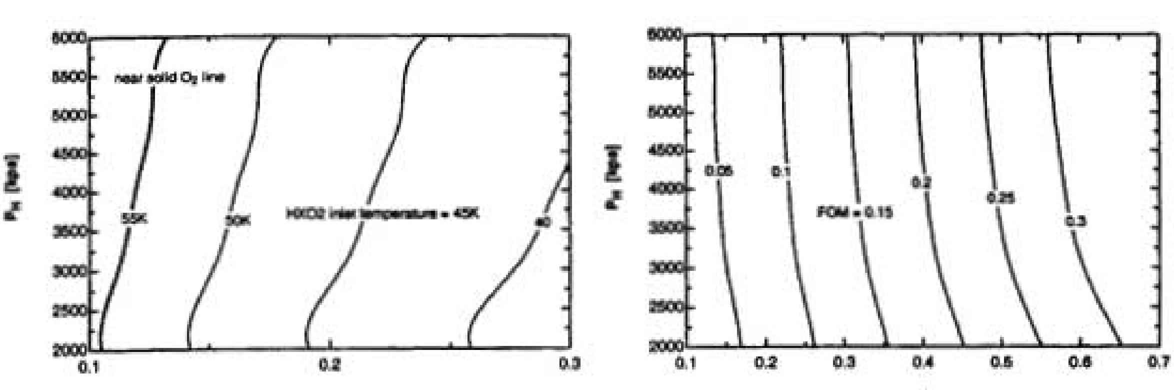
As in the previous analysis, real properties of hydrogen[4] are incorporated into the reverse Brayton-Claude hydrogen cycle analysis. First, various ranges of compressor discharge pressures were explored to obtain appropriate operating conditions that satisfy specific cooling requirements. Figure 5 shows that it is difficult for this hydrogen cycle to find the densification temperatures within a reasonable range. Again, the main reason for these imbalances is associated with the assumption that the ratio of cooling requirements associated with the ratio of mass flow rates of densified propellants (hydrogen:oxygen = 1:6) at each densification temperature are fixed. Also, the system efficiency becomes much lower than that of a two-stage reverse Brayton helium cycle because of the higher pressure ratio for J-T expansion. In addition, using hydrogen to cool oxygen in a heat exchanger has safety issues and may not be allowed at a launch site.



(a) (b)

Figure 4. Selected analysis results of the two-stage reverse Brayton-Claude helium cycle. ($P_{discharge}$ = 2020 kPa, $P_{suction}$ = 101 kPa, heat exchanger effectiveness = 0.95, expander efficiency = 0.8)

From the thermodynamic analysis for the three two-stage refrigeration configurations, one of the best candidates for the cryogenic propellants densifier application seems to be the two-stage reverse Brayton helium cycle. This configuration has many attractive advantages. For instance, it uses helium as the working fluid, which is one of the most common fluids in the cryogenic engineering industry. It consists of heat exchangers, a helium compressor, and expanders; thus, all these system components are commercially available. This configuration can be dedicated to both propellants or to one of them independently. The cooling temperature and cooling power can be controlled by the operating pressure, the total mass flow rate and the mass flow fraction through the 1st expander. In addition, this cycle has proven to be scalable from the range of a few watts—for example, for the Hubble's Near Infrared Camera and Multi-Object Spectrometer (NICMOS) cooler—to a few kilowatts for particle accelerators, to many megawatts for large hydrogen liquefiers. In general, efficiency increases with increased capacity of the refrigerator due to increases in cycle complexity and greater efficiency in physically larger compressors and turbines. A useful rule of thumb to estimate the power required for hydrogen liquefiers is a simplified assumption of 2 kWh/100 scf for midsized units[5], so 834 kW of cooling power would be required for liquefaction of 1 million scf/day of hydrogen. This rate of hydrogen production is available via methane reformers in skid mounted systems, and an efficient liquefier to handle this capacity may have a market demand as hydrogen power becomes widely accepted. For this reason, this configuration might be a very promising design concept for other liquid hydrogen applications such as liquid hydrogen stationary storage facility for hydrogen fuel infrastructure development.



(a) (b)

Figure 5. Selected analysis results of two-stage reverse Brayton-Claude hydrogen cycle. (P_H : compressor discharge pressure, heat exchanger effectiveness=0.95, expander efficiency=0.8)

Table 1. Comparison of thermodynamic performances between selected two single-stage cycles and one two-stage cycle.

Propellant	System	Power required	FOM
Hydrogen (1kg/s, 48kW@ 15K)	TVS+Claude cycle	1408 kW	0.648 (COP_{ideal}= 0.053)
Oxygen (6kg/s, 268kW@ 65K)	TVS+Claude cycle	1698 kW	0.571 (COP_{ideal}= 0.277)
Total	Two single-stage cycles	3106 kW	
Hydrogen(1kg/s)+Oxygen(6kg/s)	One two-stage reverse Brayton helium cycle	3990 kW	~0.54

This cycle is also a candidate for a combined hydrogen and oxygen liquefier for use on the surface of the moon or Mars, if a water source is found. One of the main concerns in realizing this concept would be obtaining appropriate expanders that provide specific cooling requirements.

COMPARISON WITH SINGLE-STAGE COOLERS

In the previous section, three two-stage systems were examined to suggest an appropriate cooling system for cryogenic densified propellants. In the recent report by authors[2], similar thermodynamic analyses were performed for various single-stage coolers for the same application. Now, it becomes interesting to compare their performance with that of two single-stage coolers for the same cooling requirements and densification temperatures. The detailed system configurations for various single-stage coolers can be found in the reference[2], and the final analysis results are discussed in this paper. Table 1 shows a comparison of the thermodynamic performance of the two single-stage cycles with that of one two-stage reverse Brayton helium cycle. In the analysis of the single-stage cycle, the same required cooling power and densification temperature are used. For both hydrogen and oxygen densification, a combination of thermodynamic venting system (TVS) and Claude cycle produces the best performance among selected single-stage systems. The total power required to operate independent hydrogen and oxygen systems becomes about 3 MW to densify 1 kg/s of liquid hydrogen and 6 kg/s of liquid oxygen. This value is comparable with the power required to operate the two-stage reverse Brayton cycle. For the same cooling requirements, the two-stage reverse Brayton helium cycle needs about 4 MW of work input and the overall system efficiency is about 54% of Carnot COP. Even if the two-stage cycle shows a slightly lower thermodynamic performance, it has considerable advantages over the combination of TVS and Claude cycle in reality regarding system reliability and potential safety concerns as listed in Table 2.

Table 2. System characteristics comparison.

Two single-stage TVS + Claude systems	One two-stage reverse Brayton helium system
• Two H_2 and N_2 compressors for main cycles	• One He compressor for main cycle
• Additional gas compressors for TVS are required	• No gas compressor for TVS is needed
• J-T expansion valve : potential clogging	• Gas expanders
• H_2 is used in main cycle	• H_2 is used in densification heat exchanger
• Liquid-to-liquid heat transfer in densification	• Gas-to-liquid heat transfer in densification

CONCLUSIONS

A two-stage hybrid refrigeration system is suggested to provide the most efficient, reliable and economic densification system for launch vehicle applications. A variety of hybrid systems, combining recuperative heat exchangers, expander and J-T expansion valve were examined by a rigorous thermodynamic analysis. In the analysis, three hybrid systems were selected based on their essential features and practical considerations to demonstrate system feasibilities. Thermodynamic cycle simulations using real fluid properties were performed for two-stage reverse Brayton helium system, two-stage reverse Brayton-Claude helium system and two-stage reverse Brayton-Claude hydrogen system. As a result, it is concluded that the two-stage reverse Brayton helium refrigeration system shows a very suitable possibility for the cryogenic propellant densification technology, and its feasibility in practical should be proved by a physical demonstration.

ACKNOWLEDGMENT

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