V.E Liquefaction

V.E.1 Combined Reverse-Brayton Joule Thompson Hydrogen Liquefaction Cycle

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Objectives

Reduce the cost and improve the energy efficiency of hydrogen liquefaction.

- Produce a small-scale (~200 kg/day) hardware demonstration of a hydrogen liquefaction plant
- Develop an efficient hydrogen turboexpander
- Demonstrate liquid hydrogen production efficiencies of 87% or greater
- Demonstrate scalability to larger sized plants

Technical Barriers

This project addresses the following technical barriers from the Hydrogen Delivery section of the Hydrogen, Fuel Cells and Infrastructure Technologies Program Multi-Year Research, Development and Demonstration Plan:

- C. High Cost and Low Energy Efficiency of Hydrogen Liquefaction

Technical Targets

We believe that liquefier power requirement of 3.6 – 5.0 kWh/kg is possible. Under this scenario, the cost of electrical energy is likely to be approximately 50% of the current $0.99/kg – which is close to the targeted cost. An overall energy efficiency of 90% is possible, which is significantly more efficient than the targeted 87%. Addition of turboexpanders is, however, expected to raise the capital cost by $0.05 – 0.08 /kg. This would have a marginal impact on the overall cost, as the operating electric cost will be reduced by about $0.50/kg.

Approach

The simplest liquefaction process is the Joule Thomson Expansion cycle (Figure 1). The gas to be liquefied is compressed (by compressor K-101), cooled (in aftercooler E-100 and heat exchanger LNG-102) and then undergoes isenthalpic expansion across a throttle valve (VLV-100). If the gas is cooled below its inversion temperature in a heat exchanger (LNG-102 in Figure 1), then this expansion results in further cooling – and may result in liquid formation at the valve outlet. For hydrogen, this temperature is -95 ºF. It is obvious that this cycle alone cannot be used for liquefaction of hydrogen without any pre-cooling of hydrogen below its inversion temperature.

A modification of this cycle in which liquid nitrogen is used to cool the gaseous hydrogen below its inversion temperature is sometimes used along with Joule Thomson Expansion to liquefy hydrogen. However, this modified cycle is still limited in overall efficiency as the primary thermodynamic process used for cooling is Joule-Thomson Expansion.

Joule-Thomson expansion is inherently inefficient, as there is no work done during expansion. The advantages are that the expansion requires no moving parts and a simple throttle valve can be used for liquefaction. The industrial gas industry departed from using Joule-Thomson as a primary process in liquefaction of atmospheric gases in the 1960s. Turboexpanders or expansion engines are now used at most industrial gas plants to provide the necessary refrigeration for liquefaction. The expansion across a turboexpander is ideally isentropic, i.e., some useful work is done in expansion. Depending on the pressure ratio across a turboexpander, this useful work may be as high as 130 Btu/lbmol (for a pressure ratio of six). Turboexpanders cannot tolerate any liquid condensing at the outlet as the turbine wheels often rotate at up to 170,000 rpm. Therefore, a clever combination of isentropic and isenthalpic expansion is required to generate a practical efficient process.

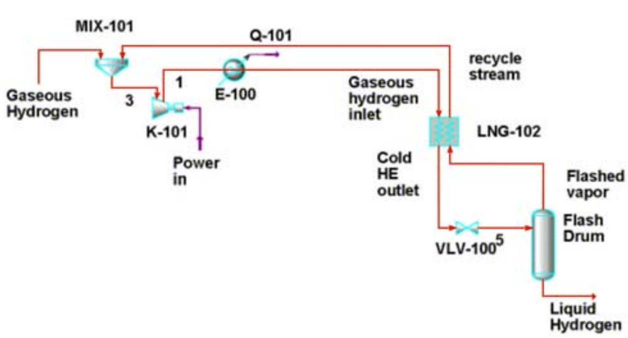

Figure 1. Joule Thompson Expansion Cycle

We propose to use a combined reverse-Brayton Joule-Thompson (CRBJT) expansion cycle (or a modified Claude cycle) to combine the benefits of highly efficient isentropic expansion and the highly reliable Joule Thompson expansion cycle. Figure 2 shows a schematic for the simplest version of the CRBJT cycle.

In this CRBJT cycle, gaseous hydrogen at atmospheric pressure is fed to compressor suction where it combines with the recycle stream from the primary heat exchanger (LNG-101). The motor driven hydrogen compressor (K-101) compresses this stream to the desired pressure. After cooling this stream in an air-cooled or a water-cooled aftercooler (E-100), it is introduced into the primary heat exchanger (LNG-101) where it is cooled by the cold return gases. When this stream is cooled to a suitable temperature, it is withdrawn and a portion of the stream is fed to an air-bearing turboexpander (Q-102). This hydrogen stream is isoentropically expanded and cooled to near saturation temperature. The remainder of the pre-cooled stream, stream 2, is fed to the secondary heat exchanger (LNG-102) where it is cooled by stream 5. Upon exiting from

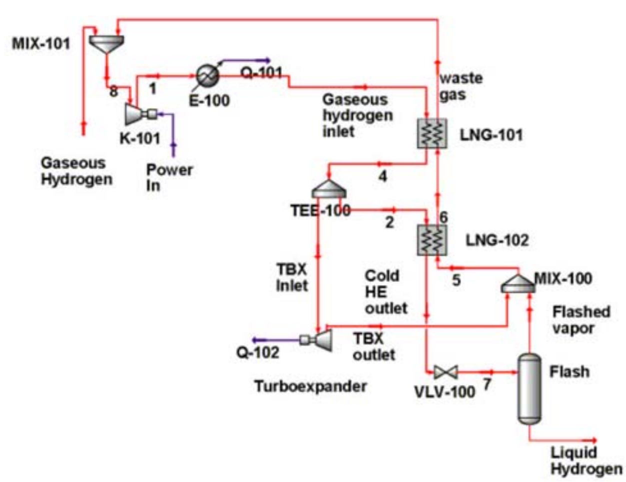

Figure 2. Simple CRBJT Cycle

the secondary heat exchanger (LNG-102), the "cold end outlet" stream undergoes isenthalpic expansion across valve VLV-100. After expansion across this valve, stream seven is partially liquefied. This stream is separated in a flash drum where the liquid hydrogen is recovered as product and the vapor stream is combined with the turboexpander outlet stream to form stream 5.

The primary advantages of this approach are

- Energy released in expansion of hydrogen by the turboexpander (Q102) is recovered as useful work and may be used for compression.
- The flow through the turboexpander allows for initial cooling of the system and allows the "cold HE outlet" hydrogen temperature to drop below the inversion temperature so that stream 7 cools down upon expansion through valve VLV-100.
- The ideal work of liquefaction defined in the NREL report [1] was based on isentropic expansion. The combined cycle minimizes the contribution of the less efficient isenthalpic (8 – 12 kWh/kg) expansion and comes close to achieving the ideal work of liquefaction (3.228 kWh/kg).

It should be noted that the flow schematic shown in Figure 2 is for the simplest CRBJT cycle. A more efficient schematic is shown in Figure 3, which may be more representative of the final liquefier design. In this schematic, two turboexpanders/ compressors are used. The useful work generated by isentropic expansion of hydrogen across the turbines is recovered to compress the inlet hydrogen stream. Clever manipulation of pressures, temperatures and flow rates can increase the overall efficiency by almost 50%.

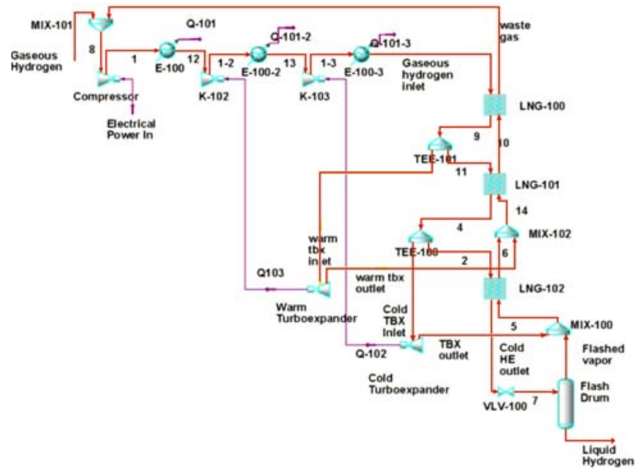

Figure 3. Twin Turboexpander-Compressor CRBJT Cycle

Accomplishments

This project has just been initiated. In the coming year, the plan is to complete the preliminary design of the system and as much of the detailed design as the funding will allow. The design of the key turbo-expander component will be completed this year. Our focus will be on producing a design that is projected to not only achieve the stated performance targets but that will provide both performance and cost scalability through the entire size range specified by DOE.

References

1. Costs of Storing and Transporting Hydrogen, Wade Amos, November 1998, NREL/TP-570-25106