

# Efficiency of Hydrogen Liquefaction Plants

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## Abstract

A medium scale hydrogen liquefaction plant is presented and its efficiency analyzed on the basis of exergy.

In a first step, the operating principal of a medium scale hydrogen liquefier is presented. The liquefaction plant consists of a compressor system and a vacuum insulated cold box where the liquefaction takes place. In the cold box, the refrigeration capacity required to liquefy the hydrogen is provided by a hydrogen refrigerant cycle and a liquid nitrogen pre-cooling step. The cooling capacity is extracted from high pressure hydrogen through oil bearing turbines and cooling takes place in aluminum plate fin heat exchangers.

Secondly, an extensive exergy analysis of the liquefaction process considering the exergy losses of each step will be presented. The exergy losses in hydrogen liquefaction are caused within the liquefier itself, for example in the compressor system or the turbines, but also occur during filling procedure of the liquid hydrogen in trailers, or distribution of the liquefied hydrogen. Within this paper the efficiency of the liquefaction process from gaseous hydrogen supply to the delivery of liquid hydrogen into the storage tank will be discussed.

**Keywords:** liquefier, exergy, efficiency, o-p-conversion

## Introduction

The medium size hydrogen liquefier described consists of a compressor system using piston compressors with three pressure levels and a liquefier cold box containing the liquid nitrogen precooling unit and the hydrogen cooling cycle with expansion turbines. Table 1 shows the main parameters characterizing the system.

Table 1: Main plant data

Liquefaction capacity	l/h	3'000
Electric power input	kW	1'555
Liquid nitrogen consumption	l/h	2'475
Product pressure	MPa	0.15
Product temperature	K	21.68
Para-content	%	> 95

Figure 1 shows a simplified flow sheet of the liquefier system. It consists of the hydrogen feed stream, which enters the cold box at approx. 2 MPa and is continuously converted from ortho to para hydrogen whilst it is cool-down using the catalyst directly placed in the heat exchangers. Between heat exchanger 7 and 8 it is throttled to tank pressure within a device called "ejector" functioning similar to a water jet blast sucking displaced or flash gas from the tank being re-liquefied in heat exchanger 8.

Refrigeration down to 80 K is provided by using a nitrogen precooler: liquid nitrogen is throttled into a phase separator flooding heat exchanger 2 with liquid and by so cooling the feed stream to approximately 81 K. Evaporated nitrogen is warmed up to ambient in heat exchanger 1 pre-cooling the feed stream in countercurrent flow.

Refrigeration from 80 K to approximately 30 K is carried out using a so-called Brayton cycle: high pressure hydrogen of about 2 MPa is expanded in three turboexpanders switched in series to medium pressure and warmed up to ambient providing refrigeration.

From 30 K to liquefaction a so-called Joule-Thomson cycle is applied consisting of heat exchangers 7, 8, and a throttle valve at the bottom, where the high pressure gas is throttled to low pressure providing the lowest temperature of the system. After warming up this gas is compressed in the first stage compressor to medium pressure and reunified with the return gas from the expanders, sucked by the high stage compressor.

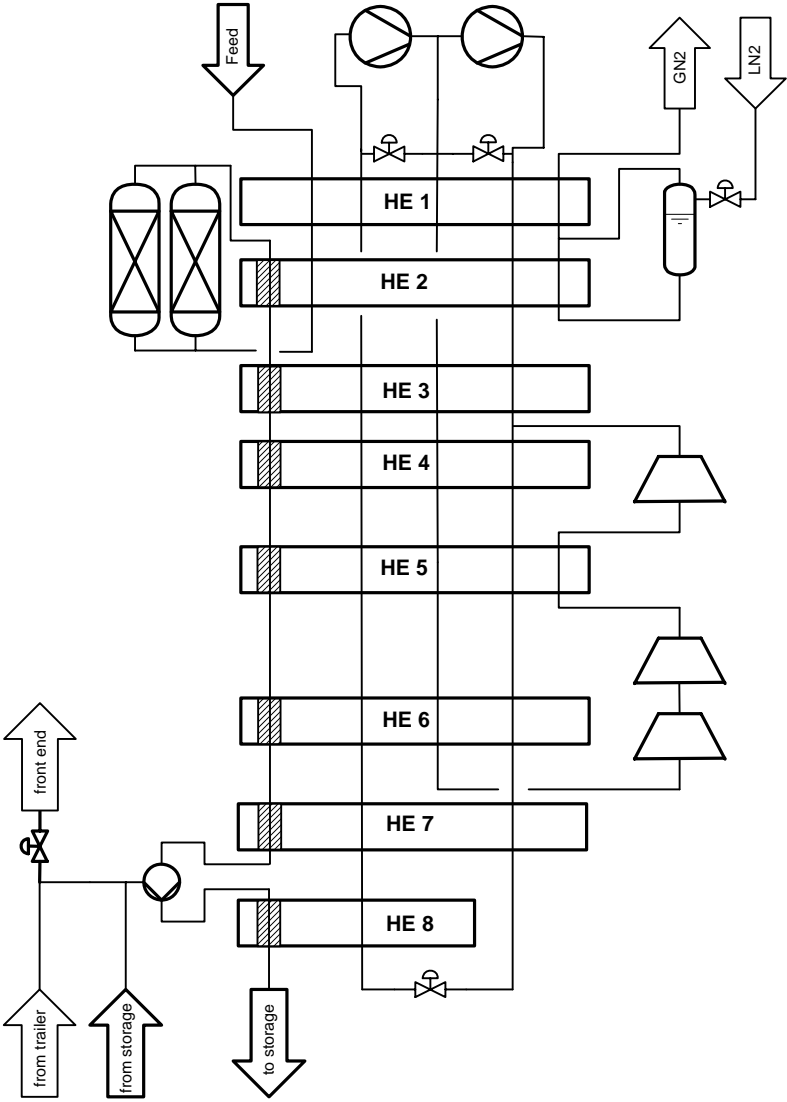


Figure 1: Flow sheet of the liquefier system

## System Analysis

The easiest approach to a thermodynamic analysis of a system is to introduce exergy as additional information for each state point. Exergy, the maximal available work, is defined as

$$de = dh - T_0 ds \quad (1)$$

or integrated

$$e_1 = h_1 - h_0 - T_0 (s_1 - s_0) \quad (2)$$

where  $e_1$  is the maximum work, that can be obtained from a periodic process between state 1 and ambient condition 0.

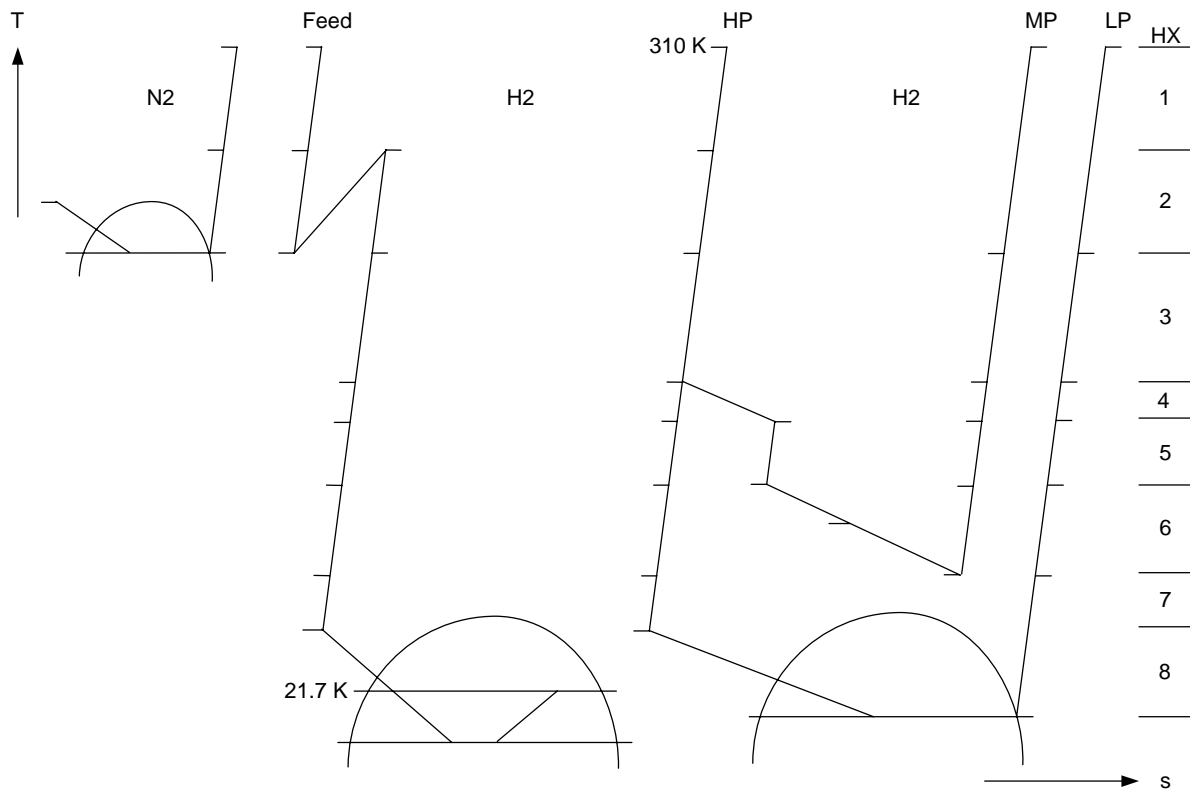


Figure 2: T-s diagram of the liquefaction process

For the whole system as well as for parts of it, thermodynamic efficiencies can be calculated as ratios of minimum exergy necessary to exergy actually applied. For a system analysis, however, it is more reasonable to calculate the exergy loss occurring in a component and to compare it to the exergy input to the system.

For the hydrogen liquefier considered, exergy flow diagrams were plotted showing the exergy losses and the exergy finally supplied to the tank as a percentage of the exergy input into the system which equals the electric power input to the electric motor of the compressors plus the exergy contained in the liquid nitrogen and feed flow supplied.

Heat leaks into the liquefier are not taken into account.

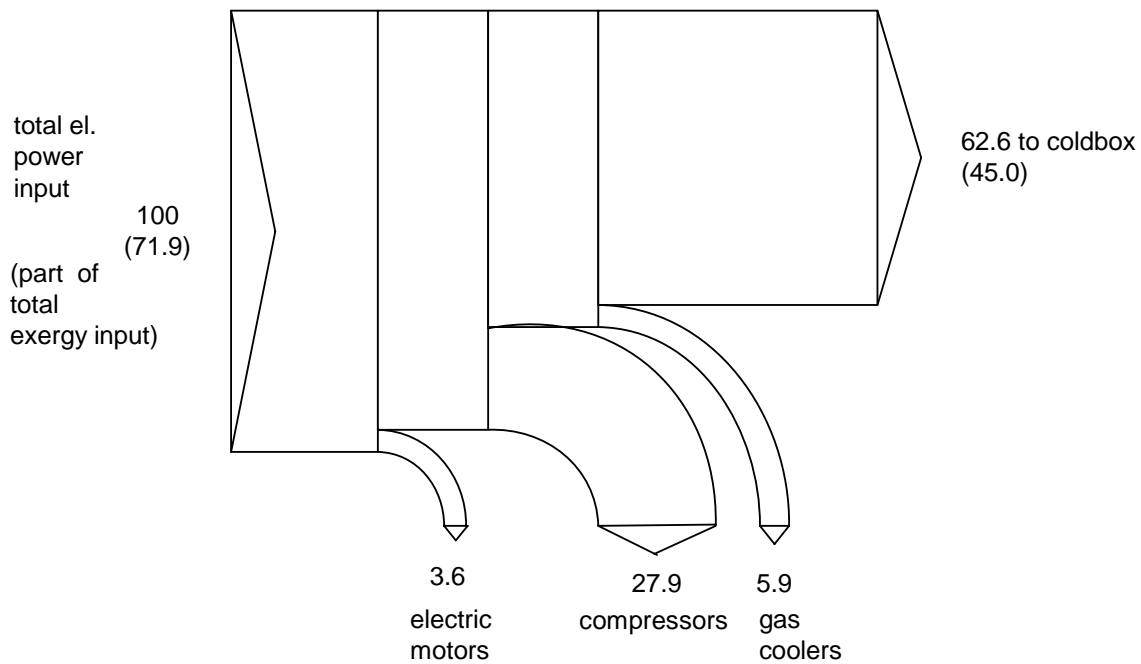


Figure 3: Exergy flow diagram of the compressor system

Figure 3 shows the exergy flow diagram of the compressor system. The power input into the electric motor drives of the compressors is only part of the exergy input to the liquefier. The percentage of the total exergy input is therefore given in brackets. A large amount of the exergy is dissipated in

the electric motors  
the compressors and  
the gas coolers.

Finally 62.6 % of the exergy input is passed onto the liquefier cold box.

The exergy losses in the cold box are due to inefficiencies of turbines, valves, heat exchangers, and the process itself.

Turbines: In an ideal turbine the exergy change of the fluid expanded equals the mechanical energy extracted. In a real turbine the following irreversibilities have to be considered:

1. The turbine extracts only part of the energy it ideally could.
2. The mechanical power extracted is dissipated in a brake cycle.

Figure 4 shows, that the lower the operating temperature of the turbine, the smaller the part of exergy loss in the brake compared to the total loss.

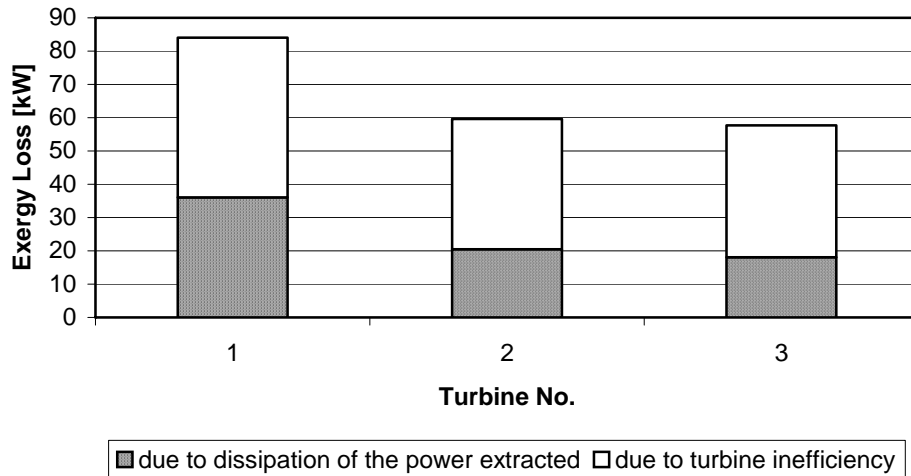


Figure 4: Exergy loss of the turbines

Heat exchangers: The exergy losses in the heat exchangers amount to 21.6 % of the exergy input to the plant. The losses are caused by

non-ideal heat transfer	3.7 %
pressure drop	2.8 %
process design	15.1 %

The figures show, that major part of the losses are due to process design and would occur even using ideal heat exchangers.

Valves: There are only three throttling valves within the plant causing a small loss, namely the Joule-Thomson valve in the cooling cycle, the ejector in the feed flow and the throttling valve for liquid nitrogen.

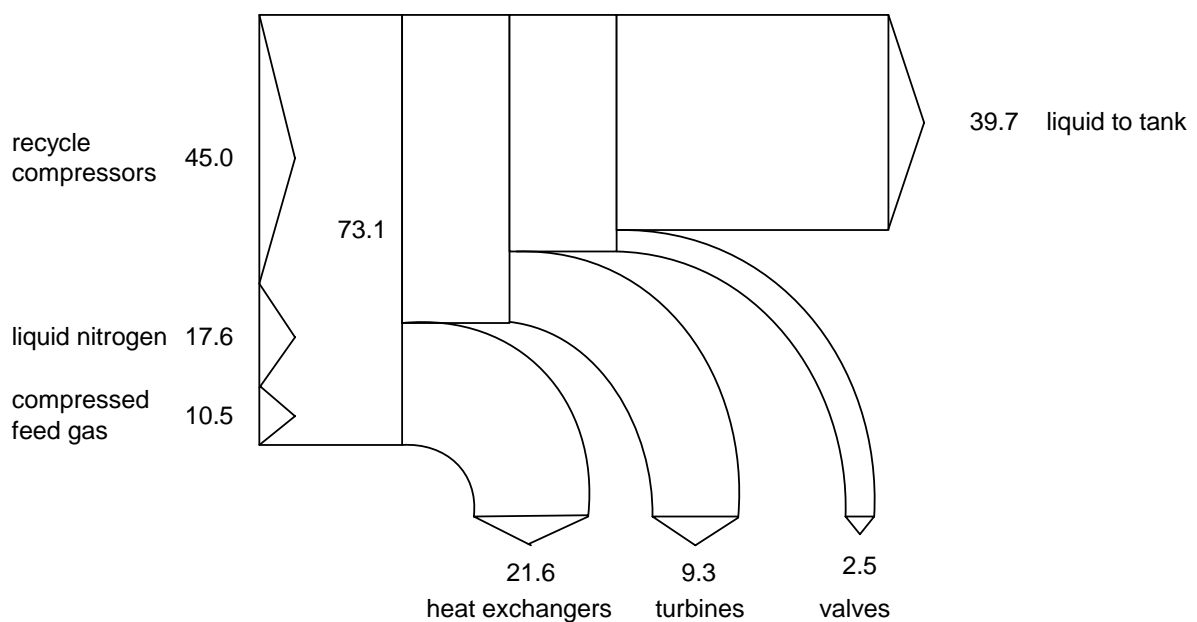


Figure 5: Exergy flow diagram of the coldbox

Figure 5 shows the exergy flow diagram of the liquefier itself. From the 73.1 % entering the box at the cold end there are 39.7 % left as the product flow.

## Conclusion

The calculation of exergy losses is a very powerful means to identify sources of irreversibilities, their portion of the total loss, the potential for improvement and to determine their effect on power input and operating costs of the plant.

## Notation

e	exergy	J/g
h	enthalpy	J/g
s	entropy	J/g K
T	temperature	K

## Indices

0	ambient (293.15 K, 0.1013 MPa)
1	general state point

## References

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