Stirling Cryogenerators for re-liquefaction of methane boil-off gas on ships

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1. Introduction

DH Industries specializes in the design and production of Stirling Cryogenerators and closed-loop cooling systems. Our customers range from universities, research centers and industries all over the world, which rely on our expertise to provide them with a reliable, on site supply of cryogenic liquids or cryogenic cooling systems for all kinds of applications.

Stirling Cryogenics, one of DH Industries trademark brands, developed the Stirling-cycle cryogenerator almost 60 years ago and it has been the cornerstone of our sophisticated cooling systems ever since. The Stirling cryogenerator makes it possible for our systems to produce temperatures ranging from -75 °C to -250 °C. More than 3.000 systems are in operation across the globe, often in extremely demanding conditions.

One of the product ranges based on the Stirling Cryogenerator is the StirLNG, specially designed for the liquefaction of methane. This can be methane from a gas source to produce LNG, or cold boil off methane gas (BOG) from a vessel or tank to be re-liquefied to condition the LNG and keep it at the desired temperature and pressure.

Depending type and system conditions, the StirLNG product portfolio has a cooling capacity equivalent from 150 kg to several tons per day of LNG, making them very suitable for small and mid-scale LNG applications.

The StirLNG is also available in a maritime version, adapted for the ships movement and to comply to the required class such as ABS, with an additional option to separate the liquefier from its electric motor by a bulkhead seal, mandatory by USGC.

In this paper for the 2016 Gas Fueled Ships Conference we will present the functionality of our BOG re-liquefiers, different concepts of integration and the system currently installed on a 2200 m^3 bunker barge.

2. Why Conditioning of LNG

All LNG tanks have heat in-leak due to which the LNG starts to boil, so gas is formed and thus pressure starts to increase. This BOG needs to be removed to avoid excess tank pressure. Question is what to do with it since it cannot be vented for economic and environmental reasons.

Being methane it can of course be used to create energy on board of the ship. While sailing it can be fed to the main engine, while moored it can be fed to a generator for power consumption on board.

However, there are several reasons due to which usage as fuel is not sufficient or appropriate. If the tank is large relative to the ship, there might not be sufficient need for power to consume all the BOG. More importantly, the LNG is property of the customer hence consuming the cargo might not be acceptable. Also, by taking out gaseous methane the composition of the LNG will change.

When the LNG evaporates, the components with a low liquefaction temperature will boil faster than the methane. Result is that while the LNG contains e.g. 0.5 mol% N_2, the BOG will contain 12 mol% N_2. For higher hydrocarbons and CO_2 this effect is inverse: they will not evaporate and remain in the liquid, while the methane content decreases.

Thus, when the BOG is not returned to the tank, the composition of the remaining liquid will change, containing less nitrogen and methane in time.

For all above reasons it is beneficial to re-liquefy the BOG so the value of the LNG is kept.

By re-liquefaction, the temperature and pressure as well as the composition of the liquid will be kept constant. Hence, *Conditioning*.

3. Creation of cooling power

Creation of cooling power by the StirLNG-4 is done by the so called reversed Stirling Cycle which is based on the compression and expansion of helium gas in a closed cycle. The Stirling cycle efficiently produces cooling power at cryogenic temperatures by input of shaft power from an electric motor. Main advantage of Stirling Cryogenerators is that the gas to be liquefied is not part of the cycle to create the cooling power.

For more detailed information on this creation of cooling power, refer to the appendix 1, “The Stirling Cycle”, which is also available on our website.

Based on the Stirling Cycle, DH Industries produces different types of Cryogenerators under the Stirling Cryogenics brand.

The StirLNG-4 Maritime is the adapted version of our standard 4-cylinder Cryogenerator used in many systems for various applications world-wide.

Picture 1: *standard StirLNG-4*

StirLNG-4 in maritime version

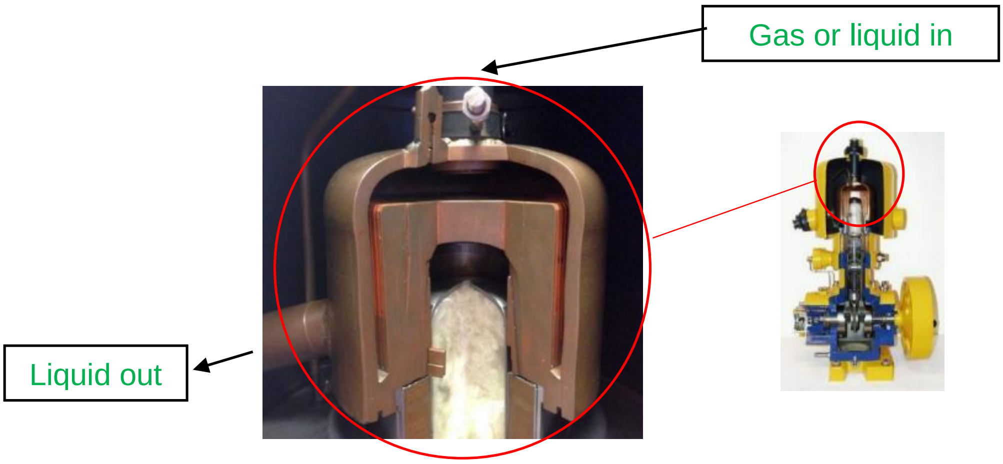
4. Cooling power to LNG

The heat in-leak into an LNG tank can be extracted with two different system concepts:

a) By direct cooling of the LNG before it evaporates. In this concept, LNG is pumped through the StirLNG-4 heat-exchanger where energy is extracted, cooling the liquid which is sprayed back in the tank header.

b) By re-liquefying the BOG after it has formed. In this case, the gas is drawn into the cold heat-exchanger of the StirLNG-4, where energy is extracted so the gas will cool down and then condensate against the cold surface.
This is a phase change at saturated equilibrium so there is no pressure change.

Either concept has its specific benefits; the choice depends on installation possibilities, circumstances and requirements of the total LNG tank system.



Picture 2: *Energy extraction from gas or liquid*

5. Direct Liquid Cooling (LC)

The concept of Liquid Cooling is based on an effective method of reducing pressure in a storage tank called “Spraying”. This method is widely used in the cryogenic industry when tanks contain ‘warm’ liquid. Pressure and temperature are reduced by filling and spraying with colder liquid supplied from a delivery truck, or by using spray pumps in larger tanks making use of the relatively cold liquid at the bottom of the tank.

Spraying can be done only during a limited period of time as the amount of ‘cold’ in the liquid is limited. Once all of the LNG in the storage tank is at the same temperature, spraying cannot function anymore.

With the StirLNG LC concept, LNG is taken from the bottom of the tank and pumped through the heat-exchanger of the StirLNG-4. Here energy is extracted due to which the LNG will cool down a few degrees. Via the spray nozzles the colder liquid is sprayed into the gas area at the top of the tank and by this process the tank pressure reduces (ref. Figure 1).
This cold spray will reduce gas pressure and cool the liquid.

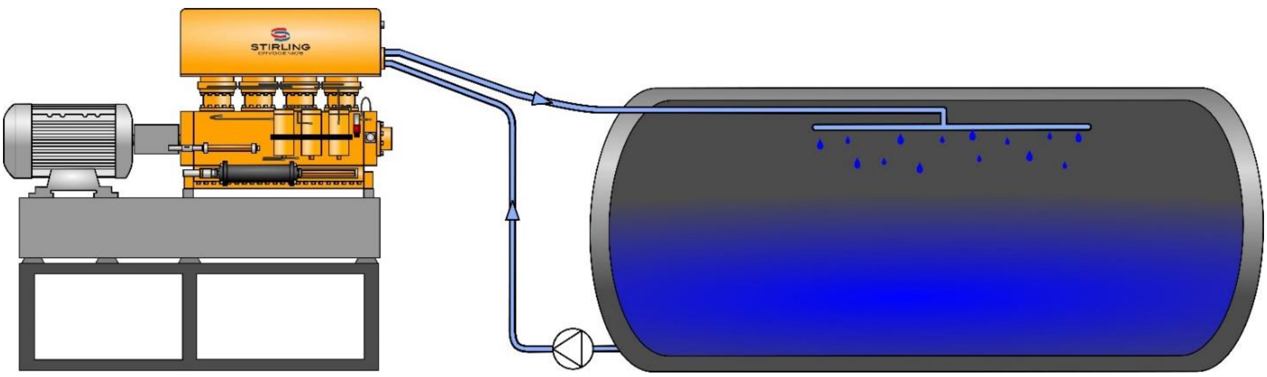


Figure 1: *Liquid Cooling concept*

Cooling of LNG can be a continuous process. The ships control system will monitor the temperature and pressure of the tank, to start and stop the StirLNG-4 when the storage tank pressure reaches a pre-set level.

Advantages of the Liquid Cooling concept:

- the StirLNG-4 can be placed anywhere because the system contains a pump to overcome height and/or distance between the storage tank and the StirLNG-4.
- the composition of the LNG or the BOG has no effect on the cooling capacity of the StirLNG-4.

6. Re-liquefaction of BOG (RL)

In this concept the BOG is fed to the StirLNG-4 and re-liquefied at its equilibrium saturated temperature (depending on the actual pressure of the storage tank). Because gas is converted in much denser liquid, the gas pressure will slowly drop. By reducing pressure the LNG will get colder, meaning that also the storage tank content will be cooled in time.

The LNG produced by the StirLNG-4 flows out downwards by gravity, meaning it is required to be placed above the LNG (storage) tank. The configuration of the total system will ultimately determine the final location of the StirLNG-4.

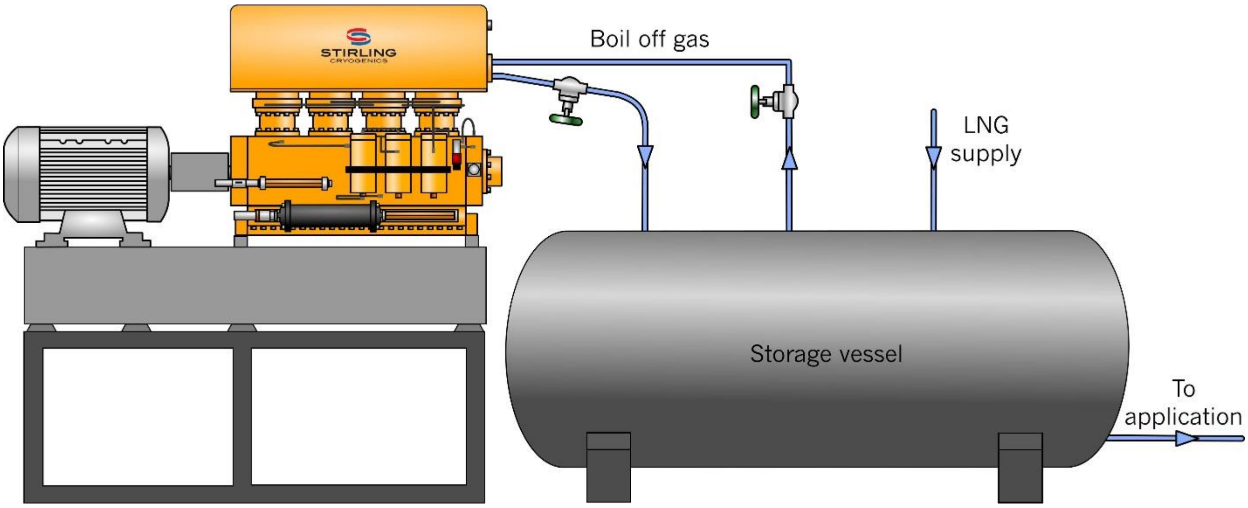


Figure 2: *Re-liquefaction of BOG concept*

Cooling of LNG can be a continuous process. The ships control system will monitor the temperature and pressure of the tank, to start and stop the StirLNG-4 when the storage tank pressure reaches a pre-set level.

Note:

The presence of other components in the composition will affect this temperature. Especially N2 is of importance since this will lower the liquefaction temperature of the mixture, resulting in a lower cooling capacity of the StirLNG-4.

Even though the quantity of N2 in the LNG may seem low, due to the fact N2 evaporates faster, the content in the BOG is much higher. As example, 0.5 mol% of N2 in the LNG in an atmospheric tank will produce BOG with a content of 12 mol% N2. This result in a liquefaction temperature that drops from 112 to near 90K, affecting the liquefaction capacity in kg/h by 16%.

Advantages of the Re-liquefaction concept:

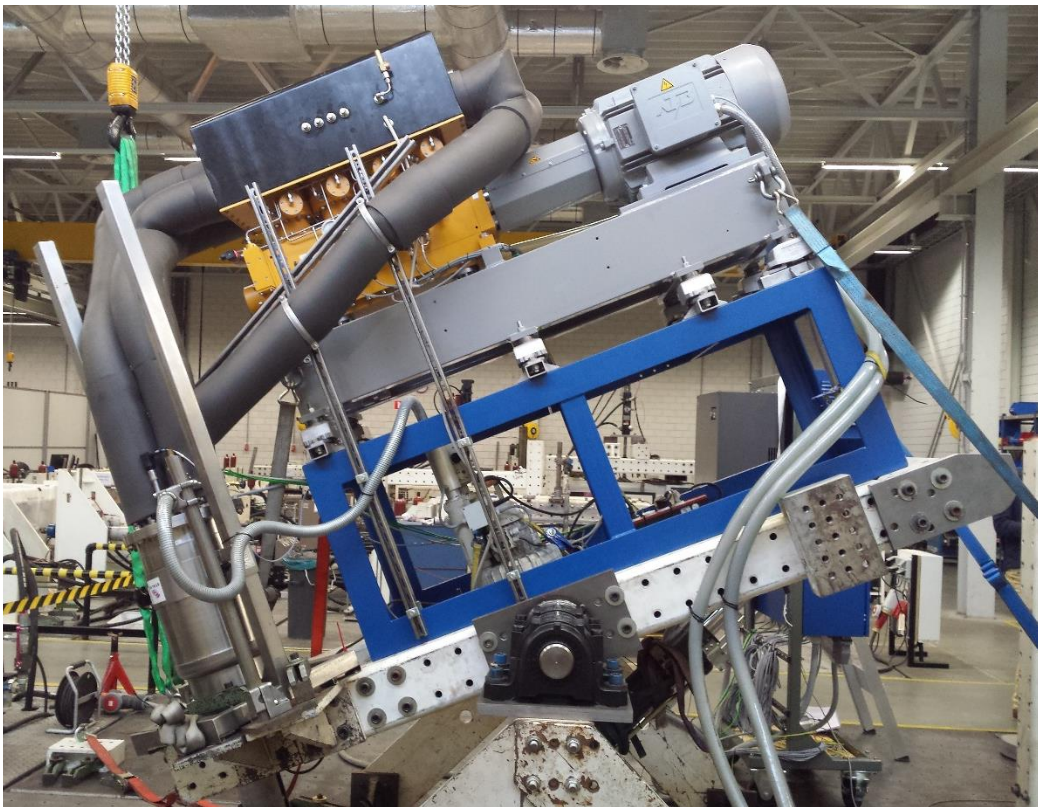
- higher net cooling capacity (no pump needed, so no pump losses)
- no maintenance for pump needed

7. Modifications for Maritime use

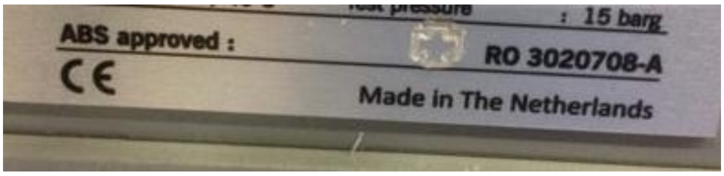
The StirLNG-4 will function exactly the same as described above in maritime applications, however will need to be adapted for maritime use.
These are not changes in the concept or process, but merely to comply with maritime conditions and regulation.

Modifications that have been made for maritime application are:

- Modification of piping to assure functionality during dynamic roll and pitch, both up to 22.5^o
- Assuring functionality during static inclination when (un)loading upto 15^o
- Vertical motion due to waves
- Vibrations
- Corrosion
- Remote operating
- Modifications to meet regulations (ABS, USCG, UL etc.)



Picture 3: *Dynamic pitch testing up to $22,5^o$ during while in full re-liquefaction mode*



Picture 4: *ABS approval*

8. First maritime project, design and production

The first project where the StirLNG-4 will be used in maritime version is the project by Tote, for which shipbuilding company Conrad is building a bunker barge of 2200 m^3 to supply Tote's two LNG fuelled containerships.

The Cargo tank of the bunker barge is of GTT Mark III Flex technology type. On top of the tank 6 StirLNG-4 units are placed to ensure that pressure is kept low, as well as the temperature of liquid. Additionally, the StirLNG-4 units will liquefy the methane gas that will flow back from the containership's tank when being filled with LNG.

Figure 3: Conrad bunkering barge

The design parameters for this BOG re-liquefaction system are:

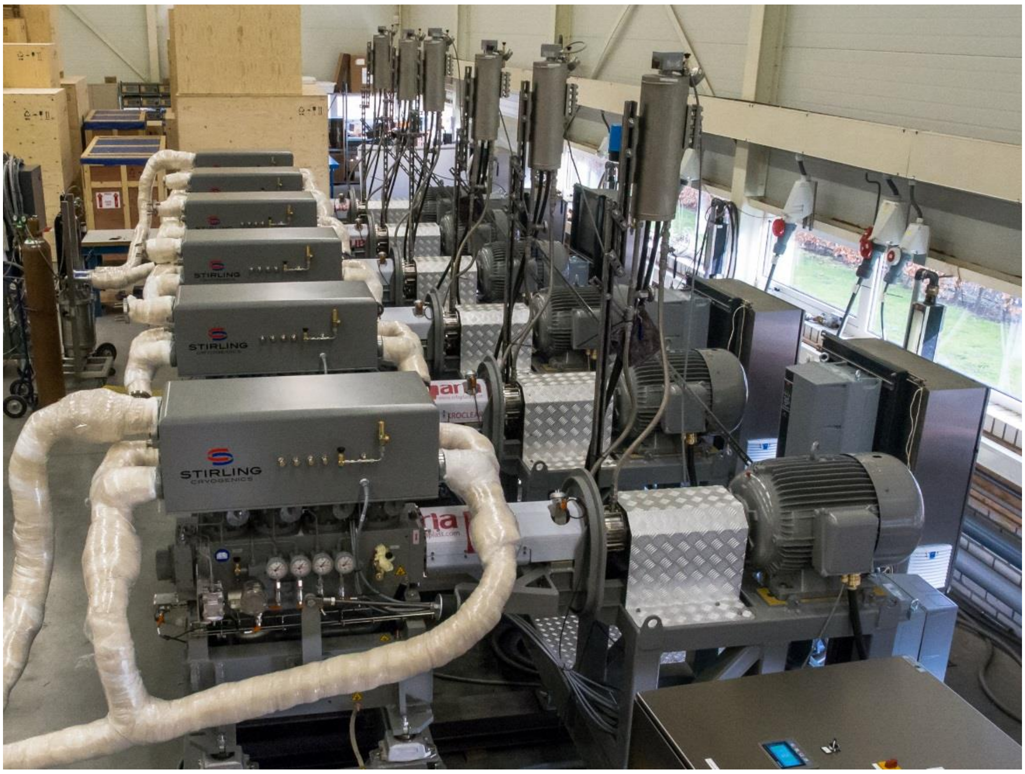
- 6 x StirLNG-4 units with capacity:
  6 x ~ 900 kg /day = ~5,400 kg/day
  @ 0 barg and 0.5% N_2
- Power consumption:
  6 x ~38 kW = ~ 228kW (+ water chillers)
- Operation: each StirLNG-4 has its own controller and can start and stop on its own
- Dimensions and weight:
  lxbxh = 7,850 x 3,000 x 1,700mm (25.8' x 10' x 5.6')
- ~ 8,500 kg (18,800 lbs)

In June and July these StirLNG-4 units have been extensively factory tested.

Each StirLNG-4 was tested for:

- Capacity
  With LN2 at 4.8 barg (same liquefaction T as the expected BOG)
- Vibrations
  at 5 points per unit, in 3 directions
- Temperatures
  at 5 points per unit
- Error test
- Each individual unit was Error tested by simulating or initiating fault conditions.

Result:
All units successfully passed and have been shipped to Conrad in August 2016 for installation.



Picture 5: Factory acceptance test

Appendix 1: The Stirling Cycle

1. Introduction

Bio-gas and bio-methane have the potential to be produced on many sites, however it is not everywhere possible to create value. Producing electric energy may not cover the costs in today's market and access to the gas grid is often not available. For these cases, liquefaction of bio-methane creates the possibility to transport bio-LNG to distant markets where there is a need for LNG as fuel or where it can be injected at high value.
This abstract explains how cooling power is created by the Stirling Cycle and how this can be used to create bio-LNG.

2. History of the Stirling Cycle

The Stirling cycle is a thermodynamic closed cycle invented in 1816 by Scottish minister Robert Stirling as an engine competing with the steam engine.

The counterpart of this hot air motor, the refrigerator, was first recognized in 1832 but only developed into an optimized machine by Philips in the early 1950's.
Since then, many thousands of these so-called Cryogenerators have been produced, most of which have been functional for several decades.

3. Working of the Stirling Cryogenerator

The Stirling cycle alternately compresses and expands a fixed quantity of helium gas in a closed cycle. The compression takes place at room temperature discharging the compression heat into a water flow, whereas the expansion is performed at the required low temperature at which liquefaction takes place.

For the purpose of explanation, the process may be split up into four distinct piston positions illustrated in Figure 1.

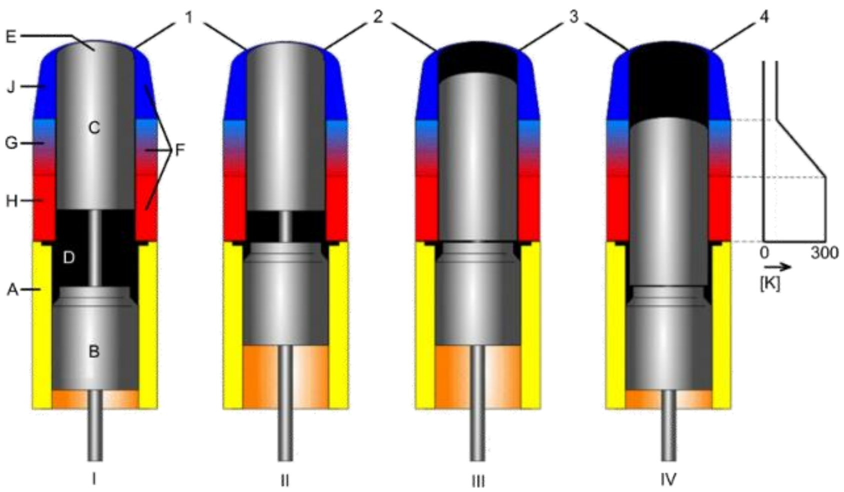


Figure 1. Piston positions of the Stirling cooling cycle

In position I, the helium is at room temperature in space D. Going to position II, this gas is compressed by piston B increasing the gas temperature to about 80ºC, refer to figure 2, column 1.

When the displacer C moves down from position II to III, the gas is displaced from space D to space E, forcing it first through the cooler H, dissipating the compression heat into the water, cooling the gas to about 15ºC (column 2).

Next, the helium flows through regenerator G which cools it to almost the final liquefaction temperature when arriving in space E (column 3).

The final and main action is displacer and piston moving down to position IV, expanding the helium gas.

This expansion creates the actual cooling power in cold head, liquefying the methane gas in its heat exchanger J, refer to paragraph 4.

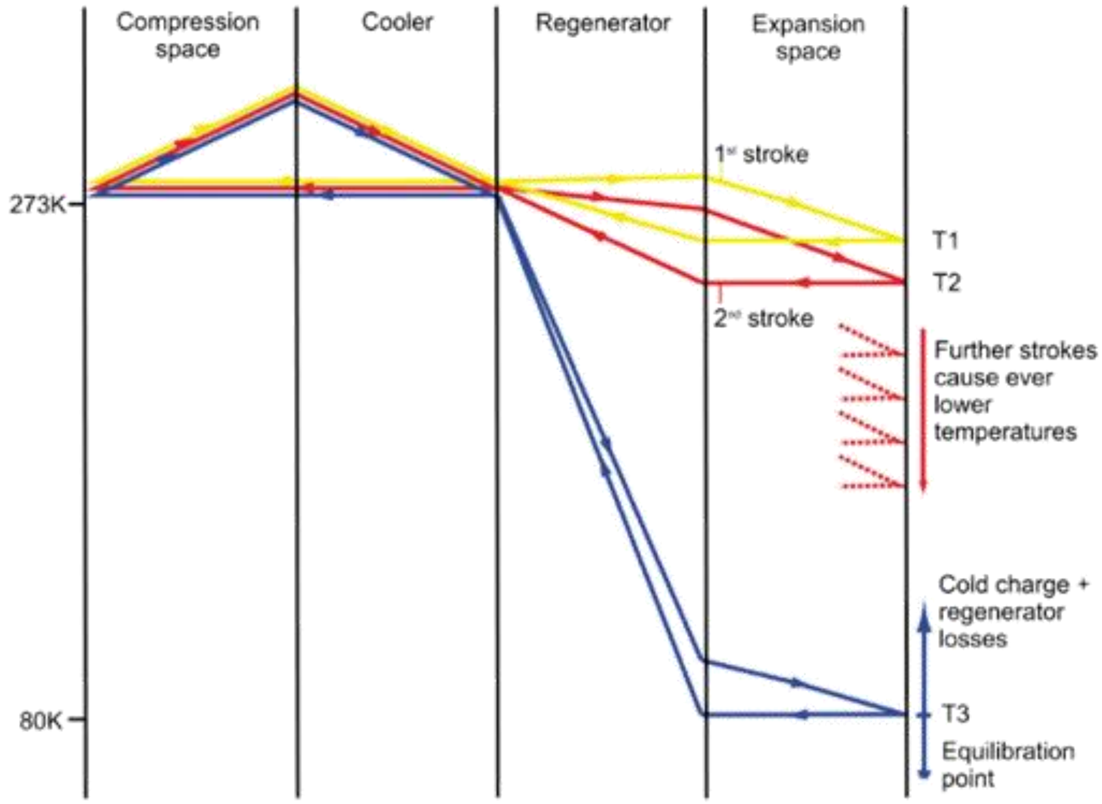


Figure 2. Variation of Helium gas temperature during the Stirling Cycle

For a new cycle to begin, the displacer moves up to positon I, returning the helium to space D. While passing the regenerator it is reheated to nearly room temperature by the regenerator. The initial situation of the cycle has now been restored for the cycle to repeat.

This cycle is typically repeated at 25 Hz, providing a continuous extraction of heat to cool and liquefy the methane.

4. Liquefaction

The actual liquefaction is done in the so-called cold head, refer to figure 3. This heat exchanger is being cooled at the inside by the expansion phase, cooling and liquefying the incoming gas at its outside.

Integration of the Cryogenerator in the total process is straightforward: the flow of cleaned bio-methane must be connected to the inlet after which the bio-LNG will flow out by gravity into the LNG tank.
To avoid freezing, water, CO_2 and higher hydrocarbons need to be removed to a level depending the prevailing pressure, before the gas enters the liquefier.

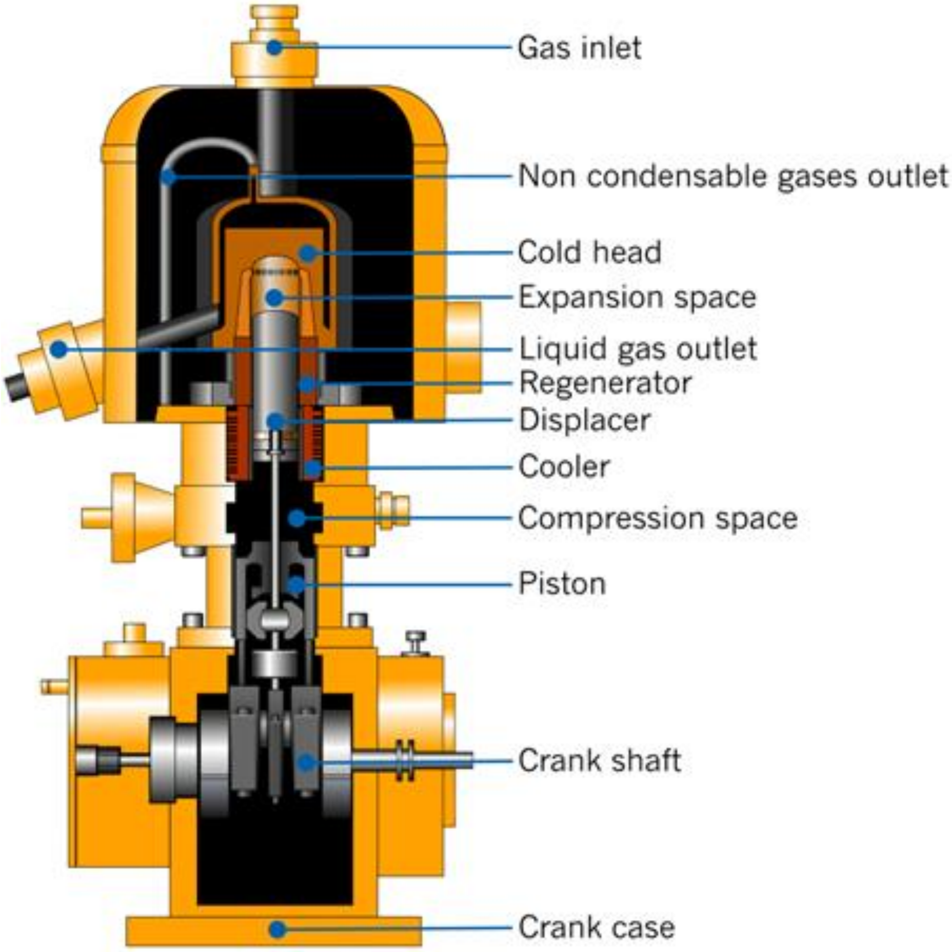


Figure 3. Cut view of the Stirling Cryogenerator showing the major components

5. Stirling efficiency

The Stirling cycle is very efficient using as little as 0,42 kWh/kg of methane, liquefied at 20 barg. This is due to the Stirling cycle itself, reaching LNG temperature in 1 stage with one electric motor.

Further, all cooling power is used only for liquefaction and not for separation. Overall efficiency of the total system from bio-gas to bio-LNG will depend on gas composition and specified LNG pressure.

6. Conclusions

Build for much lower temperatures than LNG, the Stirling Cycle is very efficient at LNG temperatures, while easy to integrate in the production chain.

In liquid form the bio-methane molecules can have a much higher value than as gas, since it can be sold as LNG fuel, or distributed to sites where gas is expensive or can be injected.