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Theoretical Analysis of Regenerator for Reversed Stirling Cycle Review

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Abstract

In first part we deal with the introduction about the regenerator about the regenerator and its comparison with counter flow heat action and importance of regenerator in cryogenic system. In second part we review with the literature deals with ideal sterling cycle and salient features of Stirling cycle and it's comparison with other cycle and operation and working principal of Stirling cycle

Keywords: Phillips liquid nitrogen plant, Cryocooler, Regenerator Test Up, Stirling cycle

Introduction

A regenerator is a very efficient compact heat exchanger, which is used, in cryogenic systems such as the Stirling cycle, Gifford-McMahon cycle, Solvay cycle, Vuilleumier cycle, and pulse tube refrigerator types. It is constructed of a matrix material (phosphors bronze, lead, European Sulphide) that has the capability of quickly transferring and storing heat from a gas, which passes through it. It is also highly resistant to heat flowing along its longitudinal direction.

The regenerator has several distinctive advantages: It can be made relatively small; its efficiency is very high; matrix material is readily available; its construction is simple; and as a result, its cost is comparatively low. In normal operation, the regenerator is relatively insensitive to plugging by impurities in the gas stream. It does not require the physical separation of the gas stream.

All cryogenic refrigerators require a heat exchanger, which separates the high temperature gas from the low temperature gas. Figure 1.1 shows the relative position of the heat exchanger in a cooling system. The use of regenerator in this position allows a large temperature difference to be produced, with the advantage of simplicity, small physical size, and high efficiency.

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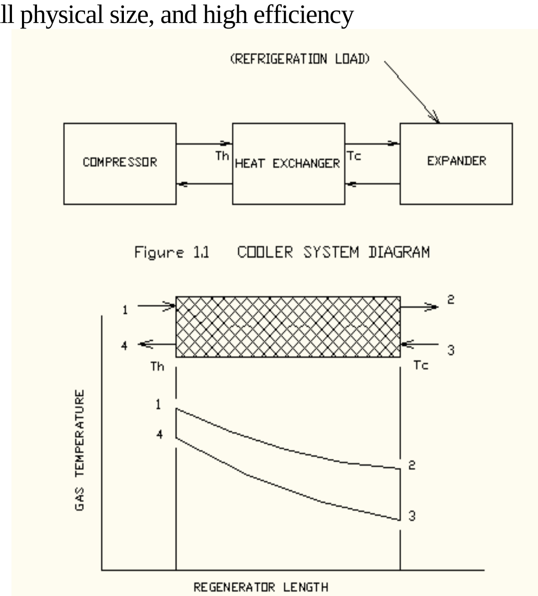

Fig.1Regenerator Temperature Cycle

Stirling Cycle Cryocooler

These small Cryocooler will generally achieve a minimum temperature of 35 K in a single stage cooler and

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below 15 K for a multistage cooler. The Stirling cycle Cryocooler is a constant volume Cryocooler-the total volume of the Cryocooler remains unchanged as the cooler proceeds through its thermodynamic processes.

- Process 1-2, isothermal compression. The gas is compressed isothermally as the compressor piston moves forward, reducing the compression volume. During the compression process, the heat of compression of the gas is rejected to the room temperature surroundings in the cooler, and the cyclic system pressure is raised to its maximum level.
- Process 2-3, constant-volume regenerator matrix heating. The displacer moves up towards the warm end to the cold end, forcing gas through the regenerator from the warm end to the cold end. The warm gas flowing through the regenerator is cooled by heating the matrix
- Process 3-4, isothermal expansion. Both the displacer and compressor piston moves upward, expanding the gas in the expansion volume. The expansion process occurs isothermally by absorbing heat from the cold surrounding in the freezer – i.e., by providing refrigeration –while the cyclic system pressure is reduced to its minimum.
- Process 4-1, constant-volume regenerator matrix cooling. Gas is forced through the regenerator from the cold volume to the warm volume by the movement of the displacer to the cold end. The heat that was stored in the regenerator during process 2-3 is transferred back to the gas during this process, cooling the matrix.

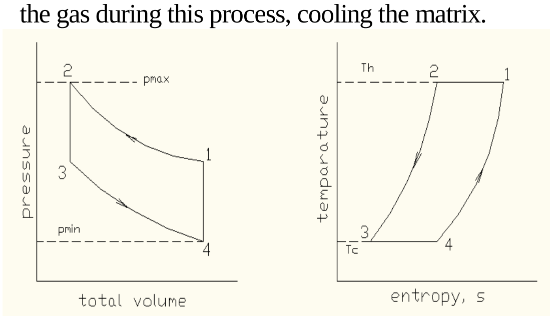

Fig.2 P-V,T-S, Diagrams For An Ideal Striling Cycle Cryocooler

Philips Liquid Nitrogen Plant- 106

The schematic diagram of Philips Liquid Nitrogen Plant is shown in figure

PLN divided into two parts

1) Cryogenerator
2) Separating column

Fig. 3 Schematic diagram of PLN-106

Comparison of Stirling Cycle with other Refrigeration Cycles

Generating sufficient cold to liquefy gases can be done in various ways. The choice is often determined by the temperature required to liquefy the gas, and the degree of efficiency within a given temperature range. Within the cryogenic range of 65 to 250 K, the least efficient process is the Joule-Thomson method. This is based on expansion of high-pressure gas by throttling. The compressor, heat exchanger and expander technology used in the Claude (turbine) process is only marginally more efficient.

The Stirling Cycle process is by far the most effective principle for cryogenic operations.Consequently, all Stirling cryogenerator feature this technique. It is a proven and tested concept that assures the highest level

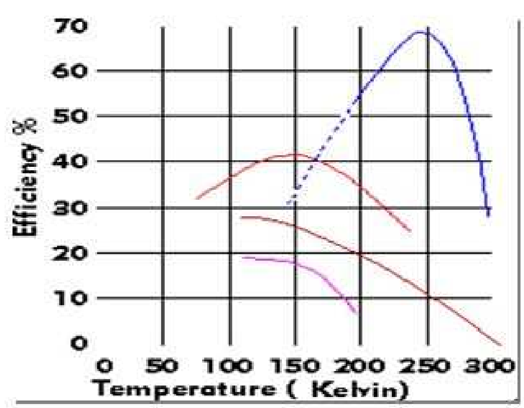

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Fig. 4 Comparison of Stirling cycle with other cycle

Regenerator

The regenerator is the heart of the cooler .Its function is to remove temperature oscillation in the gas passing through it. It must do this by providing a large surface area for heat exchange with a solid material of substantial heat capacity. At the same time, it must not excessively impede the gas flow. Here this material is composed of phosphorous bronze screens. A larger surface area for heat exchange can be obtained by making the screen mesh openings and the wire diameter very small, but this greatly impedes the gas flow so that the gas loses all its capacity for doing work in the regenerator and none is left for cooling. It is critical that the regenerator be designed to find the best compromise between these conflicting requirements

4.2 Advantages and Disadvantages of Philips Regenerator:

1. They are relatively cheap and easy to manufacture
2. They enable a very large surface area to be concentrated into a small volume. For example, 150-mesh screen matrix has an area density of the order of 65 cm2/cm3, compared with a maximum of 13 to 20 cm2/cm3 of cold-side plus hot-side areas available in the most compact direct-transfer type of parallel-, counter-, or cross-flow extended surface heat exchanger.

Properly designed regenerators have a low hydraulic resistance and thus allow the passage of large quantities of gas with a very small loss in pressure.

Periodic flow reversals eliminate permanent flow-stagnation regions, and consequently the surface tends to be self-cleaning.

The major disadvantages:

1. Some mixing of the hot and cold steams is inevitable because of the carryover from the periodic flow reversals.
2. With dynamic (rotary)-type regenerators, sealing requirements between the two streams represent a major design complication

Reduction in Refrigeration Effect Due To Pressure Drop

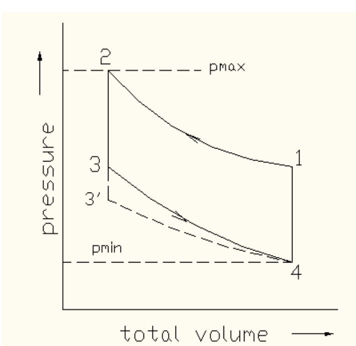

Fig.5 Reduction In Refrigeration Effect Due To Pressure Drop

The effect of pressure drop on refrigeration capacity can be gauged from the work diagrams for expansion and compression spaces as shown in figure 2.14 The shaded areas are the reduction in area of expansion space diagram due to regenerator pressure drop. The refrigeration capacity is decreased approximately by the same proportion as the area of work diagram

Significance of the Regenerator for Stirling Cycle

The success of the Stirling cycle Cryogenerator depends largely on the effectiveness of regenerator. The analysis given below shows the importance of the regenerator. Referring back to the p-v and T-s diagrams of the figure 2.1 we can develop the following expression and condition.

The refrigerator produced QR is the expansion work of the p-v diagram (or area below isothermal expansion process in the case of T-s diagram)

$$Q_{ideal} = m_g R T_c \ln \frac{v_4}{v_3}$$

Total heat transfer in regenerator $= m_g C_v (T_h - T_c)$

Loss of refrigeration effect due to thermal losses in the regenerator

$$\Delta Q = (1 - E') m_g C_v (T_h - T_c)$$

$$\frac{\Delta Q}{Q_{ideal}} = \frac{(1 - E) m_g C_v (T_h - T_c)}{m_g R T_c \ln \frac{v_4}{v_3}}$$

here,

$$\frac{\Delta Q}{Q_{ideal}} = \frac{(1 - E') m_g C_v (\frac{T_h}{T_c} - 1)}{(\gamma - 1) \ln \frac{v_4}{v_3}}$$

for helium γ =1.67, for well designed machine v_4/v_3=1.24

$$\frac{\Delta Q}{Q_{ideal}} = 7(1 - E')(\frac{T_h}{T_c} - 1)$$

for Stirling cycle with Th = 75 K and

Tc=300 K

$$\frac{\Delta Q}{Q_{ideal}} = 7(1 - E')(\frac{300}{75} - 1) = 21(1 - E')$$

Regenerator effectiveness of 99 % results in 21 % loss of refrigeration effect, similarly regenerator effectiveness of 98 results in 42 % loss of refrigeration

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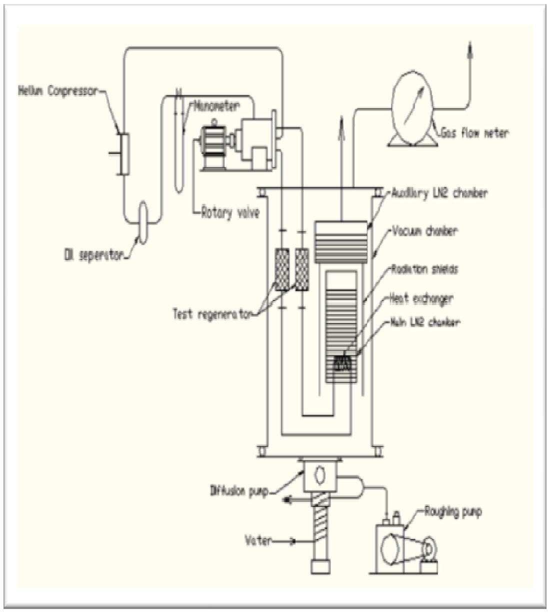
effect, with refrigeration effectiveness of 95.238 % the loss of refrigeration is 100 % i.e. no net cooling is produced. Although all the condenser are perfect.

Regenerator Test Up



Test Procedure

(1) It is to ensure that the regenerator packing is properly packed, after selecting the size and mesh of the matrix.
(2) It is to be fitted in the assembly of the given test set up (fig.2.17)
(3) The opening of the valves of the regenerator assembly to be checked during evacuation.
(4) Evacuation of the system shall start with roughing pump. After 1pascal of vacuum level diffusion pump shall be started. A final vacuum of the order of 10^{-2}pascal shall be obtained before starting the experiment.
(5) Fill both the liquid nitrogen chambers
(6) Starts the motor of rotary valve assembly and set it to the required speed.
(7) Record the flow of nitrogen boil-off periodically until the becomes relatively constant. A large boil-off will result initially the reading becomes relatively constant. A large boil-off will result initially as the chambers and other components are high temperature.

The test is repeated at different helium flow rates and speeds of the rotary valve in order to study the influence of the same on the inefficiency of the regenerators.

` The regenerator inefficiency $I_e$is defined as the ratio of $Q_L$which represents the quantity of heat which is not transferred from the regenerator (loss in regenerator) and Q_T which is the maximum quantity of heat that can be transferred.

$I_e=Q_L/Q_T$

$I_e$is the regenerator inefficiency

$Q_L$is the loss in regenerator

$Q_T$is the maximum quantity of heat that can be transferred.

$$\mathbf{Q_L=H\rho_{n2}(B_0-B_L)}$$

Where

H=latent heat of vaporization of nitrogen(kj/kg)

$\rho_{n2=}$Density of liquid nitrogen at standard condition(kg/liter)

$B_{0=}$operating boil off rate(liter/min)

$B_{L=}$non operating boil off rate(liter/min)

The maximum quantity of heat, Q_T that can be transferred is a function of gas flow through the regenerator, which is measured by orifice meter.

$Q_T$can be expressed as

$$\mathbf{Q_{T=}\ m_{g*}c_{pg*}(T_h-77)}$$

Where

$m_g$is the mass flow rate of helium through regenerator

$c_{pg}$is the specific heat constant of helium

T_{h} =temperature of helium at standard condition

Conclusion

The purpose of regenerator test is to simulate the condition in which the regenerator is actually used. A very important objective in design of test apparatus would be to measure the inefficiency to a high degree of accuracy

A steady state method would be adopted for determining the ineffectiveness of the regenerator by supplying known quantity of liquid nitrogen to compensate loss. The regenerator under investigation can be simulated to a condition of those in cryo-refrigerator. The present test set-up is simulated very close of that of giffored-mcmohancryo-refrigerator.

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