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Development and investigation of a regenerator for a reverse Stirling cycle based cryogenerator

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Abstract. The regenerator is considered to be the heart of the Stirling cycle gas liquefier and it is an efficient compact reversing type heat exchanger. Its packing material is first cooled by the cold gas displaced from the expansion space to the compression space and subsequently this matrix material in turn cools the working gas displaced from the compression space to the expansion space. A regenerator is successfully developed by using copper wool matrix having 50 gauges (0.022 mm). The outer and inner casing has been fabricated from fiber glass reinforced plastic. The matrix material is filled in the casing and sealed with a brass ring of 24 gauges (0.51mm). The regenerator is tested successfully by replacing the original regenerator from ZIF-1002 Cryogenerator machine and by liquefying air. The present paper describes the details of the Regenerator development, its testing and evaluation of its relative effectiveness and the result is encouraging.
Keywords: Reverse Stirling Cycle, Regenerator, Cryogenerator.

1. Introduction

The practical realisation of Stirling cycle has only become possible with the development of efficient compact reversing type heat exchangers, viz. regenerators. Reversing heat exchangers usually operate continuously, and their typical flow pattern is for the warm stream to run counter current to the cold streams during any one period. However, regenerators do not operate continuously, instead they operate periodically storing heat in a packing during the first half of the cycle and then of the cycle. The regenerator packing material is first cooled by the cold gas displaced from the expansion space to the compression space and subsequently this matrix material in turn cools the working gas displaced from the compression space to the expansion space. With the application of regenerator in Stirling cycle machine, it is possible to attain low temperatures with moderate pressure ratio. Regenerators provide the simultaneous cooling and purification of gases in low temperature processes.

It is very difficult to avoid leakage of small of lubricating oil vapour or liquid to the regenerator packing material through the piston during operation of the compressor. This oil forms a thin film over the heat transfer surfaces regenerator packing material which in turn reduces heat transfer coefficient and effectiveness of the regenerator. As this is a cumulative effect, the effectiveness of the regenerator gradually decreases resulting in the reduction of the production rate of the liquefier. This necessitates periodic cleaning of the regenerator with petroleum ether solvent. But each time some amount of oil cannot be removed. As a result, after a few such operations, the regenerator is no longer suitable for the liquefier. Thus after several hours of operation of the plant (liquefier), replacement of regenerator is a must. Regenerator of Stirling cycle liquefier is an imported item and is very costly to procure. In this regard local development and fabrication of a regenerator with cheap materials becomes essential for the eventual replacement of foreign Cryogenerator.

Various theories of regenerators are available in the literature [1-5]. It is very important that the efficiency of regenerator in a Stirling cycle Cryogenerator should be very high and should approach 100%. The analysis of a regenerator is more complex than that of other conventional heat exchangers because of the time and position depending on its operating temperatures.

The P-V diagram and T-S diagram of Reverse Stirling Cycle Cryocooler are depicted in Figure 1.

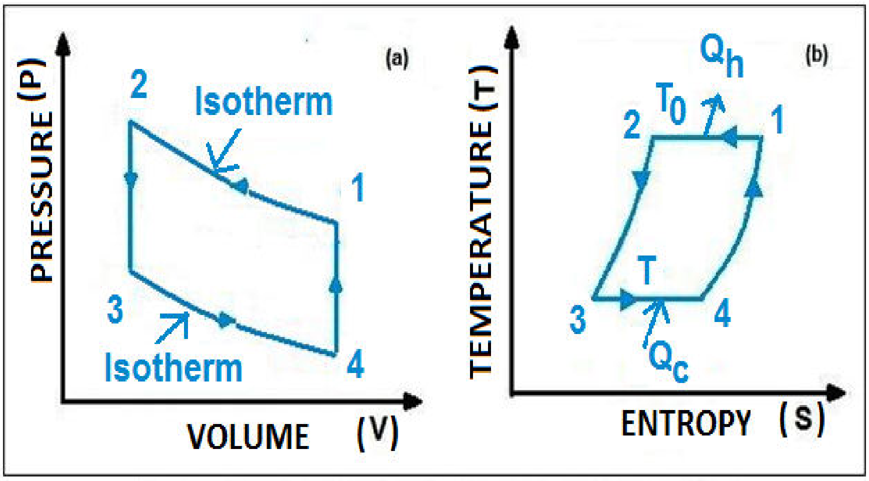

Figure 1. Stirling Refrigeration Cycle (a) P-V diagram (b) T-S diagram

2. Regenerator Material

Different matrix materials are used in the regenerator depending upon the application. Copper wool, copper grains, copper wire mesh, wire mesh of phosphor bronze (94.75% copper, 5% tin, 0.25% phosphorus etc.) are often used for temperature range 300-60K. For the temperature below 60K lead balls can be used as the matrix material. Lead can be used at 15 K with good efficiency and 7.5K to 15K with poor efficiency. Both copper and lead show a sharp decrease of heat capacity with decreasing temperature. Activated charcoal could also be used as the regenerator packing materials. Charcoal itself has small heat capacity at low temperatures, but it may absorb many times its own volume of helium gas. If the adsorbed helium has heat capacity similar to that of liquid helium, such a regenerator would have sufficient heat capacity to operate down to very low temperatures. Brittleness of charcoal offers some difficulties towards its use as the packing material. The use of polycrystalline iron whiskers as matrix material is also reported in literature [4]. Experimental study was carried out by Andeen [7] on small Stirling cryocooler, using phosphor bronze and stainless steel screens as the packing materials. It is observed that regenerator performance is insensitive to matrix material in the temperature range 300 – 80K. He also demonstrated that plastic such as nylon can also be used as the regenerator material provided the cycle rate is not high.

The variation of mesh size and its influence on the effectiveness of regenerator for PLN-106 liquid nitrogen machine has also been studied [5]. The mesh size influences the effectiveness significantly and it is observed that the maximum effectiveness is obtained at the minimum dead volume or porosity combination for a given mesh size. The results show that as the mesh number is increased for the same wire gauge, the effectiveness of regenerator in-creases. This is due to the fact that heat transfer area per unit volume increases with denser mesh. Also, if the wire gauge is increased while keeping the mesh number the same, the effectiveness of the regenerator decreases due to an increase in the porosity. Mesh material and mean pressure of the system do not affect the effectiveness significantly.

3. Fabrication of Regenerator

Regenerator, a self-cleaning reversing flow type compact heat exchanger, is considered as heart of the Cryogenerator. It has to maintain a temperature gradient of around 250 K. Regenerator outer and inner casing (bush) have been fabricated from fiber glass reinforced plastic (IS: 10192 Grade EP-3), matrix material collected from local source has been filled in the casing with appropriate density of packing and sealed with a brass ring of 24 gauge. The entire fabrication of the regenerator unit as whole has been tested successfully. A successful developed regenerator is shown in Figure 2.

Figure 2 depicts the cross-sectional view and Figure 3 represents the pictorial view of the regenerator developed.

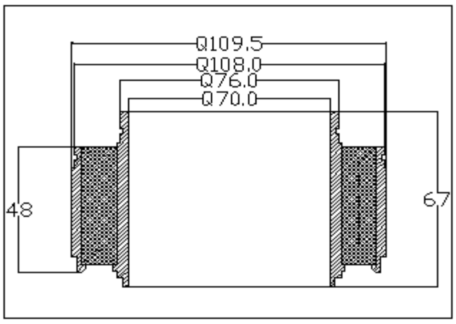

Figure 2. Cross sectional Diagram of the Developed regenerator

Figure 3. Pictorial View of Regenerator developed

4. Construction of Regenerator

For the actual development of an indigenous regenerator, copper wool having 50 gauge (diameter of wire = 0.022 mm) is procured. A number of rings are constructed from copper wool. A wooden male-female arrangement is fabricated and it is utilised for uniformly packing the rings. Copper wool weighing 300 g is packed. Stiff wire mesh supports are used at the ends which are retained with the help of inner and outer brass collars. The total weight of the regenerator is found to be 590 g i.e. the weight of shell including stiff wire mesh and brass collars are only 290 g weight.
Regenerator is built by fabricating a casing made of insulating material and subsequently filling it with copper wool as matrix material.

5. Experimental operation of ZIF-1002 Cryogenerator machine for evaluation of the efficiency of the regenerator developed

The Distillation column is dismantled from the liquid nitrogen machine (ZIF -1002) under study, i.e. the Cryogenerator part is now separated from the rectification column. At the top of the Cryogenerator an additional adsorber fabricated with molecular sieve tower is fixed so that the air fed to the top of the Cryogenerator is free from moisture and carbon dioxide. Now Cryogenerator working space is filled by the helium from the cylinder attached to the working space through a separate line. The gas is filled up to a 2.0 MPa (20 kg/cm^2) pressure indicated in the instrument panel of the plant. Cooling water is then circulated.

The plant is now ready for operation. When the plant is switched on, air is sucked into the condenser through the adsorber and gets liquefied by the cold generated in the refrigeration process and comes through the pipe line. The plant is first run with original ZIF-1002 regenerator. Then the original regenerator is removed from the Cryogenerator and the newly fabricated regenerator is assembled and the plant is run for several days. The results are presented in Table 1 and Table 2.

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Table 1. Operation of Gas liquefaction installation ZIF-1002 with the original Russian regenerator

Days		Day1	Day2	Day3	Day4	Day5
Room temperature		30.5°C	30.7°C	31°C	30.6°C	31.7°C
Starting time		12:00PM	12:00PM	12:00PM	12:00PM	12:00PM
Inlet cooling water temperature		7.0°C	7.2°C	6.9°C	7.8°C	8.0°C
Hydrogen pressure	**Initial**	2.0MPa	2.0MPa	2.0MPa	2.0MPa	2.0MPa
	working	2.5MPa	2.5MPa	2.5MPa	2.5MPa	2.5MPa
Oil level indicator		OK	OK	OK	OK	OK
Vacuum created by water jet		OK	OK	OK	OK	OK
Circulating cooling water pressure		0.2MPa-0.25MPa	0.2MPa-0.25MPa	0.2MPa-0.25MPa	0.2MPa-0.25MPa	0.2MPa-0.25MPa
Switch off time		03:00PM	03:00PM	03:00PM	03:00PM	03:00PM
Total yield of liquid air		21.0 kg	21.6 kg	20.8 kg	21.9 kg	20.4 kg
Rate of production of liquid air per hour		7.0 kg	7.2 kg	6.93 kg	7.3 kg	6.8 kg

Table 2. Operation of Gas liquefaction installation ZIF-1002 with the Regenerator developed

Days		Day1	Day2	Day3	Day4	Day5
Room temperature		30.5°C	30.7°C	31°C	30.6°C	31.7°C
Starting time		12:00PM	12:00PM	12:00PM	12:00PM	12:00PM
Inlet cooling water temperature		7.0°C	7.2°C	6.9°C	7.8°C	8.0°C
Hydrogen pressure	**Initial**	2.0MPa	2.0MPa	2.0MPa	2.0MPa	2.0MPa
	working	2.5MPa	2.5MPa	2.5MPa	2.5MPa	2.5MPa
Oil level indicator		OK	OK	OK	OK	OK
Vacuum created by water jet		OK	OK	OK	OK	OK
Circulating cooling water pressure		0.2MPa-0.25MPa	0.2MPa-0.25MPa	0.2MPa-0.25MPa	0.2MPa-0.25MPa	0.2MPa-0.25MPa
Switch off time		03:00PM	03:00PM	03:00PM	03:00PM	03:00PM
Total yield of liquid air		21.0 kg	20.7 kg	20.4 kg	21.3 kg	20.7 kg
Rate of production of liquid air per hour		7.0 kg	6.9 kg	6.8 kg	7.1 kg	6.9 kg

6. Relative effectiveness of the Regenerator Developed

It is observed that when the plant is run with a fresh ZIF-1002 regenerator the average production rate is 7 kg/hr of liquid air. But the plant can produce only 6.93 kg/hr of liquid air as an average when it is operated under similar condition with the ZIF-1002 regenerator replaced by the regenerator developed. This fall in production rate is definitely connected with the efficiency factor of the regenerator under study. For finding out the relative effectiveness of the regenerator, it is assumed that the original regenerator has got an effectiveness of 100%. Then loss in refrigeration is equal to the refrigeration associated with production of (7- 6.93) kg or 0.07 kg of liquid air under specified condition as stated earlier.

Therefore, loss in refrigeration (L_R) = 205* 0.07 kJ/hr = 14.35 kJ/hr. [where, refrigeration required for air for its liquefaction is 205 kJ/kg].

The fraction of the cold lost due to inefficiency of the regenerator is

$$\frac{\Delta Q}{Q_{ideal}} = [\frac{(1-E)C_v(T_2-T_3)}{RT_3 \ln(\frac{V_4}{V_3})}] \quad where, E = (Q_{ideal} - \Delta Q)/Q_{ideal}; C_V = (3/2)R; (V_4/V_3) = 1.24$$

ΔQ = the energy which is not absorbed in the regenerator due to deviation of its effectiveness from 100 % and

Q_{ideal} = the heat is absorbed in a regenerator of 100% effectiveness.

Refrigeration effect loss due to 1% decrease in effectiveness for a Cryocooler/Cryogenerator operating between 60K and 300K with helium as the working fluid, can be given with the help of above equation as follows

$$\frac{\Delta Q}{Q_{ideal}} = [\frac{(1-0.99)\frac{3}{2}(300-60)}{60\ln 1.24}] = 0.279$$

It is analytically shown earlier that there will be a loss of 27.9% in refrigeration due to 1% decrease in effectiveness.

In the present case, the refrigeration loss is 14.3/4200 * 100% = 0.34% which corresponds to a loss in effectiveness of 0.34% only. Therefore, for an effectiveness of 100% for the original regenerator, the relative effectiveness of regenerator developed would be 99.6% [2].

7. Result and Discussion

From the operational data of the plant it is clear that the production of liquid air falls from 7 kg/hr to 6.9 kg/hr (approx) when the fresh Russian regenerator using copper wool as the matrix material is replaced by the regenerator developed. Therefore, the effectiveness of the regenerator developed is slightly lower than the original one, the other operational parameters remains the same. Effectiveness of this regenerator with respect to the Russian regenerator is found to be 99.6%. Therefore, regenerator developed is quite capable of handling the purpose.

This investigation enables us to develop one of the important components of Stirling cycle Cryogenerator. Replacement of regenerator becomes essential after several hours of operation because washing with petroleum ether cannot remove all the oil accumulated. As a result it becomes ineffective after a definite period and can no longer serve the purpose. Effectiveness can be optimised by changing matrix materials in various proportions.

8. Conclusion

Therefore, the regenerator developed can be effectively used in the Cryogenerator development as a highly efficient component.

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