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Review of heat exchanger for subcooling of liquid Nitrogen in GM cryocooler

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ABSTRACT

Heat exchanger is a device which exchanges heat between two flow lines. The goal of this article is to emphasis and presents briefly the heat exchanger designs used for liquefaction of nitrogen gas and subcooling of liquefied gas. Different researchers proposed various heat exchanger designs for liquefaction and subcooling of liquid nitrogen. The liquefied nitrogen gas has many applications. In this article, the heat exchanger designs developed by researchers over the time for effective subcooling of liquid nitrogen are addressed and studied. Further content is focused on increasing effectiveness of this type of heat exchangers for effective subcooling. The gaps in research identified and mentioned in the article.

Keywords— *Liquid nitrogen, Heat exchanger, Subcooling*

1. INTRODUCTION

1.1 Cryocoolers

A refrigerator designed to reach cryogenic temperatures (below 120°K / -153 °C) is often called a cryocooler [1]. A significant number of improvements to cryocoolers have occurred in the past 20 years, which in turn has allowed many more applications of cryogenics to flourish and find their way into the marketplace. Still, there are many attributes of cryocoolers that prevent many other applications of cryogenics from competing successfully with ambient temperature approaches. Although cryogenics can offer many benefits, as listed below. The successful utilization of any benefit occurs only when that benefit outweighs the disadvantages associated with the cryocooler. For example, the use of cryocoolers for space applications did not occur in a major way until the reliability was improved to the point where a ten-year lifetime could be achieved with a very high probability. The cost of cryocoolers has been a major factor hindering a more widespread use of cryocoolers in commercial applications. Cryocooler signatures, whether they are in the form of audible noise, vibration, or electromagnetic interference (EMI) also hinder the use of cryocoolers in many applications, especially those associated with sensitive electronics.

1.2 Gifford-McMahon Cycle

Gifford-McMohan cycle is closed refrigeration cycle. GM cycle consist of mainly four phases explained as follows.

- 1st phase is also called as pressurization phase in which the high pressure compressed gas is allowed to pass through the cylinder. In this phase, regenerator extracts heat from the gas to produce more cooling effect at the time of expansion.

- 2nd phase is called as intake phase. Intake valve i.e., at high pressure is remain open during this phase. The displaced is allowed to move in upward direction. This upward motion of displacer causes the passing of hot gases through regenerator.

- 3rd phase is called as Expansion phase. During this phase, the intake valve closes followed by expansion of gas. The low-pressure exhaust valve is now opened and the expansion of gas leads to cooling effect.

- The last phase is called as exhaust phase. The displacer is allowed to move in downward direction to push out the cold gases through the regenerator. After that the exhaust valve in closed and cycle is repeated. The heat picked up in 1st phase is released in this phase by regenerator.

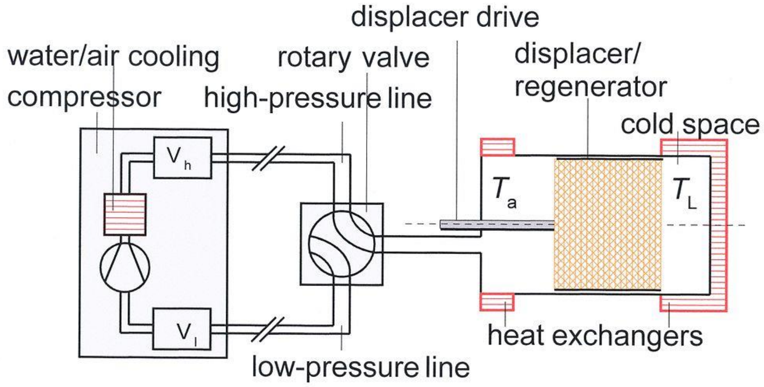

Fig. 1: GM cycle working [1]

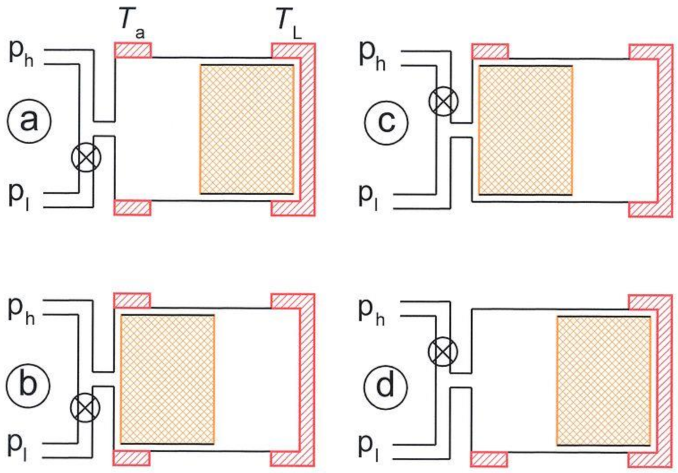

Fig. 2: Steps in GM cycle [1]

2. LITERATURE SURVEY

Liquefaction of gasses gives the easiest way to low temperatures and this remains to be the most sophisticated process till now. Anything might be cooled essentially by contact with the fluid. That contact can be indirect or direct which depends on upon the cooling procedure. Liquefaction of gasses is physical transformation of a gas into a liquid form. It is the way toward refrigerating a gas to a temperature lower than the critical temperature with the goal that, liquid can be formed at pressure below critical pressure of the gas. For quite a while, it was assumed that air stays in the vaporous state at all temperatures. In this way, gasses like nitrogen, oxygen, helium and so on were named as permanent gases. In 1823, Faraday initially discovered hints of fluid chlorine in a closed glass coil created by the pressure developed in the closed rigid coil. It started by this manner.

At Royal Institution in London, Faraday [2] condensed chlorine by warming and cosequent disintegrating in a sealed glass coil.

Cailletet [3] created a fog of oxygen by compressing the gas in specific conditions and then all of a sudden discharging it. After six years, it was Von Wroblewski and Olszewski who really liquified it with some enhanced conditions. They did it effectively for CO2 & N2. They initially utilized a second chamber outside the chamber containing the cryogen.

Sir James Dewar [4] using Joule Thomson effect liquified the hydrogen gas. They also invented the Dewar vessel for storing the condensed gases in it. Dewar vessel is basically made up of insulating material having radiation shield in it. Therefore it was very helpful step in the field of cryogenic liquifaction and storing of these condensed gases as well.

H. K. Onnes [5] at Leiden condensed helium (4He), not deliberately though. He was attempting to construct extensive limit air and hydrogen liquefiers. This opened up a tremendous domain of research for the researchers. Most of the advanced research in the field of low temperature was carried out in the University of Leiden. Truth be told, H. K. Onnes is considered as "The Father of the Low-Temperature Physics".

The Gifford-McMahon (GM) cooler belongs to a class of cooling systems utilizing a gas-compression refrigeration cycle. The refrigeration effect of the GM cooler results from a series of thermodynamic processes acting on the gas, including charging and compression, displacement and heat exchange with the regenerator, expansion and heat absorption (cooling effect). It seems that progress in the development of system design tools for GM coolers is still limited since only a few researchers have carried out system performance analysis.

Gifford [6] assumed that the GM cycle is composed of a cycle similar to the Brayton cycle but with an intermediate expansion pressure which varies with the displacer motion and the gas intake/exhaust process. In addition, the two isenthalpic processes of gas moving through the intake and exhaust valves were considered. Gifford derived an expression for COP in terms of pressure and temperature ratios based on the ideal analysis.

Thirumaleshwar and Subramanyam [7] further modified the Gifford model by considering the thermal losses in the cooler and derived an expression for cooler performance. It was, however, shown experimentally that their analysis over-estimates actual values in practice [8].
Instead of using the aforementioned thermodynamic approach, Ackermann and Gifford [9] derived a transient heat transfer model for the regenerator of a GM cooler according to a parallel flow analogy to account for the regenerator loss. The model can only be used, however, to evaluate the regenerator heat transfer property NTU using the test results of a GM cooler.

Minas and Hualde [10] derived a dynamic model for a GM cooler using a pneumatically-driven displacer. The model includes the dynamic, fluid dynamic and thermodynamic effects and consists of a non-linear time-varying system of differential equations which are solved numerically. The predicted system performance is shown to coincide with experimental results only qualitatively.

To overcome these difficulties, B.J. Huang and S.C. Chang [11] carried out system performance analysis of a Gifford-McMahon (GM) cooler using the half-cycle mean model of a regenerator and instantaneous solutions of the mass and momentum equations. A PC-based simulation package GMSYS was also developed for system design analysis of a single-stage GM cryocooler. It is shown experimentally that the predicted values agree very well with test results.

Thirumaleshwar et al. [12] has presented heat balance analysis of single stage GM cycle refrigerator. Ideal refrigeration, actual refrigeration, net refrigeration and various losses are tabulated. It is obsereved that P-V loss account for major fraction of total losses.

Choi et al. [13] subcooled liquid nitrogen with extended surface of copper connected at the end of coldhead. Thermofoil heater is installed at the coldhead to avoid freezing of liquid N2. Initially liquid N2 at 77.3K is cooled down to its freezing temperature i.e. at 63K. To investigate the performance of extended surface, uniform heat flux supplied to heater and heating plate and heat transfer coefficient is calculated.

C. Wang and P.E.Gifford [14] worked on existing GM cryocooler and redesigned rotary valve and regenerator to reduce losses in rotary valve and low temperature regenerator of regenerative GM cryocooler. They increased the size of rotary valve by 125% and optimized the valve timing.

To overcome the problem of evaporation of liquefied nitrogen, Chang et al. [15] subcooled liquid nitrogen from 77.3K to 65-70K. A test heat exchanger is attached at the end of cold head, they used coldhead model AL300 for their experimental study. The experiment is carried out on different size of helical coil heat exchanger and suggested the optimum size of D = 100mm and H = 100mm.

one year later Chang et al. [16] successfully developed analytical method to predict the cooling rate of LN2 with test heat exchanger in contact with regenerative cryocooler. Analytical results compared with experimental results which are in fair good agreement.

During subcooling of LN2 the problem of freezing is encountered, to overcome this problem Chang et al. [17] proposed and investigated cross flow heat exchanger for anti-freezing of LN2. Plate fin Heat exchanger are fabricated as typical counter flow and newly proposed two pass cross flow and tested with cold helium gas at temperature below 60K. Experimental results shows that cross flow heat exchanger is less vulnerable to freeze out condition. Cross flow heat exchanger are effective in avoiding complete clog up of passages and reducing risk of freeze out of LN2 (Liquid Nitrogen).

Choi et al. [18] studied natural convection in subcooled liquid nitrogen. They subcooled liquid nitrogen near to freezing temperature i.e. at 63K at atmospheric pressure by vertical copper heat transfer plate anchored to coldhead of GM cryocooler. Parallel constant heat flux plate is placed at a distance so that liquid between this plates may develop circulating flow by natural convection. Temperature distribution of both plate surface is measured and from which heat transfer coefficient calculated. Experimental data compared with existing correlation for rectangular cavity where each vertical surface has uniform temperature.

K. Yamada [19] of Sumitomo Heavy Industries (SHI) developed large cooling capacity single stage GM cryocooler for HTS application. Also low mechanical vibration and low acoustic noise have been achieved because displacer is driven by motor instead of pneumatic force. As Lead is hazardous substance for health, so it's replaced by Bismuth as regenerator material.

Waele A.T.A.M de [20] analyses temperature- time dependence in GM cryocooler near its low temperature limit. Some attention also focused on pulse coil refrigerator. Attention is paid to the thermodynamics of cycle by considering the isentropes in the T-P diagram.

3. CONCLUSION

- In most of the research papers, the study regarding Liquid Nitrogen generation and improvements towards LN2 plant designs are made.

- Choi et al. subcooled liquid nitrogen with extended surface of copper connected at the end of coldhead. Because of lower temperature of coldhead, freezing problem of Liquid nitrogen encountered.
- Chang et al. subcooled liquid nitrogen with the help of helical coil heat exchanger and cross flow heat exchanger. The problem of vapourization of LN2 in dewar flask takes place results in reduced efficiency of plant.
- Subcooling is one of the option to store LN2 in insulated container for longer period of time, because small heat addition in subcooled liquid will not make phase change process. So, in this research there is wide scope for subcooling liquid nitrogen by inventing effective heat exchanger design in GM cryocooler.

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