sciendo
Mechanics and Mechanical Engineering 2019; 23:291–296

Research Article

Debajyoti R. Chowdhury, Nathuram Chakraborty, and Swapan C. Sarkar*

Development of a cryogenic condenser and computation of its heat transfer efficiency based on liquefaction of nitrogen gas

https://doi.org/10.2478/mme-2019-0039
Received Feb 5, 2018; revised Sep 1, 2018; accepted Nov 20, 2018

Abstract: The typical cryogenic condenser described here transfers the refrigerating effect from its inner side to its outer side through the wall of the condenser. The separate close refrigeration cycle operates on Reverse Stirling Cycle using hydrogen or helium as working fluid. The nitrogen gas gets liquefied when it comes in contact with the cold outer surface of the condenser. We have successfully developed a cryogenic condenser using copper of electrolytic grade for a liquefaction duty of 10 liters of liquid nitrogen per hour. Condenser effectiveness is evaluated by assembling it in Cryogenerator model, ZIF-1002 and by noting the liquefaction rate. Both the results are satisfactory. Selection of material, fabrication, testing of the condenser developed for a Cryogenerator have been described in the paper to assess its suitability for a Cryogenerator based on Reverse Stirling cycle liquefier.

Keywords: Reverse Stirling cycle, Condenser, cryogenerator, heat exchanger effectiveness, liquid Nitrogen

Nomenclature

ΔT	Temperature gradient
η_C	Heat exchanger effectiveness
C_p	Specific Heat of Nitrogen
L	Latent heat of nitrogen
m	Mass flow rate of nitrogen
Q	Total refrigerating load

***Corresponding Author: Swapan C. Sarkar:** Centre for Rural & Cryogenic Technologies, Jadavpur University, Kolkata 700032, India; Email: swapansarkar1959@yahoo.in
Debajyoti R. Chowdhury: Centre for Rural & Cryogenic Technologies, Jadavpur University, Kolkata 700032, India; Email: debajyotiroychow_123@yahoo.co.in
Nathuram Chakraborty: Centre for Rural & Cryogenic Technologies, Jadavpur University, Kolkata 700032, India; Email: nathuramchakraborty@yahoo.in

1 Introduction

Atmospheric air is the raw material for all cryogenic air separation units and cryogenic air separation principle forms the base for most of the plants, which, however, have been further optimized regarding variable product scope and energy consumption. The level of product purity varies and ranges from approximately 99.9 to 99.8%. The concept of Nitrogen separation from the atmospheric air by cryogenic systems involves compression of purified air followed by isothermal cooling and adiabatic expansion to obtain liquid air, which is distilled to get liquid nitrogen.

Kotz *et al.* [1] reported that oxygen and nitrogen are most extensively used by industries and they are annually the top chemicals used worldwide. Cryogenic air separation plants are currently the only efficient and economically viable method of producing air products on large scale. [2] In this study, experimental determinations of heat-exchange coefficient at hydrogen condensation on various geometry types of condensers were reported. [3] Various types of cryogenic condensers find many applications such as refrigerator, condenser for organic vapor, large scale air separation plant, cryocooler and liquid level meter and so on. Ameen *et al.*, [4] in their study, developed a model using finite element method as a design tool for designing and predicting the performance of a wire-on-tube condenser of a domestic refrigerator. Here, the author replaced the R-12 refrigerants by R-134a. Pitting induced failure occurred in cryogenic condenser, which is made of SS304 and 304L SS material for acetone-methanol condensation using a brine solution. A pinhole had appeared on the surface of the cryogenic condenser. Investigation of failure was carried out by visual and dye penetration examination and by using various instruments by Mudali *et al.* [5] Wu *et al.* [6] developed a new condenser-evaporator by replacing the old one for a large scale air separation

Open Access. © 2019 D. R. Chowdhury *et al.*, published by Sciendo. BY-NC-ND This work is licensed under the Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 License

plant of capacity 30000 m^3/hr. with oxygen as the output. Here, the author described the condenser-evaporator as Quasi-annular flow condenser-evaporator type by altering the boiling and condensation mechanism of heat transfer and found that the developed condenser-evaporator was more efficient in all respect.

Wang *et al.* [7] modified the cold head of the Cryomech PT410 pulse tube cryocooler by adding helium condenser and increased the liquefaction rate from 12.8 to 21.4 L/day. After modifying the cryocooler, they carried out the experiment by improving the use of natural convective heat transfer on the cryocooler to precool the helium vapor to its liquefaction stage. The author invented a cryogenic condenser with liquid level sensor and control device for sensing the level of a cryogenic liquid in a high-pressure condenser system to separate the cryogenic liquid from a gas. [8] Messer *et al.* [9] investigated the energy exchange between gases and solid surfaces by constructing a cryopumping system with liquid helium and two cryogenic condensers equipped with an evaporator for molecular beam experiment. Cristescu *et al.* conducted an experiment to determine the heat-exchange coefficient on different types of condensers. Cold surface of various types of condensers were measured based on the liquid flow-rate from the condenser. They found that the condensate film temperature drop occurred for different shapes and geometry of the condensers. [10]

The present work is unique in nature for small scale production of liquid nitrogen. PSA-Cryogenerator is preferred as compared to the complex Cryogenerator-Distillation column system. The air is separated into its component nitrogen and oxygen by Pressure Swing Adsorption system and pure nitrogen is fed to the exposed side of the cold condenser, where the nitrogen is liquefied. The liquid nitrogen flows through a channel and is collected in a cryogenic vessel. The refrigeration cycle, operated in closed Reverse Stirling Cycle, produces the required cold in the inside slots of the condenser. The refrigerant gas must have its normal condensation point below that of the gas being liquefied.

The present article highlights the development of a cryogenic condenser in detail and its efficiency testing methodology in-situ by placing it in the Cryogenerator for liquefying nitrogen.

2 Material and Methods

2.1 Material selection

Materials should be prudently selected for any cryogenic application as there can be extreme changes in the properties of the material being used when exposed to low temperature. [11–13] Mechanical properties of materials used in making cryogenic based condenser play a very important role. Some metals become brittle at sub-zero temperature, while in other metals, an increase in their ductile properties is observed. Once the material is selected, fabrication techniques like brazing, soldering, or welding are to be applied in order to ensure the best performances. [14–16] Materials like stainless steel, copper, brass, Monel, carbon, aluminum and its alloy are useful in making cryogenic equipment, due to their lower coefficient of expansion. [17] Copper is selected as a raw material in construction, as it is most suitable for cryogenic temperature applications. [18, 19] Most materials experience a thermal contraction when cooled to cryogenic temperature. In the metallic elements such as copper and aluminum, electronic thermal conductivity is much larger than the lattice conductivity at all temperature. [20] Generally, FCC (face centered cubic lattice) metals do not become brittle at cryogenic temperature. Stainless steel, nickel, aluminum and copper are categorized as FCC metals. The increase in strength of the metal is due to a reduction in the thermal energy at low temperature. Silver, aluminum and copper are common electrical conductors or thermal conduction straps in cryogenic systems.[21] Thermal conductivity measurement on copper wires down to 20 mK have been reported. [22] Samples in the form of rod and foil are also used for their conduction measurement. [23] Measurement of thermal conductivity down to 30 mK was carried out on copper of three different commercial varieties. The experiment was conducted to select the thermal link. [24–26]

The typical material composition of electrolytic tough pitch copper is fixed as per ASTM B224 under ASTM B170. ASTM B224 specification is given by the American Society For Testing and Materials for classification of various types of copper available in refinery shapes and wrought products in commercial quantities. It includes those varieties of copper in which the copper is as high as 99.85% or more. High resistance of copper to hydrogen embrittlement is determined by ASTM B170.

Thus, considering all the aspects as discussed above, and its heat transfer characteristics, electrolytic tough pitch copper bar is chosen as a material of construction.

Table 1: Specification of cryogenerator Model ZIF-1002

Specification	Single Cylinder Model ZIF-1002, Russia
Refrigerating ability	4200 kJ/hr.
Refrigerant used	30 gm Helium/Hydrogen
Type of compressor	Piston displacement type, vertical, two crank, without valves, closed cycle
Compressor cylinder diameter	101.6 mm
Piston stroke	52 mm
Displacing unit dia.	70 mm
Displacing unit stroke	30 mm
Crank displacement angle	70 (with an advance of displacing unit)
Operating oil	Turbo-27
Filling capacity of oil system	1.25 liters
Cooling system	Liquid under pressure
Rate of coolant consumption	Not less than 1 cu m/hr.
Motor power	17 kW
Motor and compressor speed	1460 rpm
Motor power supply	Three-phase four cable mains, 50 Hz 380V
Operating pressure of refrigerant	25 atm.
Cooling liquid temperature	+15°C
Ambient air temperature	+20°C
Ambient air pressure	760 mm of Hg

The indigenous condenser was assembled in the Cryogenerator model, ZIF-1002 by replacing its original condenser. The specification of ZIF-1002 (Russia make) is given in Table 1. [27]

2.2 Methodology of fabrication

The cryogenic condenser development is one of the most critical components of the Reverse Stirling Cycle based liquefier. The condenser component is fabricated from a copper bar. The fabricated condenser has 160 slots of 0.5 mm length and depth of 56 mm, which is maintained within a 70 mm diameter on the inner side. Outer side of the unit has 120 slots of 0.5 mm width and 78 mm depth within a diameter of 124 mm.

The above complicated fabrication is accomplished by using the HMT vertical milling machine, which is a multitooth rotating cutter and a work piece is placed for cutting in this machine. It was taken through 0.5 mm milling moving, cutter holder arrangement within 30 mm diameter area.

Brazing, a metal joining technique, which differs from soldering in the respect that the filler melting temperature is higher and the strength of the brazed joint is also much higher than the soldered joint. Flux is also required for protecting the filler material above its melting point. [28, 29] In the present brazing process, Rupatam wire having a diameter of 0.8 mm and 43% Ag melt at 750°C has been used. Various dimensions of the condenser are depicted in Figure 1.

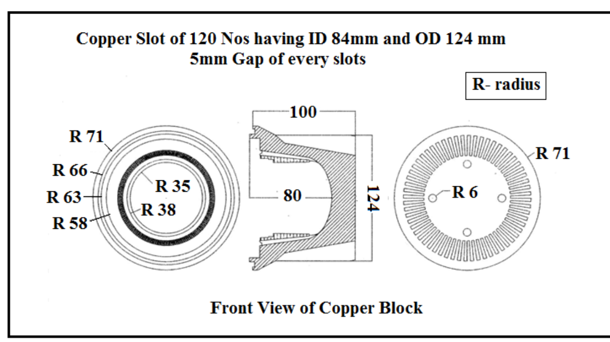

Figure 1: A view of the developed condenser showing various dimensions

3 Non-Destructive Testing

Non-destructive testing (NDT) are flaw detection techniques used in metal fabrication industries to evaluate the properties of a material, component or system without causing any damage to it. The condenser developed is first exposed to liquid nitrogen. The product is tested using the ultrasonic method, which is a non-destructive testing technique for finding any structural defect developed for the liquid nitrogen treatment.

3.1 Liquid nitrogen testing

The condenser is immersed in liquid nitrogen bath for 30 minutes. Thereafter, it is lifted from the bath and is exposed to the atmosphere at room temperature. After the initial frost that forms on the surface of the condenser vanishes, the condenser is subjected to non- destructive testing using ultrasonic method. Figure 2 shows the pictorial views of the frosted condenser immediately after the liquid nitrogen treatment. This test assesses the compatibility of the condenser material for cryogenic services.

Figure 2: Pictorial view of the frosted condenser after liquid nitrogen treatment

3.2 Ultrasonic testing

Ultrasonic Testing (UT) is a very useful technique in detecting flaws and material characteristics. Ultra sound in the range of 0.5 MHz and 15 MHz is normally used for the purpose. Generally, ultrasonic testing is dependent on the measurement of either the reflected waves (pulse-echo) or the transmitted waves (through-transmission). Out of the two waves, pulse echo system is more useful as it accesses one-side of the object. [30]

The condenser was tested for ultrasonic testing by 100% back reflection method (+6dB), to conform the micro-pores defects as per ASTM A-388 standard. It was tested by the method of pulse echo using longitudinal wave. Normal operational mode of scanning was performed. The accessible surface was scanned radially and axially. The pictorial view of the condenser after testing is shown in Figure 3.

Figure 3: Pictorial view of flawless Cryogenic condenser ready for assembling

4 Efficiency Testing of the Condenser

Air is purified by passing through a Pressure Swing Adsorption system. Pure nitrogen is fed to the condenser of the Cryorefrigerator for liquefaction. The Reverse Stirling Cycle based refrigeration system produces the necessary cold for the liquefaction in a separate circuit involving compressor, cooler, regenerator and expander. Schematic diagram of the experimental setup is shown in Figure 4.

The developed condenser is assembled in the cold box as an efficient part of the ZIF-1002 Cryogenerator, and the Cryogenerator is then run for 10 hours for liquefaction of nitrogen. The liquefaction is successfully achieved at the rate of 7.7 kg/hr. Photograph of the Cryogenerator and liquid nitrogen production using the indigenous condenser is depicted in Figure 5 (A and B).

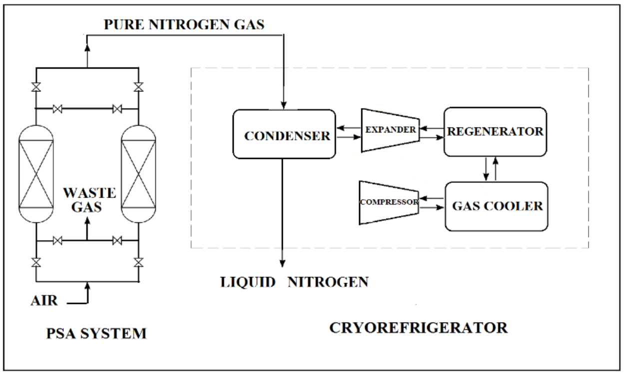

Figure 4: Schematic diagram of the experimental setup

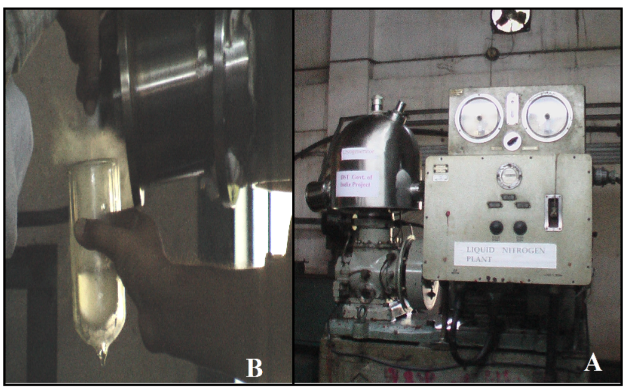

Figure 5: A. photograph of Cryogenerator; B. Photograph of Liquid Nitrogen collection

5 Result and Discussion

Copper used for the development of condenser was tested as per ASTM B224 and percentage of copper was found to be as high as 99.95%, with traces amount of silver, bismuth, tin, aluminum, zinc and lead, and with no traceable amount of iron, nickel and antimony. Again, for assessing the suitability of cryogenic condenser thus developed for its application below 123K, it was exposed to liquid nitrogen for 30 minutes and tested for any flaws by ultrasonic method. The component successfully passed the test as no crack developed on the tested sample during the test.

The compatibility of the condenser in terms of its ability to transfer refrigerating effect from the expansion zone of Cryogenerator to the incoming gas at room temperature is tested in situ by replacing the condenser of Cryogenerator model ZIF-1002 and liquefying nitrogen gas by the indigenously built condenser. Relevant parameters for nitrogen gas to be liquefied are presented in Table 2.

Total refrigerating load required to liquefy 7.7 kg/hr. of pure nitrogen can be expressed as follows:
Q = Heat to be removed off nitrogen from 303.15 K to 77.5K

Table 2: Different parameters of the pure Nitrogen gas

Inlet Temperature of Purified Nitrogen gas (K)	303.15
Inlet pressure of purified Nitrogen gas (MPa)	0.12
Normal Boiling point of Nitrogen gas (K)	77.5
Specific Heat of Nitrogen (kJ/kgK)	1.039
Latent Heat of Nitrogen (kJ/kgK)	200
Mass flow rate of Nitrogen gas (kg/hr.)	7.7
Pressure of condensed nitrogen (MPa)	0.1
Temperature of condensed nitrogen (K)	77

+ latent heat of nitrogen, is expressed as follows:

$$\begin{aligned} Q &= m \cdot C_p \cdot \Delta T + m.L \qquad (1) \\ &= (7.7 kg/hr. \cdot 1.039 kJ/kg \cdot 225.65 K) \\ &+ (7.7 kg/hr. \cdot 200 kJ/kg) = 3345.26 kJ/hr. \end{aligned}$$

The actual refrigerating ability at 77 K of Cryogenerator model, ZIF-1002, is 4200 kJ/hr., as given in its specification.

Therefore, the effectiveness of the Indigenous Cryogenerator condenser with respect to ZIF-1002 condenser is the ratio of actual refrigeration ability of the ZIF-1002 to the refrigeration ability as determined by nitrogen liquefaction rate.

Therefore,

$$\eta_C = \frac{3345.26 kJ/hr}{4200 kJ/hr} = 0.796 = 0.8 (approx..)$$

The heat transfer efficiency of the condenser is computed as 80% based on the refrigeration ability of the old ZIF-1002 machine. The actual refrigeration ability of old machine may be slightly less than 4200 kJ/hr., and in that case, the computed value of the condenser developed is expected to be more than 80%, which is very encouraging for the development of Cryorefrigerator from indigenous material.

6 Conclusions

The condenser thus developed from the electrolytic grade copper will have an immense potential to build the Cryogenerator for liquefaction of nitrogen or other cryogenic gases whose boiling point lies in the range of 123K to 77K. The small scale nitrogen liquefaction plant based Reverse Stirling Cycle thus can be built indigenously. Refrigeration ability of the condenser is based on the liquefaction rate and the refrigeration ability of the ZIF-1002 machine.

In the present case, the relative efficiency of the indigenous condenser in terms of transferring refrigerating effect has been evaluated, which is practical for the eventual development of the entire Cryogenerator. The heat exchange efficiency of the condenser is expected to be more than 80%. It can help substitute the imported component of the Cryogenerator for the eventual development of laboratory scale liquid nitrogen plant. The present investigating group in the process of development of such a liquid nitrogen plant based on PSA- Cryogenerator combination utilizing the condenser developed.

Acknowledgement: The present study is a part of research work of the project entitled 'Development of liquid nitrogen plant (7–10 liters) capacity utilizing the conceptual design of the first phase'. Dr. Swapan Chandra Sarkar, the principal investigator of the project, is grateful to the Department of Science and Technology, Govt. of India for the financial assistance bearing the grant number DST/TSG/NTS/2009/63 towards this technology development project. Authors are thankful to Mr. Sujit Das and Mr. Atanu Mukherjee for their technical help for the work.

References

[1] Kotz J. C., Treichel P.: Chemistry and Chemical Reactivity, 3rd edition. Harcourt Brace & company: Orlando, USA, 1996.
[2] Smith A. R., Klosek J.: A review of air separation technologies and their integration with energy conversion processes. Fuel. Process. Technol., 70, 2001, 115–134.
[3] Cristescu I., Cristescu Ioana., Zamfirache M., Brad S.: Determination of heat-exchange coefficients at hydrogen condensation in various geometry of condensers. Romanian Reports in Physics, 52 (3–4), 2000, 333–343.
[4] Ameen A., Mollik S. A., Mahmud K., Quadir G.A., Seetharamu K. N.: Numerical analysis and experimental investigation into the performance of a wire-on-tube condenser of a retrofitted refrigerator. Int. J. Refrigeration, 29, 2006, 495–504.
[5] Mudali U. K., Raju V. R., Dayal R. K., Khatak H. S.: Pitting induced failure of austenitic cryogenic condenser coil for acetone service. Eng. Failure .Analysis, 10, 2003, 37–44.
[6] Wu Y. Y., Chen L. F., and Wu T. H.: Chapter-199-A new type of condenser-evaporator safely operated in large air separation plant, Proc. Twentieth. Int. Cryogenic Eng. Conf. (ICEC 20), Beijing, China. Elsevier Ltd., 2005, 841–844.
[7] Wang C., Scurlock R. G.: Improvement in performance of cryocoolers as condensers. Cryogenics, 48, 2008, 169–171.
[8] Post A. H., Belmont Jr., and Hogan W. H.: Cryogenic condenser with liquid level sensing and control, US Patent, Patent no. 3,340,699, 12 Sept 1967.
[9] Messer G., Schulze W.: A cryopumping system with two cryogenic condensers for Molecular beam experiments. Cryogenics, 10(2), 1970, 161–163.
[10] Cristescu I., Cristescu Ioana., Zamfirache M.: Determination of heat transfer coefficients for hydrogen condensation in condensers of various geometries. Int. J. Therm. Sci., 39, 2000, 659–666.
[11] Lyakishev N. P., Alymov M. I., Dobatkin S. V.: Bulk constructional nanomaterials. metally, 3, 2003,3.
[12] David E.: Materials for Cryogenics applications, Proc.12th Inter. Sci. Conf. Achievements in Mechanical & Materials Eng., AMME' 2003, Gliwice-Cracow-Zakopane, Poland, December 07–10, 2003.
[13] Haas V., Cho M., Ishii H., Inoue A.: Behavior of quasi crystal-reinforced AL94CR1MN3CU2 under fatigue conditions. Nanostruct. Mater, 12 (5–8), 1999, 829.
[14] McClintock P. V. E., Meredith D. J., Wigmore J. K.: Matter at low temperature, Blackie & Son, Ltd. Glasgow, UK, 536: 56, 1984.
[15] McClintock P. V. E., Meredith D. J., Wigmore J. K.: Low temperature Physics, Blackie & Son, Ltd., 536: 56, 1992.
[16] Depoy S. W.: Subzero Treatment of High Speed Steel. The Iron Age, 13 April 1994, 52.
[17] Summers L. T.: Editor Advances in Cryogenics Engineering-Materials, Plenum Press. Vol.42A and 42B, 1995.
[18] Reed R. P., Mikesell R. P.: (eds.), Compilation of Low Temperature Mechanical Properties of Copper and Selected Copper Alloys, NSB Monograph 101, National Bureau of Standards, 1967.
[19] Simon N. J., Drexler E. S., and Reed R. P.: Properties of Copper and Copper Alloys at Cryogenic Temperatures, NIST Monograph 177, National Institute of Standards and Technology, Sponsored by International Copper Association, Ltd. 708 Third Avenue, New York, NY 10017, 1992.
[20] Timmerhaus K. D., Flynn T. M.: Cryogenic Process Engineering, Plenum Press, New York and London, 1989.
[21] Woodcraft A. L.: Recommended values for the thermal conductivity of aluminum of different purities in the cryogenic to room temperature range, and a comparison with copper. Cryogenics, 45(9), 2005, 626–636.
[22] Suomi M., Anderson A. C., Holmstroem B.: Heat transfer below 0.2ºK. Physica, 38, 1968, 67–80.
[23] Gloos K., Mitschka C., Pobell F., Smeibidl P.: Thermal conductivity of normal and superconducting metals. Cryogenics, 30, 1990, 14–18.
[24] Risegari L., Barucci M., Olivieri E., Pasca E.,Ventura G.: Measurement of the thermal conductivity of copper samples between 30 and 150 m K. Cryogenics, 44, 2004, 875–878.
[25] Arnaboldi C., Avignone F. T., Beeman J., Barucci M., Balata M., Brofferio C. et al.: CUORE: a cryogenic underground observatory for rare events. Nucl. Instrum. Methods Phys. Res. Sect. A., 518(3), 2004, 775–798.
[26] Astone P.: Resonant mass detectors: present status. Class. Quantum Grav., 19, 2002, 1227– 1235.
[27] Operation manual for low temperature installation for gas liquefaction-ZIF-1002 Moscow, Russia.
[28] Rohde H., Katic J., Paschold R.: ESAB pulsed gas shielded metal arc brazing of surface coated sheets, Svetsaren, publisher ESAB, 55 (3), 2000, 1–36.
[29] Gartner W.: MIG brazing of galvanized light-gauge sheets, Fronius, http://www.fronius.Com/weld. 1999.
[30] Corsepius H. W.: Nondestructive testing of materials using ultrasonics, introduction to basics. Special Issue 218. Krautkramer GmbH & Co., 1990.