Innovative neon refrigeration unit operating down to 30 K

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ABSTRACT

A new compact, low-cost, economically competitive and environmentally friendly cryogenic system for cooling a continuous gas flow down to about 30 K is under developing at the ILK Dresden, reported in this paper. The paper shows thermodynamic calculations of cycles on neon and neon-helium mixtures. The assessment of the degree of thermodynamic perfection of the neon cycles in comparison of neon-helium cycles is provided. The use of neon and neon-helium mixture in cryogenic cycles for cryostatting at a temperature level of 27…63 K will increase the thermodynamic efficiency of the cryogenic system and reduce the energy costs of obtaining cold at this temperature level. A technological chain/process, as well as the main economic indicators of the system under development are presented. The availability of such an innovative refrigeration system can be used in a wide range of cryogenic and cooling applications.

Keywords: neon refrigeration unit, neon-helium mixtures, cryostatting.

INTRODUCTION

The appearance of high-temperature superconductors (HTSC) has intensified interest in using neon as a cryogenic refrigerant. So far the main factor limiting the widespread use of neon in cryogenic technology is its high cost in comparison with helium. In connection with the growth in the consumption of neon in industries that are not related to cryogenics, the cost of production decreases, since the high cost of neon is associated with small volumes of its production. However, at present time, the price of neon is not so high as to neglect its use as a refrigerant.

Modern high-temperature superconducting materials can operate at temperatures up to 100 K, which makes it possible to use liquid nitrogen for cooling. However, when the operating temperature is lowered, the characteristics of HTSC materials and devices are substantially improved. At the moment, for applications in the field of energy, it is necessary that HTSC have a current density of up to 10^5 A/cm^2 at a magnetic field of up to 10 T [1]. These parameters are now realized with cooling to temperatures below 50 K. At temperatures above 63.15 K, liquid nitrogen can be used as a coolant. Mixtures of nitrogen with hydrocarbons can be used at temperatures from 63 to 50 K. For continuous cryostatting (either using a refrigerating cycle or a liquid coolant), helium, neon, and hydrogen can be used at T < 50 K. The main problem with the use of helium is its low density, which complicates compression and leads to the need to increase the dimensions of the channels through which cooling helium circulates. The use of hydrogen is limited by its explosive nature. Therefore neon and neon-helium mixture, despite the higher cost of neon, is the most probable refrigerant for use in the temperature range 27...63 K. Neon is inert, has a high density (density of gaseous neon at 273 K and 1 bar is equal to 0.88 kg/m^3, the density of liquid neon is 1207 kg/m^3), and it is possible to use various compressor machines, including vane compressor type for its compression. The volumetric heat of evaporation of neon is 103 kJ/l, which is 5.7 times greater than the heat of evaporation of 1 liter of liquid helium and its heating up to 27 K, and 3.3 times greater than the heat of evaporation of hydrogen.

Although the low-temperature cycles which use helium as a working medium are thoroughly investigated, unfortunately, there are not many data on the thermodynamic efficiency of cycles on neon and neon-helium mixture available. There are only a number of works devoted to cycles working on the use of mixtures of neon, helium and hydrogen with different proportional composition [2]. However, these studies are not enough to assess the advantages of using neon as a refrigerant. Preliminary thermodynamic calculations of cycles on neon and neon-helium mixture show that their degree of thermodynamic perfection is higher than in helium cycles, so the use of neon and neon-helium mixture in cryogenic cycles for cryostatting at a temperature level of 27…63 K will increase the thermodynamic efficiency of the cryogenic system and reduce the energy costs of obtaining cold at this temperature level.

Choosing of the working medium

Currently there is a huge amount of cryogenic cycles, which can be used for the cryostatting at a temperature level of about 30 K. Usually these schemes consist of several precooling stages. The precooling stage can be realized by the use of pumped liquid nitrogen, which allows lowering the temperature of the precooling stage down to about 64 K. The refrigeration cycle with hydrocarbons or hydrocarbon mixtures can be chosen also.

For the main cooling circuit pure neon is used (neon-helium mixture also can be considered). Generally, the medium pressure cryogenic cycle, named Claude-cycle, is used for this purpose. For achieving a higher cycle efficiency it will be better to use a vapor-liquid expansion device and additional nitrogen precooling. It should be noted that, in some cases, for example with using of a neon as a coolant, a throttle valve can be excluded from the cryogenic cycle. Also, by using a neon as a refrigerant in the Claude cycle with vapor-liquid expander, the pre-cooling nitrogen unit can be omitted.

In some research a neon-helium mixture was used for cryostatting at a temperature level of about 20 K [2-5]. In these papers, the work of cryogenic systems on a mixture of neon with helium and hydrogen based on balance equations was investigated. However, the classical approach to the description of such systems

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based on balance and exergy equations has one very significant drawback. This approach idealizes the system and neglects the complex interaction of some elements of the system with others. However, when e. g. there is a phase transition, the equations of state do not complete describe the real system conditions. The outlet temperatures of the flows from heat exchangers determine each other. This has to be taken into account especially in systems operating on mixtures of substances, where the relationships between pressures and temperatures of phase transitions are distorted. So, the mathematical model cannot provide accurate results. Hence, to describe such systems, a multi-parameter method describing the elements with the help of nonlinear equations can be solved numerically.

However, in our case, cryostatting will be performed at a temperature level of 27…30 K, and only neon will be used. At these operating temperatures, neon is in the vapor-liquid state, and when heat is transferred from the neon to the cooling object, a phase transition occurs. The intensity of heat transfer in the presence of a phase transition increases significantly due to the superimposition of the thermal effect of the phase transition. There is a change in the aggregate state of the substance, which significantly affects the heat transfer coefficients [6, 7]. Therefore, the efficiency of heat exchange is significantly increased when the required surface of heat exchangers is reduced, thereby increasing the energy characteristics of the whole cycle.

The calculations show that in the case of using a certain composition mixture of Ne-He for providing a maximum degree of perfection of the system the cycle parameters should be selected. As an example, the graph in Figure 1 shows the results of calculations of perfection degree depending on the composition of Neon-Helium refrigerant for classical refrigeration cycle with an expander (Claude cycle without J-T valve). The calculations show that the most energy-efficient cycles would be with pure neon as a refrigerant. The degree of thermodynamic perfection of the cycle with neon is about 28 % at about 28 bar of the cycle circulation pressure.

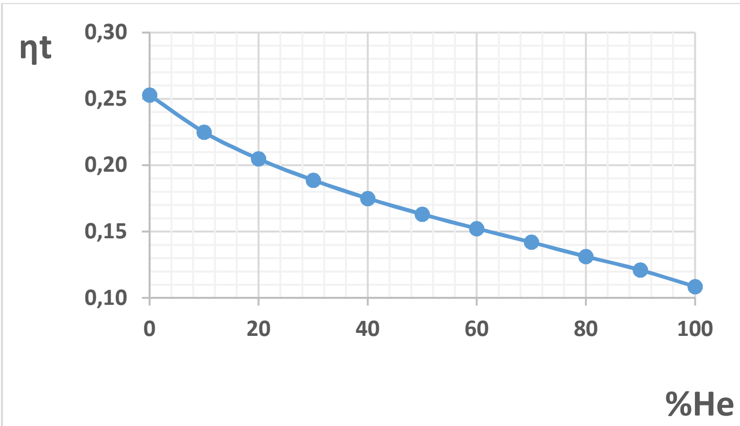

Figure 1. Thermodynamic efficiency ηt of a classical Claude process with an expander without Joule-Thomson choke as a function of the fraction of He in a Ne-He mixture. Refrigerating capacity is 500 W @ 30 K.

By adding and using helium as a refrigerant the additional pre-cooling unit should be used. In this case, the degree of thermodynamic perfection of the cycle slowly decreases with increasing of the helium content. It should be noted that in the absence of gas loss the value of operating costs with neon would be less since the energy for cooling with neon is less than for helium or mixture neon with helium.

Selection of operating parameters of the refrigeration cycle

For choosing the optimal compression pressure, efficiency and energy expenses for cooling/liquefaction of neon or other media various cryogenic cycles were calculated and optimized. The preliminary results of the chosen cryogenic cycles are shown in Table 1. These calculations will help to choose the type of neon refrigeration cycle.

№	Cycle type	Optimal pressure, [bar]	COP max
1	Single throttling with LN2 precooling	185	0,164
2	The double throttling with LN2 precooling	150	0,185
3	Claude cycle without pre cooling	120	0,169
4	Claude cycle with pre cooling	150	0,215
5	Cycle with vapour-liquid expander	200	0,21
6	Cycle with ejector	180	0,195
7	Ideal Carnot cycle	-	1

Table 1. Type of the Neon refrigeration classical cycles and their optimal parameters.

As can be seen from Table 1, the cycle efficiency that can be realized for a small-scale refrigerator is in the range of 16...22 %. In this project, for refrigeration to the temperature level of 30 K, the medium pressure Claude cryogenic cycle was chosen. This cycle for the realization of refrigeration down to 30 K has great advantages and can be used for different applications such as:

- Low-temperature thermal stabilization systems for the study of samples of high-temperature superconductors;
- Small-scale Hydrogen liquefaction plants for the automotive industry;
- In a wide range of science and technology etc.

A very important point during the design of such type of installations is the choice of the main parameters of the cycle. One of the important parameters is the optimal working pressure in the cycle which must be determined by calculating the selected cycle type with different pressures. The main indicator in these calculations will be the minimum energy consumption at a constant specified cooling capacity. For this, preliminary calculations were carried out, showing that the optimal working pressure of the cycle with the expander is within 28...36 bar, see Figure 2.

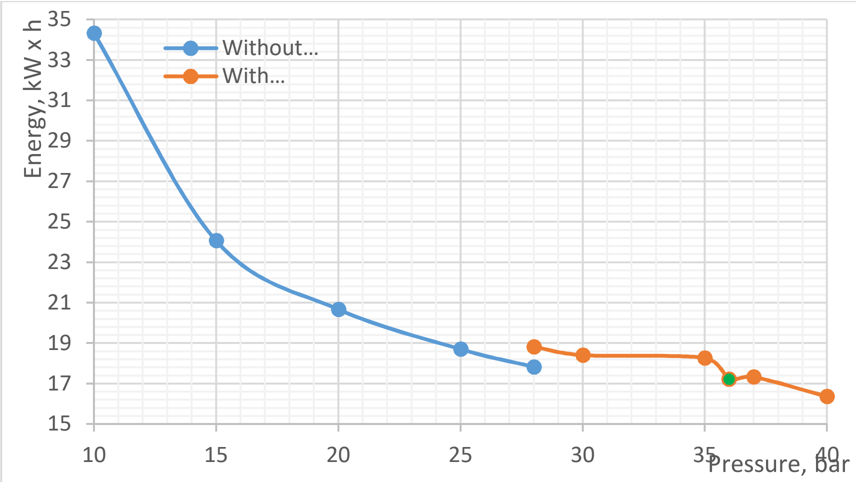

Figure 2. Required amount of energy for the cooling capacity of 500 W @ 30 K, depending on the pressure in the cycle.

As can be seen from Figure 2, to obtain a given cooling capacity of 500 W at 30 K, it is necessary to expend about 17.8 kW electrical energy for the expander cycle without pre-cooling, provided that the working pressure of the cycle corresponds to 28 bar. At the same time, the degree of thermodynamic perfection of the cycle is about 25 %. In order to increase the degree of thermodynamic perfection of the cycle, it is necessary to increase the degree of compression of neon in the cycle. However, at the same time, the heat load on to the heat exchanger and on to the expander will increase and there will not be enough cold to cool the direct flow of neon. This problem can be solved by using a pre-cooler with a high cooling power, e. g. a pulse-tube cooler or a mixed refrigerant cooler based on Linde-Hampson cycle operating down to a temperature level of around 80 K [8, 9]. By using such pre-cooling in a cycle, it will be possible to offset the costs of cold production and heat loss. Preliminary calculations show (see the graph in Fig. 2) that in this case the degree of thermodynamic perfection of the cycle will increase to 26.1 %.

The required power consumption, taking into account the operation work of the neon compressor, the compressor for the pre-cooling cycle and the operation work of the expander, is about 17.2 kW. Obtaining this level of thermodynamic perfection is possible with the circulation pressure of neon in a cycle at the level of about 36 bar. Thus, the constructive execution of the expander will correspond to the specified pressure, which once again indicates a completely new, not typical expander, which will be designed and tested in the project.

The basic units of the 30 K Refrigeration cycle

The process diagram of the middle-pressure Claude refrigeration cycle which is planned to be realized in the project is shown in Figure 3. To obtain a cooling capacity of 30 K, two cryogenic cycles are considered, i. e., the cycle with the expander without pre-cooling and the cycle with the expander with pre-cooling to a temperature of 80 K.

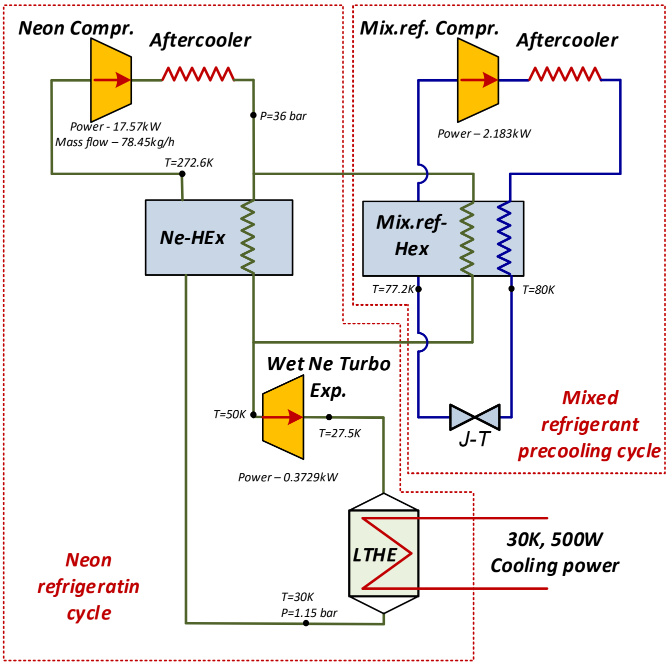

Figure 3. Simplified process diagram of the middle-pressure Claude refrigeration cycle with implemented Linde-Hampson mixed refrigerant precooling unit.

From Figure 3 it can be seen that the refrigeration neon cycle consists of two cooling circuits. The first circuit represents a neon pre-cooling cycle to a temperature level of 80 K, which is implemented on a mixed refrigerating machine. The second circuit is a low-temperature refrigerator with an expander and neon as refrigerant. The main innovative component of the low-temperature part is a turbo-expander operating in a two-phase area and a specially designed heat exchanger operating in the phase transitions region.

The system being developed consists of two interdependent / mutually determining systems, see Figure 3. Accordingly to that the thermodynamic calculation of the system can be split into two parts: first, the calculation of the neon precooling stage and second, the calculation of the neon refrigeration part. The calculation results of the neon precooling part are used as input data for calculating the refrigeration part.

The preliminary initial data and results of calculations of specific thermodynamic states of neon stream and the working heat load (the refrigerating capacity) upon the low temperature heat exchanger of the low temperature heat exchanger (LHMR) refrigerating machine are presented below in Table 2.

As a result, to produce a steady stream of refrigerated neon with the required parameters given in Table 1, a refrigerating machine with cooling capacity of

$$Q_0 = 500\,W$$

has to be developed. The main flow of the neon will be pre-cooled down to 80 K. In this case the temperature of the neon at the outlet of the turbo-expander must be at the level of:

$$T_0 = T_c - \Delta T = 30 - 2.5 = 27.5\,K$$

Neon data			
N/N	**Parameter**	**Value**	**Units**
	GIVEN		
1	pressure of Ne in the cryogenic cycle: P_{Ne}	28 or 36	Bar
2	pressure of Ne flow after the turboexpander: P_d	1.15	Bar
3	Neon precooling temperature: $T_{prec.}$	80	K
4	ambient temperature: T_{amb}	285	K
5	the outlet temperature of the refrigerated neon flow at the outlet port of the low pressure side of the turboexpander: T_0	27.5	K
6	neon heating temperature at the outlet of at the outlet port of the low temperature heat exchanger of: ΔT	2.5	K
	CALCULATED*		
7	the required mass flow rate of neon in cryogenic cycle (T = 285K; P=1.15 bar; ρ_L =0.9791 kg/m^3) With precooling: Without precooling:	 78 82	 kg/h kg/h
8	enthalpy of the Ne flow before the turboexpander: h_c With precooling (T_c = 50K, P_c = 28 bar): Without precooling (T_c = 50K, P_c = 36 bar):	 -285.3 -276.5	 kJ/kg kJ/kg
9	Ne liquid percentage after the turboexpander: x_L With precooling (T_c = 27.5K, P_c = 1.15 bar): Without precooling (T_c = 27.5K, P_c = 1.15 bar):	 32 24	 % %
10	total idealized system power consumption: P With precooling: Without precooling:	 17.21 17.82	 kW kW
11	degree of thermodynamic cycle perfection: η With precooling: Without precooling:	 26.1 25.2	 % %
12	turboexpander power: W_{exp} With precooling (T=50K, P=36bar): Without precooling (T=50K, P=28bar):	 0.3729 0.5266	 kW kW

Table 2. The initial data and results of calculations of the neon flow thermodynamic parameters [10].

CONCLUSIONS

The Neon cycle with an expander is more efficient comparing with throttling cycle. Capital cost for expander may cover the costs for expensive high-pressure compressor, which will be necessary for the J-T throttle cycle. Also, in the cycle with expander it will be possible to omit a preliminary nitrogen pre-cooling stage. The practical realization of neon cycle for liquefaction or cryostatting is similar to helium systems. However, depending on the required tasks the type of cycle should be chosen and its optimization provided.

REFERENCES

1. P. Chaddah, *Critical current densities in superconducting materials*, Sādhanā 28(1–2) (2003), DOI: 10.1007/BF02717137.
2. S. Kloeppel , C. Haberstroh , F. Holdener , H. Quack (CEC-ICMC, Tempe, 2015); https://indico.cern.ch/event/344330/contributions/806687/
3. H. Quack, C. Haberstroh, I. Seemann, M. Klaus, Phys. Proc., 67 (2015)
4. S. Kloeppel, N. Dittmar, C. Haberstroh, H. Quack, IOP Conf. Series: Materials Science and Engineering 171 (2017)
5. S. Kloeppel, H. Quack, C. Haberstroh, F. Holdener, IOP Conf. Series: Materials Science and Engineering 101 (2015)
6. Z.Tan, Y. Yao, C. Yao, J. Yang, Y. Ruan, Q. Wang, Inventions 3, 37 (2018); https://doi.org/10.3390/inventions3020037
7. Refrigeration Handbook of SWEP; https://www.swep.net/refrigerant-handbook/1.-basic-heat-transfer/as5/
8. M. Kuhn, G. Kaiser, T. Schildbach, G. Schroeder, J. Klier, R. Herzog (The 12th CRYOGENICS, Dresden, 2012)
9. P. Dalakov, J. Klier, A. Rozhensev (The 15th Cryogenics 2019, IIR Conference, Prague, 2019); PAPER ID: 0022. DOI: 10.18462/iir.cryo.2019.0022
10. The calculations of the thermodynamic parameters of the neon cycle and the pre-cooling unit with mixer refrigerant as a working fluid were carried out using the thermodynamic equation of state of PR-Two-alpha or MBWR and Refprop 10.0 (NIST Standard Reference Database v.10.0)