

CRYOGENIC HELIUM CYCLES WITH MINIMAL LOSSES DUE TO
IRREVERSIBILITY OF THE THERMODYNAMIC PROCESSES

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Results of investigations on the production of cryogenic helium cycles with minimal losses due to irreversibility of the thermodynamic processes are elucidated.

One of the characteristic features of scientific-technical progress is the rapidly expanding utilization of cryogenic engineering in fundamental and applied investigations and in different branches of the national economy. Thermostatting different apparatus at liquid helium temperatures, used all the more extensively in producing high-intensity magnetic fields, in development of charged-particle accelerators, powerful highly efficient electric generators and motors, high-speed transport on magnetic suspension, MHD generators, thermonuclear reactors, highly responsive electronic units and other items using the phenomenon of superconductivity, is of special interest [1]. New, considerably elevated demands on cryogenic helium units (CHU) to assure the cooling of superconducting apparatus are hence advanced.

Besides the rise in reliability and the level of automation of CHU, one of the most important problems is the substantial reduction in the energy expenditure in this quite power-consuming production of up to a level of 225-300 W per 1 W of cold at $T = 4.5^{\circ}\text{K}$. Up to now, available reserves for the specific energy expenditures have practically been exhausted in the traditional construction of CHU schemes on the basis of known cycles.

All this has determined the need to search for new, economically efficient cryogenic helium cycles based on known reversible cycles but taking account here of the special thermodynamic properties of helium.

As has been shown in [2], the combination of the known ideal cycle for gas liquefaction with other reversible cycles, particularly the Siemens (Claude) cycle, resulted in a reversible liquefaction cycle (Fig. 1), which can be used for real degrees of helium compression in the compressor while pressures on the order of 10^6 bar must be used in the known ideal cycle.

Several moles of gas must be compressed during the liquefaction of a single mole in the cycle of Fig. 1, and then expanded isentropically at different temperature levels so that the forward and reverse flow in the preliminary cooling stages (PCS) will always go into heat transfer in a one-to-one ratio, while isentropic expansion of the liquefied mole of working body is terminated by the boundary curve of the fluid in the liquefaction stage (LS), as in the well-known ideal cycle. For instance, if four moles of helium were to be compressed in such an ideal cycle (Fig. 1), then theoretically the pressure needed would be 30 bar [2].

The cycle of Fig. 1 is completely reversible even in application to the refrigeration mode when cold is used not only at the boiling temperature level for the cryogenic agent in process 4-5, but also at a variable temperature level in process 5-1, i.e., when the whole store of cold of the liquefied cryogenic agent is used.

If cold is used at both the boiling temperature of the cryogenic agent and in process 5-6 (Fig. 1), then in this case just one mole of helium will circulate in the cycle 1-2-3-4-1 instead of the four moles (Fig. 2), and the energy consumption will correspondingly be

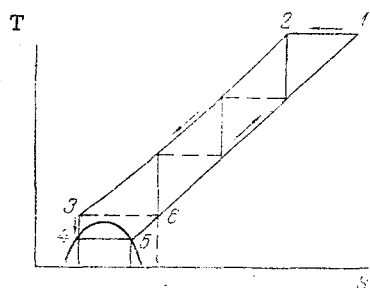


Fig. 1

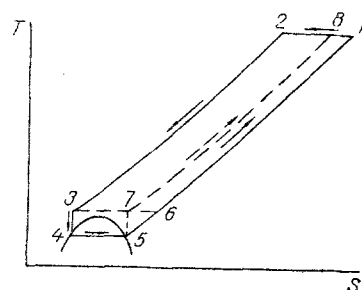


Fig. 2

Fig. 1. Ideal liquefaction cycle; T) temperature; s) entropy.

Fig. 2. Reversible refrigerator cycle.

reduced. The PCS will hence be a regenerative stage with the reversible heat transfer processes 2-3 and 6-1. The cycle 1-2-3-4-5-1 in Fig. 2 is completely reversible in this case.

Cold is used most often at the helium boiling point in cryogenic helium systems, and in this case the cycle 1-2-3-4-5-1 in Fig. 2 cannot be considered completely reversible since irreversibility is manifest at the cold end of the LS heat exchanger because of heat exchange between flows with the different temperatures T_5 and T_3 . However, even in this case such a cycle with isentropic expansion of the helium at the boundary curve of the fluid would be the most efficient of all the helium cycles known to this time, and particularly in comparison with the cycle described by Scott [3] in 1959 and realized by Collins et al. [4] in 1970.

In subsequent stages of our researches the cycle 1-2-3-4-5-1 in Fig. 2 was the basis for the search for reversible cycles or the closest approximation to them for even those cases when the cold obtained in the refrigerator units was used only at the boiling temperature level of the cryogenic agent.

Further investigations in this area permitted making the deduction that a completely reversible cycle could be realized for the case of obtaining cold at only the boiling temperature level of the cryogenic agent by combining (Fig. 2) the processes 7-3-4-5-7, i.e., the Carnot cycle with isentropic expansion to the boundary curve of the fluid in the process 3-4 and isentropic expansion from the boundary curve of the vapor in the process 5-7, and the processes 8-2-3-7-8, i.e., the Ericson regenerative cycle when two isothermal processes 8-2 and 3-7 are connected by two isobaric processes 7-8 and 2-3 [6].

In this theoretical refrigeration cycle, the degree of compression in the compressor at the 300°K temperature level is 10.8 to obtain cold at the helium boiling point level at atmospheric pressure, as compared to 30 in the initial cycle 1-2-3-4-5-1. Consequently, the energy expenditures are diminished 1.4 times.

The cycle 8-2-3-4-5-7-8 in Fig. 2 is of great interest for obtaining cold at the helium boiling point level not only because its utilization will afford the possibility of approaching the theoretically minimal energy consumption in helium apparatus, but also because the strict dependence between the reverse flow pressure and the temperature level of the cold being obtained is reduced in this case, and also the influence of the hydraulic resistance of the heat exchangers to the reverse flow of the cryogenic agent is diminished, which is quite important. The problem of obtaining cold at temperature levels from 4.0-1.8°K and below is solved efficiently, in principle, on the basis of such a cycle with a cryogenic heater used by using both helium-4 and helium-3, or a mixture, as the cryogenic agent. The use of this cycle permits raising the coefficient of heat emission from the reverse flow side and therefore, decreasing the heat exchange surface and the size of the apparatus substantially.

For a practical realization of the cycle, it must be kept in mind that as the temperature level is reduced for the use of the cold, the ratio between the latent heat of evaporation and the change in enthalpy during isentropic expansion at the boundary curve of the fluid increases substantially, and hence it can turn out that it is expedient to perform an isentropic expansion in the Carnot cycle in the moist vapor domain in some cases.

In some cases a cycle can turn out to be useful in which the lowest temperature is obtained not because of expansion but by cooling the forward flow to the temperature of the user of the cold in heat exchange with the reverse flow. In this case the Carnot cycle will be located between two Ericson cycles.

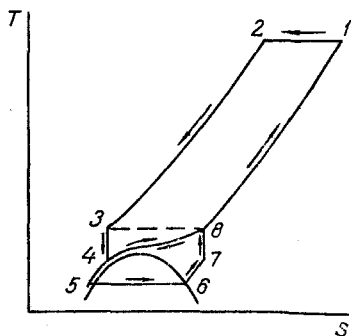


Fig. 3

Fig. 3. Reversible refrigerator cycle on the basis of conjugate cycles.

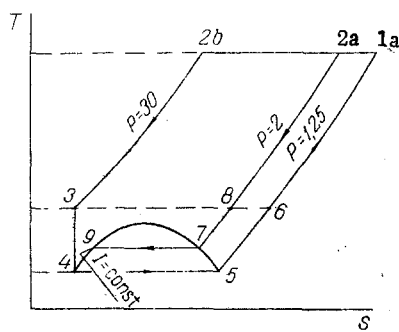


Fig. 4

Fig. 4. Process proceeding in an LS refrigerator cycle with auxiliary flow.

A cycle consisting of two independent cycles, as is shown in Fig. 3, can be of considerable interest. Here the conjugation of the cycles occurs by heat transfer along the line 4-8, i.e., along the near-critical isobar, and can be realized, in particular, in heat exchange between evaporating and condensing cryogenic agents. If helium-4 is used in the first cycle, then it is expedient to use helium-3 in the second [6].

It is perfectly natural that the question of what are the paths by which irreversible losses in the cycle 1-2-3-4-5-1 in Fig. 2, which occurs because of the temperature difference at points 3 and 5, can be diminished maximally in the organization of CHU schemes operating in the refrigerator mode without using a cryogenic heater, arose during execution of the investigations elucidated above.

It is here necessary to turn attention to the fact that the temperature rises at point 3 with the rise in pressure, and therefore, the temperature difference at points 3 and 5 will increase, and consequently, the losses due to irreversibility will increase.

Moreover, irreversible losses will grow still larger in the practical realization of the cycle 1-2-3-4-5-1 in Fig. 2 because of the different nature of the change in specific heat due to temperature for the forward and reverse flows.

The unfavorable nature of the change in the temperature difference during heat exchange between the forward and reverse flows in the LS can be assessed by determining the temperature of the reverse flow from the heat balance as the forward flow temperature changes.

Data are presented below for the forward flow pressure of $P = 30$ bar and the reverse flow pressure of $P = 1.3$ bar, as well as the optimal temperature difference if we start from considerations of acceptable sizes of the heat exchange surface and a sufficiently high exergetic efficiency:

Forward flow temperature, °K	6	8	11	29
Reverse flow temperature, °K	4.5	5.4	7.9	28.4
Temperature difference, °K	1.5	2.6	3.1	0.6
Optimal temperature difference, °K	0.12	0.16	0.22	0.6

If we start just from the above, then utilization of a helium pressure of about 30 bar is undesirable. However, an even higher pressure [5] should be used in the cycle to achieve the highest specific cold productivity and compactness of the CHU.

As analysis has shown, reduction of the losses due to irreversibility because of the temperature difference at the points 3 and 5 can be realized not only by compression of the reverse flow but also by cooling and liquefaction of the auxiliary forward flow.

It turns out that the introduction of at least an auxiliary forward flow in the LS will permit resolution of the above-mentioned contradiction between the tendency to use high pressure in the cycle and to cut the exergy losses in the LS during heat exchange. To do this, the pressure of the auxiliary flow is selected in such a manner as to permit the different nature of the change in the specific heat of the forward flows to perform heat exchange with the reverse flow with a minimal temperature difference.

A process which proceeds in an LS for a cycle with an auxiliary flow is shown in Fig. 4 [6]. A part of the helium flow expanding in the PCS to compensate the irreversible losses in these stages is used as the auxiliary flow.

In the case under consideration, the expansion of this flow will proceed not to the reverse flow pressure but to a higher pressure, for instance, the almost critical pressure permitting realization of its liquefaction in heat exchange with the reverse flow. In practice, all the helium compressed in the compressor can also be liquefied and the cold productivity of the unit can thereby be raised considerably with a simultaneous reduction in the specific energy expenditures.

In conclusion, let us note that the use of the research results elucidated in application to specific problems affords a possibility of a 60-70% increase in cold production of the apparatus, a 20-40% reduction in the energy expenditures to produce the cold at a 4.5°K level, and an improvement in the scale and mass factors. For units of medium cold productivity, as well as those operating at temperature levels below 2°K, the technical specifications will be better by approximately two and more times than for existing units.

The results of the researches were the basis for modernization of CHU produced earlier and the development of new efficient CHU. The serial unit of medium cold productivity is modernized by the cycle 1-2-3-4-5-1 of Fig. 2 and the cycle of Fig. 4. A unit whose rated cold productivity is 2200 W at a 3.8°K temperature level without the reserves ordinarily used is produced according to the cycle 8-2-3-4-5-7-8 of Fig. 2. The specific energy expenditures in this CHU are 250 W/W, which noticeably exceeds the specifications known up to now.

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