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CRYOGENIC UNIT FOR AIR LIQUEFACTION

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Recommended as a study guide

for 16.04.03 “Refrigeration, Cryogenic Equipment and Life Support Systems” Master program

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In this study guide, the students are presented with a brief overview of the Stirling engine, its operational principle and design, as well as the theoretical background. Furthermore, methodological guidance is provided on preparing for and successfully conducting a test work on a ZIF-700 cryocooler.

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Preface

The study guide is aimed at developing students' research skills to study thermal gas dynamic processes in cryocoolers operating in the reverse Stirling Cycle, to conduct experiments and calculate operation parameters considering the characteristics of machines and apparatus working at cryogenic temperatures. The study guide is intended for students of Master's Refrigeration, Cryogenic Equipment and Life Support Systems (16.04.03).

To complete laboratory works 4 academic hours are required.

As a result of completing the laboratory works the student will comprehend:

- thermal gas dynamics processes and principles of cryocoolers and cryogenic machines;
- methods for CGM analysis;
- modern principles of designing cryogenic equipment and methods for calculations of thermal and mechanical parameters;
- application of physico-mathematical models to nonstationary processes in CGMs.

As a result of completing the laboratory works the student will learn:

- nature of physical processes in CGMs;
- principles to describe transient processes under nonstationary thermal load;

As a result of completing the laboratory works the student will be able to:

- determine suitable conditions for usage of CGMs;
- analyse thermodynamic efficiency of the cryostating technology selected;
- use approximate methods to estimate insulation quality and structural factors impact;
- perform thermal, hydraulic and structural calculations;
- mathematically model thermo-mechanical processes in CGMs;
- optimise cryogenic systems.

Main terms

Match the terms to their meaning.

1. *Working substance*
2. *Cooling performance*
3. *Piston*
4. *Cryocooler*
5. *Regenerator*
6. *Connecting rod*
7. *Crankshaft*

A. a complex-shaped member which possesses crankpins (parts eccentric to the rotation axis) onto which connecting rods might be fixed, allowing for conversion of rotating motion into reciprocating one
B. a rigid member capable of both pushing and pulling as necessary, that can be utilised in conversion of rotating motion into reciprocating one
C. the quantity of heat removed per unit time by artificial cooling
D. typically, a fluid substance, with the help of which energy is transformed into mechanical work, heat and/or cooling. When cooling is the goal, it can be referred to as a *refrigerant* or a *coolant*
E. type of a heat exchanger, in which heat from the hot fluid is temporarily stored in a thermal storage medium before being transferred to the cold fluid
F. a mobile cylindrical member tightly adjoined to a cylinder’s walls and used to create pressure and pump fluids
G. a machine used to cool something to cryogenic temperatures characterised primarily by its compactness

Overview

Cryocoolers of various types are some of the most widespread and relevant machines in cryogenics. They are used in both refrigeration and liquefaction cycles. Exactly what constitutes a cryocooler is a matter of some debate and various definitions have been proposed over the years. However, there is a general agreement that a cryocooler's principal feature is its relative compactness. Units which include expanders (such as those operating in Claude or Heylandt cycles) might require significant spaces, whereas the smallest cryocoolers can entirely fit on one's palm.

In the Russian practice, a specific type of cryocoolers is referred to as "cryogenic gas machines" or "CGMs". A CGM is a cryogenic machine that has an isolated working substance entirely separate from the gas being liquefied or the object being refrigerated or cryostatted. This study guide uses the broader term "cryocooler" as is standard practice in English-language literature.

Still, the particular machine employed in this test work and all reverse Stirling cycle machines in general also belong to this narrower category of CGMs.

Over the years, a great number of cryocooler designs have been developed and used, and the following diagrams (Fig. 1) display just some of the most common examples. Please note that the Joule-Thompson unit is not a CGM, unlike the others mentioned.

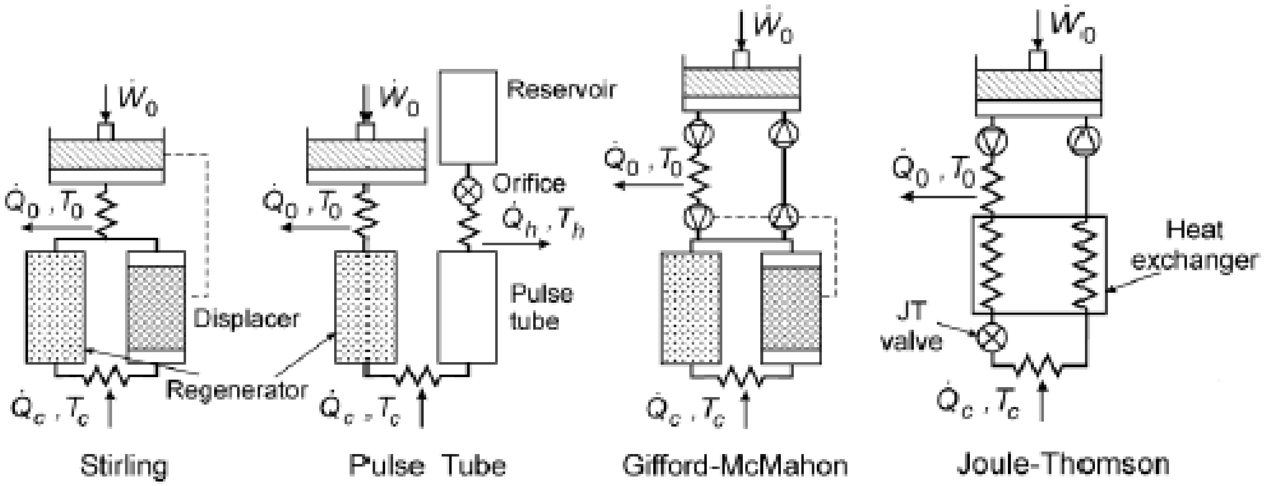


Fig.1. Diagrams of common cryocooler designs. Modified from [7].

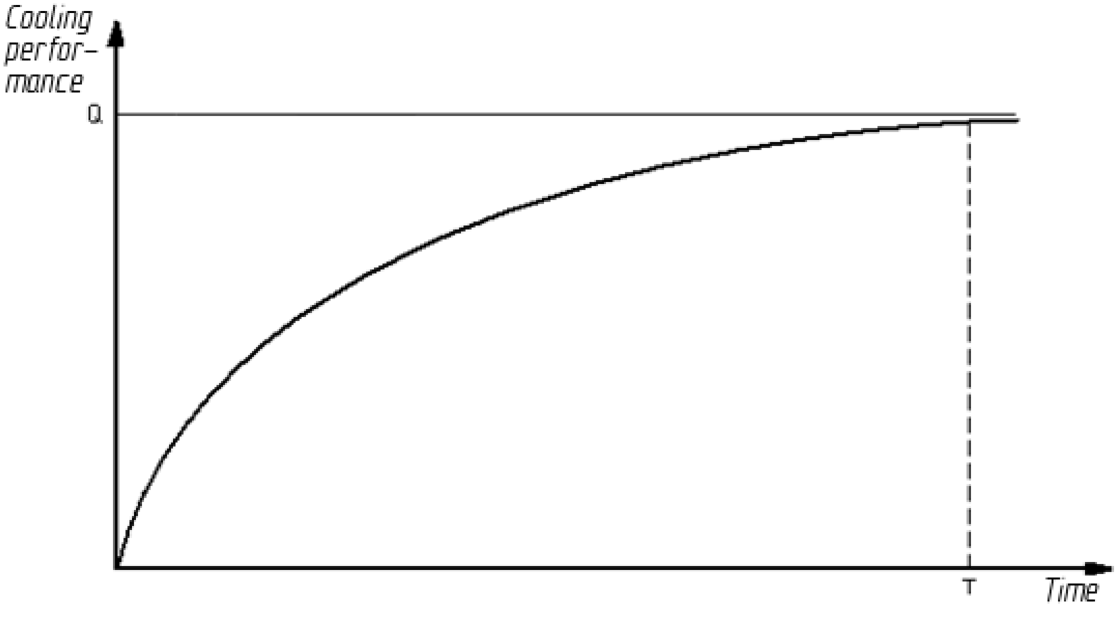
In addition to these particular designs, Vuilleumier-Taconis cycle is also notable. Being effectively a Stirling cycle with an additional displacer, it uses a separate source of high temperature to operate. Therefore, it does not require a more conventional input from an electric motor (at least, before losses are taken into account). It finds only niche utilisation, compared with the cycles aforementioned.

Introduction to the ZIF-700 machine

Regenerative cryocooler ZIF-700 (ЗИФ-700) is designed for refrigeration of air in a temperature range from 150 to 80 K. It is further intended for liquefaction of gases such as nitrogen and oxygen or their mixtures (e.g., air) with a condensation temperature not lower than 73 K. The gas being liquefied does not undergo compression in the machine. One advantage of the machine is that there is no contact between the gas being liquefied and oil, which allows the liquid product to remain pure.

Helium serves as the working substance or refrigerant as it possesses a much lower condensation temperature than the gases the machine is intended to liquefy. In the filling process, helium's pressure inside the machine is set at approximately 1.9 MPa (~19 kg/cm^2). The machine operates in a closed cycle with a constant quantity of helium.

Naturally, the machine needs time to ramp-up to the steady-state mode to successfully liquefy air at its nominal cooling performance. The reason for that is that it takes time to cool the working substance to a low enough temperature. The ramp-up to the steady-state mode takes 12-15 min, during which helium cools gradually. The following qualitative graph of the cooling performance versus time illustrates the essence of this process.



Graph 1. Qualitative graph of cooling performance versus time.

It can be noted that the graph approximates the process as an exponential function. Once the steady-state mode has been achieved, the cooling performance should approximately fall within the range of 700÷750 W.

Brief technical characteristics of the ZIF-700 machine

Cooling performance to liquid nitrogen, W	no less than 700
Working pressure of helium, MPa	2.5÷2.6
Amount of helium in the machine, g	~30
Mass of the machine, kg	471
Time of ramp-up to steady-state mode, min	12÷15
Flow rate of cooling liquid, m^3/h	no less than 1
Power consumption, kW	11

Simplified description of the reverse Stirling cycle

Reverse Stirling cycle makes the basis of the cryocooler’s operating process. The simplified diagram (fig. 2) provides an insight into the process.

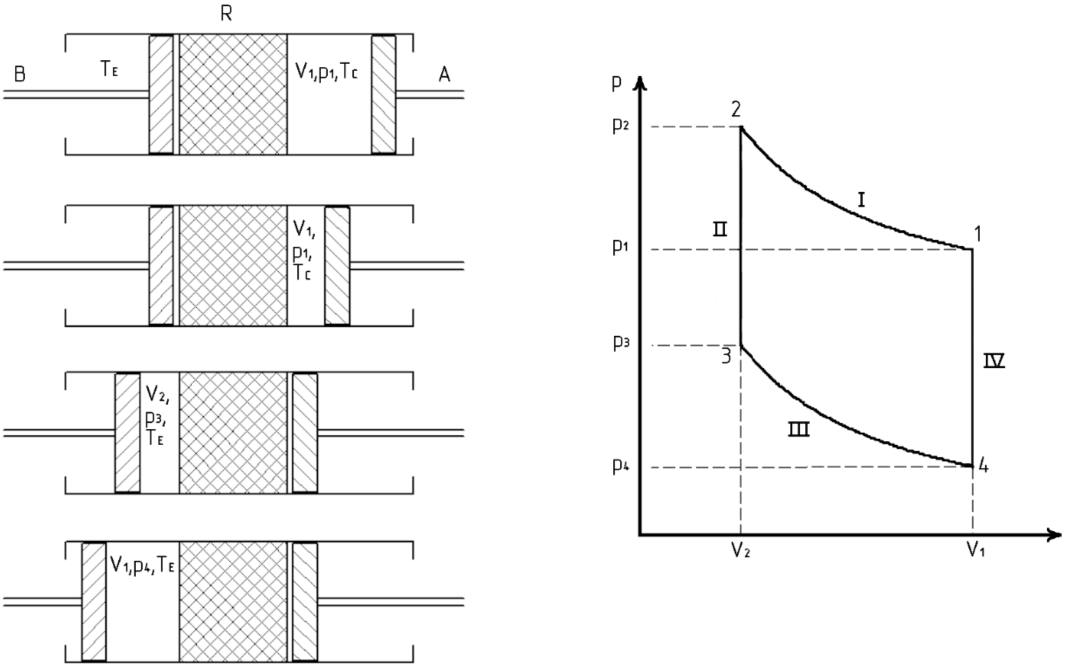


Fig 2. The ideal cycle of the cryocooler

The ideal cycle consists of two isotherms and two isochors.

In the course of the cycle, the pistons A and B make the following motions:

I – isothermal compression.

Piston A compresses the gas isothermally at temperature T_c. The gas volume decreases from V_1 to V_2, and the pressure increases from p_1 to p_2. Meanwhile, piston B remains static.

II – isochoric process with heat removal.

As pistons A and B move simultaneously to the left, the gas is pushed through the cold nozzle of the regenerator R at a constant volume V_2. The temperature and pressure of the gas decrease (to T_E and p_3 respectively).

III – isothermal expansion of the gas.

At temperature T_E the gas volume increases from V_2 to V_1, and the pressure decreases from p_3 to p_4 as piston B moves to the left.

IV– isochoric process with heat addition.

Both pistons move to the right as the gas is pushed through the regenerator at constant volume V_2, heating up to temperature T_c again as its pressure becomes p_1.

The practical implementation of such a cycle is not manageable. In the actual cycle the pistons make harmonic rather than intermittent motion, in the course of which pressure and volume change sinusoidally. The exact mechanism of this motion will be elaborated upon in a later course, in which the students will be offered a full calculation of a Stirling cryocooler.

Robert Stirling (1790 – 1878) is a British engineer known for his invention of the Stirling Engine. It used a closed circuit of hot air instead of a constant flow of steam unlike most engines of that time. Additionally, he was the first to introduce the idea of a regenerator, which he called “heat economiser”. Through his innovation he sought to make work in mines safer, as steam engines were prone to dangerous explosions. His invention was not based on any theoretical work, only on practice.

Brief description of the operational principle and design of the ZIF-700 machine

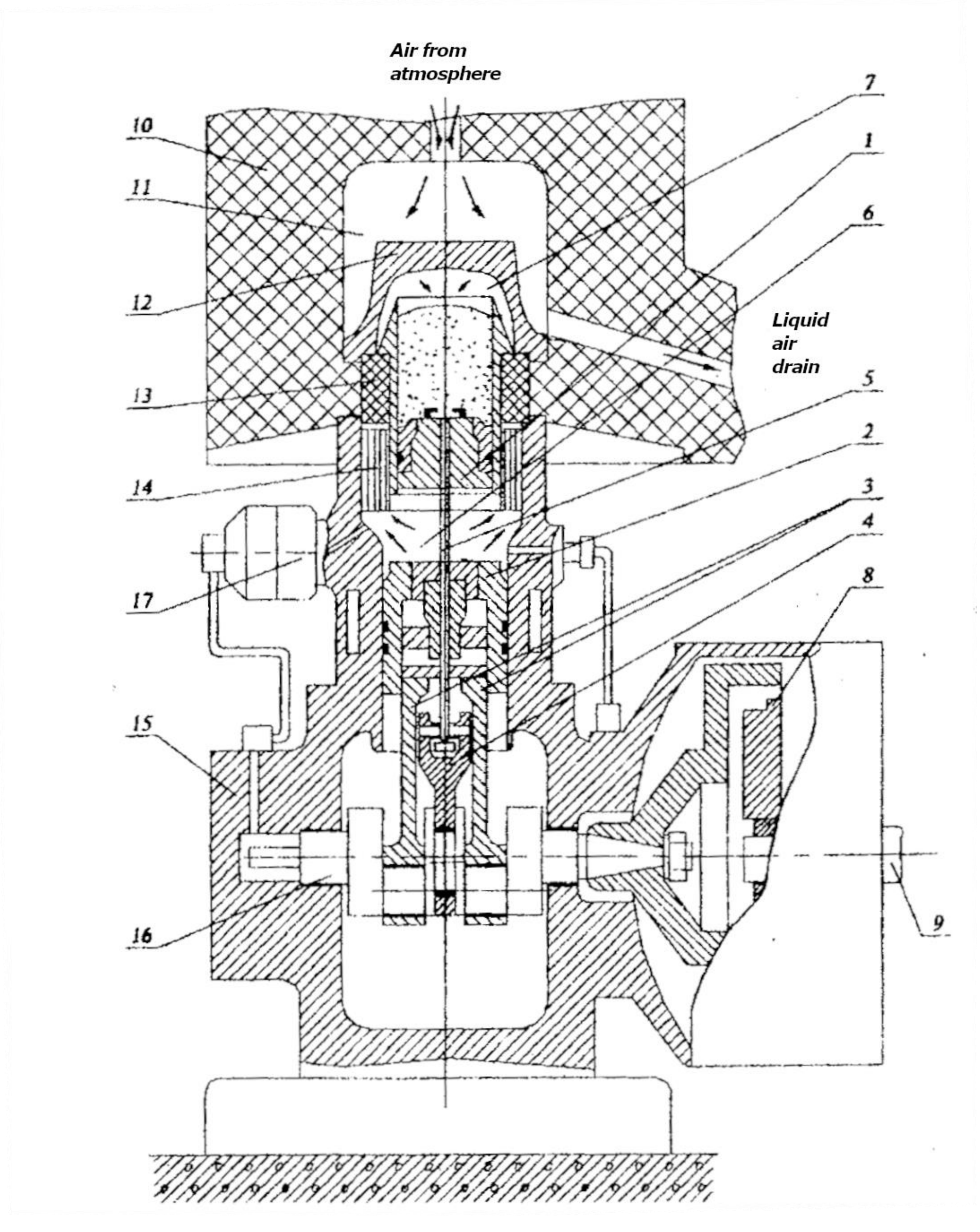


Fig 3. A schematic longitudinal section of the machine:

1 – displacer piston; 2 – main piston; 3 – forked connecting rod of the main piston; 4 – connecting rod of the displacer piston; 5 – rod; 6 – compression space; 7 – expansion space; 8 – clutch; 9 – electric motor's shaft; 10 – thermal insulation; 11 – liquefaction space; 12 – liquefier-exchanger; 13 – regenerator; 14 – refrigerator; 15 – case; 16 – crankshaft; 17 – inverted valve

The machine's diagram is presented in fig. 3. The machine has two pistons – the main piston 2 and the displacer piston 1. Accordingly, it also has compression space 6 and expansion space 7. Rod 5 of the displacer piston goes through the main piston 2 and joins with the connecting rod 4.

Crankpins of the crankshaft 16, connected with the connecting rod 3, are displaced by 70° relative to the crankpin of the middle connecting rod 4 in such a way that the displacer piston has a phase lead over the main piston during its motion. Periodic compression and expansion of helium occur in the corresponding zones of the machine during the reciprocating motion of the piston and the displacer due to phase shift and path difference between them.

To better comprehend the process, we can separate the motion of both pistons into four phases per one revolution of the crankshaft.

Phase I – compression: displacer 1 moves slightly being near its uppermost position. Piston 2 travels upwards, compressing helium in the whole workspace. As helium is compressed, it heats up to 375÷425 K.

Phase II – pushing through: piston 2 moves slightly being near its uppermost position. Displacer 1 travels downwards, pushing the compressed helium through the refrigerator 14 and regenerator 13 into the expansion space without a change in volume. In the refrigerator, heat is removed from the compressed helium by cooling water. In the regenerator, most of the remaining heat is absorbed by a thin copper wire nozzle, cooled in the prior cycles.

Phase III – expansion: piston 2 and displacer 1 simultaneously travel downwards. Meanwhile, the space above the displacer increases and the compressed gas does work over the displacer at the cost of its internal energy. Expansion process in a steady-state mode cools the helium down to 73 K.

Phase IV – pushing through: piston 2 moves slightly being near its bottommost position. Displacer 1 travels upwards, displacing the cold helium from the expansion zone to the compression one. Thus, the gas cools the internal channels of the heat exchanger 12 and then the regenerator 13.

Leaving the regenerator, the gas heats up to 290÷300 K. Having gone through the refrigerator 14, the gas returns to the compression space 6.

During the ramp-up to the steady-state mode, which lasts 12÷15 min, helium cools gradually. The heat exchanger 12 is cooled at the same time. In the steady-state mode, the temperature at the heat exchanger’s external surface becomes sufficient for the condensation of the atmospheric air. Thus, per each revolution of the crankshaft there is a useful output of cold to the internal channels of the heat exchanger 12. The unused cold of the helium with the temperatures within the range of 77÷119 K, which cannot be transferred to the heat exchanger, is transferred to the regenerator's nozzle instead.

As seen from the machine's operation principle, two processes occur simultaneously: the process of refrigeration (an internal process) and the process of gas liquefaction (an external process).

The machine's operation is automatically controlled by the control apparatus via the following parameters:

- cooling water flow rate in the cooling system;
- oil pressure in the lubrication system;
- working pressure of helium in the machine.

Should any of these parameters fall outside the permitted range, the machine stops automatically.

The operation principle and design features of the cryocooler are described in more detail in refs [1,2,3] (in Russian).

Questions for self-examination

1. Why is helium the working substance utilised in this machine?
2. What processes does the ideal reverse Stirling cycle consist of?
3. What is the role of the regenerator in the machine's operation?
4. What is the mechanism of the heat removal from helium?
5. How is rotating motion turned into reciprocating one in the machine?
6. What limitations exist on the machine's operation?

Test objectives

As a result of the machine's test, the following is to be determined:

1. The machine's performance by draining a mass of liquid air, kg/h.
2. The machine's cooling performance, W.
3. Specific energy consumption per kg of liquid air, kW*h/kg.
4. Specific cooling water flow rate per 1 kg of liquid air, l/kg.
5. Quantity of heat removed from the machine by the cooling water, W.

Conditions to conduct the test

The test should be started once the machine is in the steady-state mode, which is characterised by a constant temperature on the machine's head. Before the test starts, the operation time should be 10÷15 min from the moment when liquid air appears. The test lasts 15÷25 min.

Before the test, the student has to:

a) study the safety instructions (app. 1);
b) clarify the operating principle of the CGM and also the arrangement of its individual units and the machine as a whole;
c) compose a diagram of the laboratory bench (fig. 4) and briefly describe it;
d) plot the points of measurement for temperatures, pressures, etc. onto the diagram;
e) prepare an observation protocol as per the form provided in app. 2

The designations of the sampling points should be analogous to the points on the diagram.

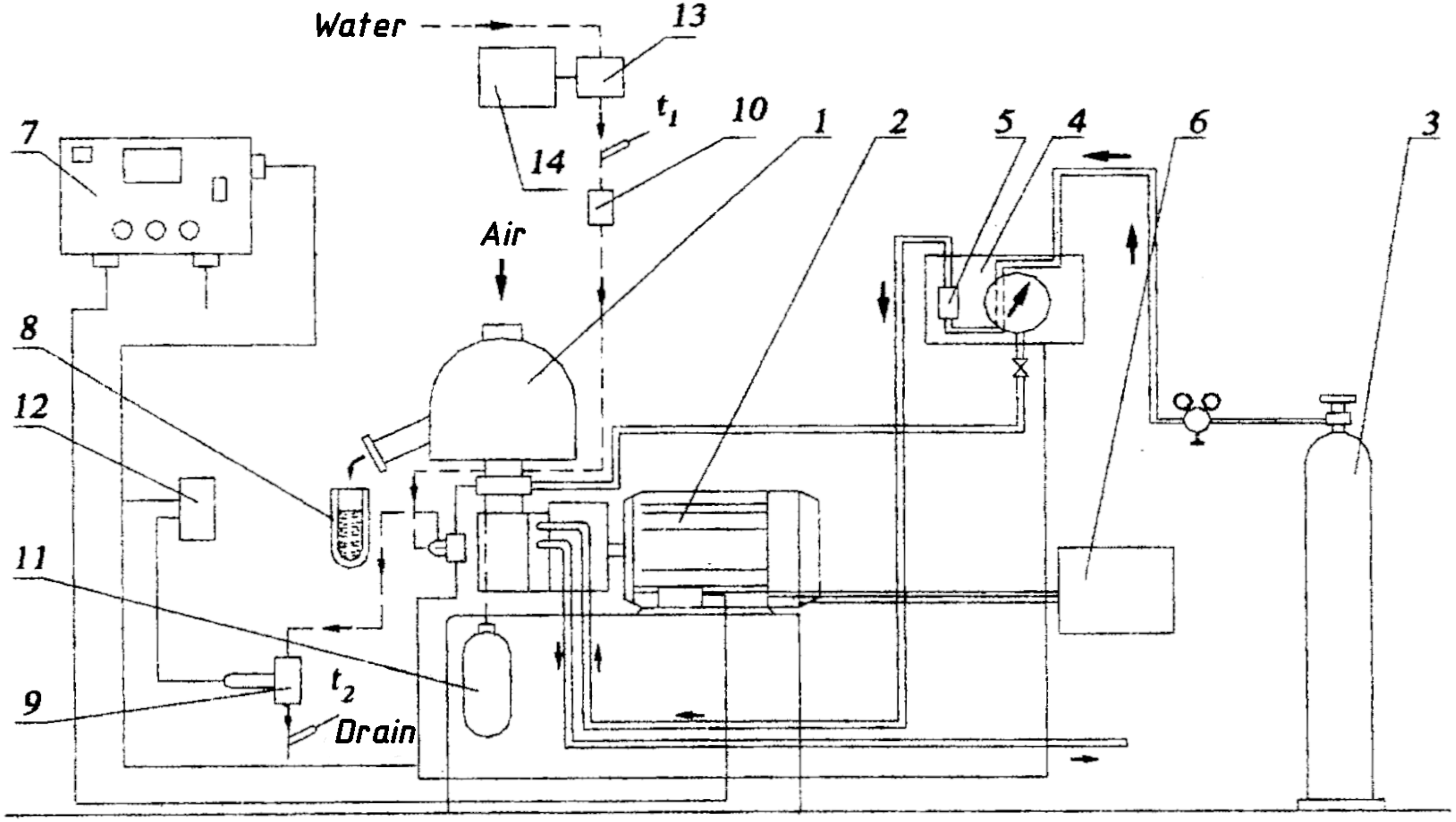


Fig 4. Diagram of the unit with sampling points indicated:

1 – ZIF-700; 2 – electric motor; 3 – helium cylinder; 4 – contact pressure gauge; 5 – dryer; 6 – power meter DK-50 (ДК-50); 7 – control panel; 8 – Dewar vessel; 9 – waterflow sensor and water-jet pump; 10 – water filter; 11 – starting cylinder; 12 – electric-contact vacuum gauge; 13 – waterflow sensor; 14 - flowmeter

Test Results Processing

1. Determination of the actual performance of the unit in respect to generation of the liquid air G, kg/h, is done by weighing the Dewar vessel containing liquid air acquired in the test, and the subsequent conversion of the acquired quantity based on one-hour work of the unit. The acquired value of the unit's performance is likely to be somewhat lower than the actual one. It occurs due to unaccounted evaporation losses of the liquid air during the draining. To reduce these losses, draining needs to be done into a pre-cooled Dewar vessel.

2. Determination of the cooling performance of the machine is done with account of the coooling expenditures on condensation and freezing-out of moisture and carbon dioxide present in the air being liquefied.

$$Q = Q_1 + Q_2 + Q_3$$

where Q is the cooling performance of the machine, W; Q_1 is heat flow removed from the air being liquefied, W; Q_2 is heat flow removed by condensation and freezing-out of moisture, W; Q_3 is heat flow removed by cooling and freezing-out of carbon dioxide (CO_2) contained in air, W.

$$Q_1 = G' (i_1 – i_0)$$

where G′ is mass flow rate of liquid air, kg/s; i_1 is enthalpy of air entering the machine (at temperature T_3 and barometric pressure p), J/kg; i_0 is enthalpy of liquid air leaving the machine (as a saturated liquid at barometric pressure p), J/kg.

Determination of the value Q_2 requires, in turn, determination of the value G_{H20}, which is the mass flow rate of moisture carried into the machine via the air being liquefied, kg/s.

$$G_{H_2O} = \frac{G'd\varphi}{\rho_A \cdot 10^5}$$

where d is the moisture content in air at φ = 100%, g/m^3, determined using tables such as in ref. [5] depending on the value of temperature T_3; φ is the relative humidity of air, %, its value is determined using the laboratory psychrometer; ρ_A is the air density, kg/m^3, at barometric pressure and temperature T_3, determined from the barometric pressure p.

$$Q_2 = G_{H20} [r' + c_1 (T_3 – 273) + r''+ c_2 (273 – T_0)],$$

where r′ is the specific heat of condensation of water (can be taken equal to 2256 kJ/kg, corresponding to the specific heat of condensation at p = 0.101 MPa); c_1 is the specific heat capacity of water, c_1 = 4.19 kJ/(kg*K); r″ is the specific heat of water crystallisation, r″ = 333 kJ/kg; c_2 is the specific heat capacity of water ice in the temperature range from 77 to

273 K, c_2 = 1.411 kJ/(kg*K); T_0 is the lowest temperature to which water ice is cooled in the machine (taken as equal to the temperature of liquid air at pressure $p = p_{bar}$), K.

Determination of the value Q_3 also requires an additional calculation in order to determine the value of G_{CO2}, the mass flow rate of CO_2 carried into the machine with the air being liquefied, kg/s.

$$G_{CO_2} = 4 \cdot 10^{-4} \cdot G' \frac{\rho_{CO_2}}{\rho'_A}$$

where ρ_{CO2} and ρ'_A are densities of CO_2 and air respectively under normal conditions (p = 760 mm Hg and T = 273 K), kg/m^3.

$$Q_3 = G_{CO2}[c'_1(T_3 - T_s) + r + c'_2(T_s - T_0)]$$

where c'_1 is the specific heat capacity of gaseous carbon dioxide; it can be taken equal to 846.4 J/(kg*K) (which corresponds to p = 101325 Pa and T = 293 K); due to the pressure of CO_2 being small, its c_p value is almost independent of temperature and is taken to be the same for the whole temperature range from T_3 to T_s; T_s is the sublimation temperature of CO_2 at normal pressure; r is the specific heat of CO_2 sublimation, r = 570 kJ/kg; c'_2 = 1215 J/(kg*K).

3. Determination of the quantity of heat removed from the machine by the cooling water:

$$Q_{wat} = \rho_{H2O} \cdot G'_{H20} \cdot c_1 \cdot (T_{W2} - T_{W1}),$$

where ρ_{H2O} is the density of water, kg/m^3; T_{W1} and T_{W2} are water temperatures upon entry and exit from the machine respectively, K; G'_{H20} is the flow rate of water, m^3/s (determined via the following function of flow rate, l/h, versus number of scale divisions).

$$G'_{H20} = n \cdot \frac{50}{3}$$

APPENDICES

Appendix 1

Work safety instructions

1. Only the students who have grasped the instructions on equipment operation, work safety and fire-protection measures and have completed the work colloquium, are permitted to perform the test work.
2. For the duration of the laboratory work, only the persons immediately engaged in servicing the unit (the tutor who conducts the lesson and the students permitted to perform the test work) are to be present in the laboratory.
3. Each student must be at the workplace specified by the tutor and conduct only his own measurements.
4. It is STRICTLY PROHIBITED to utilise open flame in the space where the machine is installed.
5. Any contact of liquid air with combustible substances (oil, petrol, spirit et al) is STRICTLY PROHIBITED.
6. Students must exclude any possibility of accidental contact with current-carrying parts of the electrical equipment.
7. The students must not allow the liquid air to come into contact with clothes or skin.
8. For the duration of the laboratory work, GOST R 12.1.019-2009 “Electrical safety. General requirements and nomenclature of kinds of protection” and GOST 12.1.004-91 “Fire safety. General requirements” are to be used as guidance.
9. Only the students who have been present at the teacher’s safety instruction and have been marked as such in the respective work safety journal, are permitted to perform the test work.

Appendix 2

Observation protocol

Quantity being measured	Designation	Unit	Value of the quantity being measured	Note
Mass of empty Dewar vessel	G_1	kg		
Mass of filled Dewar vessel	G_2	kg		
Flowmeter readings	G'_{H20}	m^3/s		
Water temperature upon entry into the machine	T_{W1}	°C		
Water temperature upon exit from the machine	T_{W2}	°C		
Electric motor power consumption	N	kW		
Duration of the test	$\Delta\tau$	min		
Time until liquid air appearance	τ	min		
Temperature of dry thermometer	t_3	°C		
Temperature of wet thermometer	t_4	°C		
Barometric pressure	p	mm Hg		

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