https://doi.org/10.15407/scine16.04.011

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SYSTEM OF CRYOGENIC SUPPLY OF CRYOMAGNETIC COMPLEX KMK — 1000 ON THE BASIS OF MICRO-CRYOGENIC SYSTEMS OF CLOSED CYCLE

Introduction. *The development of the enrichment industry has identified significant requirements for the development of new technologies and equipment, including the method of magnetic separation.*

Problem Statement. *Advantages of cryomagnetic separation complexes are determined by the efficiency of solving the problem of creating their cryogenic support systems.*

Purpose. *The purpose of this research is to develop a cryogenic supply system (CSC) by solution scientific technical and design and technological problems of cryomagnetic systems creation based on micro-cryogenic closed cycle systems (MCS).*

Materials and Methods. *The material of the research is the design of SCS with built-in superconducting magnetic system (SMS) and two MCS. The efficiency of MCS use is determined by the method of thermal balance analysis of their modules.*

Results. *SCS design on the basis of the nitrogen-free cryostat with integrated SMS and two close-cycle MCS and the solution of R&D problems of effective use of the MCS by method of the heat balance analysis of their modules have been proposed. The input units of the MCS modules and neck, as well as the tank, supports and screens are design in such a way as they can operate simultaneously as a system of rigidity and a system of efficient removal of heat from them to the appropriate stages of the MCS modules. The design of SCS provides operation in a stationary mode with a super small supply of liquid helium through the liquid-gas recondensation ring process, in which the gas-liquid helium mixture is an ideal cool conductor. The design of the SCS provides the manufacturability of routine maintenance, even with the change of the modules of the neck and the MCS, without depressurization of the cryostat.*

Conclusion. *Solutions of design and technological, research and technical problems are based on patents of Ukraine No. 103949 and No. 88830. The expediency of creation of the complex on the basis of a nitrogen-free cryostat with built-in SMS and two MCS operating in a stationary mode with a very small reserve of liquid helium has been substantiated.*

Keywords: cryomagnetic complex, cryogenic supply system for cryomagnetic complex.

Citation: Demishev, A.G. System Cryogenic Supply Cryomagnetic Complex KMK–1000 on the Basis of Micro-Cryogenic Systems of Closed Cycle. *Sci. innov.* 2020. V. 16, no. 4. P. 11—22. https://doi.org/10.15407/scine16.04.011

In the Internet, there are many advertising publications about cryomagnetic separators designed to operate in the production environment of concentrating mills for high-gradient magnetic separation of low-magnetic ores, kaolin, other minerals, and coal directly in thermal power plants. These are the HGMS cryofilter for enrichment of kaolin by *Carpko* (Brazil), *Outokumpu* 5T Cryofilter Models Industrial 5T/360,500,1000 by *Outokumpu Technology Inc.* (Finland), Physical Separation Division 6100 by Phillips Highway (USA), Jacksonville, FL3221 (USA), as well as tanks and tankers for the transportation of liquefied gases. One of the key issues that determine the advantages of the designed complexes, which are interesting for the proposed development, is the superconducting magnetic system, the design of helium tanks, screens, and modules of closed-loop microcryogenic systems (MCS), and efficient use of their cooling capacity. Of course, the above R&D, design, and technological problems have been successfully implemented by corporations, but detailed design solutions have not been described anywhere, since it is a commercial secret. So it doesn't make sense to refer to commercials. A relatively new direction of creating cryogenic supply systems with MCS with the use of *Cryogen Free* technology (dry, nonliquid cryoagents, in which the cryostat has been already used as a heat-insulating screen) is worth noting. Despite all the advantages of this solution, the creation of cryogenic supply system (CSS) of large heavy complex cryomagnetic systems (MCS) is a complicated process.

The advantage of cryomagnetic complexes for separation is determined by the effectiveness of solving the problem of creating their cryogenic supply system. The MCS-1000 complex is located near the boiler unit. The pulverized coal separator with a temperature of about 100 ° C is located directly inside the cryostat hole. Important problems are to prevent the interaction of the solenoid magnetic field with closely located steel structures, as well as to protect service staff from the harmful effects of the scattered magnetic field. This significantly distinguishes the development from all abovementioned ones.

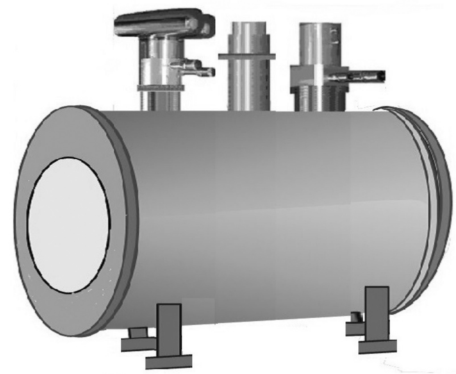

Fig. 1. Appearance of cryomagnetic part of the complex

The purpose of this research is to develop the basic design of cryogenic supply system based on closed-loop microcryogenic systems and to create a prototype MCS in order to test and to elaborate the design and procedures for further implementation at other thermal power plants (TPPs) for purification of pulverized coal and minerals from harmful impurities and industrial enrichment of minerals by high-gradient magnetic separation.

The cryomagnetic part of the MCS-1000 complex includes:

- cryogenic supply system based on cryostat and two built-in MCS;
- superconducting magnetic system (SMS).

The appearance of the cryomagnetic part of the complex is shown in Fig. 1.

Based on the design of the CSS, the efficiency of cooling capacity of the MCS modules has been determined by the method of complex analysis of their heat balance with the total incoming heat load. The MCS-1000 complex is developed based on the patents of Ukraine No. 103949 and No. 88830 [1, 2], research [3], and the project of Teploelectroproekt Donetsk Institute for the modernization of the Dnieper Thermal Power Plant (TPP) implemented by the Department for Cryogenic Instrument-Making at the Galkin Physical and Technical Institute of the NAS of Ukraine.

The CSS scheme is shown in Fig. 2.

Structurally, the cryogenic supply system includes:

- helium nitrogen-free cryostat with a system of screens and supports, modules of introduction of MCS, a neck module with a set of safety devices, and a module of introduction of control and indication systems of the CSS status;
- two built-in MCS manufactured by *Cryomech*, INC (PT 415 / PT415-RM - 40W @ 45K, 1.5 @ 4.2 K and AL 200-190W @ 80K) with autonomously located compressors, their power supply, diagnostics, and control systems. The total power consumption in the 60 Hz network by two MCS compressors and their power supply, diagnostics, and control systems is about 14 kW. Retention of helium in the tank is determined only by the density of the introduction of neck elements. The practice of operation of similar plants has shown the tank shall be refueled with helium every six months or once a year.

The solenoid of the superconducting magnetic system is built into the helium tank of the cryostat. Power current leads and indicators of the SMS status are built into the cryostat neck; SMS safety devices are located on the neck of the cryostat outside.

The responsibility and complexity of the operating conditions of the complex near the boiler unit have led to very specific features and unconventional solutions of design, technological and R&D problems in the development of MCS. First of all, it is necessary to mention the problems and risks in the operation of CSS in the conditions of TPP and to provide ways for preventing them. Given the possible consequences of the accident, it makes sense to develop, assuming even an incredible coincidence of all the risks of an accident. Particular problems are the accumulated energy of the SMS solenoid and the huge volume of liquefied helium in the cryostat tank. In the case of an emergency transition of the solenoid or depressurization of the heat-insulating vacuum cavity of the cryostat, there is a possibility of instantaneous release of a significant volume of the gas-liquid mixture of helium with unpredictable

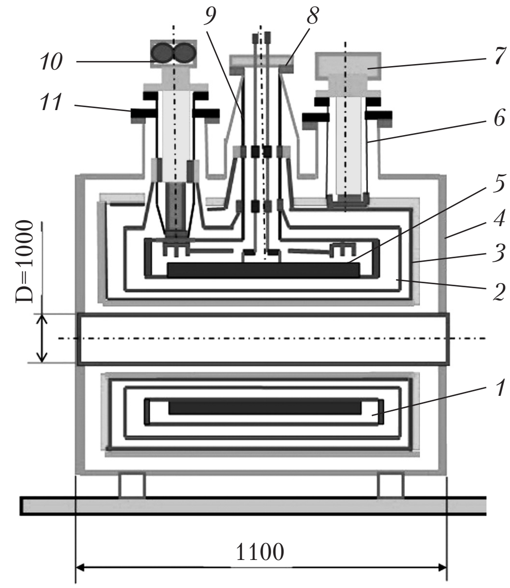

Fig. 2. Configuration of CSS-MCS-1000 complex: *1* — helium tank; *2* — screen E1; *3* — screen E2; *4* — outer casing; *5* — SMS solenoid; *6* — input node MCS AL200; *7* — MCS AL200; *8* — input module of current leads and of indication and protection devices; *9* — neck; *10* — MCS PT415 / PT415-RM; *11* — node input module MCS PT415 / PT415-RM

consequences. The dimensions and design of the cryostat neck, with the inputs for powering the solenoid and the inputs for indicating the status of all systems, are important. Therefore, the neck module designed for rapid removal of the accumulated energy of the SMS and discharge of a gas-liquid mixture of helium is located separately. In view of the above, it is necessary to consider important problems related to the superconducting solenoid and the helium tankage necessary for steady operation of the system.

Creating a solenoid from a partially stabilized superconducting cable requires solving the problem of guaranteed discharge of accumulated energy through non-detachable current leads to external devices for its dissipation. Therefore, it is important to consider a solenoid option with a fully stabilized superconductor. This eliminates the risk of an instantaneous transition of the solenoid from the superconducting to the normal state, however significantly increases the dimensions of the solenoid and, as a consequence, the entire cryostat of the CSS and the MCS complex as a

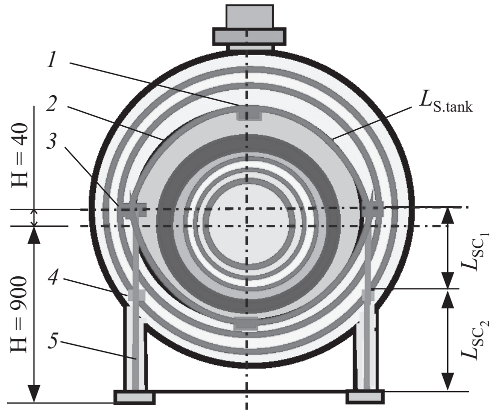

Fig. 3. Configuration of supports: *1* — node of helium tank support; *2* — helium support frame; *3* — node of helium tank and screen E1 support; *4* — E2 screen support node; *5* — support frame

whole. In addition, it solves only the problem of the solenoid transition and does not eliminate the problem of instantaneous release of the gas-liquid helium mixture in the case of an emergency depressurization of the cryostat or for any other reason. The final and decisive problem is a huge amount of liquefied helium in the tank and its possible release in the case of emergency.

A comprehensive solution to this problem has been proposed in patent of Ukraine No. 88830 for the method of cryosystem operation based on the patent *Cryosystems GLR* [2]. The defining feature of the proposed method is the ability to steadily operate the CSS with a very small feed of liquefied helium. However, because of a large heat capacity of the tank with built-in SMS and an incoming heat load on the tank, the accumulation of helium is necessary to ensure power supply to the solenoid, its transition to steady operation and even a too small excessive reserve of liquefied gas, is almost unsolvable task. Therefore, putting CSS into a steady mode is more practicable to realize in two stages. The first stage is cooling the system and accumulating the required tankage of helium, while operating both MCS; it is realized by pouring helium from a Dewar vessel. The stage ends with powering up the solenoid and putting it into steady mode with a superconducting key. The second stage is the transition of the CSS to the steady operation by the method of "liquid-gas-recondensation". This process ensures continuous operation as a closed physical process that does not require any external action. The helium tankage is determined experimentally, provided it is sufficient for the process. It should be noted that the lower part of the solenoid in the tank is placed in liquefied helium, and the recondensing vessel with an extended surface is located in the upper part of the copper tank, directly along the contour of the tank and the solenoid.

Natural ventilation in the tank is established due to the fact that helium vapor rises up to the recondensing vessel, with condensate drops from it falling down on the solenoid. The principle is that, above the liquefied helium mirror, the helium gas-liquid mixture in the closed liquid-gas-recondensation process is an ideal conductor of cold to the recondensing vessel from all elements of the tank and SMS, regardless of their complexity and location. Compliance with all conditions eliminates the temperature gradient in the tank, and, accordingly, overheating of the SMS solenoid and its transition to the normal condition. As a result of the above solution, the creation of CSS complex on the basis of the proposed method for operating the "liquid-gas-recondensation" cryosystem in the steady mode is quite realizable.

The solenoid is made of partially (about 30%) stabilized superconducting cable equipped with a system of discharge and outside dissipation of accumulated energy. The inner diameter of such a solenoid is 1200 mm, the outer diameter is 1300 mm, and the length is 700 mm. The operating current of the solenoid, 350 A, is almost twice less than the critical one. Accordingly, the outer diameter of the tank is 1400 mm, and the length is 800 mm. As a result, the overall dimensions of the CSS cryostat have been determined: the outer diameter is 1550 mm and the length is 110 mm. The solenoid in a horizontal cylindrical container is placed with a shift from the center down by 40 mm. All elements of the screen openings and the outer casing with flanges are displaced accordingly.

The configuration of supports is given in Fig. 3.

The bearing structure is based on support frame. The ends of the cylindrical copper tank for helium are made in the form of bearing copper flanges suspended (at the top and at the bottom) by two nodes *1* to ring frames *2* of a square tube. The frames *2* are mounted on a support with two nodes *3*. Similarly, the ends of the copper screens E1 and E2 are made in the form of bearing copper flanges. The screen E1 is mounted on a support frame in the same node *3*, while the screen E2 is mounted on a support frame in the node *4*. Thus, the copper screens fastened by end bearing copper flanges mounted on support frames play two important roles: they are elements of supports that ensure the stability of the side support frames, and, at the same time, ensure an effective heat dissipation from the support nodes to the appropriate stages of the MCS modules, at all three temperature levels.

Schematically, the design of the input node of the MCS module PT415 / PT415-RM is shown in Fig. 4.

The MCS, based on the length of its stages and the expected installation of the magnetic protection screen, is elevated above the cryostat casing. The first stage of the module is connected to the screen E1 *5* through the cooler *7*. The face of the module of the second stage is connected to the bottom of its casing with the help of disconnecting flexible cold conducting pipe *4*. The face of the bottom of the casing is connected with the recondensing vessel *2* by a disconnecting cold conducting pipe *3*. The recondensing vessel is located directly above the solenoid, in the upper part of the helium copper tank *1*, over its total length.

The configuration of the input unit of the MCS AL-200 module is shown in Fig. 5.

The pipe of the MCS input casing *6*, based on the length of its module and the possible installation of a magnetic protection screen, is elevated above the cryostat casing. The module is connected to the bottom of the input casing with the help of a disconnecting cold conducting pipe *5*. The bottom of the input casing is connected to

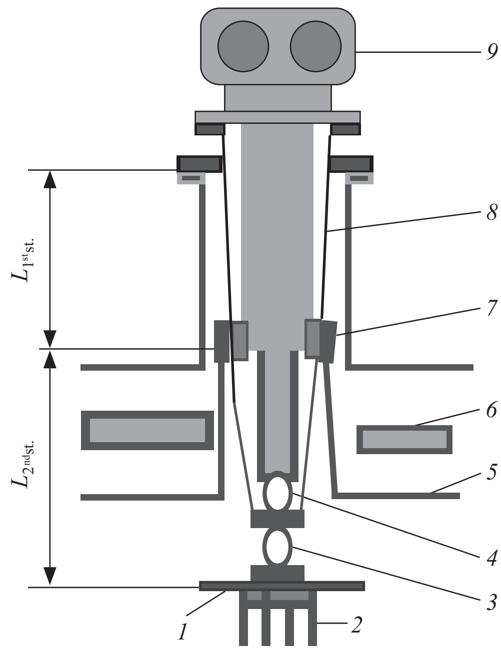

Fig. 4. Configuration of the input unit of the MCS module PT415 / PT415-RM: *1* — helium tank; *2* — recondensing vessel; *3* — cooling pipe of the input unit of the MCS module; *4* — cooling pipe of the MCS module; *5* — screen E1; *6* — screen E2; *7* — Xe1 screen cooler; *8* — casing of the input node of the MCS module; *9* — MCS PT415 / PT415-RM module

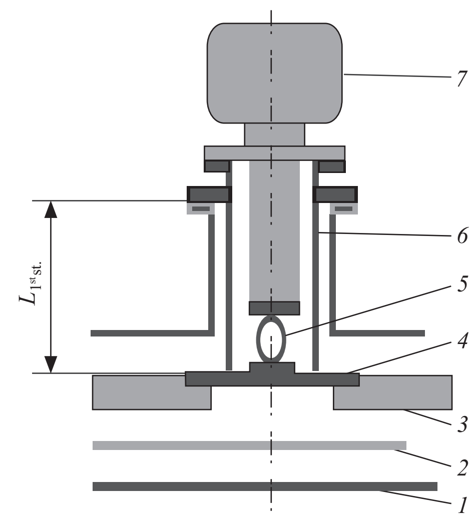

Fig. 5. Configuration of the input unit of the MCS AL-200 module: *1* — helium tank; *2* — screen E1; *3* — screen E2; *4* — XE2 cooler of the E2 screen; *5* — flexible cooling pipe; *6* — casing of the input unit of the MCS AL-200 module; *7* — MCS AL-200 module

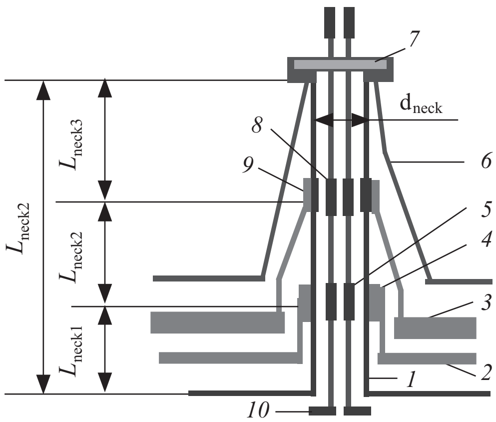

Fig. 6. Configuration of the neck: *1* — neck of the helium tank; *2* — screen E1; *3* — screen E2; *4* — cooler X1neck; *5* — cooler Xcurrent1; *6* — casing; *7* — input module of current leads and of indication and protection devices; *8* — cooler Xcurrent2; *9* — neck cooler X2; *10* — node connecting the current leads

the screen E2 *3* by means of a flexible cold conducting pipe *4*.

In the scheme (Fig. 6), the neck *1* with a detachable module with current leads and nodes connecting to the screens is conventionally divided into three parts. The first one is the lower part of the neck, directly attached to the helium tank. The heat inflow to it is an integral part of the load on the second stage of the MCS PT415 / PT415-RM. The second one is the middle part. Thanks to coolers *4* and *5*, through the screen E1 *2*, it is cooled by heat dissipation on the first stage of the MCS PT415 / PT415-RM. The third one is the upper part of the neck. Thanks to coolers *8* and *9*, through the screen E2 *3*, it is cooled by heat dissipation on the MCS AL-200. Heat dissipation from the neck wall is carried out by means of coolers *4* and *9*. Heat dissipation from internal structures to the neck wall is carried out by means of coolers *5* and *8*.

ESTIMATED ANALYSIS OF CSS HEAT BALANCE

The heat balance is analyzed by the calculation method under the condition of providing compensation of the total heat inflows from the elements of the CSS structures by the cooling capacity of the MCS modules at three corresponding temperature levels.

Calculations are performed based on the above configurations using the method proposed in [3]. Comprehensive analytical studies of the heat balance are carried out taking into account the heat inflows by current conductor and inputs of the indication of the operation status of the CSS and MCS built into the neck of CSS cryostat.

Proceeding from the above, the following studies have been made:

- analysis of the heat balance at a temperature of 4.2 K of the second stage of the MCS PT415 / PT415-RM with a permissible total heat supply of 1.35 W to the helium tank, with a ten percent margin taken into account;
- analysis of the heat balance of 40 W at a temperature of 45 K of the first stage of the MCS PT415 / PT415-RM with the total heat supply to it;
- analysis of the heat balance at a temperature of 80K of MCS AL200 with a permissible total

Table 1. **Average Values of Physical Parameters of Austenitic Steel 12X18H10T**

Design temperature range *T*, K	Average heat conductivity, λ, W/m · K	Design temperature range *T*, K	Average heat conductivity, λ, W/m · K
45—4.2	3.22	300—45	10.5
80—45	7.0	300—80	11.65

Table 2. **Average Values of Physical Parameters of Copper M1**

Design temperature range *T*, K	Average heat conductivity, λ, W/m · K	Design temperature range *T*, K	Average heat conductivity, λ, W/m · K
45—4.2	1260	300—45	485
80—45	825	300—80	475

Table 3. **Average Values of Physical Parameters of Helium Gas**

Design temperature range *T*, K	Average heat conductivity, λ, W/m · K	Design temperature range *T*, K	Average heat conductivity, λ, W/m · K
45—4.2	28.825	300—45	101.65
80—45	56.075	300—80	110.12

heat supply of 180 W, with a ten percent margin taken into account.

Below there are the results of calculations of the CSS heat balance.

Here and further in calculations it is assumed as follows:

$T_{\text{ємн.}}$ = 4,2 K; T_{E1} = 45 K; T_{E2} = 80 K; $T_{\text{кож.}}$ = 300 K; $F_{\text{ємн.}}$ = 7,3 m^2; F_{E1} = 8,95 m^2; F_{E2} = 9,8 m^2; $F_{\text{кож.}}$ = = 11,0 m^2; б is the Stefan—Boltzmann constant = = 5,67 × 10^{-8} W/ K^4 ×m^2; ε is blackness degree. For containers and screens covered with a layer of PET-DA film ε = 0,05; $\varepsilon_{\text{reduced}}$ is degree of blackness of surfaces in radiation heat exchange.

$$\varepsilon_{\text{reduced}} = 1/\{1/\,\varepsilon_2 + F_2/F_1\,(\,1/\varepsilon_{E1} + 1)\} \qquad (1)$$

λ_{average} is average heat conductivity in the calculated range of temperature, W /m × K;

The average values of the physical characteristics of the materials in the design temperature range, as assumed in the calculations, are given in Tables 1, 2, and 3.

The average values of physical parameters of copper, steel, and helium are calculated on the basis of standard reference data provided in the regulatory document *List of Tables of Standard Reference Data* effective as of January 1, 2008, in the Member States to the Agreement in the field of joint development and use of data on physical constants and properties of substances and materials [4].

It should be noted that the physical properties of the materials used to create the actual configuration may differ significantly from those shown in the tables. Atb the same time, the given average values can be considered near real, but still indicative.

ANALYSIS OF HEAT BALANCE AT THE FIRST TEMPERATURE LEVEL OF 4.2K OF THE SECOND STAGE MCS PT415 / PT415-RM

The analysis of heat balance is carried out based on a permissible total heat supply to the helium tank, assumed to be equal to 1.35 W, which is compensated by the recondensing vessel built directly into the helium tank and cooled by the second stage of the MCS.

The total heat flow to the helium tank is defined as:

$$Q_{\text{сум.ємн.}} = Q_{\text{випр.E1-ємн}} + Q_{\text{опор.ємн.}} + Q_{\text{кож.мод.2ступ.-ємн.}} + \\ + Q_{\text{сум.горл.1}} \le 1.35 \text{ W.} \qquad (2\,)$$

Here $Q_{\text{сум.ємн.}}$ is total heat inflow to the helium tank; $Q_{\text{випр.E1-ємн.}}$ is heat inflow from E1 2 screen radiation (Fig. 2) on the external surface of the helium tank; $Q_{\text{опор.ємн.}}$ is heat inflow from heat conductivity by the tank supports *3* (Fig. 3); $Q_{\text{кож.мод.2ступ.-ємн.}}$ is heat inflow to the helium tank on the input casing of the second stage of CNS PT415/PT415 — RM (Fig. 4); $Q_{\text{сум.горл.1}}$ is total heat inflow in the lower part of the neck (Fig. 5).

Respectively:

$$Q_{\text{випр.E1-ємн}}. = б \times \varepsilon_{\text{привед.ємн.}} \times F_{\text{ємн.}} \times \\ \times [T^4_{E1} - T^4_{\text{ємн.}}] \text{ W.} \qquad (3)$$

According to equation (1) $\varepsilon_{\text{привед.ємн.}}$ = 0.025. Based on the calculations by equation (3) $Q_{\text{випр.E1-ємн}}$ = 0.042 W.

$Q_{\text{опор.ємн.}}$ is calculated according to the configuration scheme in Figs. 2 and 3.

The tank supports are shaped as ring frames 2 made of square 12X18H10T steel pipe fastened in the nodes *3*. The cross section $S_{\text{опор.ємн.}}$ = 0.00025 m^2. The length of the suspension sector (in total, there are 8 sectors) of the ring frame $L_{\text{опор.ємн.}}$ = 1.0 m.

$$Q_{\text{опор.ємн.}} = 8 \times \{\lambda_{\text{опор.ємн.}} \times S_{\text{опор.ємн.}} \times \\ \times [T_{\text{мод.1.}} - T_{\text{ємн.}}]\}/L_{\text{опор.ємн.}}. \qquad (4)$$

The total heat inflow from the 8 sectors of supports $Q_{\text{опор.ємн.}}$ amounts to 0.26 W.

Heat inflow $Q_{\text{мод.2-ої ступ.-ємн.}}$ is calculated by the equation:

$$Q_{\text{кож.мод.2ступ.-ємн.}} = \lambda_{E1\text{-ємн}}. \times S_{\text{кож.мод.2-ємн.}} \times \\ \times [T_2 - T_{\text{ємн.}}]\}/L_{\text{кож.мод.2-ємн.}}, \qquad (5)$$

where $L_{\text{кож.мод.2}}$ = 0.25 m, $S_{\text{кож.мод2ступ.-ємн.}}$ = 0.00026 m^2/ pipe Ø 0.14 m, ð = 0.0006 m.

According to the calculation by the mentioned equation $Q_{\text{кож.мод.2-ой ступ.-ємн.}}$ = 0.14 W.

The heat inflow in the lower part of the neck $Q_{сум.горл.1}$ is calculated based on the neck configuration scheme shown in Fig. 6.

Given the results of the above calculations and the condition $Q_{сум.ємн.} \le 1.35$ W, the permissible heat inflow $Q_{сум.горл.1}$ shall be equal to ≤ 0.9 W.

The heat inflow in the neck $Q_{сум.горл.1}$ is defined as:

$$Q_{сум.горл.1} = Q_{ст.горл.1} + Q_{газ.горл.1} + Q_{сум.струм.1}, \quad (6)$$

where $Q_{ст.горл.1}$ is heat inflow from heat conductivity on the neck wall; $Q_{газ.горл.1}$ is heat inflow from heat conductivity through standing gas column in the neck; $Q_{сум.струм.1}$ is total heat inflow through current leads.

$$Q_{ст.горл.1} = \{\lambda_{ст.горл.1} \times S_{ст.горл.1} \times \times [T_{2\text{-ої ступ.}} - T_{ємн.}]\}/L_{горл.1}. \quad (7)$$

For the calculation purpose, it has been assumed that the neck diameter is 0.06 m, the wall thickness is 0.001 m, $S_{ст.горл.} = 0.0002$ m^2, $L_{горл.1} = 0.25$ m; material is 08X18H10T steel.

Accordingly $Q_{ст.горл.1} = 0.10$ W.

CALCULATION OF HEAT INFLOW BY MEANS OF HEAT CONDUCTIVITY THROUGH STANDING GAS COLUMN IN THE NECK

$$Q_{газ.горл.1} = \{\lambda_{газу1} \times S_{газ.горл.1} \times [T_{E1} - T_{ємн.}]\}/L_{горл.1} \quad (8)$$

$S_{газ.горл.1}$ is gas cross section in the neck = 0.002 m^2; $L_{горл.1}$ is 0.25 m.

Accordingly $Q_{газ.горл.1} = 0.01$ W.

CALCULATION OF THE PERMISSIBLE PARAMETERS OF CURRENT LEADS

Given the above results of calculations, the permissible total heat inflow through the current leads in the stationary mode, at a zero current on them is $Q_{сум.струм.1} \le 0.79$ W.

Accordingly

$$Q_{сум.струм.1} = Q_{сум.індик.струм.1} + Q_{сум.сил.струм.\,1} \le \le 0.79 \text{ W}. \quad (9)$$

The heat inflow by indicator inputs $Q_{сум.струм.індик.1}$ is defined as:

$$Q_{сум.індик.струм.1} = \{\lambda_{індик.1} \times S_{сум.індик.струм.1} \times \times [T_{E1} - T_{ємн.}]\}/L_{інд.струм.1}, \quad (10)$$

where $S_{сум.індик.струм.\,1}$ is cross section 1×10^{-6} m^2; $L_{інд.струм.1}$ is length of twisted inputs = 0.4 m; відповідно $Q_{сум.індик.струм.1} = 0.13$ W.

CALCULATION OF THE PERMISSIBLE PARAMETERS OF CURRENT LEADS IN THE STATIONARY MODE

In the stationary mode $Q_{сум.сил.струм.1}$, in the standing gas column, at a zero current, fixed current leads are considered passive heat lines.

Given the results of the above calculations, the permissible cross section of current leads is estimated under conditions $Q_{сум.сил.струм.1} \le 0.66$ W.

$$Q_{сум.сил.струм.1} = \{\lambda_{струм.1} \times S_{сум.сил.струм.1} \times \times [T_{E1} - T_{ємн.}]\}/L_{сил.струм.1} \le 0.66 \text{ W}, \quad (11)$$

where $L_{сил.струм.1}$ is design length of twisted current leads; it is equal to = 0.4 m.

Accordingly, the total cross section of two current leads is $S_{сум.сил.струм.\,1} \le 5.1 \times 10^{-6}$ m^2.

ANALYSIS OF HEAT BALANCE AT A TEMPERATURE OF 45K OF THE FIRST STAGE OF MCS PT415/PT415-RM

The analysis is made in terms of permissible heat inflow $Q_{сум.мод.1}$ to the first stage of MCS compensated by its cooling capacity of 40 W:

The total heat load $Q_{сум.мод.1}$ is defined as:

$$Q_{сум.мод.1} = Q_{опорE1} + Q_{кож.мод.1\text{-}E1} + Q_{випр.E2\text{-}E1} - - Q_{випр.E1\text{-}ємн.} + Q_{сум.горл.2} \le 40 \text{ W}, \quad (12)$$

where $Q_{сум.мод.1}$ is total heat inflow to the first stage of MCS; $Q_{опорE1}$ is heat inflow from the supports of screen E1 2 Fig. 3); $Q_{кож.мод.1\text{-}E1}$ is heat inflow in the upper part of the input casing 8 (Fig. 4) of the MCS first stage module; $Q_{випр.E2\text{-}E1}$ is heat inflow through radiation from the screen E2 3 to the screen E1 2 (Fig. 2); $Q_{випр.E1\text{-}ємн}$ is determined in the previous section of calculation 0.042 W; $Q_{сум.горл.2}$ is heat inflow from the middle part of the neck with current leads from heat exchanger 4 (Fig. 6).

The heat inflow $Q_{опор.E1}$ is calculated according to the configuration scheme shown in Figs. 3 and 4.

$$Q_{опорE1} = \{\lambda_{опор.E1} \times S_{сум.опор.E1} \times \times [T_{E2} - T_{E1}]\}/L_{опор.E1}, \quad (13)$$

where $S_{сум.опорE1} = 0.0015$ m^2, $L_{опор.E1} = 0.4$ m.

According to the calculation $Q_{опорE1} = 0.9$ W.

The calculation of heat inflow $Q_{кож.мод.1\text{-}E1}$ to the screen E1 on the input casng of the first stage of MCS PT415/PT415-RM, according to the configuration scheme given in Fig. 4.

$$Q_{кож.мод.1\text{-}E1} = \{\lambda_{кож.мод.1\text{-}E1} \times S_{кож.мод.1\text{-}E1} \times \times [T_{кож.} - T_{E1}]\}/ L_{кож.мод.1\text{-}E1}, \quad (14)$$

where $L_{кож.мод.1\text{-}E1} = 0.2$ m, $S_{кож.мод.1\text{-}E1} = 0.00035$ m^2 (pipe Ø 140 mm, ð = 0,8 mm, 12X18H10T steel).

According to the calculation $Q_{кож.мод.1\text{-}E1} = 4.7$ W.

The heat inflow by radiation $Q_{випр.E2\text{-}E1}$ from the screen E2 to the screen E1 is defined as:

$$Q_{випр.E2\text{-}E1} = \sigma \times \varepsilon_{привед.E1} \times F_{E1} \times [T_{E2} - T_{E1}], \text{ W}. \quad (15)$$

Based on the calculation by equation (1) $\varepsilon_{привед.E1} = 0.025$. Accordingly, $Q_{випр.E2\text{-}E1} = 0.57$ W.

Given the results of calculating the heat balance components and the condition $Q_{сум.мод.1} \le 40$ W the permissible value is $Q_{сум.горл.2} \le 33.8$ W.

The total heat inflow in the middle part of the neck is defined as:

$$Q_{сум.горл.2} = Q_{ст.горл.2} + Q_{газ.горл.2} + + Q_{сум.струм.2} \le 33.8 \text{ W}, \quad (16)$$

where $Q_{ст.горл.2}$ is heat inflow by means of heat conductivity on the neck walls; $Q_{газ.горл.2}$ is heat inflow by means of heat conductivity in the standing gas column in the neck; $Q_{сум.струм.2}$ is total heat inflow in current leads.

The heat inflow in the neck walls $Q_{ст.горл.2}$ is defined as:

$$Q_{ст.горл.2} = \{\lambda_{ст.горл.2} \times S_{ст.горл.2} \times \times [T_{E2} - T_{E1}]\}/L_{горл.2}, \quad (17)$$

where $L_{горл.2}$ is neck wall length, 0.2 m; $S_{ст.горл.2}$ is cross section of neck wall, 0.0002 m^2. Accordingly $Q_{ст.горл.2} = 0.23$ W.

The heat inflow from the standing gas column $Q_{газ.горл.2}$ is defined as:

$$Q_{газ.горл.2} = \{\lambda_{газ.горл.2} \times S_{горл.2} \times \times [T_{E2} - T_{E1}]\}/L_{горл.2}, \quad (18)$$

where $S_{горл.2}$ is gas cross section in the neck, 0.002 m^2. Accordingly, $Q_{газ.горл.2} = 0.019$ W. Finally, $Q_{сум.струм.2}$ shall be ≤ 33.5 W.

The calculationof permissible parameters of current leadsin the middle part of the neck:

$$Q_{сум.струм.2} = Q_{сум.ідик.струм.2} + + Q_{сум.сил.\ струм.2} \le 33.5 \text{ W}; \quad (19)$$

$$Q_{сум.індик.струм.2} = \{\lambda_{індик.2} \times S_{сум.індик.струм.2} \times \times [T_{E2} - T_{E1}]\}/L_{індик.струм.2}, \quad (20)$$

where $S_{сум.ідик.струм.2}$ is cross section of indicator inputs = 1×10^{-6} m^2, $L_{індик.струм.2}$ is length in the twisted shape = 0.4 m. Accordingly, $Q_{сум.індик.струм.2} = 0.1$ W.

Calculation of cross section $S_{сум.сил.струм.2}$ of current leads. Given the results of previous calculations, the permissible cross section of current leads is calculated based on the condition $Q_{сум.сил.струм.2} \le 33.4$ W.

$$Q_{сум.сил.струм.2} = \{\lambda_{сил.струм.2} \times S_{сум.сил.струм.2} \times \times [T_{E2} - T_{E1}]\}/L_{сил.струм.2} \le 33.4 \text{ W}, \quad (21)$$

where $L_{сил.струм.2}$ is design length in the twisted shape, 0.4 m.

According to the calculations, $S_{сум.сил.струм.2} \le 4.76 \times 10^{-4}$ m^2.

ANALYSIS OF HEAT BALANCE AT THE THIRD TEMPERATURE LEVEL OF 80 K OF MCS AL2000

The heat balance at a temperature level of 80 K, in accordance with the scheme of MCS AL200 (Fig. 5), is analyzed for the assumed for the calculations of permissible total heat inflow $Q_{сум.3} \le 180$ W defined as:

$$Q_{сум.3} = Q_{кож.мод.\text{-}E2} + Q_{опор.E2} + Q_{випр.кож\text{-}E2} - - Q_{випр.E2-E1} + Q_{сум.горл.3} \le 180 \text{ W}, \quad (22)$$

where $Q_{кож.мод.\text{-}E2}$ is heat inflow to the screen E2 through the casing *6* (Fig. 5) of the MCS input module; $Q_{опор.E2}$ is heat inflow from the supports of screen E2 *3* (Fig. 3); $Q_{випр.кож\text{-}E2}$ is heat inflow through radiation from the casing to the screen E2 *3* (Fig. 2); $Q_{випр.E2-E1}$, is heat discharge as a result of radiation from the screen E2 to the screen E1. Based on the analysis, at a temperature level of 45 K it has been calculated that $Q_{випр.E2-E1} = 0.57$ W; $Q_{сум.горл.3}$ is heat inflow to the screen E2 from the cooler *9* (Fig. 6) in the upper part of the neck with current leads.

The heat inflow $Q_{кож.мод.-E2}$ is calculated by the equation:

$$Q_{кож.мод.-E2} = \{\lambda_{кож.-E2} \times S_{кож.мод.-E2} \times \times [T_{кож.} - T_{E2}]\}/L_{кож.мод.-E2}, \quad (23)$$

where $L_{кож.мод.-E1} = 0.35$ m, $S_{кож.мод.-E2} = 0.00022$ m^2 (pipe diameter is 90 mm, thickness 0.8 mm).

Accordingly $Q_{кож.мод-E2} = 1.61$ W.

The heat inflow through the supports $Q_{сум.опор\ E2}$ is estimated by the equation:

$$Q_{сум.опорE2} = \{\lambda_{опор.E2} \times S_{сум.опор.E2} \times \times [T_{кож.} - T_{E2}]\}/L_{опор.E2}, \quad (24)$$

where $\lambda_{опорE2} = 11.65$ W/m × K; $S_{сум.опор.E2} = 0.002$ m^2, $L_{опор.E2} = 0.5$ m.

Accordingly $Q_{опорE2} = 10.25$ W.

The heat inflow through radiation from the casing to the screen E2.

$\varepsilon_{кож.}$ is equal to 0.06 for the casing made of 12X18H10T steel, ε_{E2} is equal to 0.05 for the screen protected with a super insulating material layer.

Proceeding from the calculation by $\varepsilon_{привед.E2} = 1/\{1/\varepsilon_{E2} + F_{E2}/F_{кож.}(1/\varepsilon_{кож.} + 1)\}$ we obtain 0.026.

The heat inflow through radiation from the casing to the screen E2 is defined as:

$$Q_{випр.кож.-E2} = б \times \varepsilon_{привед.E2} \times F_{E2} \times \times [T_{4кож.} - T_{4\ E2}]. \quad (25)$$

Accordingly, $Q_{випр.кож.-E2} = 145$ W.

Given the results of previous calculations, the heat inflow to the screen E2 from the upper part of the neck $Q_{сум.горл.3}$ is ≤ 23.0 W.

ANALYSIS OF THE TOTAL HEAT INFLOW IN THE UPPER PART OF THE NECK $Q_{СУМ.ГОРЛ.3}$

The analysis is made based on the configuration schemen given in Fig. 6.

Proceeding from the above analysis of the heat balance of MCS AL 200, the permissible value of $Q_{сум.горл.3}$ is ≤ 23.0 W. Hence,

$$Q_{сум.горл.3} = Q_{ст.горл.3} + Q_{газ.горл.3} + + Q_{сум.струм.3} \le 23{,}0 \text{ Вт}, \quad (26)$$

where $Q_{ст.горл.3}$ is heat inflow from heat conductivity along the neck wall; $Q_{газ.горл.3}$ is heat inflow along the standing gas column in the neck; $Q_{сум.струм.3}$ is total heat inflow through the current leads.

The heat inflow from heat conductivity along the neck wall $Q_{ст.горл.3}$ is defined as:

$$Q_{ст.горл.3} = \{\lambda_{ст.горл.3} \times S_{ст.горл.3} \times \times [T_{кож.} - T_{E2}]\}/L_{горл.3}, \quad (27)$$

$L_{горл.3}$ is design length of the neck wall, 0.2 m; $S_{ст.горл.3}$ is cross section of the neck wall, 0.0002 m^2. Accordingly, $Q_{ст.горл.3} = 2.44$ W.

The heat inflow along the standing gas column in the neck $Q_{газ.горл.3}$ is defined as:

$$Q_{газ.горл.3} = \{\lambda_{газу.3} \times S_{газ.горл.3} \times \times [T_{кож.} - T_{E2}]\}/L_{горл.3}, \quad (28)$$

where $S_{газ.горл.3}$ is cross section of gas in the neck, 0.002 m^2; $L_{горл.3}$ is length of the heat conducting gas column, 0.2 m. Accordingly, $Q_{газ.горл.3} = 0.24$ W.

The calculation of the permissible parameters of current leads in the upper part of the neck.

Given the results of the previous calculations $Q_{сум.струм.3} \le 20.3$ W.

Accordingly,

$$Q_{сум.струм.3} = Q_{сум.індик.струм.3} + +Q_{сум.сил.струм.3} \le 20.3 \text{ W}, \quad (29)$$

where $Q_{сум.індик.струм.3}$ is total heat inflow by indicator current leads; $Q_{сум.сил.струм.\ 3}$ is total heat inflow by two current leads.

The heat inflow $Q_{сум.індик.струм.3}$ is defined as:

$$Q_{сум.індик.струм.3} = \{\lambda_{індик.3} \times S_{сум.індик.} \times \times [T_{кож.} - T_{E2}]\}/L_{індик.3}, \quad (30)$$

where $S_{сум.ідик.струм.3}$ is inputs cross section, 1×10^{-6} m^2; $L_{індик.3}$ is design length in the twisted shape, 0.4 m. Accordingly, $Q_{сум.індик.струм.3} = 0.26$ W.

The permissible parameters of current leads are estimated based on the condition:

$$Q_{\text{сум.сил.струм.3}} = \{\lambda_{\text{сил.3}} \times S_{\text{сум.сил.струм.3}} \times \times [T_{\text{кож.}} - T_{E2}]\}/L_{\text{сил.3}} \leq 20.04 \text{ W}, \quad (31)$$

where $L_{\text{сил.3}} = 0.4$ m.

As a result, $S_{\text{сум.сил.струм.3}} \leq 7.7 \times 10^{-5}$ m^2.

The calculations have shown that the heat inflow through the indicator current leads is relatively small, so it does not significantly affect the heat balance of the MCS modules.

The more significant permissible parameters of power current leads by the neck sections are as follows:

$S_{\text{сум.сил.струм.1}} \leq 5.1 \times 10^{-6}$ m^2; $Q_{\text{сум.сил.струм.1}} \leq 0.66$ W;
$S_{\text{сум.сил.струм.2}} \leq 4.76 \times 10^{-4}$ m^2; $Q_{\text{сум.сил.струм.2}} \leq 33.4$ W;
$S_{\text{сум.сил.струм.3}} \leq 7.7 \times 10^{-5}$ m^2, $Q_{\text{сум.сил.струм.3}} \leq 20.04$ W.

Hence, this research is the final one in the series of studies related to solving R&D and design problems of developing systems for cryogenic support of large multi-ton cryomagnetic complexes based on microcryogenic closed-loop systems. The research is based on the author's patents of Ukraine № 103949 and № 88830 [1, 2] and research [3], as well as on the development of the CSS within the project of the MCS-1000 complex, which aims at creating a prototype for the modernization of Prydniprovska TPP for pulverized coal purification. The project deals with testing the design and procedures/operation manuals of the complex in order to create a basic design of MCS for its further implementation at other TPPs and for industrial beneficiation and purification of minerals from harmful impurities by the high-gradient magnetic separation method.

Many important solutions have been implemented in the development: the feasibility of creating a cryogenic supply system based on two closed-cycle MCS has been shown; the configuration of CSS with the appropriate design of supports, screens, and tanks which act as monolithic system of rigidity and effective removal of heat inflows at the corresponding stages of MCS modules has been proposed; the configuration of the neck module and input modules of two MCSs has been designed; the method for efficient use of MCS cooling capacity has been developed based on the comprehensive analysis of heat balance of their modules with total heat supply to them from all CSS systems at all temperature levels; the heat balance at the second stage of the MCS PT415 / PT415-RM module and the MCS AL 200 module, under the condition of a ten percent margin in terms of their cooling capacity, has been calculated. The maximum permissible parameters of power current leads have been calculated. In fact, they can be much smaller in the upper and in the middle parts of the neck, with the lower part of each power current conductor shunted with a superconducting cable.

The research has shown the efficiency of the CSS in the stationary mode with a very small supply of liquefied helium to the tank in the "liquid-gas-recondensation" closed physical process that operates continuously and does not require any external action. It is important that in the process of heat exchange, the helium gas-liquid mixture is a constant ideal cooling pipe to the recondensing vessel from all elements of the tank and SMS, regardless of their complexity and location. Also, it should be added that the lower part of the solenoid in the tank is in liquefied helium, and drops of condensate fall on it from the recondensing vessel located in the upper part, directly along the contour of the tank and the solenoid. All together eliminate a temperature gradient in the copper tank, and, accordingly, prevent overheat of the SMS solenoid and its transition to a normal state.

In general, the above development radically solves the problem of safety, even in the case of instantaneous release of too small amount of helium gas-liquid mixture for any reason. In order to indicate the status of all systems and to prevent accidents, the boiler control system has an integrated automated control system of the CSS. Also, to prevent possible heating of the cryostat casing pipe, it is made of copper, with the ends connected by heat line to the external magnetic screen at room temperature.

The proposed CSS design provides simplicity of manufacturing technology and, importantly, the easiness of routine operation in industrial conditions of thermal power plants, even with the possible change of the neck module and MCS modules without depressurization of the cryostat vacuum cavity.

The development and creation of the MCS CSS complex is a particularly sophisticated R&D, design, and technological problem. In Ukraine, no similar developments of such a significance and R&D level have been known.

Many thanks to the vacuum technology and cryogenic instrumentation engineer M.O. Demisheva for unquestionable creative contribution and assistance in the implementation of the whole complex of research works related to solving design and technological problems of the development and creation of cryostats, cryogenic installations, and cryomagnetic complexes.

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Received 26.02.19
Revised 24.07.19
Accepted 16.09.19

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СИСТЕМА КРІОГЕННОГО ЗАБЕЗПЕЧЕННЯ КРІОМАГНІТНОГО КОМПЛЕКСА КМК–1000 НА БАЗІ МІКРОКРІОГЕННИХ СИСТЕМ ЗАМКНУТОГО ЦИКЛУ

Вступ. Розвиток галузі збагачувальних виробництв означив вимоги з розроблення суттєво нових технологій та обладнання, зокрема й методу магнітної сепарації.

Проблематика. Перевага кріомагнітних комплексів магнітної сепарації визначається ефективністю вирішення проблеми створення їхньої системи кріогенного забезпечення.

Мета. Розробка системи кріогенного забезпечення (СКЗ) кріомагнітного комплексу на базі мікрокріогенних систем замкнутого циклу (МКС).

Матеріали й методи. Матеріалом роботи є конструкція СКЗ з вбудованою надпровідною магнітною системою (НМС) і двома МКС. Ефективність використання МКС визначається методом аналізу теплового баланса їхніх модулів.

Результати. Розроблено конструкцію СКЗ на базі безазотного кріостата з вбудованою НМС і двома МКС та рішення проблеми ефективного використання МКС методом аналізу теплового балансу їх модулів. Конструкція вузлів введення модулів МКС та горловини, а також ємності, опор і екранів одночасно є системою жорсткості та ефективного відводу теплоприпливів з них на відповідні ступені модулів МКС. Конструкція СКЗ забезпечує ефективність роботи в стаціонарному режимі з надмалим запасом зрідженого гелію по кільцевому процесу «рідина–газ–реконденсація», в якому газорідинна суміш гелію є ідеальним холодопровідом. Конструкція СКЗ забезпечує технологічність регламентних робіт, навіть зі зміною модулів горловини та і МКС, без розгерметизації кріостата.

Висновки. Рішення конструкторсько-технологічних та науково-технічних проблем створення СКЗ базується на патентах України № 103949 та № 88830. Обгрунтовано доцільність створення СКЗ комплексу на базі кріостата з вбудованою НМС і двома МКС, що працює в стаціонарному режимі з надмалим запасом зрідженого гелію.

Ключові слова: кріомагнітний комплекс, система кріогенного забезпечення кріомагнітного комплексу.