Superconducting lines cable inputs. Thermal processes modelling

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Abstract. The article considers the thermal state in the basic elements of a cryogenic energy transfer line with high-temperature superconductors. The temperature fields distribution in the heat-stressed elements of the cryogenic energy transmission line with high-temperature superconductors depends on the methods of supplying the cryogenic coolant to cable cryostats and current leads. A large contribution to the total heat flux, especially in cable power lines of short length, falls at the current leads. Computations of complex real current lead structures consist in the joint solution of the hydrodynamics and heat transfer equations for the flux, and the energy equation for the wall. The article considers a three-dimensional non-stationary motion of weakly compressible media (gas and liquid) with a free surface in a semi-closed volume at Mach numbers up to 0.3. The mathematical model is based on the Navier-Stokes equations and total enthalpy. These equations are being solved in conjunction with the equation of state for gas or liquid, the equations for the low Reynolds k-ε turbulence model, and the three-dimensional energy equation for the wall. Recently, FlowVision application package, or specially designed software are being used for complex three-dimensional thermal calculations.

1. Introduction

The thermal state in the heat-stressed elements of a cryogenic power transmission line with high-temperature superconductors (HTSC) depends on the methods of supplying cryogenic coolant to cable cryostats and current leads. A large contribution to the total heat input, especially in cable power lines of small length, is accounted for by current leads.

Current leads are designed for electrical connection of current-carrying elements of the HTSC power electric cable located in the low-temperature area with current-carrying elements of the cable industrial network. Current leads must provide the necessary current load in the power cable with minimal heat input from the environment to the low-temperature area. According to the total value of heat flows, the cooling capacity of the cryo-refrigerator in the cryostat loop is been selected.

The value of AC or DC current passing through the current-carrying elements of the current lead and cable usually does not exceed 3500 A at a high voltage (more than 20 kV) and the operating temperature of the current-carrying elements of the industrial cable network from 223 to 323 K. The modern cryostats uses liquid nitrogen or liquid hydrogen as a heat carrier. The temperature range in cryostats with liquid nitrogen varies from 65 to 78 K, and in hybrid power lines with liquid hydrogen-from 19 to 35 K.

The main coolant heating sources in the path of a closed cryopreservation system for extended power cables when transmitting AC and DC currents are:

- heat flows to the low-temperature zone through current leads determined by the design features of the current leads (the value of heat inflows on a single current lead can vary from 100 to 350 W), and not depended on the length of the cable;
- heat flows through passive thermal insulation of cryostats (in modern flexible nitrogen cryostats - from 1 to 3 W/m);
- heat generation due to hysteresis losses during AC passage (in first generation HTSC conductors they are from 1 to 3 W/m per phase in the presence of a superconducting screen).
• heat generation in the cable path due to irreversible hydraulic losses (channel walls friction, local resistance losses), which are determined by the cryostat mass flow rate, liquid temperature, flow path design features (roughness of the channel wall, turbulence of the flow due to twisting, local hydraulic resistances presence, etc.);

• heat release in the pumping units path (determined by the pump efficiency, mass flow rate, amount of pressure generated by the pump).

The most urgent problem is to determine the values of heat flows through current leads calculated numerically or experimentally [1].

2. Results and Discussion

The complex real structures of current leads calculations consist in the joint solution of hydrodynamics and heat exchange equations for the flow and the energy wall equation. In power HTS systems, liquid nitrogen or hydrogen is used as a heat carrier. Recently, FlowVision and ANSYS application packages or specialized programs have been used to calculate heat flows.

A three-dimensional mathematical model was created to calculate the values of heat flows from the environment to liquid nitrogen and hydrogen passing through the flow paths of the current lead and cryostat system. The model provides solutions to the thermal conductivity equations for the wall and the Navier-Stokes equations for a flow with variable thermal properties. Three-dimensional unsteady motion of weakly compressible media (gas and liquid) with a free surface in a semi-closed volume is considered for Mach numbers up to 0.3.

The mathematical model is based on the Navier–Stokes and total enthalpy equations:

\[
\frac{\partial (\rho V)}{\partial t} + \nabla (\rho V \otimes V) = -\nabla P + \nabla ((\mu + \mu_t)(\nabla V + (\nabla V)^T));
\]

\[
\frac{\partial \rho}{\partial t} + \nabla \rho V = 0;
\]

\[
\frac{\partial (\rho H)}{\partial t} + \nabla (\rho VH) = \frac{\partial P}{\partial t} + \nabla \left( \left( \frac{\lambda}{c_p} + \frac{\mu_t}{Pr} \right) \nabla H \right);
\]

These equations are solved together with the equation of state for a gas or liquid, the equations for the low-Reynolds k-ε turbulence model, and the three-dimensional energy equation for the wall. A solid-state three-dimensional “volumes” geometry corresponding to the current lead actual geometry was developed to perform calculations.

The FlowVision software package allows to study the processes in the current lead and get a movement detailed view in the current leads and cables flow elements. Figure 1 shows the current lead characteristic design for the HTSC industrial frequency AC cable line (50 Hz). The structure and operating principle are discussed in detail in [1].

Figure 2 shows the upper part characteristic design area of the current lead. The vertical axis of the current lead is combined with the y axis. The FlowVision numerical algorithm is implemented on a rectangular grid with local adaptation to the third level and complex geometry subgrid resolution. This approach allows to perform calculations efficiently with a sufficient degree of accuracy, using minimal computing resources.

A multi-level adaptation of the finite-difference grid is applied to ensure the necessary accuracy of calculations. The calculation is carried out by a non-stationary method with a gradual thickening of the finite-difference grid near the input and output holes and in the zone bounded by the gradient of the Mach number change.
The following initial data were used: working fluid - nitrogen (or hydrogen); working fluid initial pressure - 1 MPa; working fluid initial temperature - 75 K; working fluid mass flow rate - 1.2 kg/s; ambient temperature - 300 K. The calculations took into account the change in thermal conductivity from temperature and the convective cooling processes. The calculation results are presented in a plane passing through the axis of symmetry of the current lead.

Figure 3 shows a temperature distribution diagram over the height of the Central copper current lead and in the annular cavity of the current lead. Heat is supplied from the environment to the external side current lead cylindrical surface due to the convection of nitrogen gas located in a closed annular cavity between the current lead external surface and the electrical insulator internal surface, as well as through the upper end surface. Heat removal is provided by convection from the current lead lower part in contact with liquid nitrogen. The temperature varies from the upper boundary ambient temperature (300 K) to the liquid nitrogen temperature at lower boundary (75 K). It can be seen the gas temperature varies from 270 K in the upper section to 160 K in the lower section of the current lead. The asymmetry of the temperature field relative to the current lead axis is noted.

Figure 4 shows a visualization of the "flash" flow. It can be noted that a system of three-dimensional vortices is formed in the annular cavity of the current lead. A helical vortex is formed in the lower zone of the current lead annular cavity. The speed of steam movement does not exceed 0.1 m/s. Non-stationary vortices transmit significant convective heat fluxes.

The value of the cross-section of the current-carrying element is determined by the results of calculations using the developed mathematical verified current lead model [3]. To solve the problem, a non-stationary one-dimensional heat equation is used, taking into account:

- current passing heat generation;
- the third kind boundary condition in the upper section (the heat transfer coefficient is set) and the first kind boundary condition in the current lead lower section (liquid and current lead temperatures equality);
- heat drains from the current lead side surface (the heat transfer coefficient is set);
- electrical resistivity and thermal properties of the material dependences on temperature.
The nitrogen or hydrogen boiling curve (heat transfer and temperature pressure dependence) is used when calculating the current line section immersed in a liquid. The program was verified in experiments on nitrogen. Typical current leads calculation results for hydrogen are shown in figure 5.

It can be seen that if an electric current is applied, the temperature change law along the current line length changes from linear to parabolic. There is a maximum temperature and its displacement with increasing load current to the lower current lead cross-section. If a load current of 2.5 kA, the maximum current lead temperature is 265 K.

Figure 6 shows the heat input to liquid nitrogen dependence on the current line cross-section. It can be seen there is an optimal current line cross-section. At a load current of 2.5 kA, the heat input is 145 W (through the current line directly 110 W, screen-vacuum insulation-10 W, due to convection-25 W). The heat input value is 70 W in the absence of a current load. The heat input to liquid hydrogen at a load current of 2.5 kA is 270 watts. Directly on the current-carrying element-170 W, due to convection-100 W. In the absence of a current load, the heat input value is 80 W.
The caprolon diaphragm transverse partitions installation in the steam annular current insulator cavity along the current line height significantly reduces the convective heat transfer by steam between the current lead upper section and the phase interface. Transverse partitions are installed along the current-carrying element height with no more than 1.5 mm gap between the current line and the partition. They reduce the three-dimensional non-stationary vortices scale by splitting the insulator volume annular cavity into lower height volumes. In this case, the resulting vortex structures scale in hydrogen gas is proportional to the distance between the partitions. When dividing the annular chamber space by partitions, a significant reduction in the unevenness of the temperature fields and the velocities of vortex gas flows along the current line is provided. As a result of using horizontally installed dielectric partitions, the heat flow to the device low-temperature zone is reduced by 15%. The changes in the convective steam movement nature are shown in figure 7.

Figure 8 shows the temperature distribution over the Central current lead (left) and the annular gas gap (right).

The total heat flow calculating results to the liquid through a current-flow channel with six partitions are shown in figure 9. It can be seen that heat flow is reduced by 50% with six partitions, compared to the original version. Thus, the partitions installation in the current leads allows to effectively reduce heat flows to the low-temperature zone of the HTSC power cable.

The thermal processes modeling in hydrogen current leads was also performed using the FlowVision package with gradual thickening of the finite-difference grid near the characteristic elements of the highway path. The calculation results for hydrogen current leads shows the same heat exchange features as for nitrogen ones.

The main heat input to the current lead low-temperature zone between the cable and liquid hydrogen comes from thermal conductivity through the copper current-carrying element 1 (see figure 1) and due to heat generation occurs when an electric current passes (100-110 W). Additional heat flows are supplied through the polyimide current lead current insulator housing and the current insulator 3 (see figure 1) (27-30 W). Hydrogen gas natural convection occurs in a closed current lead annular cavity without partitions between the electrical insulator inner surface, the current lead upper flange, the current-carrying element surface and the liquid, provides a heat flow of more than 250 W, since hydrogen gas has a significant thermal conductivity ($\approx 0.1$ W/(MK) at 20 K). The total heat flow through the current according to the calculation results will be 370-390 watts.
As for nitrogen current leads, when the electric current increases, the temperature change law along the current line length changes from linear to parabolic. There is a movement of the maximum heating zone to the cold section. The current line maximum temperature reaches 50°C with a rated load current of 2.5 kA. According to the calculation results, the total heat input at a current load of 2.5 kA through the current lead with partitions will be 370–390 watts. The total heat input without electric current is 320–350 watts. Figure 10 shows the temperature field measured on the silicone high-voltage insulator outer surface and obtained using the ThermaCAM P60 "FLIR systems" thermal imager. It can be seen that the temperature of the silicone shell exceeds -10°C.

The selected design solutions to ensure electrical strength in an extended cryostat and current leads (the use of lining, etc.) excluded the possibility of breakdown both in areas with liquid hydrogen and gaseous. The test results confirmed the created structural elements high electrical strength at a voltage of up to 60 kV.

3. Conclusion
Mathematical models were developed for calculating extended high-temperature superconducting cables and their current leads. The proposed current leads mathematical models were used for calculations using the FlowVision software package and for creating an experimental device.

The caprolon diaphragm transverse partitions installation in the current insulator steam annular cavity along the current line height significantly reduces the convective heat transfer by steam between the current lead upper section and the phase interface. The heat flow to the device low-temperature zone is reduced as a result of using horizontally installed dielectric partitions.

The selected design solutions for ensuring electrical strength in an extended cryostat and current leads eliminated the possibility of breakdown in both liquid and gaseous zones. The test results confirmed the high electrical strength of the created structural elements.

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Figure 9. The number of partitions influence on the heat flow to the liquid through the current channel.

Figure 10. The temperature field measured on the silicone high-voltage insulator outer surface and obtained using the ThermaCAM P60 "FLIR systems" thermal imager.