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Research Paper

Algorithm and simulation of heat conduction process for design of a thin multilayer technical device

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HIGHLIGHTS

- The cryogenic cell realizes thermal gate valves for the millisecond pulse injection.
- The developed algorithm gives stable solution for fast oscillating of source.
- The temperature regime in the cell has two stages: setting mode and working mode.
- The optimal choice of cell characteristics provides the required pulsing regime.

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ABSTRACT

A model of a multilayer device with non-trivial geometrical structure and nonlinear dependencies of thermodynamic material properties at cryogenic temperatures is suggested. A considered device, called cryogenic cell, is intended for use in multicharged ion sources for pulse injection of gaseous species into ionization space of ion sources. The main requirement for the cryogenic cell operation is the permanent opening and closing for gaseous species injection in a millisecond range, while cell closing is provided by freezing of the gaseous specie at the outer surface of the cell and the cell opening – by the corresponding pulse heating of the cell surface up to definite temperature. The thermal behavior of the device in a millisecond time range is simulated. The algorithm for solving the non-stationary heat conduction problem with a time-dependent periodical heating source is suggested. The algorithm is based on finite difference explicit–implicit method. The OpenCL realization of the algorithm is discussed. The optimal particular choice of the parameters to provide the required pulse temperature regime of the designed cryogenic cell for the chosen working gas is presented. Based on these results further optimization can be formulated.

1. Introduction

In modern science the phenomena of thermal conductivity is a very common technology for studying of complex objects with complex geometric and physical structure. The main goal of this work is to suggest a model of temperature evolution for a multilayer cylindrical object, called cryogenic cell, which has application in sources of multicharged ions [1]. The function of the cryogenic cell is a pulse injection (in the millisecond range) of the working gases into the working space of the ion source.

In the modern applied thermal engineering the dependences of physical properties of materials on temperature (even in small interval) can ensure elegant way for the diagnosis, monitoring and management of complex systems. Such interesting examples are presented in [2] and [3].

Pulse injection of a gaseous species could be provided by fast mechanical gate valves, however, robust operation in millisecond range in cryogenic environment is out of their possibilities. The use of temperature properties of gases at cryogenic temperatures could be a real alternative to pulse mechanical gate valves in a millisecond range time operation. Indeed, dependency of vapor pressure of all gases on temperature is very strong in a cryogenic temperature range, i.e. between liquid helium temperature 4.2 K and liquid nitrogen temperature 78 K. Typical data for Krypton is given in Table 1 (see [4]).

It is known in ion sources technology [5], that if a working gas vapour pressure is around 10^{-6} Torr, its typical injection time from the injection cell into the ionization space of ion source is about 1 ms. For example, for Krypton it corresponds to the temperature of 42.2 K. Injection cell in this case should be placed in a vicinity

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Table 1
Krypton vapor pressure as a function of temperature.

Temperature, K	27.9	29.4	30.9	32.7
Krypton vapor pressure, Torr	1.3×10^{-13}	1.3×10^{-12}	1.3×10^{-11}	1.3×10^{-10}
Temperature, K	34.6	36.8	39.3	42.2
Krypton vapor pressure, Torr	1.3×10^{-9}	1.3×10^{-8}	1.3×10^{-7}	1.3×10^{-6}

of working space of ion source, about 1 cm aside of ionization region of ion source. Another side, if gas vapor pressure is about 10^{-13} Torr it means that all gas molecules are frozen at the cell surface which has such temperature; for Krypton, for example, this temperature is 27.9 K. This opens possibility to use such temperature dependencies for gas injection in millisecond time range.

One needs to create such cryogenic cell which provides change of its surface temperature from, say 20 K up to, say, 45 K, and back during few milliseconds and with a frequency about 50 Hz.

Some additional requirements for such cryogenic cell construction are inspired by some basic aspects of ion source technology and cryogenic technics: there are two natural temperature terminals in cryogenics – liquid helium temperature terminal 4.2 K and liquid nitrogen temperature terminal 78 K, thus it is natural to use such temperature terminals as a thermostats with big capacity; cryogenic cell surface should be heated up by pulse electric current, passing through conductive layer in a vicinity of cell surface; in order to prevent disturbances in a working space of ion source it has to be placed in a vicinity of a working ionization space of ion source. The maximal electric current I and through the cell a corresponding voltage should be restricted to $I\times R<1000\,\mathrm{V}$, where R is a resistance of the conductive layer.

Design of such cryogenic cell has been elaborated and recently tested in JINR [6,7]. Which shows, that the cell exhibited expected above mentioned time and temperature parameters. For the reason of practical use in ion sources one needs to create a sample of cryogenic cell which fits more precisely the time and temperature requirements in millisecond time range at cryogenic temperatures. The present work describes details of numerical strategy, which is used to create suitable numerical tool for optimization of cryogenic cell construction.

So, one needs to simulate thermal process in a cell of a chosen geometry, which is governed by the periodic passage of electric current through one of the layers of the cell. The period of the process is requested to be $t_{\mathrm{prd}}=t_{\mathrm{src}}+t_{\mathrm{clg}}$. Here t_{src} is a period of heating and t_{clg} is a period of cooling down. The period is divided in two parts: when the cell evaporates working gases from its surface ($T>T_{\mathrm{crit}}$) and when the rest of the working gas (which is not penetrated into ion source ionization space) freezes on the surface ($T<T_{\mathrm{crit}}$). The cell itself should work at the cryogenic temperature range from temperature of liquid helium ($T=4.2\mathrm{K}$) up to the temperature of liquid nitrogen. The cell structure has a cylindrical symmetry; therefore, the heat conductivity inside it can be simulated by a model with two spatial cylindrical coordinates, r and z, and time variables (Fig. 1). Similar but more simple model has been discussed in [8] and [9].

2. Main equations and boundary conditions

The thermal processes in the object can be described by the following system of parabolic partial differential equations with temperature depended coefficients [10]:

$$\rho_m c_{Vm}(T)\frac{\partial T}{\partial t}=\frac{1}{r}\frac{\partial}{\partial r}\left(r\lambda_m(T)\frac{\partial T}{\partial r}\right)+\frac{\partial}{\partial z}\left(\lambda_m(T)\frac{\partial T}{\partial z}\right)+X_m(T,t), \qquad (1)$$

where $r\in[0,r_{\max}(z)]$, $z\in[0,z_{\max}(r)]$ (or $(r,z)\in\Omega$) and $t\geq 0$. The object consists of different materials in construction with different

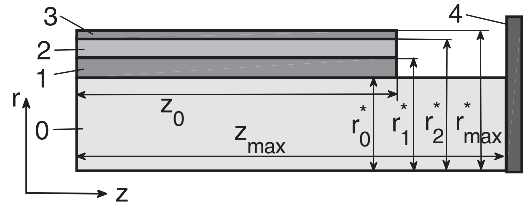

Fig. 1. Schematic view of the object half-slice. The bottom line is the axis of a cylinder (axis of the symmetry), $r=0$. The slice of the object: 0 – cooler, 1 – electrical insulator, 2 – heat source (conductive layer), 3 – external insulator, 4 – liquid helium temperature terminal with $T=4.2\mathrm{K}$.

densities and thermal coefficients; thus, the index m is introduced for each material ($m=0$ – cooler (copper), $m=1$ – electrical insulator, $m=2$ – heat source (graphite), $m=3$ – external insulator). In the frame of this work, physical and engineering needs of the object geometry are not discussed. The source function in Eq. (1) is $X_m(T)\equiv 0$ for the layers $m=0,1$, and 3 (there is no source) and it has a periodical time dependence:

$$X_2(T,t)=\chi(T)\frac{I^2(t)}{S_2^2}, \qquad (2)$$

where S_2 is the cross-sectional area in units of cm^2 and $\chi(T)$ is temperature depended resistivity of the conducted layer $m=2$. The current can be expressed in the form:

$$I(t)=I_0 v(t)p(t), \qquad (3)$$

where I_0 is the amplitude of current and $v(t)$ represents the time structure:

$$v(t)=\begin{cases}1, & nt_{\mathrm{prd}}\leq t<nt_{\mathrm{prd}}+t_{\mathrm{src}},\\ 0, & nt_{\mathrm{prd}}+t_{\mathrm{src}}\leq t<(n+1)t_{\mathrm{prd}},\end{cases} \qquad (4)$$

here $n\in\mathbb{N}_0$ – is index of a period of the electric current. Function $v(t)$ has a uniform rectangular waveform (definition of this function one can find in [11]), and $p(t)$ is a model of the transient response function for the turn-on process (it is introduced in analogous with similar function in electrical engineering, see for example [12]). In a simple case, it can be the Heaviside step function. For this work the function $p(t)$ is discussed in Section 3.1. In the formulas, $I(t)$ stands for electric current in the graphite slice along z direction. In a common case, the thermal coefficients are nonlinear functions of the temperature and the spatial coordinates with discontinuities of the first kind (for $m+1$ materials, there are m points of discontinuities).

The initial condition is given by

$$T(r,z,t=0)=T_0, \qquad (5)$$

where $T_0\equiv 4.2\mathrm{K}$ (liquid helium temperature) and the boundary conditions are taken as

$$\begin{cases}\dfrac{\partial T}{\partial \mathbf{n}}=0 & \forall(r,z)\in\delta\Omega\setminus\{(r,z):z=z_{\max}\},\\ T=T_0 & \forall(r,z)\in\{(r,z):z=z_{\max}\},\end{cases} \qquad (6)$$

where $\delta\Omega$ is the boundary of the Ω, and $\mathbf{n}$ is the normal vector of $\delta\Omega$. The temperature at the right side is always equal to T_0 because of contact with liquid helium.

The parameter ρ and the functions c_V, λ, and $X_i=X(T_i)$ have discontinuities of the first kind at the following surfaces with radii: r_0^*, r_1^*, and r_2^* in the interval $[0,r_{\max}]$. Conjugation conditions between materials are considered to be ideal: