Current pulse restored according to the penetration rate of electric field induced inside the tubular electrode

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Abstract. We study the evolution of tube material during the power current pulse is passing. Modelling this process, we need the time dependence of current, restored according to the time dependence of the electric field intensity, measured at the inner tube surface. For this purpose, the inverse problem was solved; the data obtained were used in the MHD-simulation.

1. Introduction

In the modern high-current generators (ZR, Angara-5-1, PTS etc.) experiments for the studying of the interaction of high power energy fluxes with matter are carried out. In these installations the submicrosecond current pulse, which generated in several sections, is transmitted then to the coaxial section, containing the load. While transporting electric energy to the load by the magnetically insulated transmission line (MITL), the megaampere current pulses flow through its components. Under these conditions the power current pulse induces in the MITL the processes which lead to the energy losses during its transportation and destruction of the electrodes (see [1–3]). This causes the loss of the MITL transmission properties. For the same reasons experimental measurement of the current flowing just through the load becomes difficult. Really, because of many effects which lead to current leakage in the MITL (electron beams, crowbar effects and so on), its measuring at some distance from the load can give a significantly overestimated value.

To study the transmission properties of the MITL in extreme conditions, we simulated the dynamics of the hollow tube, which exposed to submicrosecond current pulse with a linear density of 1–3 MA/cm. We analyzed the parameters distribution over the thickness of tube material during the passing of the current pulse. The simulation was carried out in the frame of the one temperature magnetic hydrodynamic (MHD) model. For closing the mathematical model we need to use the time dependence of the current flowing through the load $I(t)$. But as was mentioned above the experimental measuring of the current has some difficulties in these extreme conditions. So we forced to restore the waveform of the current pulse using some another experimental data, for example, the electric field intensity $E = j/\sigma$ (here j, σ are the current density and the conductivity respectively) measured at the inner surface of the tube.

To measure the field penetration rate into the tube thickness, a series of experiments in the Angara-5-1 installation was carried out. Tubes made from stainless steel with height of 15 mm and outer diameter of 12.2 mm respectively were used as load. The electric field produced at the inner surface of the tube was measured by the resistive divider. Due to the fact that during the initial stage ($\sim$ 100 ns) the wall thickness of the tube ($h = 1$ mm) is appreciably greater than the skin depth (calculated for the cold metal and the rising time of current of about 100 ns), the electric field at the inner surface of the tube appears to the moment of the peak current. This can be explained by the long-time current diffusion through the thickness of the metal tube.

In all experiments, after reaching the maximum value of the current, the electric field intensity is gradually decreasing; i.e. during a long time, it has a value comparable to its peak value. This may indicate that the decrease of the electric field at the inner surface of the tube is not caused by the formation of hot plasma on it, but occurred due to other processes, such as change in the resistance of the tube or the plasma formation at its outer surface. Therefore, we can state that this electric field is determined just by the current flowing through the tube and after solving the inverse problem, it will be possible to restore the time dependence of the current, which will be used to study the transmission properties of the MITL.

2. The numerical results and discussion

Numerical simulation was used to study the evolution of the distribution of tube material parameters through the tube thickness during interaction with the submicrosecond current pulse with a linear density of 1–3 MA/cm flowing through. A similar problem was studied previously [1–3] for the case of "thin" electrodes (its wall thickness was compare with the thickness of the skin layer). The problem was solved in the framework of a single-temperature MHD model. To describe the properties of the tube material there was used the semi-empirical wide-range equation of state [4] taking into account the phase transformations and metastable states in tabular form [5], as well as semi-empirical model for the conductivity of the condensed (liquid and solid) phases [6, 7].

We can see in figure 1 the time dependence of the current and of the electric field intensity at the inner surface of the tube for different variants. The first of them presents the experimental result; the second is sinusoidal current pulse up to 200 ns and zero after this moment. The third is the current pulse restored according to the experimental data on the electric field intensity. The restoration was made in accordance with the model of thin wall tube (its thickness should be close or less than the skin depth, $h \le \delta$) for Cartesian coordinate system ($R \gg h$) assuming that the temperature was constant ($T(t) = \text{const}$) [8]:

$$I(t) \cong C[V + \frac{1}{6}\frac{4\pi\sigma h^2}{c^2}\dot{V} + \frac{1}{120}(\frac{4\pi\sigma h^2}{c^2})^2\ddot{V}], \tag{1}$$

where R is the outer radius of the tube; $V(t)$ is the signal from the detector placed at the inner surface of the cylinder and C is the scaling factor (for example, if one measures the voltage between two electrodes separated by the distance l along the system axis, this factor is equal to $2\pi\sigma hR/l$); $\dot{V}$ and $\ddot{V}$ are the first and the second time derivatives of $V(t)$.

It is necessary to mention that we have to make some corrections in the time dependence of the current. These corrections were concerned with initial stage while electric field intensity yet equaled to zero and the later stage when the current polarity changed and integral current had negative value. The formula (1) is not valid during initial stage in our case because of the man-made assumption that the thickness of the tube wall is comparable to the skin depth. In our case this assumption becomes valid, starting from the time of $\sim$ 100 ns (see figure 1b). So until the time of $\sim$ 140 ns there were used the values of the current measured in the experiment.

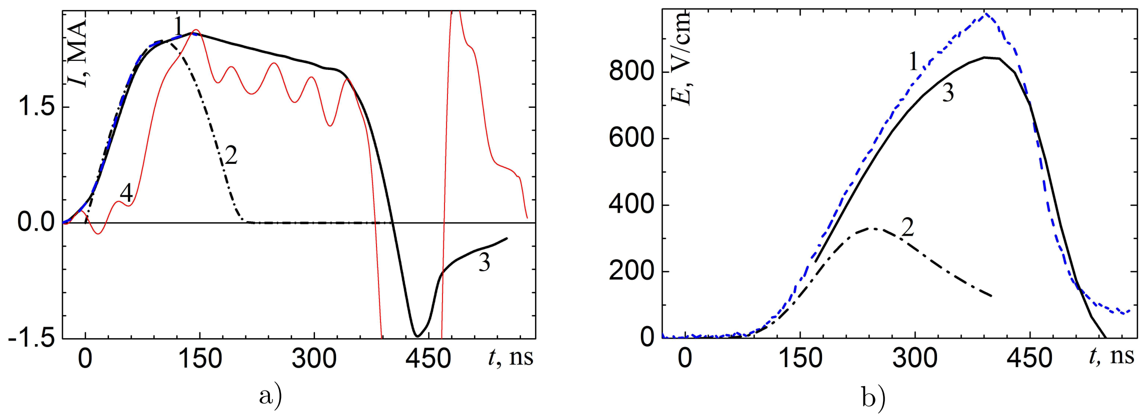

Figure 1. The time dependencies of (a) the current I flowing through the tube and (b) the electric field intensity E measured at the inner surface thereof obtained in the experiment 1 and in the MHD simulations in the case of sinusoidal current pulse 2 and also in the case of the current pulse restored according to the formula (1) with the correction 3 and without correction 4.

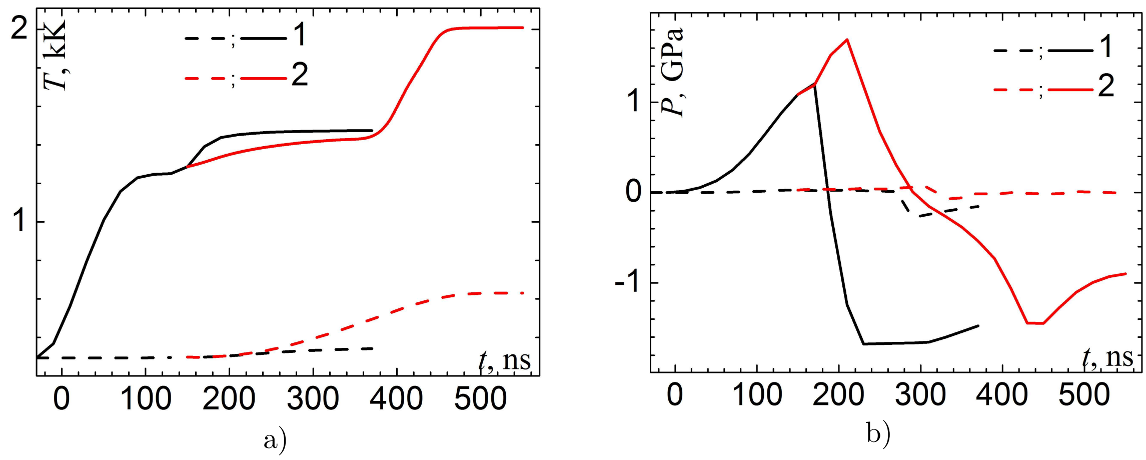

Figure 2. The time dependencies of the temperature (a) and the pressure (b) obtained in the simulations in the cases of the different current pulses: sinusoidal form 1 and the current pulse restored according to the formula (1) with the correction 2; solid lines denote the temperature at the outer surface and the pressure in the central layer of the tube and the dashed indicate these parameters at the inner surface.

The reason of the correction during the last stage is the temperature rising (see figure 2) and as result the change of thermophysical properties of metal and the skin depth, δ. The ill-posedness of the inverse problem was the third reason of our corrections. Really to find the derivatives of experimental data we have to smooth those data, but the result depends on smoothing methods and besides after the smoothing we lose some information. The last cause is responsible for our current pulse correction of the later stage also. Comparing the data presented in figure 1b we can state that the results of calculations in which were taken into account the corrections of the restored current are in a good agreement with the experimental data.

We can see in figure 2 the numerical results, obtained in simulation using the current pulse restored according to (1) with corrections. For the same current pulse in figure 3 it is shown the pressure distributions over the tube thickness at different moments.

Figure 3 shows that in the volume of the tube the metastable states of tube material with

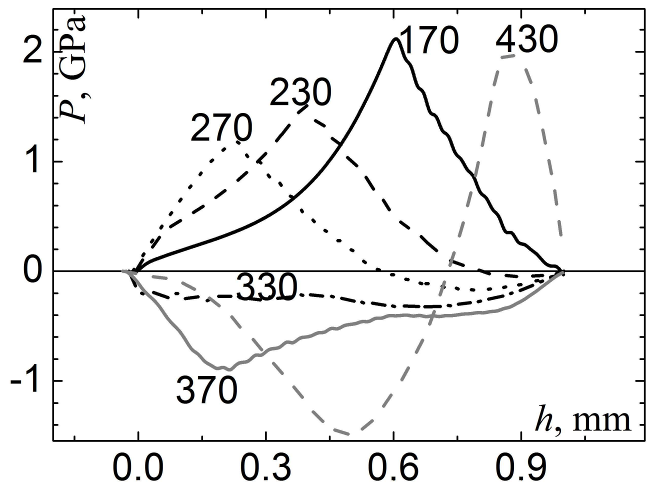

Figure 3. Profiles of the pressure through the tube thickness; distance is reckoned from the initial position of the inner surface of the tube; the figures indicate the moments in the nanoseconds.

a negative pressure are realized (see also [7]). It should be noted that in our case two reasons cause the appearance of metastability. In [9] the metastable states appeares due to the pressure pulse reflection from the axis of the wire, and the pressure pulse was formed at the melting wave front during the uniform wire heating. In our case, the skin effect is strongly marked, resulting in the temperature differing over the cross section (see figure 2a). Pressure pulse is formed by the recoil pulse during the expansion of the heated tube material. Upon reflection of this pressure pulse from the inner surface of the tube, and because of sharp current reduction and consequently the magnetic compression pressure, the tensile stress is formed. Because the thickness of the tube is sufficiently large, tensile stress acts on the tube material during tens of nanoseconds. Since the outer layers of the tube are heated to the temperature slightly exceeding the melting temperature (see figure 2), the tensile strength decreases (see [9]). This can lead to the destruction of the tube.

3. Conclusions

We restored the current pulse according to the experimental data on the electric field intensity. We can state that the results of the electric field intensity calculations are in a good agreement with the experimental data. Using the restored current pulse we study the evolution of the parameters distribution (temperature T, pressure P and density ρ) of the tube material exposure to the submicrosecond current pulse with a linear density ~ 1 MA/cm. The findings confirm the possibility of the usage of the electrodes made of stainless steel to transmit the current pulse with the linear current density of ~ 1 MA/cm to the load during the first 200 ns.

Later on under such intensive exposure some components of the MITL may be destroyed because they are exposed to the long-run large tensile stress (see figure 3), and the time of its destruction depended on the rate of current decrease.

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