Influence of space plasma on the work of the liquid droplet radiator

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Abstract. The effect of the charging of the droplet flow, resulting from the interaction of dispersed particles with space plasma, on the work of low-potential liquid droplet radiator has been studied. The critical value of the particle charge at which the curvature of the particles trajectories is unacceptably large is determined. The dynamics of charged droplet flow is investigated; its vibration stability is analyzed. A model for the electrification of free-circulate droplet flow is proposed. The results of numerical calculations of the electrification and distribution of droplet flows are given.

1. Introduction
The solution of new scientific, technical, informational and telecommunication tasks related to the use of outer space implies an increase in the power supply of spacecrafts. Due to the high meteoric vulnerability of panel cooler-radiators, one of the advanced ways to increase the power of spacecraft power systems is the use of fundamentally new frameless heat removal systems - liquid droplet radiator (LDR). The idea of LDR is to dissipate heat using the heated droplet flow (Fig. 1). The droplet generator disperses the heat carrier; the hydraulic collector collects the cooled droplet flow.

![Figure 1. LDR configuration item.](image)

When droplet flow interacts with the plasma surrounding it in outer space, various physical phenomena arise. The electrification of the dispersed flow has the most significant influence on the
operation of the droplet radiator. The trajectories of drops become distorted under the action of electrostatic forces, as a result of which the loss of the working medium from the system can occur. The charge accumulated on the particles depends on the parameters of space plasma, ionizing radiations and the action of various space factors, the properties of the working fluid, the geometric structure of the droplet flow, the configuration of the LDR and the layout of the spacecraft, the operation of propulsion system of the spacecraft, the density and degree of ionization of its own external atmosphere of spacecraft, and etc. The problem of the influence of the electrification of droplet flow on operation of LDR was previously independently solved by several research groups (for example [1, 2, 3]). The results obtained are often contradictory to each other. Thus, according to one of the models for the electrification of the droplet sheet, the dispersion of particles reaches several meters, because of which it is necessary to take special measures aimed at countering the effect of the curvature of particles trajectories. At the same time, calculations made with the help of other models show that the effects associated with the electrification of the droplet sheet are negligible. The qualitative difference between the results obtained is due to the high complexity of the task, due to the action of large number of interdependent multidirectional factors. The task of analyzing the results obtained earlier and developing the methodology for simulation the influence of space factors on the operation of droplet cooler-radiator is relevant.

2. Simulation the trajectories of particles in the liquid droplet radiator

The presence of space charge in the droplet flow of LDR will lead to the curvature of the trajectories of particles under the action of Coulomb forces. The dynamics of charged dispersed flow was performed in work to determine the critical magnitude of drops charge, at which the curvature of particles trajectories in LDR is unacceptably large. Information on the critical value of drops charge was used to select the degree of details of physical model of droplet flow electrification. The dynamics of dispersed flow consisting of several layers of particles was simulated. The influence of boundary effects was assumed to be negligible. It was considered that drops charge in each of the layers depends only on the time of flight. The deviation of the particles trajectories was described by the time function \( z = z(x, t) \) (Fig. 1). The system of dynamic equations of dispersed layers motion was solved numerically. The mutual influence of changes in the trajectories of particles and the electric field was solved by an iterative method. It was considered that the electric field strength does not change along the \( y \) coordinate and is equal to the intensity at the center of the droplet plane (\( y = 0 \)). In the calculations, the length of drops span was 25 m, the width of droplet flow was 5.5 m, and the velocity of particles was 2 m/s. The radius of drops was \( r = 100 \mu m \), the density of working fluid — 1000 kg / m³. The packing of particles in droplet layers was taken square with the distance between adjacent particles of 4.76\( r \). The initial thickness of the droplet flow was 0.1 m. The charge of particles \( q \) was calculated in the number of elementary charges per one drop. The distribution of the sheet was

![Figure 2](image.png)

**Figure 2.** The dynamics of droplet flow of seven droplet layers. a) \( q = -1.0 \cdot 10^4e \). b) \( q = -2.5 \cdot 10^4e \).
studied during the first series of computational experiments, the drops charge $q$ in which was the same and did not depend on time. The calculation results are presented in Fig.1. From Fig. 2, it can be seen that the curvature of drops trajectories of the flow increases rapidly with the increasing of charge. Performed calculations show that the critical value of drops charge in the case when the charge of all particles is the same is $\sim 4.0 \cdot 10^4$ of elementary charges per the drop.

In the second series of calculations, the effect of the laws of particles electrification on the curvature of their trajectories was investigated. In the model calculations, the electrification model proposed in work [2] was used. It was considered that the charge of the droplet sheet was not evenly distributed over its thickness. The dynamics of the droplet sheet of seven droplet layers was studied. The charge distribution from the number of the droplet plane varied as follows. The charge of solitary $q$ drop interacting with the space plasma was set. Then, the charge of particles in different droplet layers was calculated. At the same time, the charge of drops depended on the layer number as follows: $0.56q$ for the first and seventh layers, $0.37q$ for the second and sixth, $0.302q$ for the third and fifth, and $0.3q$ for the fourth. The choice of coefficients is determined by the assumption that the charge of the drops is different due to their mutual shading from the external flow of charged particles. The magnitude of the coefficients was determined on the basis of shading patterns. Fig. 3 shows the distribution dynamics of such a flow. Comparison with similar dependencies shown in Fig. 2, demonstrates that when taking into account the nonuniformity of the charge distribution in the flow, it is possible to increase the estimate of the critical value of drops charge in $3 \sim 4$ times - up to $\sim 10^5$ elementary charges per drop.

**Figure 3.** The dynamics of droplet flow of seven droplet layers. The charge of drops in the flow core is less than on the periphery. a) $q = -1.0 \cdot 10^5 e$. b) $q = -2.5 \cdot 10^4 e$.

**Figure 4.** Influence of the initial vibration of the central droplet plane on the dynamics of charged droplet flow. Dependencies are given at different scales. The charge of all particles is the same and equal to $q = -2.5 \cdot 10^4 e$.

The simulation of vibration stability of droplet flow was realized additionally. Numerical
calculations have shown that with drops charge of \( q \sim 2.5 \times 10^4 e \), nonlinear phenomena begin to appear in the flow, distorting the shape of the artificially created waves (Fig. 4). With further increase in the charge of particles, the phenomenon of vibration instability arises. Figure 5 presents the results of simulation of the instability in the case when \( q = 1.0 \times 10^6 e \). It can be seen that the assumption about the preservation of the structure of the droplet flow does not hold for such a large value of the distributed charge.

\[ \frac{\partial q}{\partial t} = I_{e,p} + I_{ph} + I_{se}, \]

where \( q \) – the charge of particles, \( t \) - time, \( I_{e,p} \), \( I_{ph} \) and \( I_{se} \) - respectively, the current of electrons and protons, photoionization and secondary electron emission. To calculate the current of protons and electrons, it is necessary to know the parameters of space plasma. The current \( I_{e,p} \) is determined by the charge flow density in space plasma \( J \), the value of which can be estimated using the relations [4]:

3. Simulation of the electrification of particles in the liquid droplet radiator

The electrification of dispersed flow is determined by the joint action of number of mechanisms. In number of cases, the interaction of particles with space plasma is decisive. In low near-earth orbits, the potential to which the droplet flow is charged relative to the surrounding plasma is small and amounts to about \(- (0.5 \div 1) \) V. At the same time, the Debye length in the ionospheric plasma is \( 1 - 2 \) cm [4]. The most dangerous for the operation of LDR are geostationary orbits and apogee areas of highly elliptical orbits, where the main factors determining the charging potential of the droplet flow are the hot magnetospheric plasma and solar radiation. Droplet flow is charged differentially, to different voltages at different points. And the absolute value of the potential can reach \(- (10^4 \div 10^5) \) V. At the same time, the Debye length in space plasma is hundreds of meters, and the charged drops in LDR interact according to Coulomb’s law. The paper considers the case of the geostationary orbit of spacecraft.

Numerous experimental studies have shown that the distribution function of space plasma particles in geostationary orbit can be approximated by superposition of two Maxwell distributions [4]. The parameters of space plasma depend in a complex way on the coordinate, time of day, solar activity, etc. In this work, we used the parameters of the space environment given in [4].

The analysis shows that the path length of the charged particles of the space plasma in drops of LDR is almost always much shorter than the radius of the drops. Therefore, the particle loading equation has the form
\[ J(\varphi, x) = \sum_i n_{ei} \sqrt{\frac{kT_{ei}}{2\pi m_e}} \exp\left( -\frac{e\varphi(x)}{kT_{ei}} \right) - \sum_i n_{pi} \sqrt{\frac{kT_{pi}}{2\pi m_p}} \exp\left( -\frac{e\varphi(x)}{kT_{pi}} \right), \]

where \( \varphi(x) \) – the potential of the space point where the current density is calculated, \( n_e \) and \( n_p \) – the concentrations of protons and electrons, \( e \) – the elementary charge, \( k \) – the Boltzmann constant, \( T_{ei} \) and \( T_{pi} \) – the temperatures of electrons and protons of the \( i \)-th component of the particle distribution function.

The calculation by formula (2) shows that under conditions of geomagnetic substratum, plasma particles per drop can reach the value in the order of \( 10^6 \) elementary charges per drop per second. This value significantly exceeds the currents of other electrification mechanisms. Thus, the calculations and experimental measurements carried out at the SSC Keldysh Research Centre showed that due to friction of the working fluid on the pipeline, drops of LDR receive the characteristic charge in the order of \( \sim 2 \cdot 10^4 \) elementary charges per drop of radius about 100 microns.

In the calculations, it was considered that the magnitude of the coefficients of the secondary electron emission, as well as ion-electron emission, was rather small and had little effect on the electrification process. Since in space plasma the dispersed flow is charged negatively, and the radiation of the Sun reduces the magnitude of the negative charge, and, moreover, the influence of solar radiation on the electrification of the droplet sheet depends on the orientation of LDR, this factor was not taken into account. For similar reasons, the effects of the influence of the plasma of electric propulsion engines on the process of droplet electrification were not taken into account.

When calculating the electrification, the droplet sheet was divided into layer along the \( x \) axis (Fig. 1, Fig. 6). It was considered that the electrification conditions for all particles in the layer are the same and are determined by the conditions in the center of the flow. To describe the process of electrification, it was considered that the electric charge is uniformly distributed over the surface of the droplet layers that make up the droplet sheet, and its surface density in the \( i \)-th droplet layer is \( \sigma_i \). Then the electrification equation can be represented as follows:

\[ \frac{\partial \sigma_i}{\partial t} + v \frac{\partial \sigma_i}{\partial x} = J_i(\varphi, x, t), \]

where \( v \) – the velocity of movement of particles along the direction of the \( x \) axis in droplet sheet. In the formula (3) it is taken into account that the process of electrification depends on the potential, which, in turn, varies in space and time and depends on the distribution of charges on the droplet sheet.

The numerical solution of problem (3) was carried out together with the calculation of the particle trajectory in the stationary formulation. Fig. 7 presents the results of calculating the particle charge and potential of the droplet flow, as well as the curvature of drops trajectories, taking into account the screening of electrons by the potential of droplet flow and also taking into account the current of
protons. The parameters of space plasma were chosen according to the conditions on the geostationary orbit in the case of geomagnetic substorm. The width of droplet flow was 5.5 m.

![Graphs showing the parameters of droplet flow](image)

**Figure 7.** Electrification of droplet flow and the curvature of drops trajectories in the geostationary orbit in case of geomagnetic substorm. Numbers mark the numbers of droplet layers. The charge was measured in millions of elementary charges.

From fig. 7, it can be seen that, due to electrostatic screening, the particle charge turns out to be comparable with value of about \(10^4\) elementary charges per drop, and the potential of droplet floe does not exceed 100 kilovolts. In this case, the curvature of drops trajectory is \(\sim 0.1\) m.

4. Conclusion
Simulation of the dynamics of droplet flow shows that critically large particle charge, which has unacceptable effects on the operation of LDR, is in the order of \(\sim 5.0 \cdot 10^4\) elementary charges per drop with the particle radius of \(\sim 100\) μm.

Interaction with space plasma is the determining mechanism for electrification of LDR drops. A solitary drop located in geostationary orbit, due to interaction with the space plasma, will receive critically large charge in \(\sim 1\) second. However at the collective electrification of particles moving in dispersed flow of LDR, the charging velocity of individual drops decreases by several orders.

Preliminary calculations show that even under adverse conditions of the geomagnetic substorm, the dispersion of particles in the droplet sheet caused by their electrostatic interaction does not exceed the value in the order of ten centimeters over span length of 25 meters - for the full-scale parameters of dispersed LDR flow. And the charge of particles, determined by the interaction of drops with space plasma, most of the time of flight does not exceed of \(\sim 2.0 \cdot 10^4\) elementary charges. Considering the
solar radiation, the presence of its own outer atmosphere of the spacecraft, the electrification of the working fluid due to friction against the walls of pipelines, etc. may slightly change the results of calculations. However, these factors in their intensity are weaker than the determining mechanism of electrification.

At the same time, it is necessary to further refine the results obtained in the part of studying the stability of dispersed flow electrification permeate through space plasma, taking into account the process of secondary electron emission.

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