Turbulent water cooler flow around uranium sphere in the horizontal tube

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The thermophysical problem of turbulent flow of a uranium sphere by a water flow for different values of heat release and Reynes numbers for the boundary regions is considered.

I. INTRODUCTION

Nuclear reactions with thermal neutrons lead to the formation of high-energy fission products. Neutral components of such fissile gas, when irradiated with these high kinetic energy products of nuclear reactions, demonstrate promising chemical properties that can be used in various technologies [1–5] . Among them, it should be noted that the main one in the Boltzmann equation is the identification of the source causing the formation of plasma, and its main characteristic is the energy distribution of fission fragments and primary electrons. The helium-3 isotope is the best known and best ionization source, with many applications in plasma chemical kinetics and vapor deposition of end products of chemical reactions. The production of fast electrons directly depends on the energy spectra of fission fragments and their mass spectra in plasma chemical kinetics, as shown below [6]. This reaction is usually presented as follows Equation (1.1) but there should be other outcomes that have not yet been recorded [7, 8] :

$$^{3}He + n \rightarrow p + T + 0.76\ Mev \tag{1.1}$$

Thus, nuclear fission plasma is considered as the most promising medium, which releases part of the energy of the field of strong interactions of nuclei into the ki- netic energy of fission fragments, which is then redistributed into excited states of neutrals, and radically changes the thermodynamic properties of the moving fissioning gas [9, 10]. In connection with the development of gas-phase nuclear reactors, where uranium hexafluoride is used as fuel, it is extremely important to know the general hydrodynamic equations of the circulation flow with fissile material [11], [12]. It will also be shown below that the presence of nuclear processes in the plasma flow significantly changes the dynamics of gas movement, and this influence occurs due to the heating processes of neutral components during nuclear fission reactions. It should be noted here that heating of neutral atoms occurs not only due to elastic collisions but mainly occurs during inelastic collisions of high-energy products of nuclear reactions with neutrals.

II. SELF-CONSISTENT BOLTZMANN KINETIC EQUATIONS FOR WEAKLY IONIZED PLASMA GENERATED BY FISSION FRAGMENTS

Gas dynamics in space, as in power plants, initially (a priori) contains fissile materials that heat the mov- ing gas with the intensity of neutron fluxes, creating oncoming and passing fluxes of varying intensity. In addition, chemical reactions are completely different, including combustion, where chemically active substances play a significant role [13] .

The gas dynamics in space, as well as in the power plants, initially (a priori) contains fissile materials that heat the moving gas with the intensity of neutron fluxes, creating oncoming and passing fluxes of different intensity. In addition, chemical reactions, including combustion, are completely different, where chemically active substances play a significant role [13]. Gas dynamics in space, as well as in power plants, are initially (a pri- ori) associated with the movement of plasma gas, which contained fissile materials, and which in turn not only heated the moving gas, but also generated sound and shock waves in it, the origin of which is in stars seems quantitatively impossible due to the lack of basic hydrodynamic equations describing this kind of hydrodynamic flows. Many problems with such physical conditions are overwhelmingly limited to including various chemical reactions in the continuity equation without analyzing their influence on the gas dynamics and energy balance of these moving systems, which can also lead to serious misconceptions and errors, for example, to a significant change in the values of transmission coefficients.

The theoretical foundations of Boltzmann's kinetic equations, which determine the energy distributions of

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neutral particles for inhomogeneous gases, are presented in one of the most famous books [14] and this function $\tilde{y}_a(t, \vec{r}, \vec{\xi})$ presented as follows Equation (2.1) :

$$D\tilde{y}_a(t, \vec{r}, \vec{\xi}) = \int \left(\tilde{y}'_a \tilde{y}'_{a1} - \tilde{y}_a \tilde{y}_{a1} \right) gbdbd\varepsilon d\xi_1 \quad (2.1)$$

Here $D = \frac{\partial}{\partial t} + \xi_i \frac{\partial}{\partial x_i} + \frac{F_i}{m} \frac{\partial}{\partial \xi_i}$ and $\tilde{y}_a(t, \vec{r}, \vec{\xi})$ is the neutral energy distribution function, and g, b, ε are the collision parameters. Construction of Boltzmann equations for a gas consisting of a gaseous fissile component such as (^3He, $^{235}UF_6$) interacting with neutrons and moving through a neutron flux in a laboratory frame of reference is presented in [6] and previously in [15, 16]. So, a neutral gas is considering, consisting of a component that can participate in the neutron fission reaction, and as a result of which high-energy fission fragments are formed. Next, this analysis of the system of Boltzmann kinetic equations considers the kinetic equations for four types of particles: neutral particles, neutrons, fission fragments, and electrons. Neutrals are denoted by index a , and their function of energy distribution is labeled as $\tilde{y}_a(t, \vec{r}, \vec{\xi})$, neutrons are denoted by index n , and function of neutrons energy distribution, respectively, is $\tilde{y}_n(t, \vec{r}, \vec{\xi})$. In the present work, the energy distribution of neutron is taken as given data. The types of fission fragment [6] are designated as j, and electrons as e, and their energy distribution functions are denoted as $\tilde{y}_j(t, \vec{r}, \vec{\xi})$, $\tilde{y}_e(t, \vec{r}, \vec{\xi})$.

Then the Boltzmann equation for neutrals, in addition to the elastic collisions mentioned in Equation (2.1), should also include the influence of fission and ionization processes, excitation charge exchange, and heating of neutrals by fission fragments and electrons. The energy spectra of neutrons depend on the type of nuclear reactor in which the neutron flux is formed in the active zone, and it is assumed that the neutron flux has already been determined. Fissile components like ^3He ,$^{235}UF_6$, interacting with neutrons, will cause the appearance of fission fragments, and these fragments, in their own turn, will create primary electrons.This article focuses on gaseous fissile gas objects that exist in nuclear power facilities on Earth and are even more common in space objects:

$$^3He + n \rightarrow p + T + 0.76Mev$$

$$^{235}UF_6 + n \rightarrow ff_h + ff_l + 165\ Mev$$

integral [14], which determines the relaxation of a moving gas as a result of elastic collisions of neutrals and has the following form:

$$S^{el} = \int \left(\tilde{y}'_a \tilde{y}'_{a1} - \tilde{y}_a \tilde{y}_{a1} \right) gbdbd\varepsilon d\xi_1 \quad (2.3)$$

Fuel burnout, as well as leakage of neutrals, which are both a source of ionization and heating of the moving gas, according to our estimates [5], are negligible and therefore are not included in the basic equation of gas motion, although the burnup value can also be presented in analytical form and is quite convenient for numerical estimates:

$$S^{ff}(t, \vec{r}) = N \int \Phi(t, \vec{r}, \vec{\xi}_n) \sigma_n^{fission}(\varepsilon_n) d\varepsilon_n \quad (2.4)$$

Here $N = n_{UF_6}, n_{^3He}$,$\Phi(t, \vec{r}, \vec{\xi})$ is the external neutron flux, $\sigma_n^{fission}(\varepsilon_n)$ is neutron's cross section with fissile neutrals.

The heating of neutrals by fission reaction products reaches significant values and can be calculated on the basis of the fundamental works of Grizinsky and Holstein [15, 17] . Moreover, during a collision, the energy of the incident and oncoming particles is exchanged in proportion to the ratio of the masses of the colliding particles. So, it states that the energy loss ΔE is equal to:

$$\Delta E = 2E_{j,e} \frac{m_{j,e}}{M_0} (1 - \cos \psi) \quad (2.5)$$

here ψ is the angle of deflection.

This approach makes it possible not only to evaluate but also to quite accurately calculate the role of internal nuclear reactions on hydrodynamics in general and on their mutual influence in particular.

Taking into account the above, the second term in the Equation (2.2) takes the following form, as well as the subsequent ones with a difference in the magnitude of the differential cross sections of the corresponding processes:

$$S_j^{el}(\tilde{y}_j) = N_o^{fissile} \int_{\xi_j}^{\xi_j^{max}} d\xi_j \delta(\xi'_j - G_j^{el}(\xi'_j, \xi_j)) * \\ * \int_0^{E_j^0} p_j^{el}(E_j) \tilde{y}_j(\xi_j) \xi_j \Omega_j^{el}(\xi_j, \Delta E_j) d(\Delta E_j) \quad (2.6)$$

Here

$$p_j^{el}(E_j) = \frac{\Omega_j^{el}}{\sum_{exc} \; {}_{ion} \; {}_{el}} \quad (2.7)$$

Taking into account the specific physical factors listed,

the Boltzmann kinetic equation for neutral atoms is equal to the following equation:

$$\partial_\mu \tilde{y}_\alpha(t, \vec{r}, \vec{\xi}) = = \int \Big(\tilde{y}'_\alpha \tilde{y}'_{\alpha 1} + \sum_j \tilde{y}'_\alpha \tilde{y}_j^{el} + \tilde{y}'_\alpha \tilde{y}_e^{el} - \tilde{y}_\alpha \tilde{y}_{\alpha 1} \Big) d\Omega \quad (2.2)$$

In the Equation (2.2) $d\Omega = gbdbd\varepsilon d\xi_1$

The first and last terms of the collision integral completely coincide with the analytical form of the collision

$$\sum_k \Omega_{j,k} + \Omega_j + \Omega_j$$

When transitioning as a result of a collision from one phase volume to the one under consideration, conservation laws make it possible to connect the outgoing and

incoming parameters through the delta function, the analytical form of which was proposed by Holstein [17] , thus the function G_j^{el} is equal to:

$$\frac{m_j \xi_j'^2}{2} = \frac{m_j}{2} \left(\frac{\xi}{1 - \frac{m_j}{M}(1 - \cos\Psi)} \right)^2 \quad (2.8)$$

The differential cross section for the elastic collision of fission fragments with neutrals is defined as follows [15, 18] :

$$\Omega^{el}_j(\Delta E_j, \xi_j) = \frac{\sigma_0}{(\Delta E)^2} \frac{1}{E(\xi_j)} * G\left(\frac{S}{\Delta E}, \frac{E_j}{\Delta E}\right), \quad (2.9)$$

and $\sigma_0 = 6.56 * 10^{-14} eV^2 cm^2$

The exact analytical form of the function G can be found in [15] .

The first term in this equation $\tilde{y}'_a \tilde{y}'_{a1}$ evaluates the income to the correspondent phase volume neutral incoming from the boundaries due to elastic collisions. The second term $\tilde{y}'_a \tilde{y}^{el}_j$ leads to the taken phase volume of neutrals incoming due to the elastic collisions with fission fragments, as well as the third term $\tilde{y}'_a \tilde{y}^{el}_e$ due to the elastic collisions with primary electrons. The leakage of neutrals due to fission fragments and electron collisions is negligibly small. The cross-section of reaction Equation (1.1) is around 5400 barns [1, 19, 20] , and this plasma might be considered as weakly ionized.

The second kinetic Boltzmann equation which should be incorporated with the Boltzmann kinetic equation for neutrals is equal to the following:

$$\partial_\mu \tilde{y}_j(t, \vec{r}, \xi) = \Omega^{fission}_j(t, \vec{r}, \xi) - \int \left\{ \tilde{y}_a \tilde{y}^{el}_j + \tilde{y}_a \tilde{y}^{ion}_j + \sum_k \tilde{y}_a \tilde{y}^{exc,k'}_j \right\} d\Omega \quad (2.10)$$

The first term in the Equation (2.10) depends on the distribution of the neutron flux, the calculation of which is beyond the scope of what is considered in this work and in general can be presented as follows:

$$\Omega^{fission}_j({}^3He + n \rightarrow p + T + 0.76\ Mev) = = n_a\, \Phi(t, \vec{r})\sigma^{fission}_n(\varepsilon) * \delta_{\vec{\xi}_j - \vec{\xi}_{j0}} \quad (2.11)$$

Subsequent terms in the Equation (2.10) are structurally identical and differ only in the form of differential sections of the corresponding process

$$S^{el}_j(f_j) = n \int^{\xi_{max}}_{0} d\xi'_j \delta(\xi_j - G_j(\xi'_j, \xi_j)) * * p^{el}_j(E_j) \int^{E^{FC}_j}_{0} f_j(\xi'_j)\xi'_j \Omega^{el}_j(\xi_j, \Delta E_j) d(\Delta E_j) - \int_{E^0} p^{el}(E) f(\xi)\xi \Omega^{el}(\xi, \Delta E) d(\Delta E). \quad (2.12)$$

nuclear-excited plasma, although some additional electrons are also formed as a result of ionization by fast electrons:

$$\Omega^{fission}(\tilde{y}_e) = = N \int \Omega^{ion}_j(\xi, \Delta E) * \xi * \tilde{y}_j(\xi, \Delta E) d(\Delta E) \quad (2.14)$$

Considering the Boltzmann kinetic equation for electrons, the approach presented above to estimating collision integrals is continued and the corresponding terms of the equation are presented in the following form:

$$S^{ion,exc,el}_{j,e} = n_a \int^{\xi_0}_{\xi_{j,e}+I} \delta(\xi_{j,e} - G^{ion,exc,el}_{j,e}(\xi'_{j,e}, \xi_{j,e})) * \quad (2.15)$$

$$* \int^{E_{j,e}}_{0} (\tilde{y}'_{j,e}(\xi') - \tilde{y}(\xi))\xi'_{j,e}\Omega^{ion,exc,el}_{j,e} p_{j,e}(\xi) d(\Delta E) d\xi_1$$

Here

$$p^{ion,exc,el}_{j,e} = \frac{\Omega^{ion,exc,el}_{j,e}}{\sum_{k=1}^{m} \Omega^{ion,exc,el}_{j,e}} \quad (2.16)$$

$$\frac{m_{j,e}\xi'^2_{j,e}}{2} = \frac{m_{j,e}}{2}\left[\frac{\xi}{1 - \frac{m_{j,e}}{M}(1 - \cos\Psi)}\right]^2 + +I + \varepsilon^{esc}_{j,e} \quad (2.17)$$

The average energy of primary electrons can be determined from the following relations:

$$\varepsilon^{esc}_{e} = \int_0^{\xi_{max}} \tilde{y}^{pe}_e(t, \vec{r}, \vec{\xi}) \frac{m_e \xi^2}{2} d\xi, \quad (2.18)$$
$$\tilde{y}^{pe}_e(t, \vec{r}, \vec{\xi}) = \int_I^{\xi^0_j} \Omega^{ion}_j(\Delta E_j, \xi) * \tilde{y}_j(t, \vec{r}, \vec{\xi}) * d(\Delta E)$$

The last term of Equation (2.13) requires special consideration of the kinetics of the formation of positive ions and their cluster formations in the plasma under consideration.

In particular, in helium plasma there is the follow- ing kinetics of the formation of positive ions, which recombine at a rate directly dependent on the distribution function in such a plasma. For uranium hexafluoride [21] , plasma affinity processes determine the further fate of electrons. Note that both the recombination pro-

$-n_{FC}$ $_{0}$ ^{j} j j j j j j j j j

The Boltzmann kinetic equation for electrons closes the self-consistent system of Boltzmann kinetic equations for fissile weakly ionized plasma and this kinetic equation is equal to:

$$\partial_\mu \tilde{y}_e(t, \vec{r}, \vec{\xi}) = \Omega_e^{fission} + \Omega_e^{ion} - \tag{2.13}$$

$$-\int \left\{ \tilde{y}_a \tilde{y}_e^{el} + \tilde{y}_a \tilde{y}_a^{ion} + \sum_k \tilde{y}_a \tilde{y}_e^{exc,k} + \tilde{y}_a^{0,+} \tilde{y}_e^{aff,rec} \right\} d\Omega$$

The formation of primary electrons as a result of the ionization impact of a fission fragment with a neutral is the main source of electron formation in this so-called

energy distribution of electrons and significantly change cess and the attachment process radically depend on the the plasma chemistry of the plasma under consideration. The introduction of average electron energy or temperature does not make the problem easier but most often distorts the final picture of plasma-chemical relaxation, and this kind of problem must be solved on a time scale, taking into account the time dependence of such energy distributions.

$$(p, T) + He \rightarrow He^{+} + (H^{*}, T) + e$$

$$He^{*} + He + He^{+} \rightarrow He_2^{+} + He* \tag{2.19}$$

$$^3He_3^{+} + e \rightarrow {}^3He_3^{**}$$

$$UF_6 + e \rightarrow UF_6^{-}$$

To conclude this section, the system of self-consistent Boltzmann kinetic equations can be rewritten as a single system of mutually determining and interdependent kinetic equations:

$$\partial_\mu \tilde{y}_a(t, \vec{r}, \vec{\xi}) = = \int \left\{ \tilde{y}'_a \tilde{y}'_{a1} + \sum_j \tilde{y}'_a \tilde{y}'^{el}_j + \tilde{y}'_a \tilde{y}'^{el}_e - \tilde{y}_a \tilde{y}_{a1} \right\} d\Omega$$

$$\partial_\mu \tilde{y}_j(t, \vec{r}, \vec{\xi}) = \Omega_j^{fission}(t, \vec{r}, \vec{\xi}) - \int \left\{ \tilde{y}_a \tilde{y}^{el}_j + \tilde{y}_a \tilde{y}^{ion}_j + \sum_k \tilde{y}_a \tilde{y}^{exc,k}_j \right\} d\Omega \quad (2.20)$$

$$\partial_\mu \tilde{y}_e(t, \vec{r}, \vec{\xi}) = \Omega_e^{fission} + \Omega_e^{ion} - \int \left\{ \tilde{y}_a \tilde{y}^{el}_e + \tilde{y}_a \tilde{y}^{ion}_e + \sum_k \tilde{y}_a \tilde{y}^{exc,k}_e + \tilde{y}^{0,+}_a \tilde{y}^{aff,rec}_e \right\} d\Omega$$

III. GAS-DYNAMIC EQUATIONS OF MOTION OF A FISSILE GAS IRRADIATED BY A NEUTRON FLUX

For homogeneous gas, the average velocity $\vec{c}_0$ [14] is defined in the following way:

$$(nd\vec{r})\,\vec{c}_0 = \sum_{i=1}^{N} \vec{c}_i. \quad (3.1)$$

where N is the number of molecules in the volume $d\vec{r}$, and n is the density of the gas (the designations from the cited monograph retained). The same definitions are introduced in the laboratory reference system:

$$n_a(t, \vec{r}) = \int \tilde{y}_a(t, \vec{r}, \vec{\xi})\, d\vec{\xi}, \quad (3.2)$$

$$\vec{u}(t, \vec{r}) = \frac{1}{n_a} \int \vec{\xi}\, \tilde{y}_a(t, \vec{r}, \vec{\xi})\, d\vec{\xi}. \quad (3.3)$$

The so-called thermal velocity is introduced, defined as follows :

$$\vec{C} = \vec{\xi} - \vec{u}. \quad (3.4)$$

It is worth noting that the hydrodynamics of this type of plasma is extremely specific, especially in cases where the neutron flux is inhomogeneous and the motion of the plasma is associated not only with the existing gradients of density and temperature but also with the magnitude of the neutron flux gradients that determines the heat release at each point under consideration. Moreover, heating, according to the conclusions of works , is the result not only of elastic collisions but it should be especially emphasized that this heating is especially effective at the initial stages of energy relaxation of fission fragments, taking into account their huge masses.

The density of a moving neutral fissile gas is defined by the following equation:

$$\frac{\partial n_a(t, \vec{r})}{\partial t} + div\,(n_a \vec{u}) = = -S^{fission}(t, \vec{r}) - \sum_k S^k_{j,e}(t, \vec{r}), \quad (3.8)$$

here

$$S^{fission}(t, \vec{r}) = \int \Omega^f(\vec{\xi}_a, \vec{\xi}_n) g_{a,n} \tilde{y}_a \tilde{y}_n d\vec{\xi}_a d\vec{\xi}_n, \quad g_{a,n} = \vec{\xi}_a - \vec{\xi}_n \quad (3.9)$$

$$\Omega^f(\xi_a, \xi_n) \rightarrow {}^3He + n \Rightarrow p + T + 0.76 Mev$$

The first term inEquation (3.8) and its analytical expression represent the leakage due to the interactions of thermal neutrons with fissile gaseous components. The second term in equationEquation (3.8) takes into account the leakage of neutral components as a result of their ionization and excitation by nuclear reaction products. This component can play a dominant role in the formation of the ionic composition of the plasma, in particular, the formation of negative ions, and thereby change the coefficients of ambipolar diffusion in probe diagnostics of such plasma in even weak external electric fields.

$$S^k_{j,e}(t, \vec{r}) = \int \Omega^{j,e}_k (\vec{\xi}_a, \vec{\xi}_{j,e}) g^{j,e}_a \tilde{y}_a \tilde{y}_{j,e} d\vec{\xi}_a d\vec{\xi}, \quad g^{j,e}_a = \vec{\xi}_a - \vec{\xi}_{j,e} \quad (3.10)$$

The Equation (3.10) represents the leakage of neutrals due to inelastic collision sources such as ionization, charge exchange processes.

Considering the proportionality of the hydrodynamic speed to the density gradient and its proportionality on

Then pressure tensor, temperature and thermal flux are defined as:

$$P_{ij} = m_a \int C_i C_j \tilde{y}_a(t, \vec{r}, \vec{\xi})\, d\vec{\xi}, \tag{3.5}$$

$$\frac{3}{2} kT_a = \frac{1}{n_a} \int \frac{m_a C^2}{2} \tilde{y}_a(t, \vec{r}, \vec{\xi})\, d\vec{\xi}, \tag{3.6}$$

$$q^i = \frac{m_a}{2} \int C_2 C_i \tilde{y}_a(t, \vec{r}, \vec{\xi})\, d\vec{\xi}. \tag{3.7}$$

the right side of the continuity equation to the processes of ionization and excitation of neutral components, it is obvious that wave processes already take place even in equilibrium stationary cases.

The continuity equations for fission fragments and electrons as previously mentioned can be obtained by integrating the second and third equations of the system of self-consistent Boltzmann equations Equation (2.20) .

As their kinetic energy relaxes, the fission fragments lose their identity through charge exchange reactions, taking electrons from the helium atoms to neutralize themselves. So, the density conservation equations for the density of fission fragments and the density of electrons look like:

$$\frac{\partial n_j}{\partial t} = S_j^f(t, \vec{r}) - S_j^{ChEx}(t, \vec{r}). \tag{3.11}$$

The source rate of formation of j-type fission fragments in the gas is shown by the first term inEquation (3.11). The second term represents their leakage due to the charge exchange of positively charged fission fragments after a sufficient loss of their energy, the losses do not permit participation in the processes of excitation and ionization. So for helium plasma, fission fragments: proton and tritium, after degradation processes of ionization and excitation of neutrals, participate in charge exchange processes forming the basis for radiation and recombination processes of electrons Equations (3.11) and (3.13) .

$$\begin{aligned}
&(p, T) + He \rightarrow He^+ + H^* + T \\
&He^+ + He + He \rightarrow He_2^+ + He \\
&He_2^+ + He + He \rightarrow He_3^+ \\
&He_3^+ + e \rightarrow He^{**} + He^* + He^* \\
&He^{**} \rightarrow He^* + h\nu
\end{aligned} \tag{3.12}$$

The equation for electrons, which is also obtained by integrating the equation over velocity space, is the following continuity equation:

$$\frac{\partial n_e}{\partial t} = S_e^f(t, \vec{r}) + S_j^{pe}(t, \vec{r}) - S_{pe}^{ion,exc,el}(t, \vec{r}) - S_e^{aff}(t, \vec{r}) - S_e^{rec}(t, \vec{r}). \tag{3.13}$$

The first term in Equation (3.13) is the number of electrons released from the outer atomic shells, the second term is the number of primary electrons created by fission fragments, and the third term is the number of electrons created by fast electrons. Further losses of electrons are associated with the processes of attachment and recombination.

Charged particles will tend to form charged layers described by the Poisson equation in the presence of an external electric field:

$$div \vec{E} = 4\pi e \left(\sum_j n_j - n_e\right). \tag{3.14}$$

The following equation is obtained in the first approximation, without taking into account the influence of fission fragments and electrons on the motion of a neutral gas:

$$\partial \rho_a u_i \quad - \quad \frac{\partial}{\partial} \quad + \frac{\partial}{\partial x_j}$$

for a moving fissile gas in the presence of neutron fluxes has the form:

$$\begin{aligned}
&\frac{\partial}{\partial t}\rho_a\left(\frac{3}{2}RT_a + \frac{1}{2}u^2\right) = \\
&= -\frac{\partial}{\partial x_j}\rho_a u_j * \left(\frac{3}{2}RT_a + \frac{1}{2}u^2\right) + u_k P_{kj} - \\
&- \frac{\partial q_j}{\partial x_j} + \frac{\rho_a}{m_a}F_i u_i + \sum_k S_k^f E_{j,e}^{f,k},
\end{aligned} \tag{3.16}$$

where the heat transfer is:

$$\vec{q}(t, \vec{r}) = \lambda_{aa}\nabla T_a. \tag{3.17}$$

The heating of neutral particles by fission fragments and electrons is taken into account in the last term ofEquation (3.16) :

$$\begin{aligned}
S_{a,e,j} * T_{e,j} = &\int_{\Delta E_{exc}} \tilde{y}_a(t, \vec{r}, \vec{\xi})\tilde{y}_e(t, \vec{r}, \vec{\xi}) * \\
&* \Sigma_{e,j}(E_{e,j}, \Delta E)\, |\xi_a - \xi_{e,j}| * \\
&* \left(\frac{m_a \xi_a^2}{2} - \frac{m_{e,j}\xi_{e,j}^2}{2}\right) d(\Delta E).
\end{aligned} \tag{3.18}$$

Sources of fast electrons and fission fragments that undergo their energy degradation due to ionization and heating of the moving gas due to elastic collisions of fast electrons and fission fragments with fissile gas molecules are presented in this term ofEquation (3.18).

The figures below are for illustrative purposes only, and verification of the results shown is beyond the scope of the material presented in this work and relates to the technologies prohibited from open publication. Detailed calculations of the last term in Equation (3.16) are presented in the following figures Figure 1,Figure 2 .

The hydrodynamic equations for fission fragments and electrons have been rewritten in full:

$$\begin{aligned}
&\frac{\partial n_j}{\partial t} + \nabla \vec{c}_j = S_j^{fission} - k_j^{ion} n_a - k_j^{chex} n_a \\
&\vec{c}_j = -D_{ja}\nabla n_j - D_{ja}^T \nabla T_j.
\end{aligned} \tag{3.19}$$

Calculations of D_{ja} and D_{ja}^T will be absolutely completely different from those calculated in [14]. The interaction potential of j-type fission fragments with electrons, with neutrals of fissile gas components should be certainly identified but has not been analytically found to date.

The influence of the energy distribution functions of electrons and fission fragments, as well as their density

$$(\rho_a u_i u_j + P_{ij}) \quad \frac{\rho_a F_i}{m_a} = 0 \,,$$

—

and temperature, one each other is demonstrated in the following two equations Equations (3.20) and (3.26).

$$P_{ij} = p\delta_{ij} + \eta \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3}\delta_{ij}\frac{\partial u_k}{\partial x_k} \right). \quad (3.15)$$

The effect of fission fragments and electrons on the viscosity coefficients in this approximation is negligible. However, the effect of fission fragments and electrons on the formation of diffusion and heat fluxes in the heat transfer

equation is significant. The energy conservation equation

$$\frac{\partial n_j}{\partial t} + \nabla \vec{c}_j = S_j^{fission} - k_j^{ion} n_a - k_j^{chex} n_a, \quad (3.20)$$

$$c_j = -D_{ja}\nabla n_j - D_{ja}^{T}\nabla T_j.$$

Subsequent terms inEquations (3.20), (3.21) and (3.22) are:

$$S_{j,e}^{ion} = \int_I^{E_{j,e}} \Omega_{j,e}^{ion}(E_{j,e}, \Delta E)\, \xi_{j,e}\, \tilde{y}_{j,e}\, \tilde{y}_a \, d(\Delta E) \quad (3.21)$$

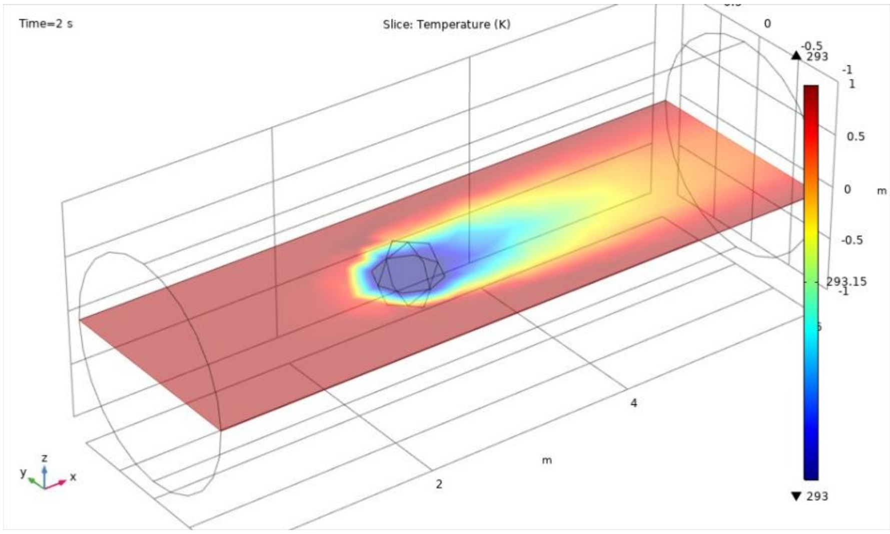

FIG. 1. Temperature distribution around a uranium sphere in a helium-3 flow in the presence of an external neutron flux (1 atm)

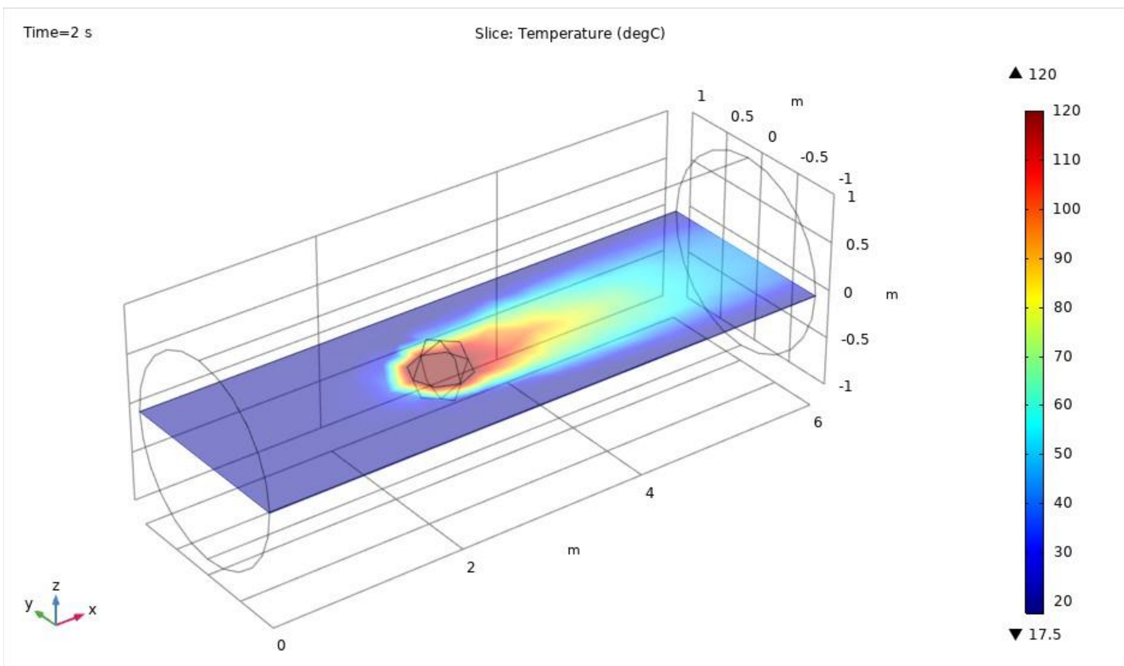

FIG. 2. The uranium sphere heated by internal fission processes in the presence of an external neutron flux (0.1atm) streamlined by helium flow.

$$S^{exc}_{j,e} = \sum_k \int_{I_{exc,k}}^{E_{j,e}} \Omega^{exc}_{j,e}\left(E_{j,e}, \Delta E\right)\xi_{j,e}\tilde{y}_{j,e} * \tilde{y}_a d(\Delta E) \quad (3.22)$$

Terms $S^{ion}_{j,e}$ $S^{exc}_{e,j}$ are sources of fission fragments of j-th type due to the nuclear fission of the fissile component by neutrons in Equations (3.22) and (**??**) :

$$\frac{\partial}{\partial t}\frac{3}{2}kT_j = S^{fission}_j E^0_j - k^{el}_j(T_j - T_a) - k^{chex}_j n_a. \quad (3.23)$$

In this equation n_a is the concentration of fissile components such as ^3He, $^{235}UF_6$, n^k_{ff} is k-type fission fragments; $\Phi(t, \vec{r})$ is the neutron flux defined by the fissile composition of the nuclear reactor active zone,$\sigma^{fission}(\varepsilon_n)$is the cross section of one of the following nuclear reactions:

$$^3He + n \rightarrow p + T + 0.76 Mev$$
$$^{235}UF_6 + n \rightarrow ff_h + ff_l + 165\ Mev \quad (3.24)$$

$\delta(\xi_j - \xi_j^0)$ is the energy distribution of fission fragments of the j-th type at the moment of their birth, represented by the delta function. The following terms in Equation (3.23) represent the rate of ionization, excitation and recharging processes formed by charged fission products and electrons created by fission fragments. Differential cross sections Ω^j_{ion} are defined in analytical form in the laboratory reference system [16, 18]. The average value of the energy of escaped electrons might be found from the energy distribution function of primary electrons, which is determined by the energy spectra of fission fragments:

$$\varepsilon_e^{esc} = \int_0^{\xi_{max}} f_e^{pe}(t, \vec{r}, \vec{\xi}) \frac{m_e \xi^2}{2} d\xi,$$
$$f_e^{pe}(t, \vec{r}, \vec{\xi}) = \int_1^{\xi_j^0} \Omega_j^{ion}(\Delta E_j, \xi) * f_j(t, \vec{r}, \vec{\xi}) * d(\Delta E), \quad (3.25)$$

here $f_e^{pe}(t, \vec{r}, \vec{\xi})$ is the energy distribution function of primary electrons.

$$\frac{\partial n^+}{\partial t} = \sum_j k_j^{chex} n_a - k^{rec}(\tilde{y}_e) n^+ n_e \quad (3.26)$$

There is the following system associated with equationsEquation (3.26),Equations (3.19), (3.20) and (3.16) for the concentrations of electrons and fission fragments and their average temperature in a moving fissile gas

$$\frac{\partial n_e(t, \vec{r})}{\partial t} + \nabla \vec{c}_e = \sum_j S_j^{pe} -$$
$$- k^{ion,ex,el}(t, \vec{r}, \tilde{y}_e) n_e - k^{aff}(t, \vec{r}, \tilde{y}_e) n_e - \quad (3.27)$$
$$- k^{rec}(t, \vec{r}, \tilde{y}_e) n^+ n_e$$

$$\frac{\partial}{\partial t} \frac{3}{2} k T_e = \sum_j S_j^{pe} E_e^{av,j} - S_e^{el} * (T_a - T_e) \quad (3.28)$$

$$\vec{c}_e = -D_{ea} \nabla n_e + b_{ea} n_e \vec{E} - D_{ea}^T \nabla T_e \quad (3.39)$$

Diffusion coefficients, mobility coefficients inEqua- tion (3.39) also require the analytical potential between incoming electrons and fissile gas components, and certainly will drastically differ from the diffusion coefficients in the case of a fully ionized plasma [22] . The procedure for calculating transport coefficients is beyond the scope of this article, nevertheless it should be noted that the solution method will differ significantly from the Chapman Enskog method [14], since the energy distribution of neutrals will also be determined by the energy distribution of fission fragments and electrons in accordance with the system of kinetic equationsEquation (2.20) .

Note that the heat flow is associated not only directly with the temperature gradient but also with the direct heating of neutrals by hot electrons and high-energy fission fragments:

$$q(t, \vec{r}) = \lambda \nabla T_a(t, \vec{r}) + x_{a,e}(T_a(t, \vec{r}) - T_e(t, \vec{r})) +$$
$$+ \sum_j x_{a,j}(T_a(t, \vec{r}) - T_j(t, \vec{r})) \quad (3.30)$$

Some definite solutions of this type of hydrodynamic flow are presented in the following article [23] . In the equation Equation (3.30), the temperature of fission fragments and electrons depends on time in explicit form and requires mandatory consideration of the time relaxation of the energy distributions of fission fragments and electrons in the fission plasma.

IV. CONCLUSION

1. The hydrodynamic equations of fissile plasma, fission fragments and electrons are obtained from the kinetic self-consistent Boltzmann equations obtained for fissile plasma, fission fragments and electrons, which are also represented as self-consistent hydrodynamic equations.

2. The temperature distribution of neutrals is strongly influenced by fission fragments and the resulting primary electrons, radically changing their velocity field and their space-time dependence. The traditional dependence on density and temperature gradients of the non-stationary transport properties of neutrals will be strongly deformed by fission fragments and electrons.

3. As an illustrative example, the solution of a system of hydrodynamic equations in a fissile plasma is given in relation to a uranium sphere flown around by a helium-3 flow in the presence of an external neutron flow. Various values of neutron flux density are presented and the corresponding temperature fields in the vicinity of the uranium sphere are shown. Calculations were performed on the basis of the ComSol software package. The figures presented above are for illustrative purposes only and verification of the results given goes beyond the scope of the material presented in this work .

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