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# MATHEMATICAL SIMULATION OF THE BLEEDING-IN OF A GAS INTO A TOKAMAK REACTOR

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*We discuss the results of mathematical simulation of the bleeding-in of a working gas into a tokamak reactor at the stage of a rise in the current in order to optimize the plasma parameters.*

Works on controlled fusion facilitate creation of a new generation of power plants, namely, thermonuclear reactors. The construction of thermonuclear electric power stations will be a solution to the energy problem of the next century. At the present time specific engineering-physics aspects of it are being investigated.

One of the urgent enginerering-physics problems is the bleeding-in of a gas. It is associated with optimum firing and maintenance of stable arcing (without discontinuties) with prescribed parameters in the regime of ohmic heating, on the one hand, and with the need for continuous replenishment of the burning-up plasma with fuel, on the other.

Recently, experiments on stabilization of the current and the equilibrium state of the plasma by means of bleeding-in of a gas were successfully carried out on a number of tokamaks [1]. However, this problem was solved experimentally by selecting a stable regime for each specific plant. We formulate a mathematical model of the bleeding-in of a gas. Using this model as a basis, we investigate the effect of the bleeding-in of a gas on the parameters of a plasma filament and the stable burning of the plasma in the regime of ohmic heating.

**Mathematical Model of the Bleeding-in of a Gas.** To study the effect of the working gas, admitted through a valve, on the parameters of a plasma filament, the transport code of the balance of particles and energy in the plasma [2-4] is supplemented by equations, averaged over magnetic surfaces, that describe the processes of ionization, dissociation, and excitation of the hydrogen molecules of the bled-in gas by an electric shock and the transport phenomena associated with the neutral gas:

diffusion of the plasma

$$\frac{\partial n}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r} rD\frac{\partial n}{\partial t} + S_0 n n_a + S_d n n_m , \tag{1}$$

where $S_0$ and $S_d$ are approximated by the relations [5]

$$S_0 = \frac{9.7\cdot 10^{-2}}{x + 0.73}\left(\frac{x}{1 + x}\right)^{0.5} \exp(-x) , \quad x = \frac{2.18\cdot 10^{-18}}{T_e} ;$$

$$S_d = 3.5\cdot 10^7 (T_e)^{1/2} \exp(-x) , \quad \text{if} \quad T_e \le I_d ;$$

$$S_d = 5.2\cdot 10^{-2} (x/(1 + x))^{1/2} \exp(-x) , \quad \text{if} \quad T_e > I_d ;$$

$$x = I_d/T_e , \quad I_d = 2.5\cdot 10^{-18} ;$$

heat conduction in an electron channel

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$$\frac{\partial}{\partial t}(nT_e) = \frac{1}{r}\frac{\partial}{\partial r} r \left(k_e \frac{\partial T_e}{\partial r} + \frac{5}{2} T_e D \frac{\partial n}{\partial r}\right) + \frac{j^2}{\sigma} - \frac{3m_e}{m_i} \nu_{ei} n (T_e - T_i) -$$

$$- S_\varepsilon n n_a - Q_B - Q_c , \tag{2}$$

where $(3m_e/m_i)\nu_{ei}n(T_e - T_i)$ characterizes the transfer of energy from electrons to ions by means of Coulomb collisions; $j^2/\sigma$ is the ohmic heating;

$$S_\varepsilon = 2.18 \cdot 10^{-18} S_0 + 1.63 \cdot 10^{-18} S_1 ,$$

$S_\varepsilon n n_a$ describes energy losses by electrons in the processes of ionization and excitation of the neutral atoms of hydrogen,

$$S_1 = \frac{5.2 \cdot 10^{-2}}{x_1 + 0.28} (x_1 (1 + x_1))^{0.5} \exp(- x_1) , \quad x_1 = \frac{1.63 \cdot 10^{-18}}{T_e} ;$$

$k_e = C_1(1 + \nu r^2)$, where $C_1$ and $\nu$ are the coefficients of variation; $D = 0.2k_e$;

energy transfer of ions

$$\frac{3}{2}\frac{\partial}{\partial t}(nT_i) = \frac{1}{r}\frac{\partial}{\partial r} r \left(k_i \frac{\partial T_i}{\partial r} + \frac{5}{2} T_i D \frac{\partial n}{\partial r}\right) + \frac{j^2}{\sigma} - \frac{3m_e}{m_i} \nu_{ei} n (T_e - T_i) - \frac{D}{n}\frac{\partial n}{\partial r}\frac{\partial n T_i}{\partial r} ; \tag{3}$$

diffusion of neutral atoms

$$\frac{\partial n_a}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r} r D_a \frac{\partial n_a}{\partial t} - S_0 n n_a , \quad D_a = C T_i/(\nu_a m_a) , \tag{4}$$

where $D_a$ is the coefficient of diffusion of atoms into the volume of a plasma filament due to the charge transfer $H + H^+ \to H^+ + H$; $C$ is the coefficient of variation; the frequency of collision of atoms and ions is approximated by the formula $\nu_a \approx 1.84 \cdot 10^4 T_i^{0.5} n$;

transfer of the energy of neutral atoms

$$\frac{3}{2} n_a \frac{dT_a}{dt} = - \frac{3}{2} \nu_a n_a (T_a - T_i) ; \tag{5}$$

diffusion of the current

$$j \left(1 - \frac{2\tau_e}{n}\frac{\partial n}{\partial t}\right) + 2\tau_e \frac{\partial j}{\partial t} = \sigma E , \tag{6}$$

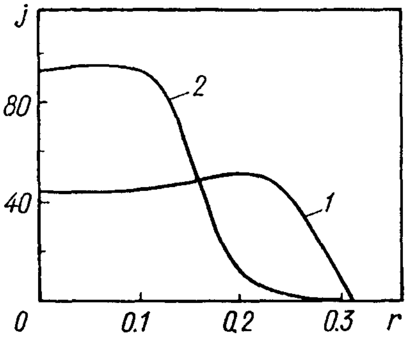
where

$$\sigma = \frac{8}{\pi \sqrt{2\pi}} \frac{T_e^{3/2}}{e^2 \sqrt{m_e} L} , \quad L \approx 15 ;$$

diffusion of molecular hydrogen

$$\frac{\partial n_m}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r} r D_m \frac{\partial n_m}{\partial t} + S_{ac} - S_d n_m n , \quad D_m = T_i/(\nu_a m_m) . \tag{7}$$

The system of equations was solved subject to the following boundary conditions:



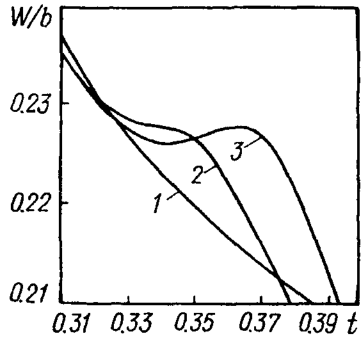




Fig. 1. Dependence of the current density on the radius of the magnetic surface in the regimes: 1) without gas bleeding-in; 2) with gas bleeding-in $S_{ac} = 1 \cdot 10^{21}$ $m^{-3} \cdot sec^{-1}$ at the time $t = 0.1$ sec. $j$, $10^7$ $A/m^2$.

Fig. 2. Dependence of the relative width of a "magnetic island" on the time in a pulse: 1) $S_{ac} = 5 \cdot 10^{19}$; 2) $10 \cdot 10^{19}$; 3) $20 \cdot 10^{19}$ $m^{-3} \cdot sec^{-1}$.

$$n|_{r=b} = 10^{15}\ m^{-3},\quad n_a|_{r=b} = 10^{15}\ m^{-3},\quad n_m|_{r=b} = 10^{15}\ m^{-3},$$

$$T_e|_{r=b} = 2\ eV,\quad T_a|_{r=b} = 0.03\ eV,\quad T_i|_{r=b} = 0.03\ eV,$$

$$j|_{r=b} = 100\ A/m^2,\quad \left.\frac{\partial n}{\partial r}\right|_{r=0} = 0,\quad \left.\frac{\partial T_i}{\partial r}\right|_{r=0} = 0,\quad \left.\frac{\partial T_e}{\partial r}\right|_{r=0} = 0,\quad \left.\frac{\partial j}{\partial r}\right|_{r=0} = 0.$$

The external-circuit equation was replaced by the change of the magnitude of the total current in time $dI/dt = 4 \cdot 10^6$ A/sec.

As initial conditions at $t = 0$ we took temperature profiles uniformly distributed over the radius, with $T_e(r, t = 0) = 2$ eV, $T_i(r, t = 0) = 0.03$ eV, $T_a(r, t = 0) = 0.03$ eV, $j(r, t = 0) = 100$ $A/m^2$, and the plasma densities $n(r, t = 0) = 10^{15}$ $m^{-3}$, $n_a(r, t = 0) = 10^{15}$ $m^{-3}$, $n_m(r, t = 0) = 10^{15}$ $m^{-3}$.

Optimization of the bleeding-in of a gas consisted in selection of its velocity $S_{ac}$ at the stage of current rise, at which the second harmonic of perturbation of the poloidal magnetic field with the amplitude $\tilde{B}_\theta$ does not lead to the development of plasma filament collapse. The indicated type of perturbation develops due to tearing instability and is characterized by two magnetic islands of width $W$. To calculate $\tilde{B}_\theta$ and $W$, the program of [6] was used.

**Analysis of the Effect of Gas Bleeding-In on the Plasma Parameters.** An investigation of the effect of the gas bleeding-in rate on the parameters of a plasma filament was carried out by solving system (1)-(7) by numerical methods. The results of the calculation showed that an increase in the gas bleeding-in rate leads to a change in the dynamics of the profiles of the current density and the temperature and concentration of the plasma (Fig. 1). A decrease in the time of transition to a nonskinned profile of the current density and a decrease in the degree of skinning of this profile are observed here: the ratio max $\{j(r)\}/j(r = 0)$.

In constructing time dependences of the relative width of a magnetic island $W/b$ (Fig. 2) it was found that in a certain range of values $S_{ac} = (4 \cdot 10^{16};\ 10^{18})$ $1/(m^3 \cdot msec)$ a "magnetic island" that corresponds to the tearing mode $m/n = 2/1$ (in Fig. 2 this corresponds to $W/b \approx$ const) appears and exists for some time. This island favors simplification of the profiles of current density and electron and ion temperatures (reshorting of magnetic induction lines in the region of the "magnetic island" and enhancement of the processes of transfer in a plasma filament occur). At lower rates of the gas bleeding-in $S_{ac}$ the effect of a cold gas on the plasma parameters is insignificant. At large values of the gas bleeding-in rate a sharp decrease in the current channel and development of a broad spectrum of MHD instabilities occur. The results of the numerical simulation agree qualitatively with the data of an experiment in which collapses were observed at small and large gas bleeding-in rates [7].

It was found that saturation of a "magnetic island" corresponds to the values of $W/b$ in the range from 0.2 to 0.35. When $W/b$ decreases below 0.2, an increase in the mode $m = 1$, $n = 1$ and collapse of the plasma filament occur.

As a result of the calculations carried out, the possibility of controlling the current-density profile by gas bleeding-in by means of the signal from the envelope of the second mode of the MHD activity was shown, and the values of the parameter $W/b$ that correspond to a stable regime were found. The present model of the bleeding-in of a gas can be used in constructing the transfer function that determines the width of the "magnetic island" as a function of the working-gas flow rate.

## NOTATION

$t$, time; $r$, radius of the magnetic surface; $n$, $n_a$, $n_m$, densities of the plasma, neutral atoms, and hydrogen molecules, respectively; $b$, radius of the diaphragm that restricts the width of the current channel; $\tilde{B}_\theta$, perturbation of the poloidal magnetic field; $E$, external toroidal field created by the inductor; $D$, coefficient of plasma diffusion; $k_e$, coefficient of heat conduction for electrons; $k_i$, neoclassical coefficient of heat conduction in the ion channel; $T_e$, $T_i$, total radiation temperatures of electrons and ions; $T_a$, total radiation temperature of the neutral component of atomic and molecular hydrogen; $S_d$ and $S_0$, rates of dissociation of molecular hydrogen and ionization of atomic hydrogen, respectively; $S_1$, reaction rate of excitation of the energy level of the hydrogen atom with $E = 10.2$ eV by electrons; $S_\varepsilon$, energy losses by electrons in ionization, dissociation, and excitation of neutral atoms and molecules per time unit; $S_{ac}$, rate of accumulation of molecular hydrogen in the surface layer of a plasma filament due to gas bleeding-in; $I_d$, potential of dissociation; $Q_B$, $Q_c$, energy losses by electrons to bremsstrahlung and cyclotron radiation; $j$, current density; $m_i$, $m_e$, mass of an ion and an electron; $\nu_{ei}$, frequency of electron-ion collisions; $\sigma$, electrical conductivity of the plasma; $\tau_e$, energetic lifetime; $L$, Coulomb logarithm.

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