Effect of Presence of Impurity on Plasma Parameters in Fusion Reactor ITER-90HP

S.M. Motevalli, N. Dashtban, F. Fadaei, F. Asadi
Department of Physics, Faculty of Science, University of Mazandaran, P.O. Box 47415-416, Babolsar, Iran

Received 31 October 2014

Abstract. One of the important problems in a tokamak is the existence of inherent thermal instability. For this reason, the control of plasma density and temperature are the most important issues in fusion reactors. We have considered the effect of presence impurity on fusion (50:50) deuterium-tritium plasma parameters in tokamak reactor. This study has been carried out on the base of the particle and energy balance equations in a zero-dimensional model, then the obtained results are compared with the particle and energy balance equations in presence of Beryllium and Argon impurities. We have shown that thermal instability in two states (without impurity and with impurity) then by using re-fueling rate removed this instability and plasma parameters have thermal stability. The results of our study show that the presence of impurity increases the time to reach steady state and that causes an increase of the plasma temperature, decrease of the plasma density and decrease of $\beta$ parameter of plasma in a controlled state.

PACS codes: 36.10.k-, 36.10.Dr, 32.30.Rj

1 Introduction

The source of energy production in stars is nuclear fusion. Nuclear fusion is one of the candidates for production of electricity, so the research onto controlled fusion has been conducted for over 60 years. The problem in producing fusion energy has been to advance a device which can heat the fuel to an adequately high temperature and then confine it for a long sufficient time so that more energy is released through fusion reactions than is used for heating. There are three ways to achieve nuclear fusion: (i) with magnetic confinement fusion [1-3]; (ii) with inertial confinement [4-5]; and (iii) by muon catalyzed fusion [6].

At present, controlled fusion reactions have been unable to construct break-even (self-sustaining) controlled fusion reactions.
The most common type of fusion power systems will be based on the Deuterium-Tritium (D-T) reaction, which is done according to the following reaction:

\[ ^2_1 \text{D} + ^3_1 \text{T} \rightarrow ^4_2 \text{He} (3.5 \text{ Mev}) + ^0_1 \text{n} (14.13 \text{ Mev}). \]  

(1)

Now, the major and most promising magnetic confinement device around the world is tokamak. Tokamak type works on under ignited or sub-ignited conditions. A fusion reactor must operate at working points characterized by a high \( Q \), that is defined as

\[ Q = \frac{P_{\text{fus}}}{P_{\text{aux}}}, \]  

(2)

where \( P_{\text{aux}} \) is the auxiliary power and \( P_{\text{fus}} \) is the fusion power. When \( Q = \infty \), \( (P_{\text{aux}} = 0) \), the reactor operates at ignition, when \( Q \prec \infty \), \( (P_{\text{aux}} \neq 0) \) the reactor operates at a sub-ignition point. An ignited plasma can be unstable against temperature perturbations. It is economically undesirable. Increasing fusion power production with temperature, which is greater than increase of energy loss leads to thermal instability. For our purposes here, we identify ‘thermal instabilities’ as those instabilities in the particle and power balances driven primarily by the unfavorable temperature and density dependence of the plasma heating and cooling rates. Control of this instability is among the most important problem in fusion reactor research. The aim of the controller is to keep the plasma at a desired operating point. In order to control the thermal instability of plasma, we should have built the plasma stable for a long time. Several methods have been proposed to control thermally unstable operating point. The controller is done in three methods: modulation of the fueling rate [7], modulation of auxiliary power [8], and injection of impurities as actuators [9]. In this work, we consider the use of modulation of the fueling rate for stabilizing the burn condition of a fusion reactor working at an ignited point \( (P_{\text{aux}} = 0) \) against a limited range of perturbation in the initial conditions.

In this paper, we introduce instability of plasma by the solving energy balance equations in the 0-D model of D-T plasma with and without impurities in Section 2. In Section 3, we focus on the control of this instability using by modulation of the fueling rate by the linear method. Finally, the conclusions and some suggestions about future work are presented in Section 4.

## 2 Thermal Instability of Plasma

The following system of equations is used to calculate the temporal evolution of plasma parameters in the presence of impurities in the zero-dimensional model, in which the assumed electrons and ions have the same temperature at all times.

\[ \frac{dn_{\alpha}}{dt} = -\frac{n_{\alpha}}{\tau_{\alpha}} + \left( \frac{n_{\text{DT}}}{2} \right)^2 \langle \sigma v \rangle \]  

(3)

210
Effect of Presence of Impurity on Plasma Parameters in Fusion Reactor ITER-90HP

\[
\frac{d n_{\text{DT}}}{dt} = -\frac{n_{\text{DT}}}{\tau_p} - 2 \left( \frac{n_{\text{DT}}}{2} \right)^2 \langle \sigma v \rangle + S.
\] (4)

In these equations, \( n_{\alpha} \) and \( n_{\text{DT}} \) are the alpha and deuterium-tritium densities respectively, \( S \) is the fueling rate and \( \tau_p \) and \( \tau_{\alpha} \) are the confinement time for the D-T fuel and alpha particles respectively. The energy balance equation is given by

\[
\frac{dE}{dt} = P_{\text{aux}} + P_{\alpha} + P_{\text{ohmic}} - P_{\text{brem}} - \frac{E}{\tau_E},
\] (5)

where \( P_{\text{aux}} \) is the auxiliary power and \( P_{\alpha} \) is the alpha power and is written as

\[
P_{\alpha} = \left( \frac{n_{\text{DT}}}{2} \right)^2 \langle \sigma v \rangle E_{\alpha},
\] (6)

where \( \langle \sigma v \rangle \) is the reaction rate and can be found to be [10]

\[
\langle \sigma v \rangle = 3.68 \times 10^{-18} \frac{1}{T^{2/3}} \exp \left( \frac{-19.94}{T^{1/3}} \right) \text{ m}^3/\text{s}
\] (7)

and \( E_{\alpha} \) is the energy of alpha particles and \( T \) is the temperature of plasma. The ohmic power is given by

\[
P_{\text{ohmic}} = \eta j^2.
\] (8)

The bremsstrahlung radiation power is

\[
P_{\text{brem}} = 4.85 \times 10^{-37} n_e^2 Z_{\text{eff}} \sqrt{T},
\] (9)

where \( Z_{\text{eff}} \) is the effective charge and the electron density \( n_e \) is determined by the charge neutrality requirement

\[
n_e = n_{\text{dt}} + 2n_{\alpha} + z_i n_i,
\] (10)

where \( n_i \) and \( z_i \) are the density and atomic number of any impurity ion present in the plasma. In this work, density of impurity is considered \( n_i = 7 \times 10^{17} \text{ m}^{-3} \) and the impurities remain constant at all the times.

Finally, the energy confinement \( \tau_E \) is assumed by the ITER-90HP scaling [11]:

\[
\tau_E = 0.082 f k I^{1.02} R^{1.6} B^{0.15} A_{i}^{0.5} \kappa_{\chi}^{-0.19} P^{-0.47},
\] (11)

where \( f \) is the factor scale depending on the confinement mode and \( A_{i} \) is the isotopic number (= 2.5 for the 50:50 D-T mixture), \( I \) is the plasma current in MA, \( R \) is the major radius of tokamak in meter, \( B \) is the toroidal magnetic field in Teslas, \( \kappa_{\chi} \) is the elongation of the plasma and \( P = P_{\text{ohmic}} + P_{\text{aux}} + P_{\alpha} - P_{\text{rad}} \) is the net heating power in MW.

The calculation has been done by solving a set of coupled particle and energy equations numerically [12] by initial condition of the plasma in Table 1. The plasma density, temperature and \( \beta \) parameter as a function of the time for the
Table 1. Equilibrium point plasma

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$n_e$</td>
<td>Electron density</td>
<td>$0.98 \times 10^{20}$ m$^{-3}$</td>
</tr>
<tr>
<td>$f_\alpha$</td>
<td>Alpha fraction</td>
<td>6.41%</td>
</tr>
<tr>
<td>$T$</td>
<td>Temperature</td>
<td>8.28 KeV</td>
</tr>
<tr>
<td>$P_{aux}$</td>
<td>Auxiliary power</td>
<td>0</td>
</tr>
<tr>
<td>$S$</td>
<td>50:50 D-T refueling rate</td>
<td>$4 \times 10^{18}$ m$^{-3}$ s$^{-1}$</td>
</tr>
</tbody>
</table>

Two cases considered (with and without impurities) are shown in Figures 1, 2 and 3, where $\beta$ is determined by the ratio of plasma pressure to magnetic pressure and is given by

$$
\beta = \frac{2nkT}{B^2/2\mu_0},
$$

where $B$ is the magnetic field strength, $\mu_0$ is the permeability of vacuum, and $k$ is the Boltzmann constant.

Figures 1, 2 and 3 show the simulation results for electron density, temperature and $\beta$ parameter of plasma with the presence of impurities in comparison with the other results without impurity. From the comparison of the two graphs in this figure, it is clearly seen that in Figure 1 the density of plasma in the presence of impurity increases in comparison with the other graph. As it is shown in Figure 2...
Figure 2. The temporal evolution of temperature of plasma in the D-T fusion reaction for uncontrolled system in the presence of impurity (solid line) compared to without impurity (dashed line).

Figure 3. The temporal evolution of the $\beta$ parameter of plasma in the D-T fusion reaction for the uncontrolled system in the presence of impurity (solid line) compared to without impurity (dashed line).
temperature of the plasma in the presence of impurity decreases in comparison with the other graph. The system leaves the desired equilibrium point unstable and settles on a higher temperature equilibrium point stable. The new equilibrium reached is uneconomical and must be avoided. Finally, in Figure 3 we can see that the $\beta$ parameter in the presence of impurity increases in comparison with the other graph.

3 Plasma Stability by Method of Modulation of Fueling Rate

It is clear from Figures 1, 2 and 3 the thermokinetically unstable nature of the equilibrium point when no controller is present. In order to control this thermal instability, we are setting $S$, as controller parameter in equations and we solve energy and particle balance equations, again

$$S = S_{eq} - K_n(n_e - \bar{n}_e) - K_f(f_\alpha - \bar{f}_\alpha) - K_T(T - \bar{T}),$$

(13)

where the feedback gains are: $K_f = 0$, $f_\alpha = n_\alpha/n_e$ and $K_T = -2.00 \times 10^{20} \text{ s}^{-1} \text{ m}^{-3} \text{ KeV}$. It can be seen that the refueling control can stabilize the thermal excursion successfully [13]. Since the linear controller depends parametrically on the equilibrium point, the controller can reject perturbation in the initial condition of the plasma parameters. Density of plasma, temperature and $\beta$ parameter as a function of time for two cases considered (with and without impurities) are shown in Figures 4, 5 and 6.

Figure 4. The temporal evolution of the electron density of plasma in the D-T fusion reaction for controlled system in the presence of impurity (solid line) comparisons to with and without impurity (dashed line).
From the comparison of two states in controlled system, Figure 4 shows the result of numerically solved equation of the controlled system for density. It is observed that the presence of impurity decreases the plasma density about \(0.1 \times 10^{20} \text{ m}^{-3}\). This comparison for temperature in Figure 5 shows that temperature of plasma increases. Figure 5 shows the result of the numerical solved equation of the controlled system for temperature. It is observed that the present...
of impurities increases the plasma temperature about 1 KeV in comparison when
neglect the impurity in the system. This comparison for density shows in Figure 4 that the density of plasma decreases of about $0.1 \times 10^{20} \text{ m}^{-3}$. Finally, from the comparison of two graphs in Figure 6, it can be seen that $\beta$ parameter decreases of about 0.1% when the impurity present, i.e., it is a suitable condition for the plasma fueling.

4 Conclusions

In this work, zero dimensional model for the D-T fusion reaction was used to represent the evolution of plasma parameters. The system of equations has been solved numerically and the results are shown in figures. We have shown the effect of presence of impurity in uncontrolled and controlled systems in ITER90-HP reactor. The parameters of plasma in the presence of impurity stable about 75 s while this time is about 50 s if the presence of impurity is neglected. There is a difference between temperature, density and the parameter $\beta$ is calculated in the presence of impurity in comparison with the other case in which presence of impurity is neglected.

References