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# Effect of different tritium fractions on some plasma parameters in deuterium-tritium magnetic confinement fusion

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**Abstract.** Nearly all reactor projects have considered deuterium-tritium (D-T) fusion. The cross section of D-T reaction is larger than those of other fusion reactions, thus it is considered to be a more favorable reaction. The mix of fuel can vary. In this work, a comparison between the effects of different mixture of D-T fuel on the plasma parameters is made. A time dependence calculation of the fusion process is performed using the zero-dimensional model based on a coupled set of particle and energy balance equations in ITER (International Thermonuclear Experimental Reactor). The time evolution of plasma parameters is also analyzed numerically.

## 1 Introduction

Nuclear fusion has been considered as an energy source for the future because of the inexhaustible fuel source, enormous energy yield and the absence of high-activity waste and/or no chain nuclear reaction [1]. Since nuclei have positive charge, they repel each other. To overcome the Coulomb barrier, the fuel temperature must exceed $5 \times 10^7$ K before a significant nuclear fusion rate is feasible [2]. Magnetic Confinement Fusion (MCF) and Inertial Confinement Fusion (ICF) are approaches to nuclear fusion, but there are differences between them. In ICF, a pallet of fuel is compressed and heated to sufficiently high temperatures and densities by a laser or particle beams, which then undergoes fusion and burns. Such experiments are carried out in places such as the National Ignition Facility (NIF) at the Lawrence Livermore National Laboratory in California [3–5]. In MCF, strong magnetic fields confine the plasma and hold it away from the wall material for a period of about a few seconds [1]. Tokamaks are devices with appropriate magnetic fields used to confine the plasma particles. The international thermonuclear experimental reactor (ITER) is able to produce fusion energy in an economically way. It would reach this goal with demonstrating controlled ignition for practical purposes [2, 6, 7]. In this work, we have considered the D-T nuclear reaction

$$ {}^2_1\mathrm{D} + {}^3_1\mathrm{T} \longrightarrow {}^4_2\mathrm{He} + {}^1_0n + 17.589\,\mathrm{MeV} \tag{1}$$

the 17.6 MeV energy is generated here. The D-D nuclear reactions

$$ {}^2_1\mathrm{D} + {}^2_1\mathrm{D} \longrightarrow {}^3_1\mathrm{T} + {}^1_1p + 4.033\,\mathrm{MeV} \tag{2}$$
$$ {}^2_1\mathrm{D} + {}^2_1\mathrm{D} \longrightarrow {}^3_2\mathrm{He} + {}^1_0n + 3.269\,\mathrm{MeV} \tag{3}$$

have almost two equal probabilities [8]. The following nuclear reaction also occurs [9]

$$ {}^2_1\mathrm{D} + {}^3_2\mathrm{He} \longrightarrow {}^4_2\mathrm{He} + {}^1_1p + 18.353\,\mathrm{MeV} \tag{4}$$

The D-T reaction produces a neutron that carries four fifths of the released plasma energy and an alpha particle that carries the remaining. Since the neutron is neutral, the particle can escape from the plasma region and slow down in a blanket, thus heating the blanket. Coolants around the blanket move the heat out of the reactor to produce steam and

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electricity. Alpha particles remain confined within the plasma to transfer their kinetic energy to other confined nuclei. The heating by alpha particles can maintain the plasma at a required temperature, the so-called "burning plasma". This amount of energy finally impinges as radiation and energetic particles on the first solid wall of the blanket [2]. The mixture of D-T ions can vary [10]. The isotopic fuel mix is a critical reactor parameter as it has a major influence on the fusion power produced [11].

We assume that the time scale of the variation of the average particle and energy densities is long, compared with both the self-equilibration times for ions and electrons, and to the alpha slowing-down times. Thus injected ions or electrons into the plasma can equilibrate in energy instantaneously with similar particles into the plasma through collisions. The produced alpha particles in the D-T reaction are supposed to distribute their energy instantaneously among the ions and electrons. So we are able to define the average energy of each particle type by a single parameter as a temperature related to the energy by $E = (3/2)nkT$, where $k$ is the Boltzman constant. We work in a system of units in which energy and temperature are measured in keV, time is in seconds, densities are per cubic meter, distances are in meters, and magnetic fields are in Webers per square meter [10].

## 2 Physical model

In this work, we consider a zero-dimensional model to describe a thermonuclear system in which ions and electrons are assumed to have the same temperature at all times. The plasma is assumed to only consist of deuterium-tritium [11,12]. In this work, we have varied the mixture of deuterium and tritium [10]. The multi-fluid description for the plasma produces three equations for the D-T density, alpha particle density and the temperature [13,14]. The coupled set of equations for particle and energy balance are

$$\frac{\mathrm{d}n_\alpha}{\mathrm{d}t} = f_T(1-f_T)n_{DT}^2\langle\sigma v\rangle - \frac{n_\alpha}{\tau_\alpha}\,, \tag{5}$$

$$\frac{\mathrm{d}n_{DT}}{\mathrm{d}t} = s_f - 2f_T(1-f_T)n_{DT}^2\langle\sigma v\rangle - \frac{n_{DT}}{\tau_p}\,, \tag{6}$$

$$\frac{\mathrm{d}E}{\mathrm{d}t} = P_{fus} + P_{ext} - P_{loss}. \tag{7}$$

The tritium ratio, $f_T = n_T/n_{DT}$ is a measure of the isotopic mix, $n_T$, $n_{DT}$ and $n_\alpha$ are the tritium, deuterium-tritium and alpha densities, respectively (defined as the number of fuel atoms divided by the core volume). We assume that electrons and ions have the same temperature [10]. In these equations, $s_f$ represents the refueling rate and $\langle\sigma v\rangle$ is the Maxwellian-averaged D-T fusion cross-section, the D-T reactivity. $\tau_p$ and $\tau_\alpha$ are the D-T and alpha confinement times, respectively [15]. In eq. (7), the $\alpha$ -particle heating power density is given as $P_{fus} = Q_\alpha f_T(1-f_T)n_{DT}^2\langle\sigma v\rangle$ where $Q_\alpha = 3.52\,\mathrm{MeV}$ is the energy of the alpha particles, and

$$P_{ext} = P_{aux} + P_\Omega, \tag{8}$$

where $P_{aux}$ is the auxiliary heating power density, $P_\Omega = \eta j^2$ is the ohmic heating power density where $\eta$ is the Spitzer constant and $j$ is the plasma current density and $P_{loss}$ is the bremsstrahlung radiation losses power density,

$$P_{loss} = P_{br} + \frac{W}{\tau_E}\,. \tag{9}$$

Here, the $P_{br}$ radiation loss is given by

$$P_{br} = A_b z_{eff} n_e^2\sqrt{T}, \tag{10}$$

where $A_b$ is the bremsstrahlung radiation coefficient and $z_{eff}$ is the effective atomic number. The plasma thermal energy, $W$, is given by

$$W = \frac{3}{2}n_{tot}kT, \tag{11}$$

where

$$n_{tot} = n_i + n_e. \tag{12}$$

Electron density, $n_e$, can be obtained from the neutrality condition, $n_e = n_{DT} + 2n_\alpha$. $i$ is the ion species of D-T and alpha. No high-Z impurities are considered. $\tau_E$ is the energy confinement time taken into account through an ITER scaling [3,12]. The energy confinement time is defined as the time during which a system loses energy to its environment [3]. We assume $\tau_\alpha = 7\tau_E$ and $\tau_p = 3\tau_E$ [15]. The net plasma heating power is

$$P_{net} = V_{core}(P_{fus} + P_\Omega - P_{br}), \tag{13}$$

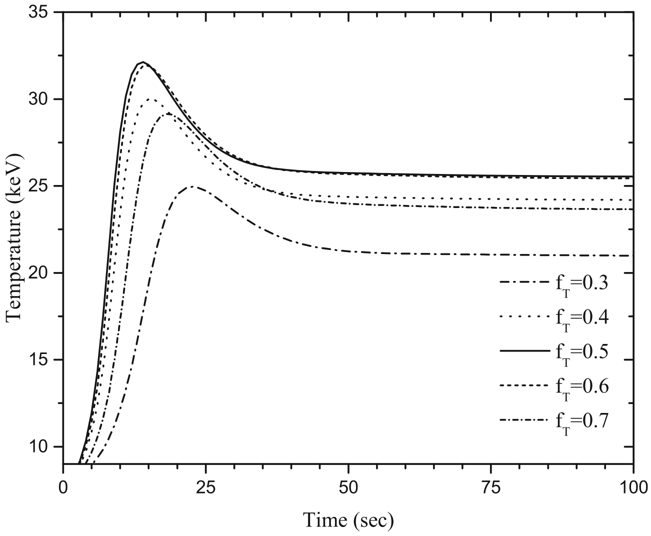


**Fig. 1.** The plasma temperature as a function of time for D-T reaction at different T-fractions.

where $V_{core}$ is the plasma volume [16]. We define the energy gain factor,

$$Q = \frac{P_{fus}}{P_{aux}} . \tag{14}$$

Here $Q$ is the ratio of auxiliary power to fusion power. In a reactor, it is necessary to minimize the auxiliary heating requirements. When $Q = \infty$ ($P_{aux} = 0$), the reactor works at the ignition point. In this case, the alpha particles provide all the heating for the D-T mixture and no extra power is needed to heat the plasma. A fusion reactor must release more energy than is needed for heating fuel. This condition is known as ignition and can be reached when the Lawson criterion is satisfied. The Lawson criterion is the condition for the sustained operation that gives a minimum required for the production of the plasma electron density and energy confinement time for a fusion reactor. It can be written in a more useful form, the triple product of density, confinement time and plasma temperature. The triple product also has a minimum required value, and the name of Lawson criterion often refers to this inequality, when $Q < \infty$, ($P_{aux} \neq \infty$), $Q$ has the infinite value, the reactor operates at a sub-ignition point, in this case, an extra heating is needed for heating plasma and the reactor is said to operate in a driven regime. The aim of ITER is to achieve $Q \geq 10$ [1, 3, 5, 17]. In this paper we work at a sub-ignition point.

The D-T reactivity $\langle \sigma v \rangle$ as a function of plasma temperature is given by

$$\langle \sigma v \rangle = \exp\left(\frac{a_1}{T^r} + a_2 + a_3 T + a_4 T^2 + a_5 T^3 + a_6 T^4\right) \tag{15}$$

and its parameters $a_i$ and $r$ are taken from [18]. We introduce the burnup fraction,

$$f_b = \frac{2 f_T (1 - f_T) \langle \sigma v \rangle}{2 f_T (1 - f_T) \langle \sigma v \rangle + (\frac{1}{n_{DT} \tau_p})} , \tag{16}$$

which describes the fraction of the injected ions that undergo fusion. Particle and energy balance equations have been solved and plasma parameters for different T-fractions as a function of the time and temperature have been shown in figs. 1–7. From figs. 1–3 it can be seen that the system leaves the desired equilibrium point (unstable) and settles on a new equilibrium point (stable). Figure 1 presents the temporal evolution of the temperature of plasma in the D-T reaction for different T-fractions, $f_T = 0.3$–$0.7$. How the system is driven from a low-temperature unstable zone to a high-temperature stable zone can be seen. The temperature of the plasma in $f_T = 0.5$ and $f_T = 0.6$ is higher in comparison with other graphs, and $f_T = 0.3$ has a lower temperature in the stable zone. The temporal evolution of the density of the plasma in different T-fractions is shown in fig. 2. The system sets on a stable equilibrium zone with the lower density. As it is seen in this figure, the density of the plasma in T-fractions $f_T = 0.5$ and $f_T = 0.4$ is lower than in the others. Figure 3 shows the temporal evolution of the net heating of the plasma in different T-fractions. It is seen that the net powers of T-fractions $f_T = 0.5$ and $f_T = 0.6$ are the highest, indicating that it is a good condition. From fig. 4 it can be found that the net power of plasma increases with the temperature until 20–25 keV, then it decreases. The net power of plasma is maximum for $f_T = 0.5$ and is minimum for $f_T = 0.3$ in accordance with fig. 3. Figure 5 exhibits the burn fraction of plasma as a function of time at different T-fractions. As it can be clearly seen, the burn fraction in T-fraction $f_T = 0.5$ is higher than other T-fractions. This shows that in the T-fraction $f_T = 0.5$ more ions undergo fusion.

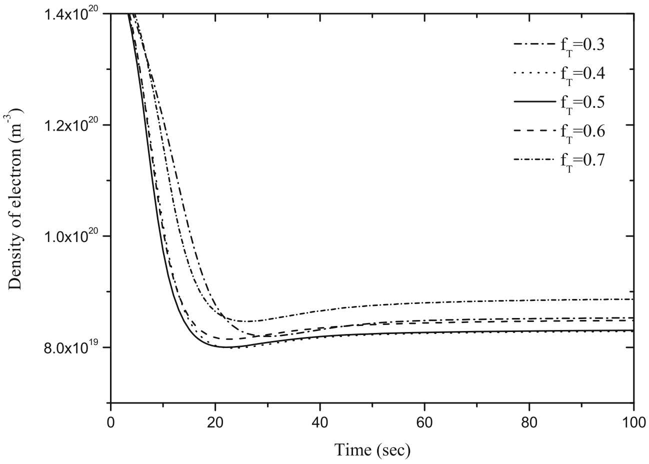


**Fig. 2.** The density of electrons as a function of time for the D-T reaction at different T-fractions.

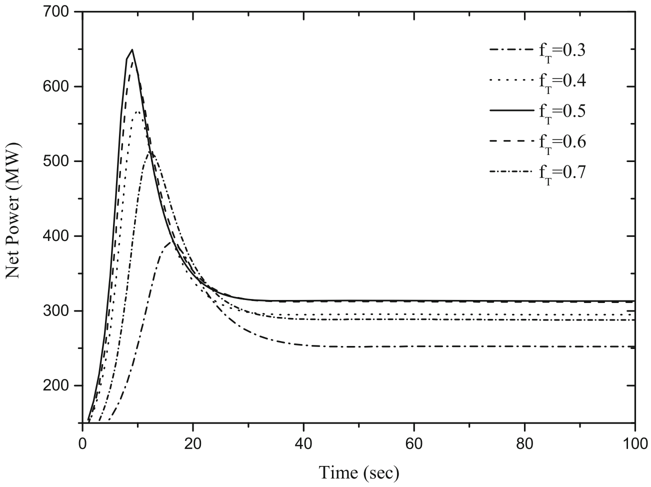


**Fig. 3.** Net plasma heating power as a function of time for the D-T reaction at different T-fractions.

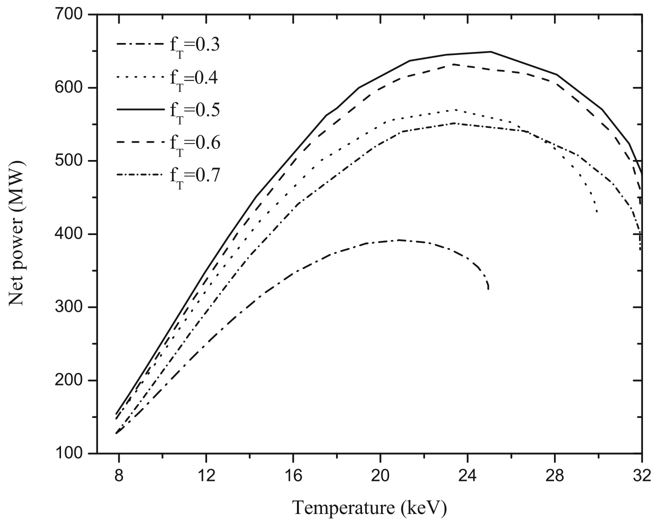


**Fig. 4.** Net plasma heating power as a function of temperature for the D-T reaction at different T-fractions.

Our calculations show that the highest reaction rates exist for the T-fraction $f_T = 0.5$ and hence it is the best choice for a D-T nuclear fusion reactor. Figure 6 is a comparison of the burn fraction for different T-fractions as a function of temperature. As it is shown the burn fraction increases with temperature, is maximum for $f_T = 0.5$ and is minimum for $f_T = 0.3$ and $f_T = 0.7$.

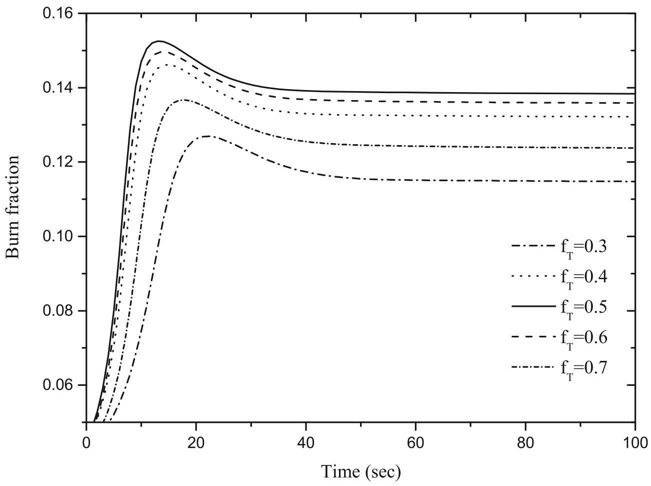


**Fig. 5.** The burn fraction of the plasma as a function of time for the D-T reaction at different T-fractions.

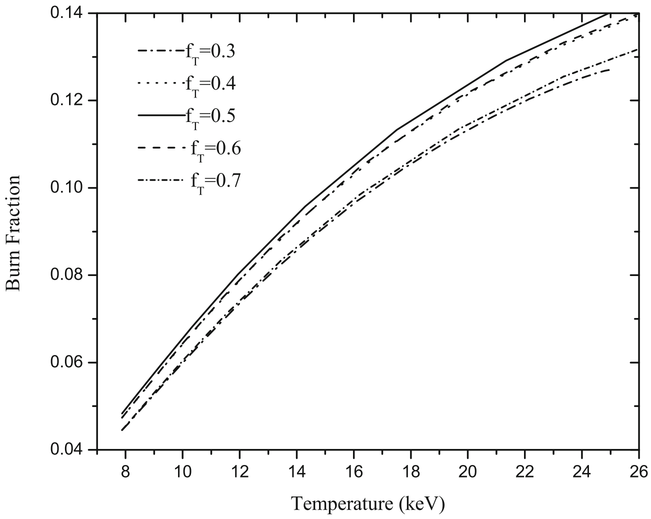


**Fig. 6.** The burn fraction of the plasma as a function of temperature for the D-T reaction at different T-fractions.

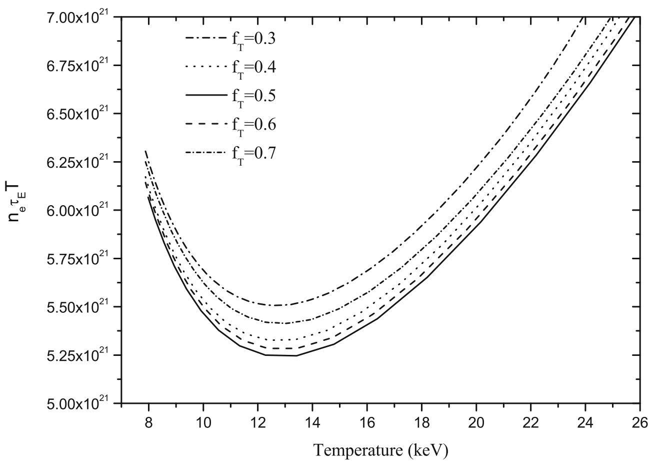


**Fig. 7.** The triple product as a function of temperature for the D-T reaction at different T-fractions.

The triple product of density, confinement time and temperature of plasma $n_e\tau_E T$ for different T-fractions $f_T = 0.3$–$0.7$ as a function of temperature is indicated in fig. 7. The triple product is a useful form of Lawson criterion and defines the combination of particles densities, confinement times, and temperature needed for reaction conditions. According to the Lawson criterion the recoverable energy from a nuclear fusion reaction must exceed the energy which is supplied to sustain the nuclear fusion reaction. This figure shows that the triple product has a minimum value in about 13 keV for all considered T-fractions. In addition, the triple product is lower for the T-fraction $f_T = 0.5$ and is higher in the T-fraction $f_T = 0.3$. The extremum point for $f_T = 0.5$ is $5.2 \times 10^{21}\,\mathrm{keVsm^{-3}}$ and for $f_T = 0.3$ is $5.5 \times 10^{21}\,\mathrm{keVsm^{-3}}$. The graph shows clearly that the T-fraction $f_T = 0.5$ performed better than other T-fractions, thus $f_T = 0.5$ has a more suitable condition for reaction.

## 3 Conclusions

In this paper, some plasma parameters have been derived by solving the particle and energy balance equations numerically. We have studied the burning plasma fusion experiment in ITER considering the D-T reaction with varying T-fractions to determine in which ratio of tritium the most efficient operation occurs. The results show that with $f_T = 0.5$, the density of plasma has the lowest temperature, and net power and reactivity $\langle \sigma v \rangle$ parameters of plasma have the highest value. The burn fraction of plasma describes the fraction of the injected ions that undergo fusion that is maximum for $f_T = 0.5$ and is minimum for $f_T = 0.3$. Then when the D-T mixture is 50-50 more ions can fuse, so we have a better condition for nuclear fusion. The triple product $n_e \tau_E T$ is minimum for $f_T = 0.5$ and is maximum for $f_T = 0.3$. The results of our study show that $f_T = 0.5$ has the best condition for operation of a D-T nuclear fusion reactor.

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