

Time Dependent Performance of ITER90H-P Fusion Reactor with Considering D-T and D-³He Fuel

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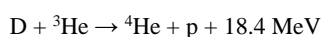
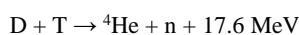
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Abstract: In thermonuclear fusion research using magnetic confinement, the tokamak is the leading candidate for achieving conditions required for a reactor. An international experiment, ITER is proposed as the next essential and critical step on the path to demonstrating the scientific and technological feasibility of fusion energy. ITER is to produce and study plasmas dominated by self-heating. This would give unique opportunities to explore, in reactor relevant conditions, the physics of α -particle heating, plasma turbulence and turbulent transport, stability limits to the plasma pressure and exhaust of power and particles. Our studies show that in the dynamical state physical quantities are dependent on temperature and time. Each has its own specific variations and also at the temperature 70 (Kev) these quantities produce the maximum fusion gain for both of fuels D – T and D-³He such that their values are equal to 81.311 for D-T fuel-and the 0.0429 for D-³He at one second after occurring fusion $t=1s$, respectively.

Keywords: Gain, Dynamics, Deuterium, Tritium, Helium.

1. Introduction

Motivation for development of fusion for power generation is ample. The world is in dire need of a safe, clean, sustainable source of power. In the future as we see it today, population growth continues its march upward, and energy demand, especially in developing countries, rises with only limited adoption of improvements in conservation and renewable. Tokamak fusion reactor that uses deuterium (D) and tritium (T) as its fuel is one of several types of magnetic confinement devices and a leading candidate for producing fusion energy. Fusion energy is produced by the following reactions:



The International Thermonuclear Experimental Reactor (ITER) project is in progress (see figure1), and the primary purposes of this project are demonstrations of controlled ignition, long-pulse burning with steady-state, comprehensive technologies for blanket, superconductive coil and plasma facing wall. The DT burn control is one of the key issues for the ITER tasks. Several types of algorithm for the plasma control were developed, and the performances and applicability of them have been considered [1]. Over the years, the physical and technological feasibility of different methods for controlling the burn condition have been studied [2, 3, and 4] considered: modulation of auxiliary power, modulation of fueling rate and con-trolled injection of impurities. The paper is organized as follows. In Section 2, nonlinear point Kinetic equations governing on the ITER 90 HP fusion reactor for the D-T and D-³He fuel is described. The reactivity parameter for D-T and D-³He in two ways (A:Buckey and B:Bocsh Hale) are presented in Section 3. The detailed of numerical calculations for

these equations and our obtained results are stated in Section 4. Finally, the conclusions and some suggestions about future work are presented in Section 4.

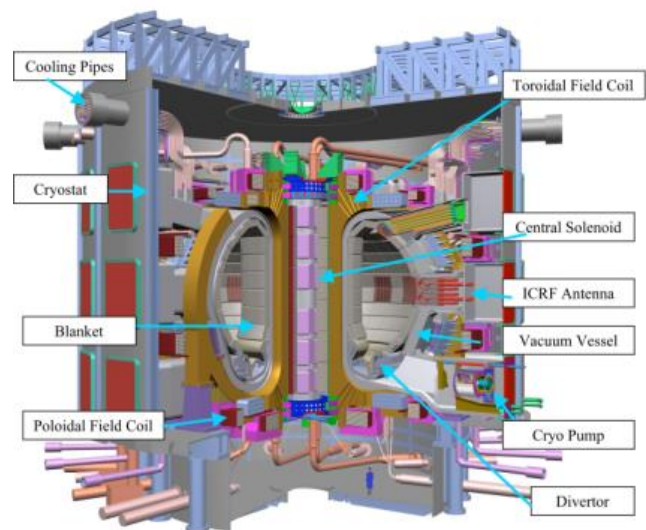


Fig1. Cut away of ITER.

2. Nonlinear Point Kinetic Equations Governing on the ITER 90 HP Fusion Reactor ITER 90 HP for the D-T and D-³He Fuels

In this work, we have used fusion reactor in which approximately particle energy balance equations for two D-T and D-³He fuels are given by:

2-1- Nonlinear Point Kinetic Equations Governing on the D-T Fuel

$$\frac{dn_{\alpha}}{dt} = \frac{-n_{\alpha}}{\tau_{\alpha}} + \left(\frac{n_{DT}}{2}\right)^2 \langle\sigma v\rangle_{DT} \quad (1)$$

$$\frac{dn_{DT}}{dt} = \frac{-n_{DT}}{\tau_{DT}} - 2\left(\frac{n_{DT}}{2}\right)^2 \langle\sigma v\rangle_{DT} + \frac{n_h}{\tau_d} \quad (2)$$

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$$\frac{dn_n}{dt} = \frac{-n_n}{\tau_d} + s \quad (3)$$

$$\frac{dn_I}{dt} = \frac{-n_I}{\tau_I} + s_I \quad (4)$$

$$\frac{dE}{dt} = \frac{-E}{\tau_E} + P_\infty + P_{ohmic} - P_{rad} + P_{aux} \quad (5)$$

2-2- Nonlinear Point Kinetic Equations Governing on the D-3He

Fuel

$$\frac{dn_\alpha}{dt} = \frac{-n_\alpha}{\tau_\alpha} - 2 \left(\frac{n_{D^3He}}{2} \right)^2 \langle \sigma v \rangle_{D^3He} \quad (6)$$

$$\frac{dn_{D^3He}}{dt} = \frac{-n_{D^3He}}{\tau_{D^3He}} - 2 \left(\frac{n_{D^3He}}{2} \right)^2 \langle \sigma v \rangle_{D^3He} + \frac{n_n}{\tau_d} \quad (7)$$

$$\frac{dn_n}{dt} = \frac{-n_n}{\tau_d} + s \quad (8)$$

$$\frac{dn_I}{dt} = \frac{-n_I}{\tau_I} + s_I \quad (9)$$

$$\frac{dE}{dt} = \frac{-E}{\tau_E} + P_\infty + P_{ohmic} - P_{rad} + P_{aux} \quad (10)$$

In these equations, n_I , n_n , n_{D^3He} , n_{DT} , n_α are the alpha particle, deuterium - tritium, deuterium - helium 3, and the neutral fuel (defined as the number of fuel atoms divided by the core volume) and impurity densities, respectively. τ_α is the confinement time for the alpha particles, S is the refueling rate , τ_{DT} , τ_{D^3He} are the confinement time for ionized fuel particles of D , T and 3He , D , respectively. τ_d is the controller lag time , E is the plasma energy, τ_E is the energy confinement time, τ_I is the confinement time for the impurities, S_I is the impurity injection rate, $Q_\alpha = 3.52MeV$ is the energy of the alpha particles. P_α , P_{aux} , P_{rad} , P_{ohmic} , P_i and P_{fu} are the alpha power, auxiliary power , Ohmic power, radiation loss, the net plasma heating power and fusion power , respectively that are given for D – T and D- 3He fuels in the following:[5]

$$P_{\infty DT} = \left(\frac{n_{DT}}{2} \right)^2 \langle \sigma v \rangle_{DT} Q_{\alpha DT} \quad (11-a)$$

$$P_{\infty D^3He} = \left(\frac{n_{D^3He}}{2} \right)^2 \langle \sigma v \rangle_{D^3He} Q_{\alpha D^3He} \quad (11-b)$$

$$P_{aux DT} = \frac{E}{\tau_E} - \left(\frac{n_{DT}}{2} \right)^2 \langle \sigma v \rangle_{DT} Q_{\alpha DT} - P_{ohmic} + A_{bDT} (n_{DT} + 2n_\alpha)(n_{DT} + 4n_\alpha) \sqrt{\frac{2E_{DT}}{3N_{DT}}} \quad (12-a)$$

$$P_{aux D^3He} = \frac{E}{\tau_E} - \left(\frac{n_{D^3He}}{2} \right)^2 \langle \sigma v \rangle_{D^3He} Q_{\alpha D^3He} - P_{ohmic} + A_{bD^3He} (n_{D^3He} + 2n_\alpha)(n_{D^3He} + 4n_\alpha) \sqrt{\frac{2E_{D^3He}}{3N_{D^3He}}} \quad (12-b)$$

E_i , N_i are the total energy and density for (i=DT, D 3He) :

$$E_{DT} = \frac{3}{2} N_{DT} T \quad (13-a)$$

$$E_{D^3He} = \frac{3}{2} N_{D^3He} T \quad (13-b)$$

And

$$N_{DT} = 2n_{DT} + 3n_{\alpha DT} + (Z_I + 1)n_I \quad (14-a)$$

$$N_{D^3He} = 2n_{D^3He} + 3n_{\alpha D^3He} + (Z_I + 1)n_I \quad (14-b)$$

$$P_{rad DT} = A_{bDT} \times Z_{eff DT} n_e^2 \sqrt{T} \quad (15-a)$$

$$P_{rad D^3He} = A_{bD^3He} \times Z_{eff D^3He} n_e^2 \sqrt{T} \quad (15-b)$$

Where

$$A_{bDT} = 4.85 \times 10^{-37} \left(\frac{Wm^3}{\sqrt{keV}} \right) \quad (16-a)$$

$$A_{bD^3He} = 5.35 \times 10^{-37} \left(\frac{Wm^3}{\sqrt{keV}} \right) \quad (16-b)$$

The effective charge (Z_{eff_i}) and electron density (n_{e_i}) for D – T and D-3He are:

$$Z_{eff DT} = \frac{n_{DT} + 4n_{\alpha DT}}{n_{DT} + 2n_{\alpha DT}} \quad (17-a)$$

$$Z_{eff D^3He} = \frac{n_{D^3He} + 4n_{\alpha D^3He}}{n_{D^3He} + 2n_{\alpha D^3He}} \quad (17-b)$$

$$n_{eDT} = n_{DT} + 2n_{\alpha DT} + Z_I n_I \quad (18-a)$$

$$n_{eD^3He} = n_{D^3He} + 2n_{\alpha D^3He} + Z_I n_I \quad (18-b)$$

Z_I is the atomic number of impurities.

$$P_{ohmic DT} = \eta_{DT} j^2 \quad (19-a)$$

$$P_{ohmic D^3He} = \eta_{D^3He} j^2 \quad (19-b)$$

is the plasma current density and n is electron density such that :

$$5 \times 10^5 \leq j (mA) \leq 1.5 \times 10^6 \text{ and } 0 \leq n_e (m^{-3}) \leq 14 \times 10^{19}$$

η is the Spitzer resistivity in which for D – T and are given by: [8,9]

$$\eta_{DT} = 1.03 \times 10^{-4} \times T^{-\frac{3}{2}} \times Z_{eff DT} \times \ln \left(\frac{T^{\frac{3}{2}}}{\sqrt{3.14 \times z_{eff DT} \times e^3 \times \sqrt{n}}} \right) \quad (20-a)$$

$$\eta_{D^3He} = 1.03 \times 10^{-4} \times T^{-\frac{3}{2}} \times Z_{eff D^3He} \times \ln \left(\frac{T^{\frac{3}{2}}}{\sqrt{3.14 \times z_{eff D^3He} \times e^3 \times \sqrt{n}}} \right) \quad (20-b)$$

Here T and e are the electron temperature and charge such that $e = 1.6 \times 10^{-19} (C)$ and :

$$P_i = P_{\alpha_i} - P_{rad_i} + P_{aux_i} + P_{ohmic_i} \quad (21)$$

Where $i = DT$ and D^3He and

$$P_{fu DT} = \frac{(n_{DT})^2}{4} \langle \sigma v \rangle_{DT} Q_{DT} \quad (22-a)$$

$$P_{fu D^3He} = \frac{(n_{D^3He})^2}{4} \langle \sigma v \rangle_{D^3He} Q_{D^3He} \quad (22-b)$$

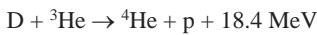
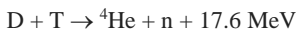
Also, the gain (Q) of this type of reactor for the D - T and D-3He reactions D - T are given in the following:

$$\bar{Q}_{DT} = \frac{\bar{P}_{fuDT}}{\bar{P}_{auxDT}} \quad (23-a)$$

$$\bar{Q}_{D^3He} = \frac{\bar{P}_{fuD^3He}}{\bar{P}_{auxD^3He}} \quad (23-b)$$

3. Reactivity parameter for D - T and D-3He fusion reactions

This paper , presents a strategy for the development of D-3He fusion for terrestrial and space power .the approach relies on modest plasma confinement progress in alternate fusion concepts and on the relatively less challenging engineering, environmental and safety features of a D-3He fueled fusion reactor compared to a D - T fueled fusion reactor. The D-3He benefits include full-lifetime materials, reduced radiation damage, less activation, absence of tritium breeding blankets, highly efficient direct energy conversion, easier maintenance and proliferation resistance. The main fusion fuels are :



Also another important parameter is reactivity of D-T and D³He which depends on the temperature.

a) Bucky Reactivity is temperature dependent (T (Kev)) and is given by: [6]

$$\langle \sigma v \rangle_{DT} = \exp\left(\frac{a_1}{T^r} + a_2 + a_3 T + a_4 T^2 + a_5 T^3 + a_6 T^4\right) \quad (24)$$

Here a_i and r are [6] :(for D-T ($a_1 = 2.7764468 \times 10^1$, $a_2 = 3.1023898 \times 10^1$, $a_3 = 2.7889999 \times 10^{-2}$, $a_4 = 5.5321633 \times 10^{-4}$, $a_5 = 3.0293927 \times 10^{-6}$, $a_6 = 2.5233325 \times 10^{-8}$, $r=0.3597$.)and for D³He ($a_1 = 2.1377692 \times 10^1$, $a_2 = 2.5204050 \times 10^1$, $a_3 = 7.1013427 \times 10^{-2}$, $a_4 = 1.937545 \times 10^{-4}$, $a_5 = 4.9246592 \times 10^{-6}$, $a_6 = 3.9836572 \times 10^{-8}$, $r=0.2935$)

b) Bosch-Hale reactivity is given by the following formula

$$\langle \sigma v \rangle = C_1 \theta e^{-3\xi} \sqrt{\frac{\xi}{m_r C^2 T^3}} \quad (25)$$

$\xi \cdot \theta$ and B_G are:

$$\xi = \left(\frac{B_G^2}{4\theta}\right)^{1/3} \quad (26)$$

$$\theta = \frac{T}{\left[1 - \frac{T(C_2 + T(C_4 + TC_6))}{1 + T(C_3 + T(C_5 + TC_7))}\right]} \quad (27)$$

$$B_G = \pi \alpha Z_1 Z_2 \sqrt{2m_r c^2} \quad (28)$$

The constants values of C_1 to C_7 and $m_r c^2$ (keV) in these equations are [7]:(for D-T: $C_1 = 1.17E-09$, $C_2 = 1.51E-02$, $C_3 = 7.52E-02$, $C_4 = 4.61E-03$, $C_5 = 1.35E-02$, $C_6 = -1.07E-04$, $C_7 = 1.37E-05$, $m_r c^2$ (keV) = 1124656)and(for D-3He: $C_1 = 5.51E-$

10, $C_2 = 6.42E-03$, $C_3 = -2.03E-03$, $C_4 = -1.91E-05$, $C_5 = 1.36E-$

04, $C_6 = 0.00E+00$, $C_7 = 0.00E+00$, $m_r c^2$ (keV) = 1124572).

According to the above equations and the data in Table (2-2) we plotted the $\langle \sigma v \rangle$ versus temperature for the fusion reaction of D - T and D-3He for both of Bucky and Bosch-Hale formulae.

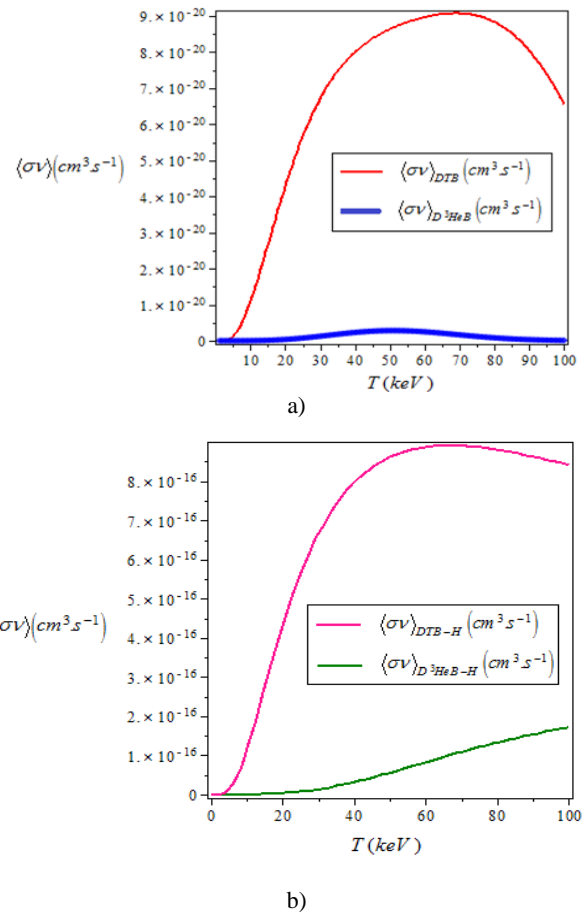


Fig2: Comparison of the graphs of fusion reactions reactivity variations for a) D - T and b) D-3He versus temperature by the two methods, Bucky ($\langle \sigma v \rangle_{DTB}$ ($cm^3 \cdot s^{-1}$), $\langle \sigma v \rangle_{D^3HeB}$ ($cm^3 \cdot s^{-1}$)) and Bosch-Hale ($\langle \sigma v \rangle_{DTB-H}$ ($cm^3 \cdot s^{-1}$), $\langle \sigma v \rangle_{D^3HeB-H}$ ($cm^3 \cdot s^{-1}$))

As shown in Figure 2, the reactivity of D – T fusion reaction is greater than D-3He. Because $\langle \sigma v \rangle_{DT}$ at 70 Kev temperature has a maximum value thus 70 keV is temperature resonance. the value of D – T reactivity at this temperature approximately 10 times is greater than D-3He. By viewing the obtained numerical values and Figure2 we find that the difference between the two ways of calculating reactivity is minimal and since that the method of Bucky is newer than Bosch-Hale in our calculations we use this.

4. Numerical calculations

For having information about the time dependent of this type of reactor in terms of the different physical parameters of the system we must solve the nonlinear point kinetic dynamical equations for fusion reactions of D - T and D-3He. And based on the available physical conditions, equations (1) to (10) can be solved as a function of time. The main objective is that from solving these equations we obtain the variations of densities n_I , n_n , n_{D^3He} , n_{DT} , n_α , energy density E and alpha particle power P_α , auxiliary power P_{aux} , radiative power loss P_{rad} , Ohmic power P_{ohmic} , net

heating power P and fusion power P_{fu} , for both of D - T and D-³He fuel and determine the optimum physical conditions ,fusion gain of choosing fuel.From the numerical solution of equations (1) to (4) for the two fuels D - T and D-³He. In terms of time, variations of particle densities n_n , n_{D^3He} , n_{DT} , n_α and energy are obtained , with respect to time .In which their graphs of variations for comparing are given in figure (3) and (4).

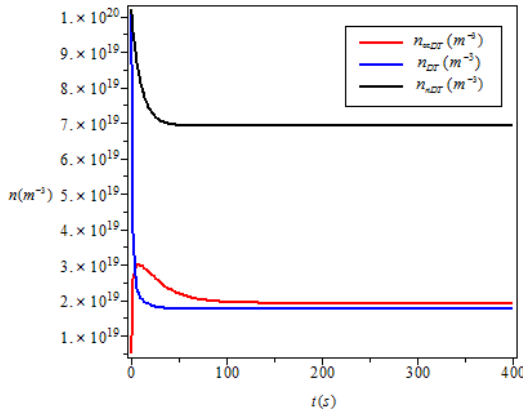


Fig 3: Comparison of densities time variations of alpha, deuterium and tritium particles for both of fuel D – T at temperature 70 Kev in time interval 0-400s.

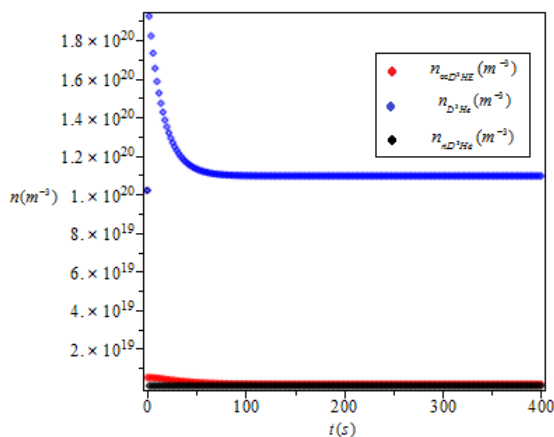


Fig 4: Comparison of densities time variations of alpha, deuterium and tritium particles for both of fuel D-³He at temperature 70 Kev in time interval 0-400s.

And from solving them, we can obtain numerical values of effective charge of all ions (Z_{eff}), electron density, (n_e) ,radiation power loss (P_{rad}), total energy (E), auxiliary power (P_{aux}) and fusion gain (Q) as a function of time and temperature. only temperature 70 (Kev). Form figs (3) and (4) for both reactions D - T and D-³He can be seen that densities variations both as a function of time have similar behaviors in each reactions. such that in both reactions alpha particles are produced and therefor value of its densities are growing then due to the existence of escape probability and leakage from the system the amounts of them are decreased and after certain time since the system goes to the relative equilibrium the values of densities are fixed. Initially the particle density D, T, and ³He is declining because due to the fusion of D with T and D with ³He particles of D, T, and ³He are consumed and their amounts are decreasing and after a certain time the system goes toward a relative balance and the values of densities can be a fixed .Over time, the density of fuel neutral particles in both reactions is

declining because in fusion of D with T and D with ³He fuel-neutral are consumed and values of them are going down, and after a certain time the system goes toward an relative equilibrium also density values can be a fixed amount. Since at temperature 70kev which is resonance temperature of D-T fusion reaction the maximum number of fusions are occurred. Therefore, we have largest consumption of D and T and highest production occurred. In this section, we calculate total energy, auxiliary power, power and fusion gain for ITER90H-p fusion reactor for two fuels D-T and D-3He in terms of time at temperature 70(Kev).Also, from equations (13 - a), and (13 - b) total energy density variations versus time at temperature 70 (Kev) for both fuel D - T and D-3He are as follows. (See fig.5).

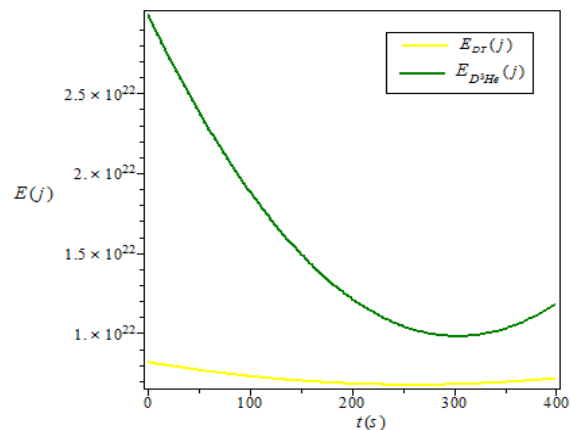


Fig 5: Comparison of the total energy density for DT fuel and D-³He at temperature 70(Kev) in the time range of 0 to 400 seconds

Figs.5 represent that the energy is directly related to temperature so that the temperature increases, the total energy increases. Also total energy of variations for D-T fuel (N_{DT}) is greater than D-³He, (N_{D^3He}) Our calculations show that highest energy is due to D – T fusion reaction at the resonance temperature (70(Kev)) .Using equations (12 - a), and (12 - b),the diagrams of auxiliary power variations versus time at temperature 70(Kev) for both fuel D – T and D-³He are given in the Figure 6.

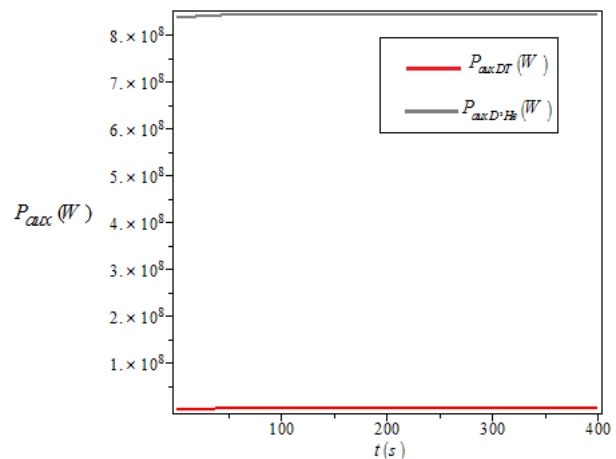


Fig 6: Comparison of auxiliary power for D-T and D-3He fuel in time range of 0 to 400 seconds at temperature 70(Kev).

By seeing numerical values at available physical conditions we conclude that auxiliary power of D-³He is greater D-T. Using equations (22-a), and (22-b) the diagram of fusion power variations versus time at temperature 70(Kev) for both fuel D -T and D-³He are given at Figure 7 .

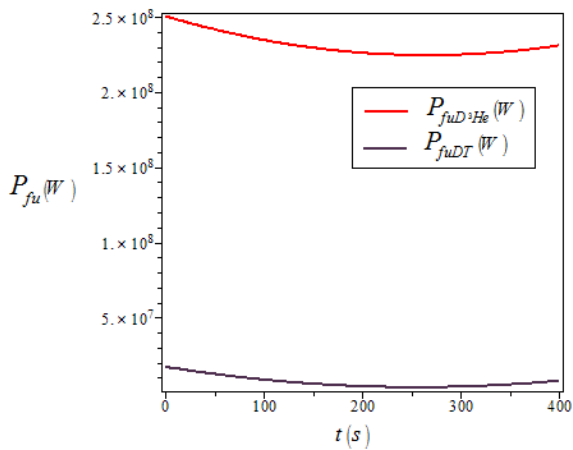


Fig 7: Comparison of fusion power for both of the D-T and D-³He fusion fuel at temperature 70 (Kev) in the time range of 0 to 400 s.

From these figures can be seen that time variations of fusion power for D-T fusion fuel at the resonance temperature 70(Kev) is more than fusion power at the other temperatures. Because in this temperature we have maximum number of fusion reactions and thus produced energy is maximized. Also we can see that at time variations of fusion power for D-³He is lower than D-T.

Also, from equations (23 - a), and (23 - b) graphs of fusion gain variations in terms of time, at temperature 70(keV), for both of fuel D - T and D-³He are as follows(see fig.8.).

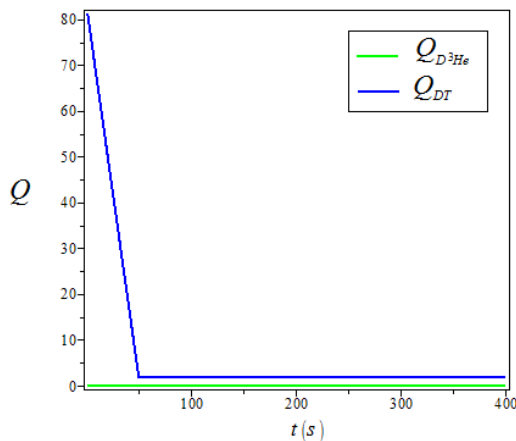


Fig 8: Comparison of fusion gain for D-T and D-³He fusion fuel in 70 (Kev) temperatures at range of time 0 to 400 s.

With Comparing the two diagrams of fusion gain for D - T and D-³He, we can conclude that fusion gain of D-T is more greater than D-³He. Such that at resonance temperature of D-T (70(Kev)) the maximum accessible fusion gain for D-T is about 80 however for is nearly equal to 0.043. Therefore we recommended that for having high fusion gain in fusion reactor ITER90H-p D - T fuel is used instead of D-³He.

5. Conclusions

With studying and analyzing of ITER90H-P fusion reactors and solving the non-linear point kinetic equations governing on the two- fuel D-T and D-³He at dynamical state, we find that the main quantities in determining the fusion gain are the densities of alpha

particles, deuterium, tritium, helium, neutral fuel, electron , fusion energy and the total energy , and density of total particles, the effective charge of all ions, radiative power loss, auxiliary and fusion power ,respectively In order to be commercially competitive, a fusion reactor needs to run long periods of time in a stable burning plasma mode at working points which are characterized by a high Q , where Q is the ratio of fusion power to auxiliary power. Active burn control is often required to maintain these near-ignited or ignited conditions ($Q = \infty$). Although operating points with these characteristics that are inherently stable exist for most confinement scalings, they are found in a region of high temperature and low density. Our studies show that in the dynamical state above quantities are dependent on the temperature and time .Each has its own specific variations and also at the temperature 70 (Kev) these quantities produce the maximum fusion gain for both of fuels D-T and D-³He, such that their values are equal to 81.311 for D-T fuel-and the 0.0429 for D-³He at one second after occurring fusion $t=1s$, respectively. Fusion using D-³He fuel requires significant physics development particularly of plasma confinement in high performance alternate fusion concepts. Countering that cost, engineering development cost should be much less for D-³He than D-T, because D-³He greatly ameliorates the daunting obstacles caused by abundant neutrons and the necessity of tritium breeding. D-³He fusion fueled fusion reactor would also possess substantial safety and environmental advantages over D-T.

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