ISSN: ۲٦٧٦-٥٧٦٤
www.jocrisar.ir

مجله پژوهش های معاصر در علوم و تحقیقات
سال ششم، شماره ۶۷، بهمن ۱۴۰۳

The balance of power in a nuclear fusion reactor

Mohammad Sedigh[1]

Masters,degree in nuclear physics, shahrood university [1]

Abstract

To have a net gain in reactor output thermal power, the total thermal output of the reactor must be more than the power required to maintain the fusion plasdma. From a physical point of view, the total thermal power from a nuclear fusion reactor includes neutrons with an energy of 14.1Mev .That pass through the plasma, braking radiation that escapes from the plasma environment and is absorbed by the primary wall and the continuous transfer of plasma energy to the primary wall by thermal conduction. To prevent the primary wall from melting, the heat is transferred by the coolant and turns into steam. The heat output from the reactor is in the from of radiation and heat conduction. For a fusion reactor with a capacity of 1000MW and an engineering profit factor Q_E=10 whose efficiency is $\eta_e \eta_a \simeq 0.5$, The maximum microwave power that can be absorbed in the plasma for external heating and creating torus current will be 50MW.

Key words: Power balance, plasma, neutron, factor, heat capacity, primary wall, spontaneous ignition.

Introduction:

First, the important issue is to calculate the ratio of the output power to the required power, or the gain, in order to be able to judge the feasibility of power generation from this reactor. The investigate issue, we introduce two dimensionless
Quantities called ((gain parameter)).the first gain parameter, which is Q, is widely used in nuclear fusion literature and is determined based on the physical conditions of the system.
The second parameter, namely $Q_E$is determined based on more realistic conditions and attempts are made to take into account. The engineering limitations in calculating the reactors benefit in a simple way.

power balance in a reactor:

our goal is to investigate the dependence of Q and $Q_E$on the value of p$\tau_E$when it is smaller than the value required for ignition.
To start the analysis, we define the exact value of Q in terms of sources and power consumption in the fusion reactor. with some simple algebraic calculation, the quantity Q in terms of variables Q(Pτ_E,t)we write. The physical interest is written as follows:

$$Q=\frac{Total\ output\ net\ thermal\ power}{Required\ thermal\ power}$$
(۱)

$$Q=\frac{Total\ output\ thermal\ power-Required\ thermal\ power}{Required\ thermal\ power}$$

$Q=\frac{p_{out}-p_{in}}{p_{in}}$, the reason for the definition of the above quantity is a follows. Finally, electricity is abtained by the total thermal power produced in the fusion reactor plasma. in order to have a net gain in the thermal power output of the reactor, the total thermal power output of the reactor must be more than the power required to maintain the fusion plasma. there fore, in the conditions that nuclear fusion reactions do not occur in the reactor, all the power input to the reactor is in the from of heat conduction and braking radiation and results in the output heat power. In other words, p_{out}=p_{in} and Q=0.
On the other hand, in full ignition mode, the heat produced by alpha particles is enough to maintain the fusion plasma and there is no need to use external power(p_{in}=0) it is with in this

ISSN: ۲٦٧٦-٥٧٦٤
www.jocrisar.ir
مجله پژوهش های معاصر در علوم و تحقیقات
سال ششم، شماره ۶۷، بهمن ۱۴۰۳

ranc Q=∞. As a result, with the definition of Q in equation(1), it can be said that the range 0f interest of the physical gain factor in a fusion reactor is $0 < Q < \infty$.

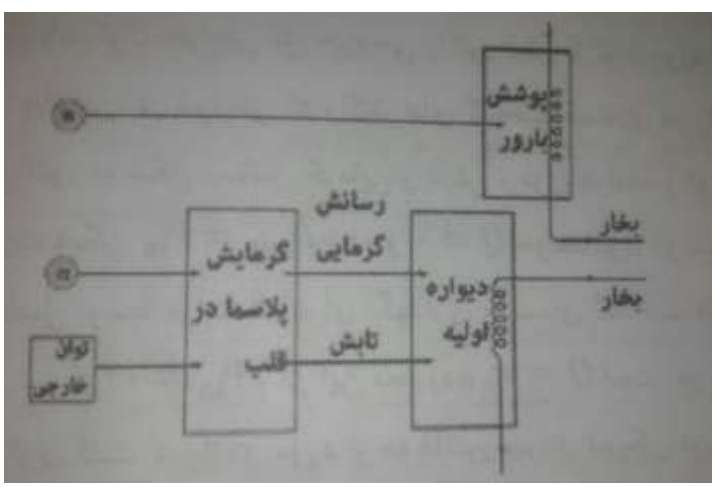
Now the more accurate and simpler from of the physical interest factor is a Q=Q(pτ_E ,T)we abtain by placing the contribution related to the thermal power output of the fusion reactor input in equation (1).

First, note that the input power to the reactor can be simplified is shows $p_{in}=s_h$v ,that we is the volume of plasma in this relationship. this power must be continuously absorbed by the plasma so that the plasma remains at the required temperature and provides the stable torus current it needs.

Now consider the total heat output from the reactor. Remember that the output electrical power is produced by the heat conversion system(ie heat exchanger- steam turbine system) which converts the heat from the plasma first in to steam and than into electricity(Figure 1).

From a physical point of view, the total heat output from the reactor must include all the heat sources that come out of the plasma. there are sources of heat production here. First, neutrons with an energy of 14.1 Mev, which escape from the plasma, are absorbed in the blanket cover and converted into heat finally into steam. The second source of heat is the bremsstrahlung radiation that escapes from the plasma environment and is absorb by the primary wall. To prevent the primary wall from melting due to radiation, the primary wall must be kept cool. As a result, the heat transferred by the coolant will be converted into steam.

The third source of heat is the continuous transfer of plasma energy to the primary wall by thermal conduction. Here to prevent the primary wall from melting, the heat must be transferred by the cooler and converted into steam. Regarding alpha particles, we assumed that the energy of these particles is transferred to the plasma before scattering and as a result, indirectly plays a role in steam production. Therefore, the heat output from the reactor is in the from of heat radiation and conduction. such a procedure also applies to external heating power.



ISSN: ۲۶۷۶-۵۷۶٤
www.jocrisar.ir
مجله پژوهش های معاصر در علوم و تحقیقات
سال ششم، شماره ۶۷، بهمن ۱۴۰۳

Figure(1):diagram of power componenets in a nuclear fusion reactor that shows how power sources including neutrons and alpha particles resulting. From fusion reactions and external heating power are finally converted into steam to produce electricity.

Based on this, the power output from the reactor is given as $p._{\square\square}$=(s_n+s_B+s_k)v it turns out that s_n=($\frac{E_n}{E_\alpha}$)s_α=4s_α.

By integrating these relationships in the definition of Q, we have:

Q=$\frac{\text{٤}s_\alpha+s_B+s_k-s_h}{s_h}$

(2)

By putting $s_h$in equation (2), the simpler from of Q is abtained:

Q=$\frac{s_f}{s_h}$

(3)

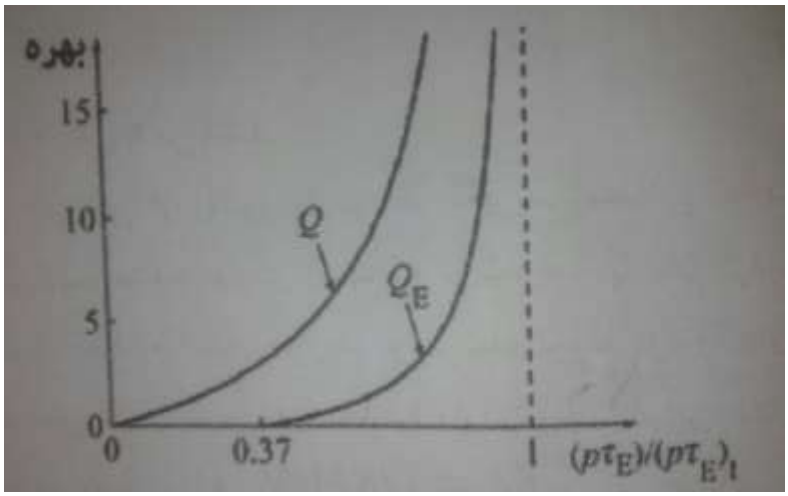
Which in the above relation is s_f=s_n+s_α=5s_α. The relation (2) clearly shows that Q is equal to the ratio of the total power produced in the reactor to the power consumed in it. The desired relationship Q=Q(pτ_E,T) is abtianed by removing $s_h$in the denominator of equation(3) with the help of the equation s_n+s_h=s_k+s_B and inserting different power shares. After that, with a little calculation and ignoring the braking radiation, we will reach the desired relationship Q:

Q=5$\frac{p\tau_E}{(p\tau_{E)_l}-p\tau_E}$

(4)

(pτ_E)$_l$=k_l $\frac{T_K^{\text{۲}}}{\langle\sigma v\rangle}$(atm.s)

Note that $(p\tau_E)_l$ indicates the required value of $p\tau_E$ to reach the ignition state. The Q curve is drawn in term of $p\tau$ in figure(2) . as expected, when $p\tau_E=(p\tau_E)_l$, will be Q=∞.
When some external heating power enters the reactor, $p\tau_E < (p\tau_E)_l$ will occur.
0f course, in this case, the interest will be reduced. For example, if we want the output power from the fusion reactor to be ten times the input power (that is Q=10),$p\tau_E$ will be smaller by $^{۲}/_{۳}$ of its value in ignition mode.



Figure(2):physical benefit factors(Q)and engineering(Q_E)
In terms of $p\tau_E/(p\tau_E)_l$ values[1]

If we compare the two equations $p\tau_E \geq \frac{K_R T_K^{۲}}{(\frac{۱}{f\alpha})k_\alpha\langle\sigma v\rangle - k_B T_k^{۱/۲}} \approx f_\alpha k_z \frac{T_k^{۲}}{\langle\sigma v\rangle}$(atm.s) and equation(4), the relationship between f_u and is abtained as follows:

$$f_u=\frac{Q}{۵+Q}$$

(5)

Therefore, if we define the mode ((flaming plasma)) the plasma power balance as equal to the power abtained from the melting alpha particles with the external heating power, $f_u=\frac{۱}{۲}$ and as a result Q=5.

The physical gain factor Q reasonably accounts for the various sources and uses of power from the perspective of the physics of nuclear fusion frequencies in the reactor. However, this factor does not distinguish between different types of power contributions in the Q relationship. for example, s_n and s_k are the thermal power density, while s_h is the microwave power density. None of this power density contributions are not really electrical power density. Engineering gain factor converts all different power densities into electrical power density by introducing appropriate power conversion coefficients. The Q_E common from is as follows:

$$Q_E=\frac{Net\ output\ electrical\ power}{Input\ electrical\ power}=\frac{Total\ electrical\ power\ output-Input\ electrical\ power}{Input\ electrical\ power}$$

$$=\frac{p_{out}^{(E)}-p_{in}^{(E)}}{p_{in}^{(E)}}$$

(6)

In the above relationship, $p_{in}^{(E)}$ is the actual electrical power required to create and transfer different sources of external heating. The η_e fraction of this electrical power is converted into a suitable from like microwave power for plasma heating. The plasma itself also absorbs a η_a fraction of the microwave power and the rest of the incoming microwave power is reflected outward from the plasma environment, therefore, the conversion factor of the input electrical power to the power absorbed in the plasma is abtained from the product of $\eta_a\eta_e$. As result, we have:

$$p_{in}^{(E)}=s_h v/\eta_e\eta_a$$

(7)

Usually are $\eta_e \approx$ ۰.۷ $and\ \eta_a \approx o.$۷ .

Now consider the electrical power output from the reactor. The argument that regarding we heat generating sentences, it is similar to the case we mentioned in the definition of Q and only two exceptions should be considered. First, it is necessary to heat produced by neutrons nuclear fusion during the generation of tritium in the blanket cover of lithium should be included in the calculation. Therefore, in addition to considering the contribution E_n=14.1 Mev, we must also calculate the amount of energy

ISSN: ۲۶۷۶-۵۷۶۴
www.jocrisar.ir

E_{li}=4.8 Mev. Second, the microwave power reflected from the plasma is absorbed in the primary wall and heats it. For the reason, we must enter this share, which is given as $(۱-\eta_a)\eta_e p_{in}^{(E)}$, in the calculation. By adding these new contributions, the output power of the entire reactor is equal to p_{out}=(s_n+s_{li}+s_B+s_k)v+(1-η_a)$\eta_e p_{in}^{(E)}$ which we have in this relation:

$$s_n+s_{li}=\left[\frac{E_n+E_{li}}{E_\alpha}\right] s_\alpha=5.4s_\alpha$$

(۸)

Assume that the heat is converted into electricity by the steam cycle and the turbine with conventional efficiency $\eta_t \approx ۰.۴$ s0 the output electrical power is written as follows:

$$p_{out}^{(E)}=\eta_t[5.4s_\alpha+s_B+s_k+\frac{(۱-\eta_a)}{\eta_a}s_h]\text{v}$$

(۹)

By placing the above sentences in the relation Q_E, the engineering power benefit is given as follows:

$$Q_E=\frac{\eta_t\eta_e\eta_a(۵.۴s_\alpha+s_B+s_k)-[۱-(۱-\eta_a\eta_t\eta_e]}{s_h}$$

(10)

After placing the terms of sources and power consumption in the fusion reactor and ignoring the braking radiation (to simplify the calculation), the above relationship can be written as follows:

$$Q_E=\frac{(۶.۴\eta_t\eta_e\eta_a+۱-\eta_t\eta_e)(p\tau)_l}{(p\tau)_l-p\tau}$$

$$\approx ۲\,\frac{p\tau-۰.۳۷(p\tau)_l}{(p\tau)_l-p\tau}$$

(۱۱)

The $Q_E$curve in terms of pτ is shown in figure(2). You can see that like Q, here also when pτ = (p$\tau)_l$, will be $Q_E = \infty$.

Also external heating power is used, we need a lower value of pτ_E than in full ignition mode, however, the decrease in p$\tau_E$is not so great with a simple calculation, the relationship between Q and Q_E is abtained as follows:

$$Q=\frac{E_n+E_\alpha}{E_n+E_\alpha+E_{li}}\frac{Q_E+۱-\eta_t\eta_e}{\eta_t\eta_e\eta_a}=4(Q_E+O.72)$$

(12)

We mention some significant numerical cases. To reach the break-even limit of the electrical power series(that is when $p_{out}^{(E)}$=$p_{in}^{(E)}$)

Which corresponds to Q_E=0, we must reach value of $\frac{p\tau_E}{(p\tau_E)_l}$=0.37.

This value results in Q=2.9. if our goal is to bring the gain factor of electrical power engineering to Q_E=10, then $\frac{p\tau_E}{(p\tau_E)_l}$=9, which corresponds to Q≈ ٤٣.

First of all, note that the physical benefit factor Q=10 is equivalent to the engineering benefit factor Q=1.8.

We summarize the achievments of the above discussion as follows. First, for complete spontaneous ignition to occur (Q=Q_E=∞),$\frac{p\tau_E}{(p\tau_E)_l}$ =0.9, pτ_E=8.3 atm.s and T=15kev must be present. If external heating is used, less amount of p$\tau_E$will be needed. Because the power of external heating is added to the power alpha particles and contribution to plasma heating(in this case, $Q_E$is no longer infinite). Thirdly, in order to reach the appropriate values of η_e, η_a and η_t, efficiency the reduction of pτ_E is not significant. If we must to reach the appropriate value of Q_E=10 in a fusion reactor, the quantity p$\tau_E$is only reduced by a factor of 0.9. fourth, even in order to achieve the break-even condition of electrical power (that is when Q_E=0, it is necessary to increase pτ_E to 0.4 of its value in the employment mode. Finally, for a fusion reactor with a capacity of 1000MW, the engineering gain factor Q_E=10 and its efficiency is $\eta_e\eta_a \approx$ ۰.۵,the maximum microvawe power that can be absorbed in the plasma for external heating and creating current torus, will be 50 MW.

Thanks:

I am deeply grateful to the honorable professors Dr. Hassan Hassanabadi, Dr. Alireza Tavasoli and Dr. Yasaman Nasirzadeh, who are always encouraging me.

Conclusion:

An important issue in the power balance of a nuclear fusion reactor is the ratio of output to its required power is (or gain). We named two dimensionless quantities as ((interest parameter)). The parameter Q and the $Q_E$when the p$\tau_E$value required for ignition the smaller is determined we did. We said that there are three sources of heat production in the total heat output from the reactor. First, neutrons with an energy of 14.1 Mev that escape from the plasma, the second heat source is the bremsstrahlung radiation that escapes from the plasma environment and is absorbed by the primary wall. The third source of heat is the continuous transfer of plasma energy to the primary wall by thermal conduction. It was also stated that if we want to reach the appropriate value of Q_E=10 in a fusion reactor, the quantity p$\tau_E$can only be reduced by a factor of 0.9 finds. To achieve the electric power series head condition that is, when if Q_E=0, it is necessary to increase p$\tau_E$to o.4 in the employment state. Finally the result for a fusion reactor with a capacity of 1000Mev and an engineering gain factor of Q_E=10 with an efficiency of $\eta_e \eta_a \approx$ ۰.۵, we get the maximum microwave power that can be absorbed in the plasma for external heating and creating a torus current, it will be 50 MW.

References:

Freidberg J., 2007 , Plasma Physics and Fusion Energy, Cambridge University Press.