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Development and application of nuclear fusion

Mi Ruomu

Beijing Jingshan school, No.35, Dengshikou Street, Dongcheng District, Beijing, China, 100010

2056529761@qq.com

Abstract. Energy is always a vital part of most of those scientific areas. Researchers are always trying to understand energetic production and take those principles into social usage. Fortunately, nuclear reactions can fix those previous questions. This paper provides characteristics and specific advantages of nuclear power generation from related literature and can give effective conclusions from those specific aspects on particular social situations. The effective use scenario of this specific power generation method can be summarized from the analysis results of the fusion reactor principle and can improve the reliability when it is actually put into use can be improved. From the data research and literature research in this paper, nuclear fusion has a huge potential in power generation and has involved much simpler method and devices. Compared with standard fission reaction and thermal power generation, the method and equipment involved in nuclear fusion are much simpler. Nuclear fusion has many advantages on radiation and application aspects, and can involve many feasible future extension research directions.

Keywords: Fusion, Stars, Magnetic confinement, Application, Radiation.

1. Introduction

There are several purposes for nuclear reactions. They can be used to investigate the structure of nuclei; in some cases, especially when the nucleus is unstable, they may be the only method available. In order to study the fundamentals of the nuclear force or to measure reaction rates, nuclear reactions also provide information about the interaction between nuclei. These data are important inputs in other branches of physics, such as nuclear astrophysics, as well as in a wide range of nuclear applications, such as nuclear power or the creation of radioactive isotopes for medical use. According to Dr. Jean-Paul Biberian in his book *Cold Fusion* [1], the present main research direction in the academic community is biased towards cold fusion. To sum up, utilized nuclear reaction can be divided into 2 different kinds: nuclear fission, and nuclear fusion. Under the present situation of scientific research, nuclear fission definitely has higher feasibility, but at the same time, the experimental fusion reaction shows better application prospects.

The completion of the ITER program means that the feasibility of the fusion reactor has been received. Meanwhile, the demand for social power supply requires the implementation of small-scale reactors. Therefore, this paper focuses on the application prospect of fusion reactor and small-scale reactors by studying the related literature to analyze the characteristics of fusion reactor and small-scale reactors.

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2. Nuclear Reactions

2.1. Fission Reaction

When an atomic nucleus is bombarded with an energetic particle, it undergoes a nuclear reaction, changing its identity or properties. An alpha particle, gamma-ray photon, neutron, proton, heavy ion, or other particle may attack the target. Whatever the case, the bombarding particle needs sufficient energy to get close enough to the positively charged nucleus to be within the strong nuclear force's range [2].

The nucleus breaks into two lighter nuclei during nuclear fission. When electromagnetic radiation in the form of different particles or gamma rays excites the nucleus, the process can either happen spontaneously or be stimulated. Numerous neutrons are emitted, radioactive byproducts are created, and a significant amount of energy is released during the fission process. These neutrons can cause neighboring fissionable materials' nuclei to split, releasing additional neutrons in the process. These neutrons have the ability to repeat the aforementioned sequence, triggering a chain reaction that causes a significant number of nuclei to fission and release a tremendous quantity of energy. This chain reaction has the potential to generate electricity for social needs if it is managed in a nuclear reactor. This chain reaction has the potential to generate electricity for social needs if it is managed in a nuclear reactor. Like the so-called atomic bomb, it will unleash immense destructive forces if left unchecked.

The "atomic age" began with the discovery of nuclear fission. In addition to laying the groundwork for a great deal of sociological, economic, and scientific advancement, nuclear fission has the potential to cause major environmental issues and raise public concern. Even from the standpoint of pure science, the nuclear fission process has created a lot of confusion and complexity, and more experiments and data are still required to provide a thorough theoretical explanation [3].

2.2. Fusion Reaction

Deuterium and hydrogen atoms fuse in the fusion reaction, also known as the thermonuclear reaction, to produce helium while simultaneously releasing energy. This kind of reaction drives the Sun and the stars. Hydrogen atom fusion reactions are the simplest to produce due to the low coulomb barrier and beneficial wave mechanical transmission factor. The threshold reaction energy (ECB(min)) for the 1H + 1H reaction is 1.11 MeV at temperature 1010 K; it is roughly 1055 at temperature 108 K; 105 at temperature 109 K; and 0.5 at temperature 1010 K. The quantum mechanical tunnel effect allows the reaction to proceed at a tolerable rate at lower temperatures: The D + T reaction ignites at 3 107 K, while the D + D and D + 3He reactions ignite at 3 108 K. These processes are the leading contenders for fusion reactions that can be controlled [4, 5].

Fusion energy has the capacity to generate safe, pure, and nearly limitless electricity. Even while lighter-than-iron nuclei can experience fusion reactions, most elements won't fuse until they are inside of a star. To create burning plasmas in experimental fusion power reactors like tokamaks and stellarators, scientists are searching for a fuel that is comparatively easy to produce, store, and bring to fusion. Deuterium-tritium is currently the finest fuel for fusion reactors. This fuel produces more energy than other fusion reactions and can reach fusion conditions at lower temperatures when compared to other elements.

2.3. The plasma states

A gas that has had a large portion of the atoms or molecules that make up its constituents ionized by the dissociation of one or more of its electrons is often referred to as a plasma. Because these free electrons enable the plasma to conduct charges, the plasma is the only state of matter where thermonuclear reactions may occur in a self-sustaining manner. A good understanding of the behavior of gas in plasma state is necessary for a variety of disciplines, including astrophysics and magnetic fusion research. Stars, solar winds, and much of interstellar space are examples of matter in a plasma state. Since plasma at very high temperatures is a totally ionized gas, there are very few neutral gas atoms compared to charged particles [6].

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By taking into account the fact that plasma particles have an energy distribution, just like in any gas, the reaction rate parameter that is more appropriate for plasma state can be determined. To put it another way, not every particle has the same energy. The Maxwell-Boltzmann distribution law predicts this energy distribution in simple plasma, and the temperature of gas or plasma is equal to two-thirds of the average particle energy within the proportional constant; i.e., the relationship between the average energy E and temperature T is $E = 3kT/2$, where k is the Boltzmann constant, 8.62 × 10−5 eV per kelvin. The intensity of nuclear fusion processes in plasma is calculated by averaging the product of the particle's speed and cross section over a range of speeds that corresponds to a Maxwell-Boltzmann distribution. The cross section of the reaction is determined by the particles' energy or speed. The averaging process yields a function for a given reaction that depends only on the temperature and can be denoted $f(T)$ [7].

2.4. Fusion Reactions in Stars

The principal energy source of stars, fusion processes also serve as the mechanism for the nucleosynthesis of the light elements. The primary source of energy released by typical stars, like the Sun, with burning core plasma temperatures less than 15,000,000 K, is the creation of helium. However, it is crucial to take into account nuclear interactions between protons and these nuclei since the gas from which a star is produced frequently contains certain heavier elements, particularly carbon (C) and nitrogen (N). The proton-proton cycle is the series of reactions between protons that finally results in helium. The CN cycle must be taken into account when protons also cause the burning of carbon and nitrogen; additionally, the CNO bi-cycle, another alternate scheme, must be taken into account when oxygen (O) is present [8].

In a star that only has hydrogen, the proton-proton nuclear fusion cycle starts with the reaction$H + H \rightarrow D + \beta + \upsilon \ Q = 1.44\ MeV$; here, it is $Q - value$ assumed that the positron will be destroyed by an electron. Due to the abundance of hydrogen, the deuterium could react with other deuterium nuclei, although the ratio is normally kept at extremely low levels (10-18). The next step is $H + D \rightarrow 3He + \gamma$ $Q = 5.49\ MeV$,therefore, which shows that some of the energy yield is carried away by gamma rays. The final link in the cycle is the combustion of the helium-3 isotope, which produces regular helium and hydrogen: $3He + 3He \rightarrow 4He + 2(H)\ Q = 12.86\ MeV$.

Because of its slow reaction rate with hydrogen and the negligibly low concentration of deuterium, helium-3 primarily burns through its own reaction when it is in the equilibrium state. If the temperature rises over approximately 10,000,000 K, the accumulation of helium -4 will cause the interaction with helium -3 to produce heavier elements, such as beryllium -7, beryllium -8, lithium -7, and boron -8.

The stage of star evolution is the outcome of long-term compositional changes. On the other side, a star's size is determined by how thermal plasma pressure and the mass of the star's gravity interact. The burning core's energy is carried to the star's surface and radiates there at a useful temperature. The sun's surface is effectively around 6000 K, and it produces a lot of radiation in the visible and infrared light spectrums.

3. Fusion Reactor and ITER Project

3.1. Magnetic Confinement

More than 100,000,000°C is needed to achieve fusion with DT. Under these circumstances, the atoms split apart to form a plasma, a fourth state of matter that consists of a sea of nuclei and electrons. Since there are no materials that can withstand the temperature of plasma, another method of keeping the plasma contained and under control must be found. The use of a magnetic field is the most effective method.

Magnetic field confinement fusion (MCF) uses a steady magnetic field to effectively confine the motion of charged plasma particles within the magnetic field lines. Researchers have developed a variety of magnetic field arrangements to make the low-density thermal plasma "float" stably away from the container wall for a long time. Under a specific arrangement, the magnetic field lines produce a completely closed nested surface. Researchers have put forward many conceptual designs of magnetic field confinement nuclear fusion devices. Among them, the most mature design is the tokamak device, and the parameters realized by the reactor of the tokamak device are the closest to the success level [8].

3.2. Muon-catalyzed Fusion

Some researchers are looking into alternatives that would enable fusion reactants to get closer to each other at considerably lower temperatures because the conventional nuclear fusion method requires to restrict the very high temperature plasma. One approach is to use muons in place of the electrons that typically surround the fuel nucleus. Similar to electrons in that they are negatively charged subatomic particles, muons are unstable and have a half-life of around 2.2 106 seconds. However, muons have a mass that is slightly higher than 200 times that of an electron. In reality, when muons were added to liquid and gas mixes of deuterium and tritium at cryogenic temperatures, fusion was seen $T \rightarrow 3He + \beta^{-}$.

The process by which a deuteron (deuteron, D+), a triton (triton, T+), and a muon combine to form a so-called muon molecule is known as muon catalytic fusion. The rate of fusion process after the formation of the muon molecule is 3 10-8 seconds. However, a number of atomic, molecular, and nuclear processes are involved in the production of muon molecules, making it a complex process. A muon initially interacts with one of the two hydrogen isotopes in a mixture of deuterium and tritium, generating an atom D+- or T+-, putting the atom in an excited state. Through a cascade collision mechanism where muons can be transported from a deuteron to a triton and vice versa, excited atoms relax to the ground state. More significantly, muon molecules (D+-T+) can also form. Despite the fact that this is a far less common reaction, as soon as the muon molecule is created, fusion takes place relatively instantly, releasing muon into the mixture, which is then again grabbed by deuterium or tritium nuclei, allowing the process to proceed. Muons serve as a catalyst for the fusion reaction in the mixture in this way. To produce enough fusion reactions prior to muon decay is essential for producing realistic energy.

Muon catalytic fusion involves many complex steps, including the production of muons (each muon requires around 5 billion electron volts of energy) and their rapid injection into the deuterium-tritium mixture. Approximately 300 D-T fusion events will occur in the half-life of a muon in order to produce energy greater than that required to start this process.

4. Advantages of Fusion Reactor

4.1. Adequate Supply of Fuel

Deuterium and tritium are isotopes of hydrogen, the most common element in the universe. All hydrogen isotopes have one proton, however tritium and deuterium both have two neutrons. As a result, tritium and deuterium have heavier ions than deuterium, a hydrogen isotope without neutrons. Two protons and two neutrons make up the helium nucleus, which is created when deuterium and tritium combine. High-energy neutrons are released by the process. Our family, business, and other requirements will be met by the fusion power plant's conversion of the energy released by the fusion reaction into electric energy.

Luckily, deuterium is widely available. Deuterium makes up about 1 out of every 5,000 hydrogen atoms in seawater. This means that there are tons of deuterium in the ocean. Just 1 gram of deuterium-tritium fuel may produce the same amount of fusion energy as 2400 liters of oil. In other words, this kind of energy production can replace the original electric system and reduce the problem of the lack of fossil fuel [9].

4.2. Lower Radiation

Radiations like Gamma rays are always a significant problem in nuclear reactions. Those kinds of rays can cause huge damage to human and other animals' cells and even pollute hydrographic nets. However, a fusion reactor can fix those problems with its low radiation and clean power generation process.

Gamma rays in fusion system mainly come from plasma reaction, including fast fusion products of primary reaction. Relativistic electrons hit the metal surface at the edge of the plasma, and then the materials around the plasma are activated by neutrons and undergo nuclear decay. Direct bremsstrahlung (“free-free”) electron collision in plasma is followed by de-excitation of inner shell transition excited by fast electron collision. The flux in operation is much larger than that after shutdown, but there are still physical hazards to health and the burden of radioactive waste. As mentioned above, linear radiation γ -rays (electron X-ray transition from the core or inner shell of heavy ions) is one of the most useful plasma diagnosis methods.

β emission from $T \rightarrow 3He + \beta^{-}$- (t/2= 12.3 yrs, 360 TBq per gram, ~4 kg expected fusion reactor site inventory) is the most important issue for fusion Health Physics and the potential environmental impact. Additionally, it gives chemical reactions energy in materials that are saturated by the, improving diffusion through plastics and, for instance, extracting carbon from steel as heavy methane. The blanket’s and structure’s neutron-activated components mostly contribute to decay heat through emission. However, the tokamak is typically maintained by an electric field acting on the plasma, thus if the ratio of the electric field to plasma density is too high, the extremely energetic “runaway electrons” may be unintentionally generated [10].

Fusion will also produce very high-energy charged products, which are very important for heating plasma, but the radiation is not harmful. The first wall may be damaged if these quick reaction products are lost from the plasma if they emerge in unfavorable orbits, but the loss flux is measured and useful for machine operation. Fast products have the potential to have a secondary reaction that emits a distinctive gamma ray, which is also helpful for diagnosing plasma. Tritium fuel’s most significant radiation is beta radiation, which encourages examination of most reactor safety problems. Radiation is dominating in the health physics of maintenance and radioactive waste problems, however it does contribute to decay heat in activated structures. The tokamak [4] may unintentionally generate a significant number of gamma rays, tens of mev runaway electrons, and even be activated in “non-nuclear” fusion systems. High-energy neutrons and gamma radiation are extremely harmful to most plasma diagnosis systems, but they can help machine control through spectrum and radiation characteristics.

5. Conclusion

Based on the data and principles from previous research, it is can be concluded that nuclear fusion can generate a large amount of energy than other power generate methods and nuclear fusion has a huge potential to supply safe, clean, and unlimited power; has involved much simpler method and devices than nuclear fission. This is not only good for particle physics, but also good for astronomy. Moreover, nuclear fusion has more available prospects such as spacecraft or community electricity consumption in the future. Still, nuclear fusion reminds some problems, like the reliability or the feasibility problem, but with further scientific research giving their certification and more experimental practical uses, those problems would be solved in the not-too-distant future. By that time, nuclear fusion can fit into applications in almost every area. It can provide stable energy for electric vehicles, stimulate the formation of clean power net worker, or even benefits human space exploration as a sustainable power source in space.

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