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Nuclear fusion and nuclear fusion materials

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Abstract. This paper introduces the basic principle of nuclear fusion and the development status of tokamak device, which leads to the core of this paper-nuclear fusion materials. The reason why this paper studies nuclear fusion materials is that up to now, nuclear fusion materials are one of the key difficulties in realizing controlled nuclear fusion. In this paper, the introduction of nuclear fusion materials is mainly the classification of nuclear fusion materials, such as structural materials, first wall materials, etc., and the main materials used in various parts at present. After that, the reasons why nuclear fusion materials are difficult to realize are also introduced. For example, at the point of temperature, the temperature of plasma during nuclear fusion reaction can reach tens of millions of degrees Celsius, while the melting point of tungsten, the known material with the highest melting point, is only over 3,000 degrees Celsius. In addition, the first wall material of nuclear fusion needs high energy resistance.

Keywords: material, nuclear fusion, tokamak.

1. Introduction

With the increasing serious environmental pollution and the gradually shortage of non-renewable resources, the development of emerging energy has aroused widespread interests over world. Among all kinds of the emerging energy, nuclear energy has become one of the most concerned new energy sources because of its advantages, such as environmental protection, high power intensity. Nuclear energy mainly divided of nuclear fission, nuclear fusion and nuclear disintegration. Compared with the nuclear fission, nuclear fusion has many advantages. First, the resource required for nuclear fusion are much better than nuclear fission. Nuclear fusion only needs water, while 70% of the earth is ocean, with plenty of water resources, while nuclear fission needs unrenewable and extremely scarce substances such as Uranium-238. Second, the materials generated after nuclear fusion will not damage the human body and are not harmful to the natural environment. Because the substances produced by nuclear fusion are mostly uncontaminated substances such as helium.. Third, the energy produced by nuclear fusion is far greater than that of nuclear fission. According to the equation E=mc^2 German-born physicist Albert Einstein's theory of special relativity that expresses the fact that mass and energy are the same physical entity and can be changed into each other, there will be released great energy during the nuclear fusion reaction. In addition, nuclear fusion is also known as the king of energy. However, it is very difficult to realize nuclear fusion in a controllable way because nuclear fusion reaction requires extremely high temperature and pressures. For example, the core temperature of the sun is about 1500 degrees, and the pressure is as high as 300 billion standard atmospheres. Therefore, it is difficult to find the proper

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materials that can substance huge temperature and pressure, and it can only last for a very short time (~100s) .

At present, the main form of nuclear fusion device is tokamak. Tokamak is a kind of annular container which uses magnetic confinement to realize controlled nuclear fusion. Its name Tokamak comes from ring, vacuum chamber, magnet and coil [1]. It was originally invented by Azimovich and others of Kurchatov Institute in Moscow, Soviet Union in 1950s. In the center of the Tokamak is a ring-shaped vacuum chamber, with coils wrapped around it [2]. When the power is on, a huge spiral magnetic field will be generated inside the tokamak, which will heat the plasma to a very high temperature to achieve the purpose of nuclear fusion [3].

From the other side. For example, the energy of the sun comes from nuclear fusion, while the surface temperature of the sun is 5,000 degrees But the pressure at the core of the sun is hundreds of billions of times that of the earth, and human devices cannot reach such a high pressure, so the temperature of human nuclear fusion devices is much higher than that of the sun. In June 2020, China's nuclear fusion device will run at 100 million degrees Celsius for 10 seconds. On August 7, 1986, the plasma temperature of Princeton Fusion Reactor in the United States reached 200 million degrees, and it operated at this temperature for 0.3 seconds. In August, 2003, the temperature of the simulated nuclear fusion device in Russia reached 100 million degrees, which was about 8 times the internal temperature of the sun and lasted for 0.3 nanoseconds [4].

2. Nuclear fusion material

On the reactor materials, there are structural materials, heat-carrying materials, insulating materials, magnet materials and shielding materials, among which liquid metal and pressurized water can be used as heat-carrying materials. Insulating materials are usually nylon, epoxy resin and ceramics, while magnet materials are divided into superconducting magnets and conventional magnets. Superconducting magnets are NbTi and Nb3Sn, and conventional magnets are Nb3Gc and V3Ga. In addition, there are some other materials used in nuclear reactors. For example, aluminum alloy can be applied to the first wall of the reactor and the reaction regeneration zone. Compared with stainless steel, aluminum alloy has the advantages of low radiation energy, good thermal conductivity and good processability in reactor application. Secondly, oxide dispersion strengthened steel is also used in nuclear fusion reactors because of its excellent high temperature performance and radiation resistance [5]. Followed by tungsten, which has the advantages of high melting point and high thermal conductivity [6].

At present, one of the key problems restricting the nuclear fusion reactor is the structural material of the first wall of the reactor facing the high temperature plasma, that is, the plasma-facing material (PFM) PFM is the armor material of the first wall, divertor and limiter directly facing the plasma in the magnetically confined controllable thermonuclear fusion reactor. The nuclear fusion device is equivalent to a furnace filled with high-temperature plasma, and the inner wall is the most tested. For the first wall material, there are mainly the following parameters: 1. It will not lose its function quickly in the relatively extreme state of high temperature, strong ionizing radiation and high neutron flux; 2. It is resistant to hydrogen embrittlement; 3. Due to the high nuclear charge, impurities will strengthen bremsstrahlung and affect the confinement effect; the first wall material is either a low-z material such as beryllium or graphite, or a material with high z but relatively difficult to enter the plasma such as tungsten; 4. The resistance cannot be too small. The geometry also needs special design (such as digging holes) to prevent excessive eddy current. Its surface has to bear high temperature and extremely high surface heat load, up to 20 MW, and it also has to bear neutron irradiation with energy as high as 14MeV released by nuclear fusion reaction, and the irradiation amount will reach hundreds of dpa. At the same time, 14MeV neutrons produced by nuclear transmutation reaction and a large number of (N P) of hydrogen and helium will have a great influence on the properties of materials. It can be said that none of the existing materials in the world can meet the working requirements of the first wall. So, what kind of solid material can withstand the impact of a large number of thermal neutrons and the thermal radiation of 100 million degrees without melting or vaporizing? Actually, no.

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So the only way is to exchange space for strength, that is, the solid shell must be far enough away from the nuclear fusion fuel in the center, so far that the inner wall of the shell is hit by thermal neutrons and 100 million degrees of thermal radiation only produces a high temperature of about 3 thousand degrees, so that the solid shell will not be melted or gasified. Because this is the temperature limit that the material solid material can bear. At present, the main first wall material is tungsten. Among the coating materials, the candidate materials are RAFM steel, mechanical alloying ODS steel, smelting ODS steel, vanadium alloy, silicon carbide composite and so on. The following figure shows the composition of these materials. However, in the fusion of deuterium and tritium, reactor fuel tritium is radioactive and highly active, which easily penetrates structural materials, causing fuel loss and radioactive harm to the environment. Therefore, a tritium barrier coating with a certain thickness is coated on the surface of the structure [7].

High-energy neutrons generated by plasma in fusion will cause damage when hitting the first wall material. This phenomenon is called radiation damage. Compared with the mature commercial nuclear reactors (Generation II-III), the structural materials in fusion reactors need to bear higher radiation damage, and the traveling wave reactor (TWR) is three times more than that of fusion reactors. A larger dose of radiation damage will not only cause the material to swell, but also cause the material to fall off in 500 seconds. At present, the austenitic steel commonly used in commercial reactors will enter the rapid swelling range of ~1% volume change/dpa after passing the initial low swelling range, while the volume change of engineering components is generally not allowed to exceed 5%. However, just 5 dpa is enough to exceed 5%, and the dpa requirements of fusion and current commercial reactors are greater than 50dpa. If this 1% swelling trend is maintained, the consequences will be unimaginable. Under the same radiation damage dpa, depending on the temperature when the material is irradiated, the way of material performance degradation is completely different.

High temperature (> 0.5Tm): material embrittlement assisted by helium, which is produced by high-energy neutrons produced by DT fusion and the transmutation reaction of structural materials. Compared with fission reactor, the neutron transmutation reaction cross section produced by fusion reactor is higher and more He is produced, so the problem of He embrittlement is more critical for fusion reactor. Based on radiation damage, many studies have also been done. 1. Compared with fcc (face-centered cubic) metal, bcc (body-centered cubic) metal is more difficult to be irradiated and swollen, so most of the materials being developed now are bcc structure, such as ferrite/martensite steel and vanadium alloy [8]. 2. The metal with 2.hcp structure seems to be related to C/A. Some hexagonal metals have almost perfect radiation damage characteristics, but the processing and smelting costs are very high. 3. The existence of interface can greatly improve the performance degradation caused by irradiation defects, and there is also the demand of creep resistance, so ODS (oxide dispersion strengthening) is also an important design direction. But the cost of ODS steel is several times that of ordinary steel. 4. Compared with ordinary metals, ordered alloys have much stronger radiation damage resistance, but their mechanical properties are poor. Only considering the radiation damage level, only bcc and hcp metals can be used, and there is no prospect of application in other short time. In addition, the cladding of nuclear fusion is extremely complicated. In addition to the first wall material mentioned just now, there are tritium-enriched materials, such as liquid lithium lead. The liquid lithium lead is limited according to the compatibility temperature of structural RAFM steel and LiPb, and the LiPb flows in from the outer tube of the double-layer concentric mother tube and enters the supply box.

1.low temperature (< 0.3Tm): the material loses ductility and strain hardening. Moderate temperature (0.2-0.55Tm): swelling, phase instability and creep accelerated by irradiation.

2. Medium temperature (0.2-0.55Tm): swelling, unstable phase and accelerated creep of materials by irradiation.

3. High temperature (> 0.5Tm): Material embrittlement assisted by helium. Helium is produced by the high-energy neutrons produced by DT fusion and the transmutation reaction of structural materials. Compared with fission reactor, the neutron transmutation reaction cross section produced by fusion reactor is higher and more He is produced, so the problem of He embrittlement is more critical for fusion reactor. Therefore, just because a material has good radiation resistance at low temperature does not

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mean that it is also stable at high temperature. However, because the fusion reactor puts forward a wider "temperature" requirement for the performance of materials than the current commercial reactor, the problem of "temperature" in this field becomes as important as the radiation damage dose dpa.

Controlled nuclear fusion cannot be achieved, and materials must be resistant to neutron irradiation. It is the key problem that affects whether nuclear fusion can be realized.

3. Application of nuclear fusion (example)

Many people think that there is no practical application field of nuclear fusion at present. Actually, it is a current application of hydrogen bomb nuclear fusion, except that hydrogen bomb is uncontrollable nuclear fusion, which is also called fusion bomb. In addition, although the phenomenon of light nuclear fusion was discovered earlier than that of nuclear fission, the invention of hydrogen bomb was much later than that of atomic bomb, and the number of countries mastering hydrogen bomb was much less than that of atomic bomb, which also reflected the difficulty of nuclear fusion conditions. In order to meet the high conditions of nuclear fusion reaction, a small bomb must be detonated inside the hydrogen bomb when it is detonated. The working principle of hydrogen bomb is to use the energy generated by the fusion of hydrogen atoms and their isotopes. As we all know, hydrogen bomb is more powerful than nuclear bomb in the case of the same equivalent, so it can be seen that the energy released by nuclear fusion is much larger than nuclear fission.

But in other civil fields, nuclear fusion has not been applied so far. This is mainly because it is not easy to achieve nuclear fusion and very difficult to achieve controlled nuclear fusion, as it requires extremely high pressure and temperature. This requires extremely high materials for controlled nuclear fusion reactor, and requires extremely high materials science technology of manufacturing process. Even if the materials meet the requirements of temperature and strength, the cost will become extremely high. Moreover, with the improvement of scientists' knowledge of nuclear fusion, we will apply nuclear fusion to power generation in the future, which is very promising. The main application field in the future is power generation. Up to now, many countries have invested in the research and development of controlled nuclear fusion technology. For example, the famous Tokamak device, but because of the extremely high temperature and pressure required for nuclear fusion, the modified device still can't run stably for a long time [3].

Besides, nuclear fusion is also used in Nuclear fission reactors use nuclear fission to generate energy to heat water, so that water boils to generate steam, which drives the turbine to generate kinetic energy. As mentioned above, controllable nuclear fusion can also be used to provide power. Nuclear fusion can generate more energy than nuclear fission with the same raw materials, so if nuclear fusion reactors are used to power ships, etc., they can make the reactors smaller and lighter. But I think controlled nuclear fusion will definitely be used in the field of power generation at the earliest, because the nuclear fusion reactor for power generation is less constrained by its volume and weight, while its volume and weight requirements are higher when it is used as power.

As we all know, the process that the sun releases heat depends on nuclear fusion reaction, why can't we achieve nuclear fusion reactor according to the working principle of the sun in a controlled way as the same as the nuclear power? The sun releases huge energy with its huge volume. The energy released by the sun is 3,860 trillion trillion trillion, and about 0.7 billion tons of hydrogen atoms are converted into about 0.695 billion tons of helium atoms every second, and 5 million tons of energy in the form of gamma rays are released. The volume of the sun is 1.412 cubic kilometers [9]. On average, only one milligram of hydrogen takes part in the reaction in the volume of several billion cubic meters, while the average heat-producing power per ton of the sun is only 0.2 watts. Even if a human nuclear fusion device is created by imitating the sun, this ratio of energy generation is not used for the current level of science and technology and the use of energy [10].

In fact, the discovery of nuclear fusion is earlier than nuclear fission, so it can be seen that the principle of nuclear fusion is not difficult. Besides realizing it, the purpose of human research on nuclear fusion is to use it to create energy, and nuclear fusion must release more energy than nuclear fission while using the same weight of materials, or have other advantages, otherwise it is not cost-effective. It

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can be seen that the difficulty of controlled nuclear fusion lies in how to commercialize it, and the key to commercialize it lies in the input and output of the reaction device. As long as it can’t achieve stable and efficient energy output, it can’t enter the commercial power generation field. Therefore, in order to make nuclear fusion release more energy in a limited volume, we can only increase the temperature and pressure during the reaction, so that more raw materials can react and release more energy. At the same time, with the increase of temperature and pressure, it is necessary to require controllability, which is also a test of human material science. The center temperature of the sun is 22 million degrees Celsius, and the surface temperature is 5,500 degrees Celsius. The material with the highest melting point currently owned by human beings is hafnium alloy, with a melting point of 4,215 degrees. Therefore, even the most heat-resistant materials that human beings have at present can’t meet the surface temperature of the sun.

What’s more, the thermal efficiency of the sun is far from meeting the needs of human beings. However, the plasma temperature of the nuclear fusion reactor that meets the needs of human beings is even tens of millions of degrees Celsius. Faced with this high temperature, the most heat-resistant materials currently available to human beings cannot meet its long-term reaction. If the reactor material is melted, it will lead to a very serious disaster. Besides the temperature, the extremely high pressure in nuclear fusion reactor is also a difficult problem. The pressure at the core of the sun is about 240 billion standard atmospheric pressure. Although the earth cannot create such a high pressure, the pressure requirement of nuclear fusion is still extremely high. Therefore, even from the material point of view, the current technology of human beings cannot achieve controllable nuclear fusion, and it is difficult to meet the requirements of applying nuclear fusion to commercial power generation.

In addition, it is extremely difficult to process the parts of high-temperature and high-pressure reactors, and the requirements for manufacturing technology and equipment are also extremely high. It not only needs materials that can be processed with high temperature resistance and high strength, but also requires extremely high processing accuracy. Besides temperature and pressure, the requirements of ideal nuclear fusion device for vacuum degree, superconductivity and inner wall radiation absorption are beyond the tolerance of modern material science. Therefore, the difficulty of the nuclear fusion device lies not in the nuclear fusion device itself, but in the material requirements of the device. In terms of inertia constraint, laser fusion, particle beam fusion and heavy ion polymerization are suitable for uncontrolled nuclear explosion, and the current laser efficiency is only 1%. For the fuel ball with a diameter of 2~3mm in national ignition facility, USA, if you want to apply it to commercial power generation, you need 1 million lasers every day, and the cost of each laser is about 50 cents, which not only needs to be replaced at any time, but also costs extremely high. It is believed that with the gradual deepening of scientists’ research in the field of materials and the development of laser technology, controlled nuclear fusion will be realized and applied in power generation and other fields in the future, making great contributions to human energy.

4. Conclusion

Through the introduction of nuclear fusion materials in this paper, it can be concluded that the progress of material technology is the most critical factor for nuclear fusion. The first wall material is the most important material in nuclear fusion reactor. Therefore, it can be said that the first wall material is one of the most important points to realize controlled nuclear fusion, and the most difficult performance index is the radiation resistance of the material. Therefore, it can be said that the improvement of the radiation resistance of the material is one of the most important points to realize controlled nuclear fusion.

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