Perspective

Dawn of clean energy: Enhanced heat transfer, radiative cooling, and firecracker-style controlled nuclear fusion power generation system

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Abstract: Global climate change has become a major environmental threat and development challenge facing humanity. Controllable nuclear fusion is a globally recognized ideal solution for clean energy, but its required high-energy triggering conditions and intense energy release prevent existing technologies from achieving safe, stable, and long-term continuous operation. Here, inspired by the traditional Chinese firecrackers, we propose a pulsed fusion reaction flywheel energy storage multi-reactor relay operation to drive the steam turbine to continuously and stably generate electricity for a long period of time; meanwhile, to install cleaning rotors in the cooling medium pipeline to enhance heat exchange, and to apply radiative cooling technology on the surface of the cooling tower to improve cooling efficiency and to reduce energy consumption, thereby improving system safety and overall energy efficiency. Proposing the combination of original technologies at both the hot end and the cold end of the system, we strive to open up a new way for controllable nuclear fusion power generation.

Keywords: principle of firecrackers; controlled nuclear fusion; flywheel energy storage; enhanced heat transfer; radiative cooling

1. Introduction

The rapid development of human society since the modern industrial revolution induced a sharp increase in energy demand, so that fossil energy resources such as coal, oil, and natural gas, which were accumulated in the past billions of years, was exploited in a short period of time. The reserve of fossil energy resources is limited, ,and the combustion produces greenhouse gases and other pollutants. For example, coal combustion produces more than 15 billion tons of CO_2 emissions per year[1]. These issues result in global warming and environmental degradation, a threat like doomsday for many! There is an urgent need to vigorously develop low-carbon clean energy. Nuclear fusion reaction can release a huge amount of energy far more than the nuclear fission reaction. Nuclear fusion reaction process does not emit radioactive pollutants, and the reserve of nuclear fuel deuterium is huge in the widely distributed seawater. Therefore, nuclear fusion has been hailed as “the ideal solution for green and clean energy for mankind”. However, there is still no breakthrough in the major scientific and technological challenge of the effective utilization of controlled fusion, i.e. its safe, stable, and long-cycle operation.

The main types of fusion reactions are deuterium-tritium fusion and deuterium-deuterium fusion, as shown in **Figure 1**. In order for the nuclei to fuse, it is necessary to compress the deuterium and tritium nuclei to within the range of the near-range strong interaction force and to overcome the Coulomb barrier between the nuclei. As a result, fusion reactions can only be triggered at extremely high temperatures (above 100 million °C). Such extreme conditions required for the explosion of a hydrogen bomb are realized by the ignition of a small atomic bomb. In order to peacefully utilize the enormous potential of nuclear fusion reactions, people

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have been conducting difficult explorations for more than half a century, and with enormous investment in international cooperation, a breakthrough has yet to be made, but it has seen the dawn. There are two main technical routes in the global research on controlled fusion, i.e., plasma fusion with magnetic or inertial confinement[2,3]. The research progress is briefly described as follows.

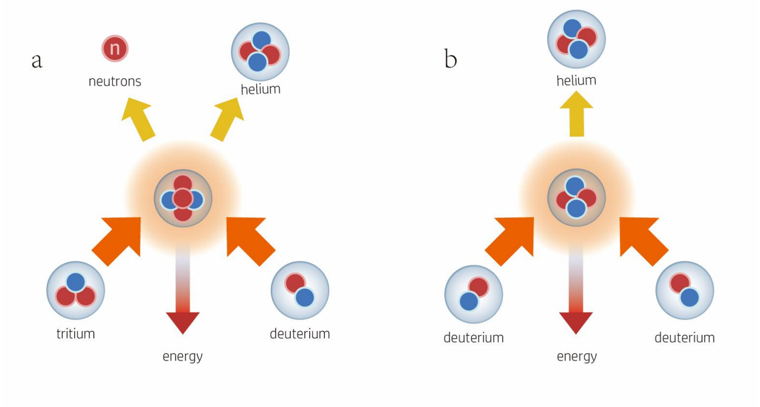

Figure 1. Typical nuclear fusion reaction diagram. **(a)** Deuterium-tritium fusion; **(b)** Deuterium-deuterium fusion.

1.1. Magnetic confinement fusion device

Magnetic confinement fusion requires deuterium and tritium to be heated to a high-temperature plasma state, and the plasma is confined by a strong external magnetic field to ensure that the high-temperature plasma is in a specific region, preventing it from damaging the device. And simultaneously, it reduces the energy dissipation, maintaining the high-temperature state of the plasma, so as to induce continuous fusion reaction[4,5]. Typical magnetic confinement devices include Tokamak, Magnetic Mirrors, and Biomimetic Ring. Currently, the most promising controlled fusion reactor considered is the Tokamak device (**Figure 2a**). Fully superconducting Tokamak devices built worldwide include the Experimental Advanced Superconducting Tokamak (EAST, **Figure 2b**) in China, the Korea Superconducting Tokamak Advanced Research (KSTAR) in South Korea, the JT-60SA developed by Japan in cooperation with Euratom[6], and the International Thermonuclear Experimental Reactor (ITER, still under construction) located in France, and developed by the seven-member entities of the European Union, the European Union, India, Japan, South Korea, Russia, and the United States. The China Fusion Engineering Test Reactor (CFETR) under construction complements the ITER facility[7]. Its first phase aims to initially demonstrate fusion energy production of up to 200 MW and pursue tritium self-sufficiency; the second phase aims to validate fusion nuclear power plant (DEMO) of more than 1 GW of fusion power[8].

China's Experimental Advanced Superconducting Tokamak (EAST) has made a number of research breakthroughs since 2006. The device set a world record of 101 seconds of sustained plasma operation in high confinement mode in 2017, an important advance in sustained stable operation. Subsequently, in 2018, EAST successfully maintained steady-state operation with a plasma center electron temperature of 100 million ℃. By 2021, the device continued to set new records, successfully realizing plasma operation at high temperatures of 120 million ℃ for 101 s as well as 160 million ℃ for 20 s. In 2023, EAST further set a world record for sustained plasma operation up to 403 s in high-power, long-pulse, and high-confinement mode[9]. This series of scientific achievements not only demonstrate EAST's leading position in nuclear fusion research, but also promote the rapid advancement of technologies in several cross-cutting fields, especially superconducting materials, high-temperature plasma diagnostics, and plasma heating and control technologies. In conclusion, EAST has laid a solid foundation for China's research in the field of nuclear fusion and has become an important milestone in the development of global controlled fusion technology.

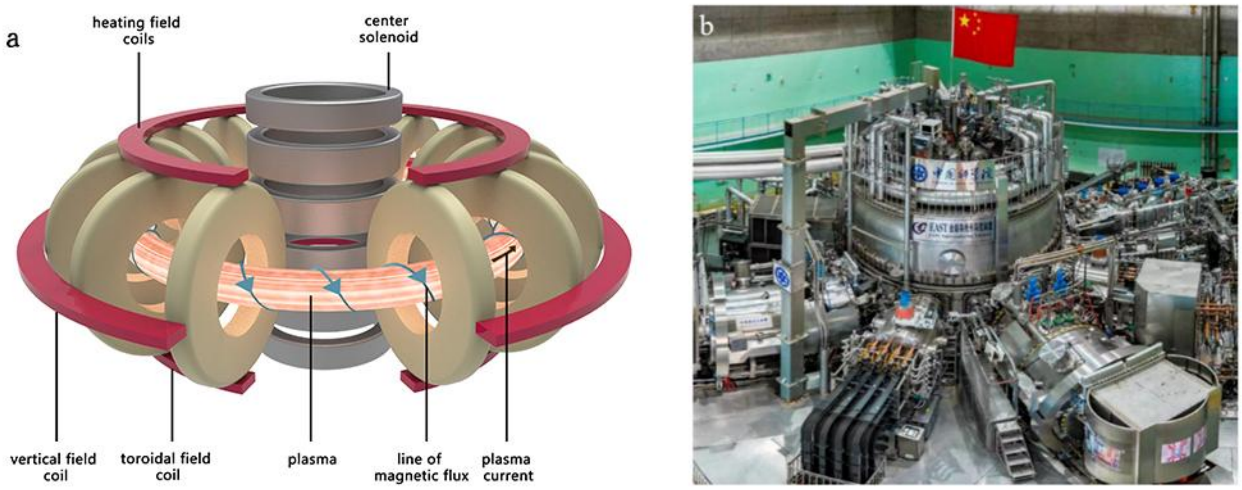

Figure 2. Magnetic confinement controlled nuclear fusion. **(a)** Schematic diagram of the principle of Tokamak devices; **(b)** China's "artificial sun", the Experimental Advanced Superconducting Tokamak (EAST, source: CCTV.com).

1.2. Inertial confinement fusion device

The basic principle of the inertial confinement fusion reaction is to utilize a powerful external energy source to rapidly and uniformly heat and compress a tiny fusion fuel target to an ultra-high temperature and ultra-high density state in a very short period of time, so as to cause a fusion reaction to occur in the plasma under the effect of its own inertia[10]. The advantage of this method is that the fuel inertia is utilized to achieve effective maintenance of the fusion reaction without the need for a continuous supply of external energy. The key to realizing inertial confinement fusion ignition is real-time monitoring, diagnosis, and feedback of the internal information of the target pellet, and then adjusting the driving power application method and the fluid design of the fusion target pellet to reduce the mixing of the absorption layer and the fusion fuel, and to improve the compression symmetry[11]. The specific implementation is laser ignition or electromagnetic ignition.

In the 1960s and 1970s, the Lebedev Institute of Physics in the Soviet Union invested heavily in laser research. At the suggestion of Basov[12], the institute started laser fusion research. They observed fusion neutrons by laser-driven lithium deuteride in 1968, and obtained fusion neutrons by laser ablation of a compressed carbon-deuterium target in 1971. This was the first fusion neutron produced by means of laser fusion[13]. Through these studies, they realized that the use of laser heating alone was not able to achieve energy gain, and gradually figured out the method of driving the implosion through laser ablation, the prototype of direct drive in the laser ignition nowadays (**Figure 3a**). Min Yu, the father of the China's hydrogen bomb, proposed the method of converting laser light into X-ray, the indirect drive. The former uniformly irradiates a number of high-energy laser beams on the surface of the miniaturized target fusion pellet containing deuterium and tritium fuels, which are driven to implosion. Its structural design is relatively simple, without complex conversion process, and with direct and efficient energy transfer. The latter irradiates the laser on the inner wall of the black cavity containing the target fuel pellet. The container is rapidly heated up, and radiates X-rays, which then uniformly heats and compresses the target fuel pellet. Compared to the former, the indirect drive method reduces the requirement for laser uniformity and compresses the target pellet more uniformly, while mitigating possible effects due to irregularities or contamination on the surface of the target fuel pellet[14].

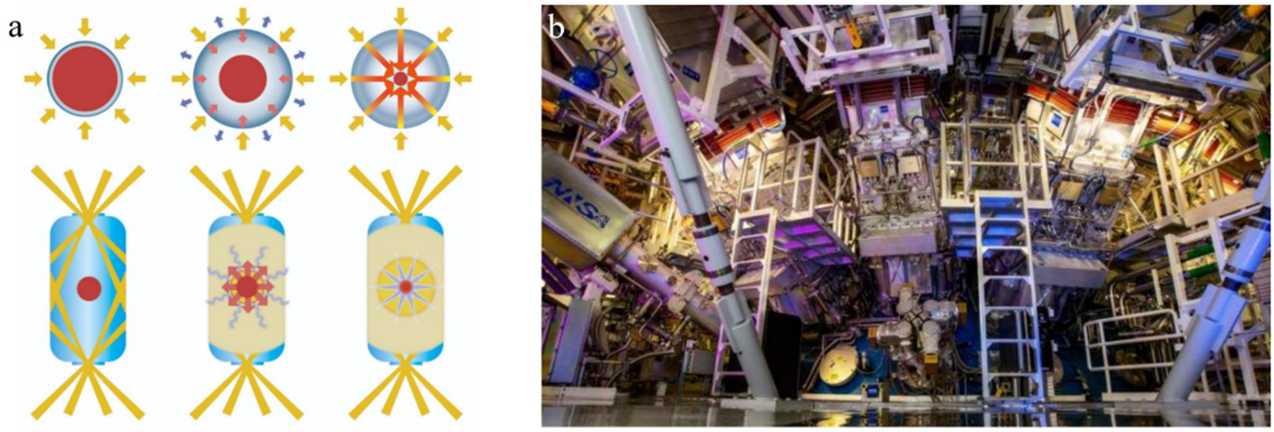

Figure 3. Inertial confinement (laser ignition) nuclear fusion. **(a)** Schematic of laser ignition driven method; **(b)** NIF device (source: Phys.org).

Electromagnetic ignition uses a powerful magnetic field to achieve compression and heating of the fusion fuel. The method places the target pellet in a cage-like structure consisting of multiple coils, which are connected to a pulsed power supply. During ignition, a rapidly changing electric current in the coils generates a rapidly changing magnetic field. The magnetic field induces a corresponding strong eddy current on the surface of the target pellet or within it. The interaction of the strong eddy currents with the externally applied magnetic field compresses the target pellet and initiates the fusion reaction.

Currently, the major inertial confinement devices in the world are the National Ignition Facility (NIF, **Figure 3b**) of Lawrence Livermore National Laboratory (LLNL) in the USA; Laser Mégajoule (LMJ) of France; OMEGA Laser Facility of Rochester Laser Laboratory (RTL) in the USA; Z Pulsed Power Facility (ZPF) of Sandia National Laboratory (SNL) in the USA; GEKKO XII of Osaka University in Japan; and Shenguang-III of China. The USA's NIF device and China's Shenguang-III device are the most powerful ones in operation in the world today. In addition, several other major laser ignition devices are in the construction or planning phases around the world. On December 13, 2022, the US Department of Energy and its affiliate, the National Nuclear Security Administration, announced a milestone: the NIF Laboratory had achieved the first net energy gain in its recent inertial confinement fusion experiments[15], where the energy released from fusion was greater than the laser energy absorbed by the target pellet. On August 6, 2023, the NIF team again announced that their experiment achieved a higher energy output than the previous year. The NIF team has confirmed for the first time that inertial fusion is feasible in principle, marking an important advancement on humanity's path toward realizing controlled fusion as a future energy solution.

In the current global energy field, research on magnetic confinement fusion and laser fusion shows high activity and great potential. That of magnetic confinement fusion is currently focusing on the development and innovation of Tokamak and monomer technologies, especially the multinational ITER project, which has become a milestone project in this field. On the other hand, laser fusion relies heavily on high-energy-density physics research. It is noteworthy that, in addition to the mainstream research institutions, a number of commercial entities are exploring more forms of fusion energy solutions in an attempt to commercialize fusion energy through innovative approaches and technologies.

In short, centered on the ambitious goal of scientific and technological breakthroughs in controlled nuclear fusion clean energy, scientific and technological workers around the world have made great strides after decades of unremitting efforts, undaunted by hardship and the courage to scale new heights. However, in the process of nuclear fusion reaction, the damage caused to the device by high temperature, strong neutron radiation and strong magnetic field is a formidable challenge, so the realization of controlled nuclear fusion technology for safe, stable and long-pulse-cycle operation is still facing great difficulties. In addition, insufficient energy efficiency in thermal management of the system is also a prominent challenge.

2. Flywheel energy storage multi-stack relay firecracker-style controllable nuclear fusion power generation system

We innovatively put forward a solution for the above problem, as shown in **Figure 4**, i.e., the hot end adopts the multi-reactor relay firecracker-controlled fusion power generation system with flywheel energy storage, in which multiple Tokamak fusion reactors are connected in series and fusion reaction occurs sequentially in multiple reactors. The heat released in the fusion reaction is absorbed by the medium in the heat exchanger, which undergoes a phase change and is transformed into the high-temperature and high-pressure gas, which impinges on the turbine to generate electricity, thus realizing the continuous fusion energy output over a long period. The cold end adopts "cleaning rotors" technology with self-cleaning and enhanced heat transfer effects, and radiative cooling technology to reduce the energy consumption during cooling, and to improve the cooling efficiency. The thermal energy released from the fusion reaction at the hot end is efficiently converted through enhanced heat transfer to improve overall energy efficiency, and effective cooling at the cold end enhances the system safety. The specific technical solution is to add "cleaning rotors" to the coolant pipeline, which is both a safety guarantee and a heat-carrying medium, in order to strengthen the heat transfer between fluids inside and outside the pipeline; and to use radiation cooling technology on the surface of the cooling tower to improve cooling efficiency, thus improving the overall system safety and energy efficiency. Our innovative clean energy technology portfolio is expected to facilitate the early application of controlled nuclear fusion technology, thereby realizing the ambitious goal of "carbon peaking and carbon neutrality" in the new era and promoting the low-carbon, green, and sustainable development of the global economy and society.

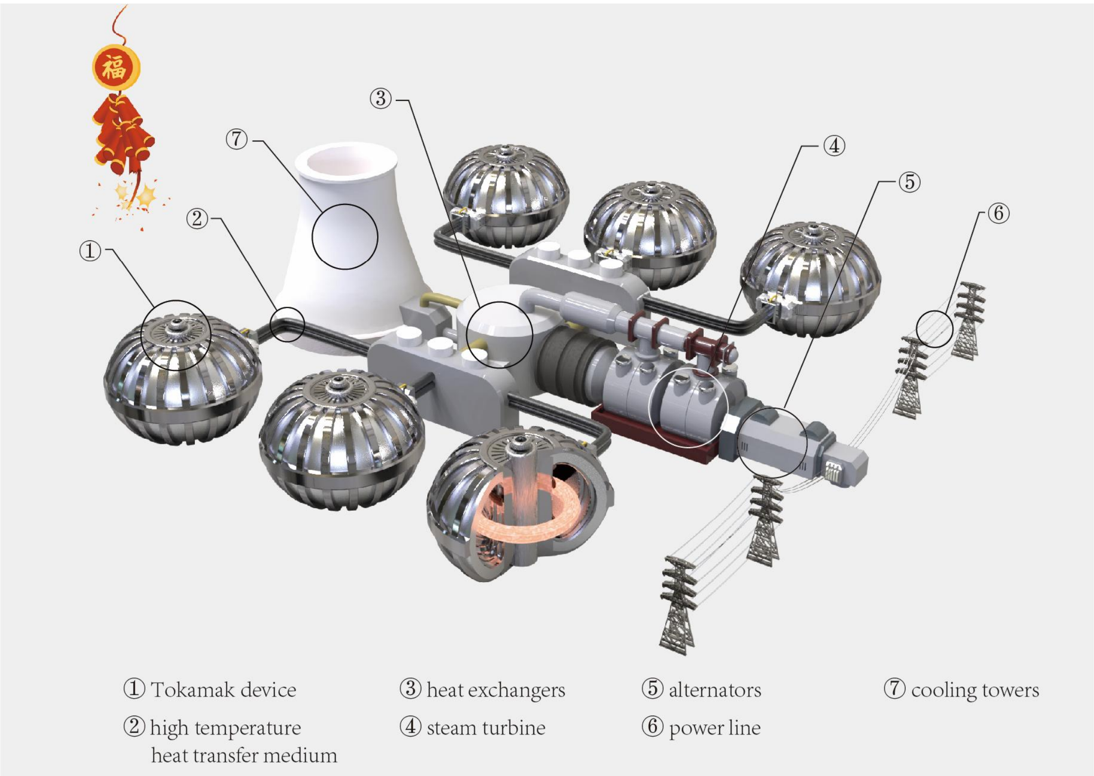

Figure 4. Schematic diagram of "firecracker-style" controlled nuclear fusion power generation system.

The flywheel energy storage multi-heap relay firecracker-style controlled fusion continuous power generation technology that we have innovatively proposed has two schemes, namely, the pulsed fusion reaction flywheel energy storage multi-heap relay continuous power generation technology, and the microfluidic deuterium-tritium collision fusion flywheel regulation continuous power generation technology. The former takes the flywheel as the energy transfer medium, the high-energy laser as the ignition device, and the deuterium-tritium fuel fusion inside the target pellet as the driver, realizing the conversion of nuclear energy to electric energy, and guaranteeing stable and controllable fusion reaction of the whole system. The latter adopts the high-energy gas pedal to accelerate the nucleus collision to realize fusion, and through controlling the amount of the plasma of the input nuclear fuel each time, it can regulate the occurrence of the nuclear fusion reaction and the degree of intensity. The flywheel energy storage is also used as a regulator to realize peak load shifting of the pulsed fusion energy output.

2.1. Pulsed fusion reaction flywheel energy storage multi-stack relay continuous operation

In view of the current problem that fusion reactors cannot be operated for a long period of time, our team, inspired by the continuity of traditional Chinese firecracker explosions, has originally proposed the "pulsed fusion reaction flywheel energy storage multi-reactor relay operation[16]" method, which can drive a turbine to generate electricity continuously and stably over a long period of time. As shown in **Figure 5**, more than two Tokamak fusion devices are set up at the hot end of the nuclear power system, and the fusion reaction occurs in sequence. A part of the energy collected from each fusion device is temporarily stored using a flywheel system, and the rest is used to generate electricity. After the previous Tokamak device operates to its limit time and stops reacting, the energy stored in the flywheel is then used to drive the next Tokamak device to carry out fusion reactions, and so on. The logic of this method is similar to the continued explosion mechanism of firecrackers, i.e., to store part of the energy of the previous firecracker explosion and to use it to ignite the next firecracker. Each short pulsed fusion reaction is analogous to the explosion of an individual firecracker, and the flywheel serves as the fuse connecting the firecrackers. The introduction of this method turns on the independent "firecracker" explosion process in series turning discrete events to continuous one. which shifts peak load of thermal energy released from the pulsed fusion reactions, consequently to reduce the load on the pressure vessel and the fatigue damage, achieving transformation of discrete fusion energy to the continuous steady-state energy output.

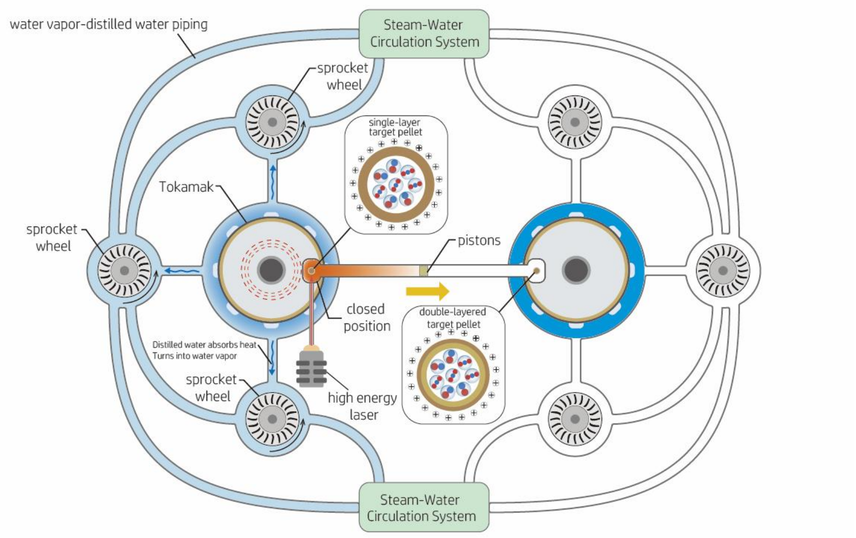

Figure 5. Schematic of the pulsed fusion reaction flywheel energy storage multi-reactor relay operation [16].

2.2. Microfluidic particle cyclotron accelerated collision fusion reaction

The single “firecracker” of the firecracker-style controlled fusion power generation system described in this work is not limited to Tokamak devices, but can also be a particle cyclotron collision fusion reactor. As shown in **Figure 6**, the device includes a particle collision reaction system, a water circulation cooling system, a power generation system with flywheels as means of energy storage and control, a particle cyclotron, a steam guide pipeline, a pump, a distilled water charging pipeline, a distilled water delivery pipeline, a magnetohydrodynamic power generation system, and a particle transfer channel. Quasi-totally reflective and spherical center focusing device is used to partially reflect the radiation back to the fusion reaction area for maintaining the temperature being above the critical temperature to keep the fusion reaction going. The ionized trace nuclear fuel plasma fluid is injected into two particle cyclotrons separately[17]. When accelerated to the desired energy, these high-speed particles are shot into the fusion furnace cavity. The two beams of particles meet and collide inside the cavity, forming a high-temperature and high-pressure plasma cluster. At the same time, the plasma mass is compressed by regulating the external magnetic field, so that the electromagnetic energy is rapidly converted into the internal energy of the plasma, which further raises the temperature and pressure of the plasma to reach the critical conditions for fusion, thus triggering nuclear fusion. This scheme uses a particle cyclotron to provide the energy required for fusion, i.e., particle cyclotron acceleration and regulation by flywheel energy storage, which connects discrete collisional fusion reactions in series into a firecracker-style sustained energy output. Obviously, the cyclotron-accelerated collisional electromagnetic ignition fusion device introduced here can also be replaced by a laser ignition fusion device or other fusion devices capable of sustaining short-lived operation.

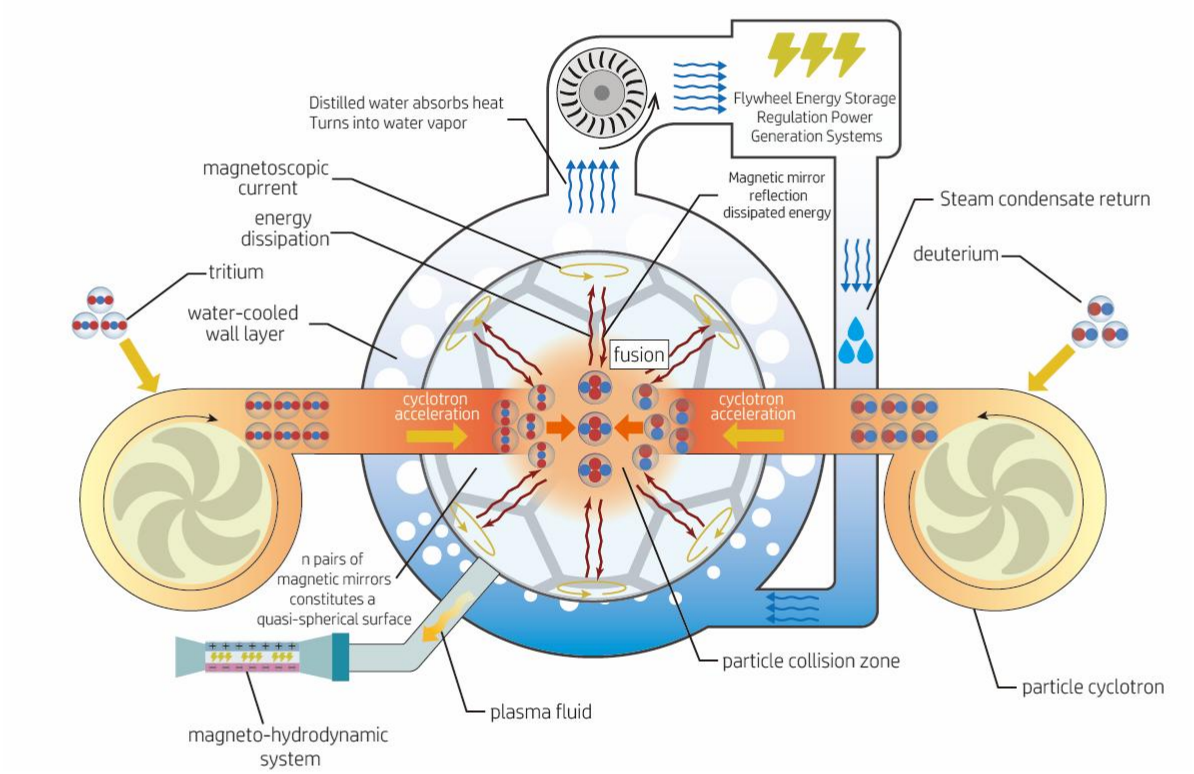

Figure 6. Schematic of particle cyclotron acceleration colliding fusion reaction[17].

2.3. Implications for the design of a firecracker-controlled fusion system

Prolonged operation at the extremely high temperatures generated by the nuclear fusion process can damage the device,or even melt the equipment. This innovative idea adopts a series of connected pulsed fusion reaction units with enhanced heat transfer and rapid cooling, and a flywheel energy storage and control system, which ensures that when one unit needs to be cooled, another unit can provide energy output, thus transforming the discrete energy output into a continuous and stable supply of energy, fulfilling the requirements of large-scale power grids.

In summary, the “firecrackers” model provides a new solution for mastering controlled nuclear fusion, but this solution still requires in-depth validation, analysis, and further research by experts in the industry to assess its practical application potential and value.

3. Enhanced heat transfer and radiant cooling

3.1. Enhanced heat transfer in condensers

In nuclear fusion technology, the cooling system is crucial. The extreme high-temperature conditions inside the fusion furnace require the use of advanced cooling systems to efficiently transfer the heat generated by the plasma to the outside, thus realizing the conversion of nuclear energy to electrical energy[18]. In addition, prolonged exposure to high-temperature conditions may gradually deteriorate and damage the materials inside the reactor, and an efficient cooling system ensures the integrity of the materials inside the reactor, which in turn prolongs the operation time of stable reactor. Liquid metals (e.g., lithium)[19] are widely used as cooling media in the core area of a Tokamak device, especially in the first wall and the deflector. This is mainly due to the excellent thermal conductivity and heat capacity of liquid metals, which ensure that heat can be conducted and dispersed quickly and efficiently, thus avoiding overheating inside the device. More critically, the ability of liquid metals such as lithium to neutralize energetic hydrogen and tritium ions[20] as they flow over the surface of the first wall, significantly reduces damage to the internal structure of the device as well as the potential for leakage of radioactive material. The fluid characteristics of liquid metals, especially their continuity and uniformity, mitigate the effects of localized thermal stresses brought about by high heat flux, which in turn provides a solid guarantee for the stability and long-term operation of the integrated device.

Bergles[21] argued that enhanced heat transfer techniques should be extended to new applications. Although liquid metal itself has superior cooling performance, with the progress of fusion technology and the pursuit of higher power output, enhanced heat transfer technology needs to be introduced. Reasonable evaluation criteria for enhanced heat transfer have been a pressing challenge for research scholars. Webb and Eckert[22] first established the evaluation criteria for enhanced heat transfer technology. Zimparov[23] proposed the criteria for enhanced heat transfer effectiveness at constant heat flux and at constant wall temperature. According to the integration of the energy equation in the range of the thermal boundary layer, Guo et al.[24–27] concluded that reducing the angle between the velocity vector and the temperature gradient can effectively strengthen the convective heat transfer process, i.e., the field synergy theory, which has been well developed in recent years. Tao et al.[28] conducted numerical simulations to investigate the flow and heat transfer processes in an alternating flow slit-type heat regenerator, and further verified the field synergy theory. Their simulation results show that the field synergy principle can be used to guide the enhanced heat transfer in the alternating flow process. He et al.[29] analyzed the synergistic relationship between the flow and pressure fields based on the synergistic flow and temperature fields. Xia et al.[30] proposed an dimensionless performance factor based on the field synergy theory for evaluating the comprehensive effect of enhanced heat transfer on surfaces. Weimin Yang et al. have carried out long-term research on enhanced heat transfer in shell-and-tube heat exchangers, and have successively completed a number of research projects such as the Beijing Natural Science Foundation and the “Twelfth Five-Year Plan” National Science and Technology Support Program (**Figure 7**), etc., and have invented the “cleaning rotor” technology, which is a self-cleaning and enhanced heat transfer technology for unit-combined rotors. The “cleaning rotor” unit combination rotor self-cleaning enhanced heat transfer technology[31]. “Cleaning rotor” improves the heat transfer effect by changing the flow pattern of the medium, through forming a rotating flow, destruction of the boundary layer, replacement of the fluid at the center of the tube and that near the wall, and producing secondary flow, etc., thus improving the internal heat exchange of the fluid. The rotating movement of the “cleaning rotor” also thins out the boundary layer, improving the heat transfer coefficient at the wall. The self-cleaning principle is to increase the turbulence of the fluid so as to increase the stripping rate while decreasing the deposition rate of dirt[32]. The “cleaning rotor” is made of polymer material with the advantages of lightweight, corrosion resistance, self-lubrication, long service life, etc. The structure of the combined units with connection of flexible shaft can adapt to the bending, and thermal expansion and contraction of the heat transfer tube. The streamlined design of the rotor minimizes the resistance to the flow of media in the tube. Yang et al.[33] and Li et al.[34] studied the performance and economy of the condenser of the Second Datang Jiamusi Power Plant after installing the combined rotors. The industrial application test showed that the vacuum of the condenser was increased obviously, indicating an apparent effect of enhanced heat transfer and self-cleaning of the combined rotors.

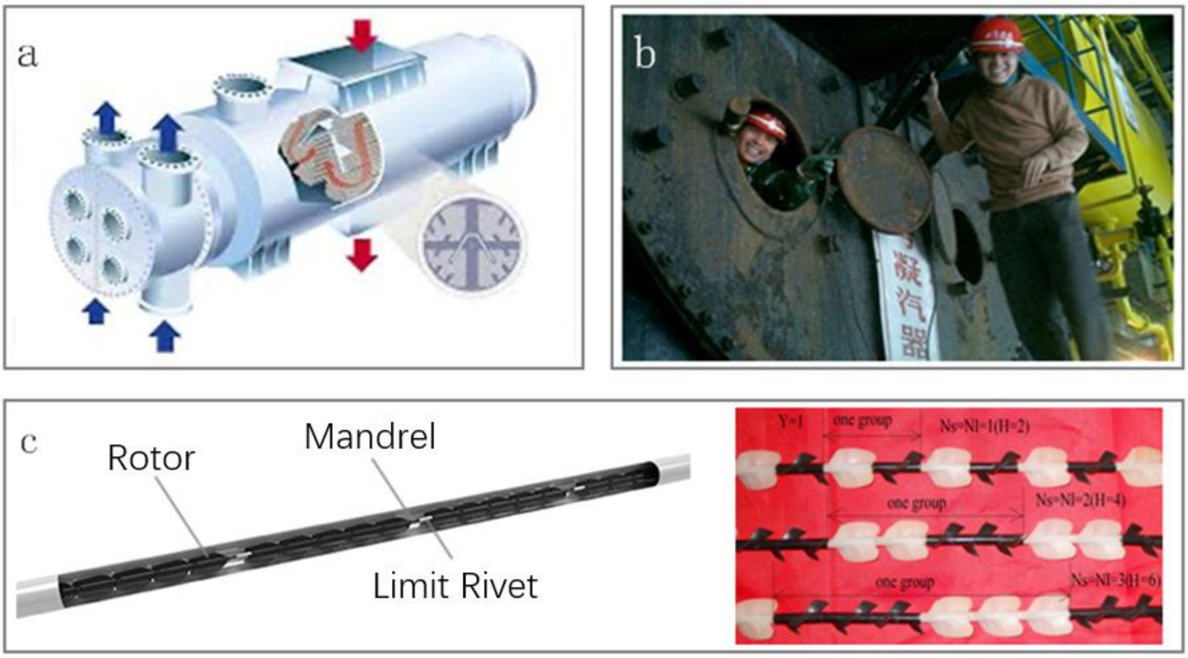

Figure 7. “Cleaning rotors” enhanced heat exchange. **(a)** Schematic diagram of condenser structure; **(b)** Installation of “cleaning rotors” in condenser piping of 600,000 kW unit (Weimin Yang on the LHS of the panel); **(c)** “cleaning rotors”, the left picture shows the schematic structure of “cleaning rotors”, and the right picture shows the combination of different rotor types.

Therefore, considering the special requirements of the fusion device mentioned above, we innovatively propose a technological solution of adding a rotor inside the cooling pipeline with liquid metal to enhance the heat transfer in a synergistic manner, which can reduce the thickness of the thermal boundary layer formed on the pipeline wall, and accelerate the heat exchange between the coolant and the pipeline wall. The enhanced heat transfer technology with “cleaning rotors” is expected to provide an optimized solution for thermal management of the Tokamak systems.

3.2. Passive radiative cooling for cooling towers

The safety and security of the fusion system require efficient cooling of liquid lithium by the cooling water, and the technological innovation of the cooling tower is of great significance. For this reason, we propose to utilize passive radiative cooling technology on the cooling tower to achieve cooling to a temperature lower than the ambient temperature without energy consumption (**Figure 8a**). This can also improve the energy efficiency of the overall system.

Unlike traditional cooling methods, passive radiative cooling technology is an emerging green method in recent years that requires no energy input, without use of refrigerants, no pollution of the environment, and with zero carbon emission, thus receiving increasing attention[35–43]. The second law of thermodynamics indicates that heat is spontaneously transferred from high-temperature objects to low-temperature ones. Heat can be transferred between objects with temperature differences by radiation in the form of electromagnetic waves. The temperature of the outer space is as low as about 3 K (about −270 °C)[44], which is close to absolute zero and can serve as an excellent cold end. As shown in **Figure 8b**, radiative cooling materials can reflect away the radiation in the sunlight band (0.3–2.5 μm) and emit the thermal radiation from the cooled object as mid-infrared rays (8–13 μm) that can penetrate the atmosphere into outer space, achieving spontaneous cooling[45–47]. High-performance radiative cooling requires both high reflectivity in the solar spectral band and high emissivity in the atmospheric window.

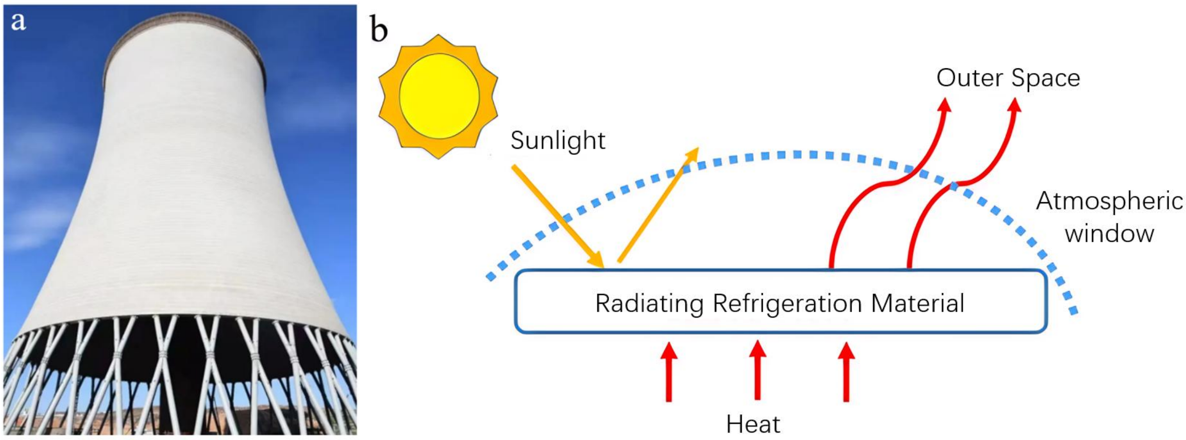

Figure 8. Radiative cooling of the cooling tower. **(a)** Cooling tower (source: Sohu, Polaris Power Network); **(b)** Schematic diagram of the principle of spontaneous refrigeration.

Through interdisciplinary research, the team has explored the optical and thermodynamic mechanisms at the micro- and nano-scale, and innovatively developed multistage porous micro- and nano-structured thin films with high solar reflectivity and high infrared emissivity. The pores of micrometer to nanometer scale can effectively reflect the sunlight energy in the visible wavelength band and reduce the temperature rise of the object, and also enhance the emissivity of the polymer in the atmospheric window, thus strengthening the radiative cooling performance. We combined the "rainbow silk" melt differential electrostatic spinning technique (**Figure 9a**), a specialty of our team, with nanofluidic technology to blend polymers and inorganic micro- and nano-particles to form composite particles for electrostatic spinning. Micro-nano bubbles were introduced by ultrasonic cavitation after the composite particles were melted. So novel composite electrospun films were prepared by adding inorganic scattering particles[52,53] with micro-nano bubbles[54–59] (**Figure 9b**). The cooling performance of the films was enhanced after a series of experiments, simulations, and process optimization. The microstructural morphology of the film was measured by using electron microscopy (**Figure 9c**), and the reflectance (99.2%) to the solar spectral band and emissivity (95%) to the atmospheric window band was measured by applying UV spectrophotometry and Fourier-transform infrared (FTIR) spectrometry. As can be seen in **Figure 9d**, the emissivity of the fabricated sample in the atmospheric window band is much higher than that of the aluminum alloy at the same temperature. After building an outdoor temperature measurement platform, the temperature drop and cooling power of the film were tested. A sub-ambient cooling of about 10 °C was achieved, and the cooling power was more than 100 W/m^2. A square meter of the radiative cooling thin film can save electricity of 928.5 kWh per year, which will bring great safety, environmental, and economic benefits if widely applied to the nuclear power system.

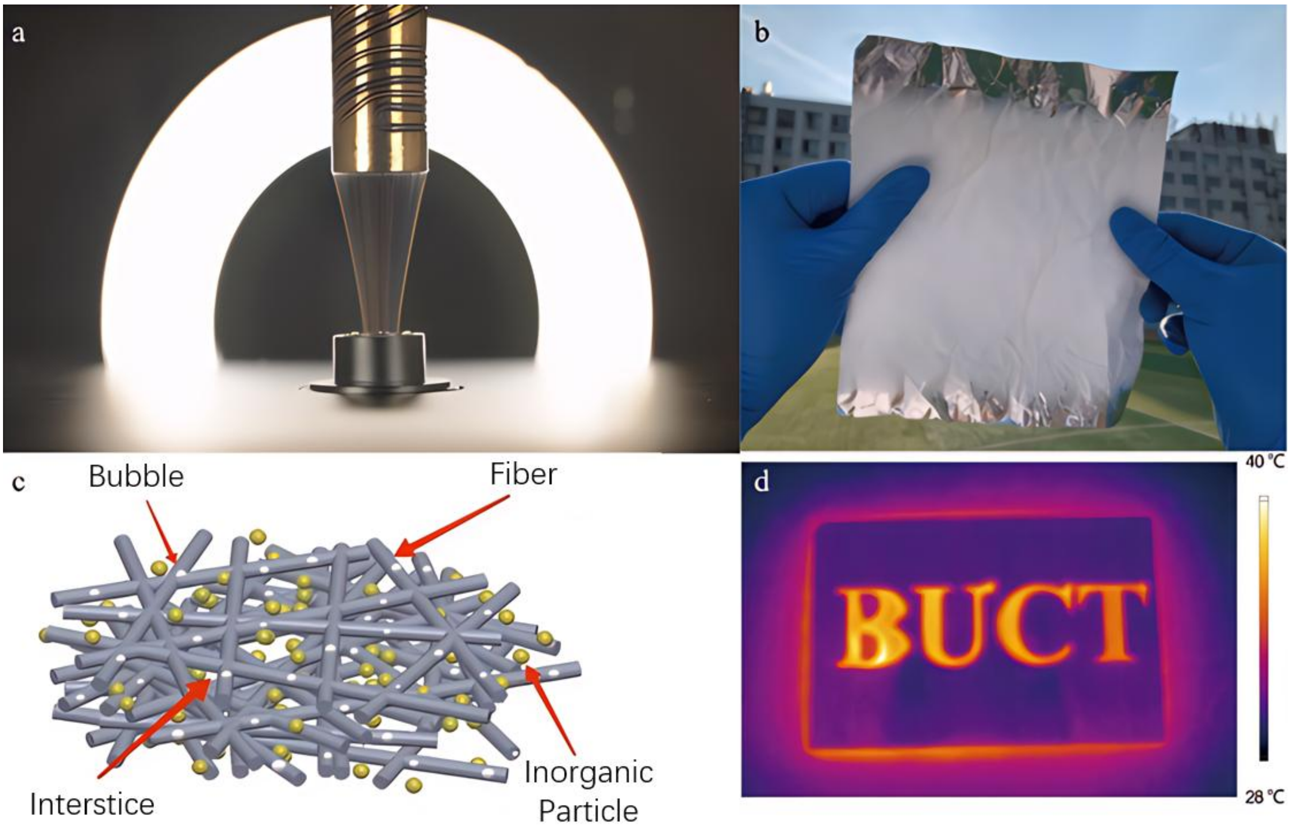

Figure 9. "Rainbow silk" nanofiber composite radiative cooling membrane. **(a)** Microdifferentiated electrostatic spinning of a rainbow filament melt; **(b)** Appearance of a radiatively cooled film; **(c)** Schematic diagram of the microstructure of a radiatively cooled film; **(d)** Infrared imaging of a radiatively cooled film at the same temperature with a sheet of aluminum alloy with a skeletonized BUCT lettering.

4. Conclusion and future direction

Controlled nuclear fusion is an important research area in clean energy science and technology. Worldwide hard exploration of more than half a century has raised hopes. In recent years, many countries have reported on the latest research progress, ranging from China's full superconduction Tokamak record of long-cycle operation, to the first net energy gain realized through laser ignition in the United States. However, feasible technological solutions for controllable fusion power generation with continuous long-cycle operation have never been reported, and solutions for thermal management and high energy efficiency of fusion power generation systems are also rarely reported.

To this end, we propose a technical program for a firecracker-style controllable fusion power generation system to ultimately achieve industrialized application in the future of safe, stable, long cycle continuous power generation of through the flywheel energy storage and regulation of multiple fusion units in series relay operation. Additionally, an optimization scheme of enhanced heat transfer and radiative cooling is proposed to enhance the efficiency of the thermal management system, by applying the "cleaning rotors" inside the heat exchanger pipelines to realize self-cleaning and enhanced heat transfer, and applying the "rainbow silk" nanofiber radiative cooling film on the cooling tower of the power generation system. Such scheme can open up a new path for the realization of high-efficiency collection, conversion and utilization of nuclear fusion energy.

In the future, accelerating the development of controlled fusion technology will require the joint efforts of scientists and technologists around the world. By supporting the validation and prototype development of innovative technology solutions, and with the aid of artificial intelligence and digital twin technology, it is hopeful to innovate and develop an industrialized controlled fusion power generation system, and finally to realize the vision of supplying humanity with low-carbon, green and clean energy by an "artificial sun".

Author contributions

Conceptualization, WY; methodology, WY, EZ, ZZ, YC and XL; investigation, EZ, JZ, YZ, KT, CL and XG; writing—original draft preparation, WY, EZ, JZ, YZ, KT and FZ; writing—review & editing, WY, FZ, CL and XG; visualization, EZ, YZ and JZ; supervision, WY; project administration, WY and FZ; funding acquisition, WY and FZ. All authors have read and agreed to the published version of the manuscript.

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Conflict of interest

The authors declare no conflict of interest.

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