Development Prospect and Application of Nuclear District Heating in China

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Abstract. With the increase of heating demand, in order to further expand the heat source channels and promote China's clean heating work, this paper investigates the development status of nuclear regional heating at home and abroad, explores the development prospect of China's nuclear heating industry, and discusses the difficulties encountered in the future application and the corresponding solutions. The research results show that China's nuclear heating has broad development prospects, but there are some problems in the construction of regional heating network and the safety, reliability and economy of nuclear power plant operation, and put forward targeted solutions, so as to promote the wide application of nuclear regional heating and realize the sustainable development of economy.

Keywords: Nuclear energy · District heating · Clean heating · Advantages

1 Introduction

The heating area in northern China has reached more than 13 billion square meters, increasing at a rate of 5%–10% per year, resulting in an increasing heating gap in many cities [1]. At present, the main heat sources used are cogeneration units and regional boiler rooms. The fuels used are still mainly fossil fuels such as coal and natural gas, which has brought great pressure to the atmospheric environment and resource supply. As a clean and efficient energy, nuclear energy is a major component of China's energy structure. At present, it has been widely used in power production. From January to June 2022, the cumulative power generation of the nuclear power generating units in operation nationwide was 1989.99 billion kWh, an increase of 2.00% over the same period in 2021 [2], but it is rarely used in the field of regional heating. From the perspective of energy utilization and green development, it is necessary to explore the prospect and application path of nuclear energy in the field of regional heating, which is of great significance to the sustainable development of central cities in heating regions in northern China.

Therefore, from the perspective of sustainable development, this paper explores the development prospect of China's nuclear energy heating industry on the basis of investigating the application experience of nuclear energy district heating at home and abroad, and discusses the difficulties encountered in the future application and the corresponding solutions, so as to further expand the heat source channel, and make contributions to improving the effective utilization rate of energy and building an environment-friendly and resource-saving society.

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2 Development Status of Nuclear District Heating at Home and Abroad

Nuclear heating is not a new concept. As early as half a century ago, there were nuclear reactors for civil nuclear heating in Europe, mainly deployed in Russia, Ukraine and Bulgaria, Georgia, Czech Republic and other countries. Due to the climate, the demand for heat supply is large and widely distributed, and the heating network is relatively developed, which provides a prerequisite for the development of central heating [3]. With the peaceful application of nuclear energy in power production, Switzerland, Bulgaria, Hungary, Finland and other countries have conducted research on nuclear heating reactors to meet the demand of urban central heating. For example, two 365 MWe pressurized water reactor nuclear power plants of Beznau nuclear power plant in Switzerland began to provide district heating for 11 surrounding cities in 1983 and 1984; The Kozloduy nuclear power plant in Bulgaria has supplied heat to the city of Kozloduy since 1990; There are four VVER-440 units in Paksh nuclear power plant in Hungary to supply heat to Paksh city [4–8]; Finland provided a comprehensive district heating application scheme for the first time in the project design stage [9]; The Bohunic nuclear power station in Slovakia not only generates electricity, but also supplies heat and industrial steam to the city of Ternava. The former Soviet Union, Canada, France and other countries developed district heating as an important part of the energy system, conducted fruitful research and development on the special low-temperature heating nuclear heating reactor, and successively built a series of verification and demonstration reactors [10]. SAFA's research shows that the nuclear reactors currently in operation can effectively realize large-scale district heating through transformation, which opens up a new path for the efficient utilization of energy in the future [11].

By 2022, there are 438 nuclear reactors in operation in the world, with a total installed capacity of 393.3 GWe, of which 56 units support regional heating, more than 10% of the total, mainly distributed in cold European regions [12]. Heating reactor types include pressurized water reactor, heavy water reactor, graphite water cooled reactor, fast reactor, etc., with thermal power output between 5–240 MW. The total distributed thermal power is about 5000 MW, and the average energy recovery rate is less than 5% [13]. In many cases, heat is used to supply nearby cities several kilometers away from the nuclear power plant.

In China, the history of research and development of nuclear heating reactor can be traced back to the 1980s. In 1983, Tsinghua University realized the first nuclear low-temperature heating experiment in China on the pool research reactor; In 1984, the State Science and Technology Commission approved the construction of a 5 MW nuclear heating test reactor [14] in the Nuclear Energy Institute of Tsinghua University; Since 1986, low-temperature nuclear heating has been officially listed as the national "Seventh Five Year Plan" science and technology project; In 1989, the 5 MW low-temperature nuclear heating reactor was officially started up, and then the 72 h full power continuous operation experiment was successfully completed [15]; In 2017, CNNC took the lead in making a breakthrough in nuclear heating and released the "Yanlong" reactor with a thermal power of 400 MW [16]. "Yanlong" is a safe, economic, green and environment-friendly reactor product developed by CNNC for the heating needs of northern cities on the basis of the safe and stable operation of the pool type research reactor for more than

50 years; In 2019, the first commercial nuclear heating project in China, the first phase of the first phase of Shandong Haiyang nuclear heating project of State Power Investment Group Co., Ltd., was officially put into use, covering an area of 700000 m^2. The heating range is the staff dormitory and more than 30 surrounding residential areas; In 2020, the National Nuclear demonstration organization held the feasibility study review of CAP1400. The maximum extraction capacity of the nuclear heating project is 800 t/h, which is designed in combination with the future heating planning of Weihai City, and is expected to be the main heat source of central heating.

Through the research on the development status of nuclear district heating at home and abroad, it is found that the development of nuclear district heating in foreign countries started earlier and the related technologies are relatively mature, and large-scale district heating has been realized. Its technology and development strategy have certain reference significance for China; Domestic nuclear heating started late and has not been widely used nationwide. However, the theoretical foundation has been established through the research of test reactor. Various enterprises are also actively promoting nuclear heating projects and continuously accumulating practical experience to provide a solid foundation for the promotion and application of nuclear heating. Therefore, nuclear district heating has a broad development prospect in China.

3 Advantages of Nuclear District Heating

At present, there are two ways of nuclear district heating in China. One is the single heating mode. The reactor in this mode does not need to generate electricity, and can be designed with smaller power and lower parameters. Generally, the heating capacity of a single module is about 200 MW, which is suitable for cities or counties with small heating area and small population [17]; The other is the nuclear power cogeneration mode, which extracts part of the heat from the steam turbines of large nuclear power plants and provides heat while generating electricity. It is suitable for cities with large population. Compared with traditional coal-fired and gas-fired heating, nuclear heating has significant social and environmental benefits, without any smoke, ash, carbide, sulfide and nitrogen oxide emissions. It is a truly “zero emission” energy technology. Nuclear district heating has advantages in technology, environment and energy utilization, which are mainly divided into the following points.

3.1 Technical Advantages

For the single heating mode, the technical advantages of nuclear heating are mainly manifested in low-temperature heating. In traditional boiler heating, the fuel combustion must maintain the high temperature of the furnace, even if the supply of low-temperature heat cannot be reduced. The nuclear fission reaction reacts at any temperature. If only low-temperature heat is required, the reactor can work at low temperature and low pressure, which can simplify the reactor structure, improve safety and reduce cost. In addition, nuclear power is transformed from nuclear power, which will release a lot of heat during the reaction process, and the direct utilization of reactor heat energy can be fully realized.

Due to the technical characteristics of low-temperature heating, the nuclear heating reactor has the characteristics of low operation cost, convenient maintenance, long service life, high safety, strong adaptability to the plant site, technically canceling off-site emergency, etc. it can be close to users and built in the plant site areas around the city and in remote inland areas, thus making it possible to supply electricity, heat, water and cold energy. After the batch and modular construction, the construction and deployment time of the nuclear heating reactor will be greatly shortened. It can be completed in only 2–3 years, and its economy will be improved.

3.2 Environmental Protection Advantages

Compared with fossil energy heating, nuclear heating has significant environmental benefits. It is estimated that a 200 MW nuclear heating reactor can meet the winter central heating demand of about 7.5 million square meters, and can replace 160000 t of coal or 80 million m^3 of gas every year. Compared with coal, it can reduce the emission of 1600 t of smoke, 50000 t of ash, 260000 t of carbon dioxide, 3000 t of sulfur dioxide and 1000 tons of nitrogen oxides. Compared with natural gas, it can reduce carbon dioxide emissions by 130000 t and nitrogen oxides by 500 t. The emission of radioactive substances is only about 2% of that of coal [16].

At present, the heat source of heating in China is still cogeneration and regional boiler room, and the fuel used is still coal. The emission of coal is the main cause of winter haze in northern China. If nuclear heating is used to undertake the basic urban heat load, it can not only solve the shortage of heat sources, but also achieve clean heating, so as to alleviate the winter haze in northern cities, which is of great significance for urban development and environmental protection.

3.3 Energy Utilization Advantages

For the nuclear district heating mode of cogeneration, any heat extracted from the secondary circuit will reduce the power output of the nuclear power plant, but the increase of thermal power will compensate for the power loss. According to the energy and exergy analysis, under the cogeneration mode, the performance of the nuclear power plant can be improved by 5–10%. Improving the energy utilization is a major achievement of nuclear cogeneration [18–20]. For the single heating mode, reactor heat can be directly used for heating. Compared with the conversion of heat energy into electric energy, the efficiency of direct heat utilization will be higher. Based on the two methods, district heating can improve the energy efficiency of nuclear power plants and realize low-cost heating network.

To sum up, nuclear district heating has advantages in technology, environmental protection and energy utilization. Compared with traditional coal-fired heating, the pool type low-temperature heating reactor reactor has a service life of 60 years, and the construction investment is about 2 to 3 times that of coal-fired boilers of the same scale. However, the operating cost is much lower than that of coal-fired boilers, and the service life reaches 60 years, which is 2 to 4 times that of coal-fired boilers. It is economically feasible [21].

Therefore, from the aspects of technology, environmental protection and energy utilization, nuclear heating is the development direction of regional heating in China in the future, and has broad development prospects.

4 Problems and Solutions of Nuclear District Heating

Based on the above analysis of the advantages of nuclear district heating, nuclear district heating is an effective means to achieve green development and efficient operation, and has a good development prospect. However, the progress of nuclear heating with many advantages is very slow, and there are many difficulties in its application in China at present. Through the study of the domestic status quo, this paper discusses the specific problems existing in the field of nuclear district heating in China, and draws lessons from foreign experience, puts forward practical and feasible solutions to promote the clean heating work in China and promote the popularization and application of nuclear district heating.

4.1 Selection of Reactor Type Scheme

In terms of reactor type selection for district heating, the heat sources of nuclear district heating in Eastern European countries are large-scale commercial reactors with mature technology, which have a large heating range, form economies of scale, and adapt to the cold climate and intensive heating demand in Eastern Europe. However, the application of large-scale reactors in regional heating in China is very limited, mainly for two reasons: first, China's nuclear safety regulations require that the radius of the planned restricted area of large-scale nuclear power units should be at least 5000 m. When nuclear power plants are used for heating urban residents, they should be at least 10 km away from the development boundary of cities and towns with a population of more than 100000 and at least 25 km away from the development boundary of cities and towns with a population of more than 1 million, Thus, the number of heating residents around large nuclear power plants is limited; Secondly, in terms of the scale of heat sources, the current power of China's main heating units is between 200 MW and 300 MW, and the power of large-scale commercial reactors is about 1000 MW, which is too large for regional heating capacity.

In recent years, the concept of small reactor has been put forward internationally. The small reactor is a 330 MW integrated pressurized water reactor developed by KAERI (Korea Atomic Energy Research Institute) together with domestic users and suppliers for power generation, seawater desalination or district heating [22, 23]. Different from the traditional large-scale pressurized water reactor, the small-scale reactor installs the core, steam generator, pressurizer, control element drive mechanism, main coolant pump and other main components in a steel pressure vessel. This innovative and progressiveness overall arrangement enhances the safety, reliability, performance and operability of small reactors, and has been fully proved in the commercial operation of foreign power reactors.

Although small reactors lack the economies of scale of large reactors, due to their system simplification, reactor system modularization, component standardization, factory manufacturing and easy on-site installation, the installation cost of large pipelines and valves is reduced, and their small floor space also reduces the construction cost and improves the economy of the reactor to a certain extent. On the other hand, small-scale reactors have small thermal energy storage and less decay heat after shutdown. Moreover, passive safety systems are widely used, with high safety performance. Theoretically, they can be built around densely populated areas such as large cities. Small-scale reactors are more suitable as heating sources in urban areas.

The modular small reactor ACP100, modular high temperature gas cooled reactor HTP-PM and 200 MW low temperature heating reactor currently being developed in China belong to the category of small reactors and have the potential to be applied to urban heating. As for the heating mode, the longest heating period in northern cities of China is only 6 months. If the simple heating mode is adopted, the economic competitiveness is poor, and the domestic thermal power cogeneration mode is more suitable. Therefore, it is relatively reasonable for China's nuclear power district heating to adopt the scheme of small-scale reactor cogeneration with high safety.

4.2 Construction of District Heating Network

At present, nuclear power plants are mainly used for power production. For safety reasons, their location is far away from residential areas, so they need a long district heating network. China has not yet developed a heating network, but there is a mature heating network in the cold northern region of Europe. Considering the climate, population density, energy price and other factors, the proportion of citizens for district heating increases from south to north, and the heating network is mostly distributed in areas with high population density and low energy availability.

The operation mode of heat supply network is similar to that of power grid. A large thermal transmission line is transmitted to the secondary pipeline and finally to the local distribution network at the customer's end. The district heating network sector benefits from improved communication, control and regulatory systems. For example, sensors that detect leaks or hot spots can relay this information to the control room to improve maintenance. However, the construction cost of heat transmission trunk line is high, which will determine the economic feasibility of the project. However, with the rise of energy prices, the demand for heating in the region is also rising. The combination of cogeneration plant and district heating is an efficient heating method, which can keep the heating price of users at a reasonable level.

According to the characteristics of heat supply areas in China, the cold regions in the north have a large population and dense urban buildings, which are suitable for the development of central district heating. The heating network can start from small and scattered, and then gradually grow and connect with each other over time, thus avoiding the need for a large amount of initial investment.

4.3 Operation and Coupling of Nuclear Power Plant

The nuclear district heating technology has not yet had mature commercial operation experience in China. The coupling technology between the reactor type itself and the heat supply network is one of the difficulties. The main challenge is to prevent radioactive substances from entering the heat supply network. Referring to the experience of foreign district heating, the nuclear power plant can be coupled to the district heating system by referring to the mode of cogeneration power plant. First, multiple closed loops are set between the primary loop of the reactor core and the end user to prevent the risk of radioactive contamination. Secondly, a specific loop is set to separate the user from the main heat transfer loop. Thirdly, an isolation valve is set on the main transmission circuit to prevent any material exchange between the reactor and the local power distribution network. Finally, ensure that the water pressure in the main transmission circuit is higher than the steam pressure, so as to prevent the secondary steam from entering the heat transmission circuit in case of accidental leakage of the hot water heat exchanger pipe.

By taking the above defensive measures, even if the reactor steam generator and water heat exchanger leak at the same time, the reliable operation of the nuclear power district heating system can be ensured.

4.4 Safety of Nuclear Power Plant

Although the safety of nuclear district heating is basically the same as that of nuclear facilities, there are some specific safety problems in the coupling between nuclear power plants and district heating systems. In the cogeneration mode, unlike nuclear power generation, which uses seawater, rivers or cooling towers as cooling, the heat transfer network system also plays a major role in cooling. Any failure, such as pipe rupture or heat exchanger defect, will affect the cooling performance of nuclear components. On the other hand, due to its huge heat capacity, the heat transmission line also provides an alternative radiator for the nuclear power plant. In this sense, the district heating cogeneration facility can even improve the safety level of the nuclear power plant. In addition, small reactors are in the initial stage in China and around the world. Although most of the current small reactor schemes apply the passive concept, simplified system design and mature equipment, and the theoretical core melting probability is very low, the safety still needs to be verified by demonstration projects.

At present, Liaoning, Shandong and other provinces in China have begun to build large-scale nuclear power projects, which can be used as the transition of small-scale reactor district heating. Nuclear power plants under construction or to be built in the north can be selected as the pilot of cogeneration, and relevant mature technologies in the world can be used for reference to heat the living quarters in the plant area or small towns around the power station. Through the pilot, the safety of the coupling technology between the nuclear power plant and the thermal pipe network can be verified, and the nuclear engineering experience can be accumulated for the subsequent gradual promotion of the coastal small reactor project.

4.5 Economy of Nuclear Power Plant

According to relevant foreign studies, the total cost of district heating system can be divided into design cost, investment cost and operation cost [24]. Design cost refers to the expenses that must be paid before the construction stage, such as market research, safety analysis, public acceptance survey, etc. The investment cost refers to the construction and installation cost of infrastructure, such as the transformation of the secondary circuit of the power plant, the laying of the heat transmission pipeline, the connection of the distribution network, etc. Operation and maintenance costs refer to the expenses related to the operation and maintenance of the project, such as the salaries of operation and maintenance personnel, maintenance expenses, etc. Different from nuclear power generation, district heating needs to lay a thermal network, so the construction cost of thermal transmission pipeline is a part that needs to be paid attention to in the future, and the economic benefit can be improved by controlling its cost. At the same time, the preliminary planning and design should be connected and coordinated with the built heating pipelines to lay the foundation for the systematic and large-scale development of the municipal heating network and improve social benefits to a certain extent.

The nuclear district heating technology has little commercial operation experience in China. At present, there are no relevant regulations and technical regulations. If the technical specifications of nuclear power generation reactor are simply applied, it will have an impact on the economy. Relevant departments can improve the laws, regulations and standard system of nuclear heating reactors through scientific evaluation of small-scale reactor demonstration projects, large-scale reactor cogeneration, large-scale nuclear power generation and other projects. In addition, compared with large reactors, if small reactors are used for district heating, the unit construction cost will rise due to the decline of reactor scale, and the economy will face greater challenges. Therefore, in the early stage of the development of nuclear district heating, it needs the strong support of the state and the government to increase subsidies, so as to make nuclear district heating competitive in the market.

5 Conclusions

As a safe and efficient clean energy, nuclear energy has multiple advantages of low-carbon and clean heating, simple system and high energy utilization rate, which can effectively alleviate the increasingly severe atmospheric environment problems caused by the burning of fossil energy. Exploring nuclear regional heating is of great significance for the sustainable development of central cities in North China's heating regions. From the large number of operating experience of nuclear heating units in the world, nuclear district heating, especially cogeneration, is technically mature and safe. Therefore, China has the conditions and technologies for urban nuclear district heating, which can be transformed into scientific and technological achievements suitable for domestic development on the basis of existing nuclear technology and international experience. Nuclear district heating has broad development prospects.

The small-scale reactor under development in China has the characteristics of systematic modularization and small scale. It is likely to be arranged around large cities as a regional heating source. It is a promising heating reactor type. The scheme of small-scale reactor cogeneration for nuclear district heating in China is relatively reasonable, but it still faces great challenges in terms of safety, economy and reliability, which brings difficulties to the application of nuclear district heating.

In order to effectively deal with the difficulties faced by the development of small-scale reactor combined heat and power supply and promote the application and popularization of nuclear heating, this paper puts forward practical suggestions: a) reasonably plan the heating pipeline according to the needs of users, change from small scattered to interconnected, and gradually improve the construction of regional heating network; b) The multi loop loop circuit is designed to realize the coupling between the nuclear reactor and the heat supply network and improve the reliability of the operation of the nuclear power plant; c) Select large-scale nuclear power projects as the pilot of cogeneration, gradually promote the small reactor type heat supply project, accumulate engineering experience, and improve the safety of nuclear power plants; d) Select reasonable pipeline materials and laying methods, control the cost of thermal transport pipelines, and improve the economy of nuclear power district heating system. Through the above measures, promote the popularization and application of nuclear district heating, and realize low-carbon economy and green sustainable development.

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