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Research on Heat Load Optimization and Cogeneration of Heat and Power Based on Nuclear Energy Heating

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Abstract:

Compared with the traditional heat and power generation, the nuclear energy co-generation method follows the principle of energy cascade utilization and energy quality matching, which avoids a large amount of cold source loss in condensing power plants, greatly improves the thermal efficiency of the power plant, and makes energy efficient and efficient. Clean Lee. As far as my country's national conditions are concerned, under the premise of the current national energy structure adjustment and the solemn commitment to energy conservation and emission reduction, the development of nuclear energy cogeneration is an important long-term strategy for national energy conservation and emission reduction, and nuclear energy cogeneration has an increasingly prominent position in the national energy strategy. Nuclear energy is a clean energy in the true sense, and its advantages such as environmental protection, high energy density and stability are the starting point of nuclear energy heating technology research. At present, China's nuclear energy heating technology is in its infancy, and a series of in-depth studies are pending in design, construction, operation management, standards and specifications. This project analyzes in detail the key technologies of China's nuclear energy heating and its main technical parameters, including the low-temperature nuclear energy heating reactor and the extraction steam heating technology of the steam turbine unit of the nuclear power plant. The mutual reference and analysis of the ventilation technology standardization of China's nuclear power plants are carried out, and relevant suggestions are put forward to further improve the HVAC standards and fire protection specifications of China's nuclear power plants. The optimal basic heat load ratio of the low temperature nuclear energy heating reactor is obtained by research and calculation. On the basis of analyzing the contradiction between supply and demand of low-temperature nuclear energy heating reactors in China, a method for determining the thermal load ratio of low-temperature nuclear energy heating reactors based on the reactor power adjustment range and thermal load duration map is proposed. Aiming at the problem of low central heating load in China's non-heating period, measures to improve the heat load factor of low-temperature nuclear heat supply reactors are proposed, including cross-season heat storage system, combined heat supply and seawater desalination, and combined cooling and heating technology. The multi-factor and multi-level orthogonal test analysis was carried out on the optimal thermalization coefficient of nuclear energy cogeneration, and the sensitivity ranking of the key influencing factors of the optimal thermalization coefficient of nuclear energy cogeneration was determined.

***Keywords**: Low temperature nuclear energy heating reactor; nuclear energy cogeneration; basic heat load; thermalization coefficient.*

I INTRODUCTION

1.1 Research background and significance

Heat production and heat supply are necessities in the northern winter heating area. In the energy consumption structure of human beings, heat energy consumption accounts for a huge proportion of energy consumption. With the rapid development of industry, air pollution is becoming more and more serious, and air quality is deteriorating. Therefore, it is necessary for human beings to research and develop new energy sources to replace traditional fossil energy sources[1]. Today, every country in the world is actively looking for clean heat sources, and the international energy structure is developing in the direction of diversification. In recent years, with the rapid development of China's economy, the volume of cities has been expanding year by year, and the heating demand of northern cities has also continued to expand[2].

1.2 Development and research status of nuclear energy heating technology

The study of the world's nuclear energy heating system began in the 1950s when the power station was officially operated as the world's first commercial power generation nuclear reactor. In 1954, the former Soviet Union's Obninsk nuclear power In 1959, Cederall proposed the Swedish nuclear energy planning policy[3]. At that time, the main purpose of Sweden's nuclear energy planning was to reduce the dependence on imported oil, and planned to use nuclear reactors for central heating or power generation[4]. In 1964, the world's first nuclear energy heating project was put into use in Agesta, a coastal area in Sweden, which was also Sweden's first commercial nuclear power plant. The electrical power is 10 MWe-12 MWe[5].

In the early stage of the development of nuclear energy heating technology, technicians studied the possibility of using the waste heat of large nuclear power plants for central heating. In 1964, the former Soviet Union proposed a nuclear heating technology scheme. In 1966, the Zheleznogorsk Mineral Chemical Plant (underground nuclear power plant) used the waste heat of the Huai production reactor for heating, and fully assumed the heat and electricity supply of the nearby Zheleznogorsk city (about 100,000 people). The nuclear power plant and heating system operated for about half a century until it was shut down in 2010 due to the Russia-U.S. agreement on the peaceful use of atomic energy. In 1969, Miller of the U.S. Department of Energy's Oak Ridge National Laboratory proposed a nuclear energy cogeneration system (as shown in Figure 1.1). Preliminary research results show that the system can utilize the heat of the back pressure steam turbine unit of the nuclear power plant or the secondary circuit of the nuclear power plant. Provide most of the heat energy for the heating system or air conditioning system of the nearby cities, reducing the waste of heat energy in nuclear power plants[6-10].

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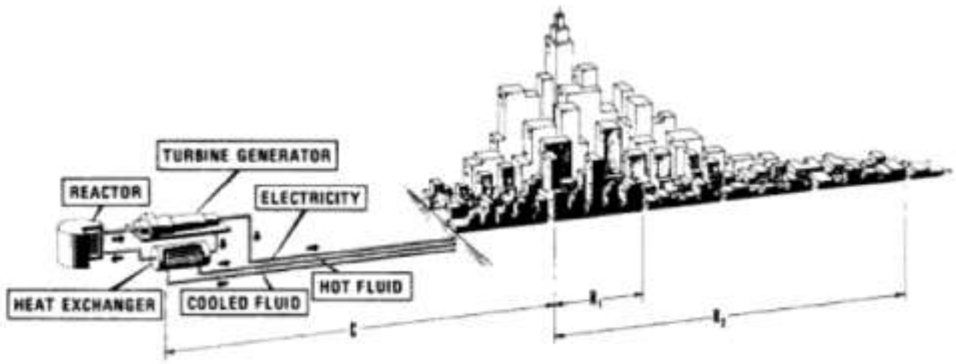

Fig.1 Map of the city near the nuclear power plant

1.2 Basic heat load of nuclear heating system

How to determine the basic heat load ratio of nuclear energy heating is one of the most critical issues in nuclear energy heating technology. Since the capital construction cost of nuclear energy heat sources is much higher than that of conventional heat sources, full load of nuclear energy heat sources is the most reasonable operating state. At the same time, the heat load of the central heating system has obvious seasonality. The heat load in winter often exceeds the heat load in summer, and the nuclear safety requirements are strict, and the nuclear reactor regulation method is much more complicated than the conventional heat source. Therefore, it is necessary to determine a reasonable nuclear energy heating system. The heat load is the key to ensure the efficient operation of the nuclear heating system[11].

In 1975, Lyon et al. studied the Canadian CANDU nuclear energy cogeneration heating system, put forward a suggestion to track the common heat load of nuclear reactors, and proved that the thermal storage system can help to regulate the load of nuclear reactors[12]. Nilsson et al. conducted a detailed technical analysis of the SECURE nuclear energy heating station developed in Sweden and Finland. The annual heat load demand of the nuclear energy heating station and the continuous time diagram of the temperature of the supply and return water of the central heating system are shown in Figure 2[13]. The design maximum water supply temperature reaches 120°C. Under the condition that the nuclear reactor bears the basic heat load, the nuclear energy heating station operates at full load for 4000-5000 h within a year, which is a reasonable operating state of the nuclear energy heating station[14].

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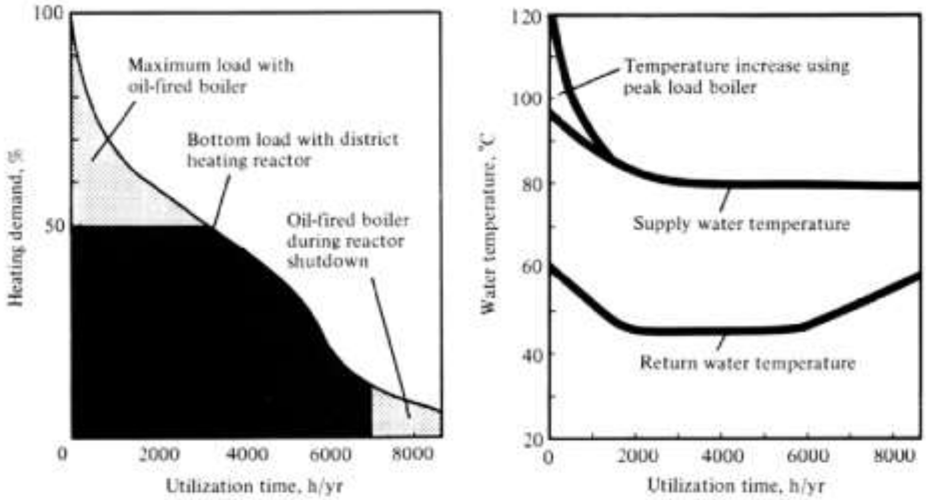

Fig. 2 Continuous time diagram of annual heat load demand of SECURE nuclear heating station and temperature of supply and return water of central heating system

II SUMMARY OF KEY TECHNOLOGIES FOR NUCLEAR ENERGY HEATING

2.1 Key technologies of nuclear energy heating

2.1.1 Low temperature nuclear energy heating reactor technology

The former Soviet Union began to build two low-temperature nuclear heating plants in Gorky and Voronezh in the 1980s. The AST-500 heating reactor used is a 500 MW boiling water reactor, and its working principle is shown in Figure 3[15]. Since the nuclear energy heating reactor does not need to generate electricity, it is only used for heat supply, so compared with the traditional nuclear reactor, the low parameters of the primary circuit (T=208 ℃, P=1.96 MPa) improve the system safety, and the nuclear energy heating station can be located in cities and towns Nearby, and the low-parameter operation of the primary circuit provides the possibility to "recycle" the waste nuclear fuel of traditional nuclear power plants. For example, the waste nuclear fuel of the Russian VVER-1000 reactor continues to be used in the AST-500 heating reactor, which can operate 10’000h or more. The nuclear heating station has a design life of 60 years[16].

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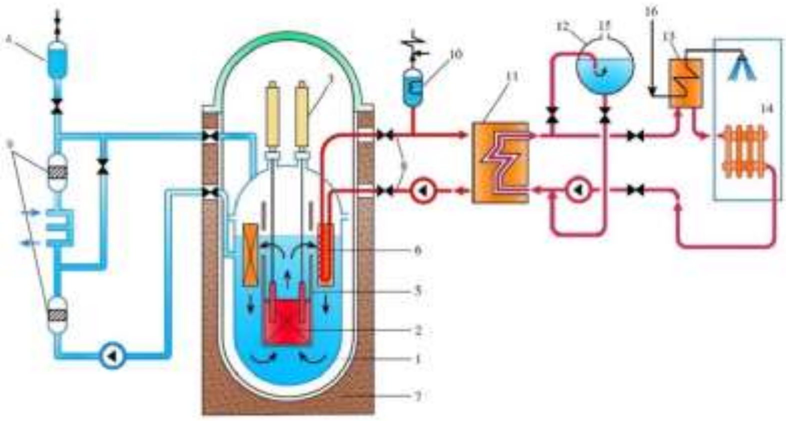
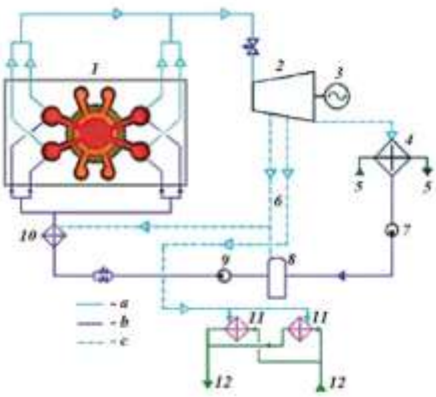


1 Reactor shell; 2 Reactor core; 3 Regulator; 4 Boron solution system; 5 Safety vessel; 6 Secondary circuit heat exchanger; 7 Reinforced concrete shaft; 8 Secondary circuit piping; 9 Primary circuit coolant bypass filter ;10 Volume compensator of secondary circuit; 11 Heat exchanger for heating pipe network; 12 Reactor emergency cooling system; 13 Thermal power station; 14 Heat users; 15 Steam; 16 Tap water

Fig. 3 Schematic diagram of AST-500 system

2.1.2 Key technologies of floating nuclear thermal power plants

At present, France, South Korea, and the United States are all developing floating nuclear thermal power plants. However, only Russia has reached the stage of construction and implementation of floating nuclear thermal power plants[17]. The overall appearance of Russia's "Academician Lomonosov" floating nuclear thermal power plant is shown in Figure 4.



1 Reactor; 2 Turbine; 3 Generator; 4 Main Condenser; 5 External Water; 6 Turbine Extraction; 7 Condensate Pump; 8 Degasser; 9 Feed Pump; 10 Feed Water Heater; 11 Heat Exchanger for Heating System ;12 heating system water

Fig.4 Thermal system diagram of floating nuclear thermal power plant

The floating nuclear thermal power plant is established on the basis of years of experience in the

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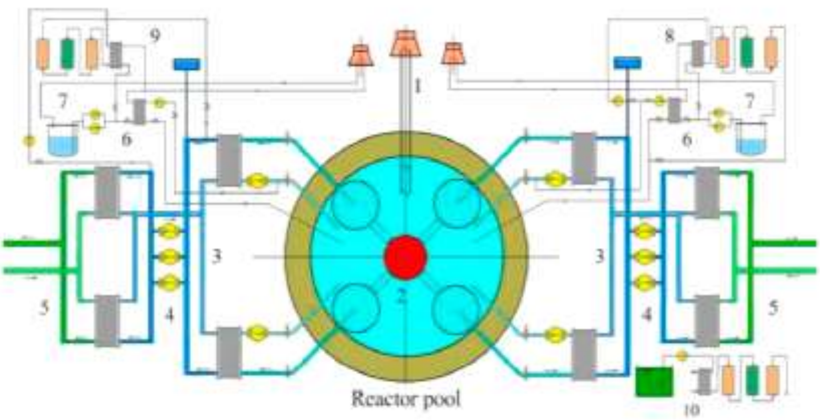
Russian nuclear power fleet[18-20]. The former Soviet Union and Russia have years of experience in operating nuclear power fleets, which can ensure the high safety and reliability of floating nuclear thermal power plants. The heat transfer facility includes 4 DN350 hoses to ensure the reliability of heat transfer under conditions such as shaking, high tide, low tide, and surge. The power transmission equipment is an iron beam placed in the middle of the floating thermal power plant and the concrete foundation on the shore. The iron beam can be turned horizontally and vertically, and the wires are erected in the cable tray. The natural water area for the construction of the floating nuclear thermal power plant shall have sufficient area and depth. In the water area, maintenance craft ships are also required, such as power transmission equipment, engineering equipment, transportation, and heat energy conversion stations for heat transmission. The mooring equipment and the safety equipment of the floating thermal power plant can firmly maintain the stability of the floating thermal power plant under the following conditions: The main function of the auxiliary buildings on the shore is to ensure the process cycle and auxiliary function of transferring electric energy and thermal energy from the floating thermal power plant. The floating nuclear thermal power plant requires only 69 workers[21].

2.1.3 Swimming pool low temperature nuclear energy heating reactor

The core of the swimming pool nuclear reactor is placed in the depth of an atmospheric pool, and the static pressure of the water layer is used to increase the water temperature at the core outlet to meet the heating demand. The schematic diagram of the thermal system is shown in Figure 2.8. The core of the pool-type low temperature nuclear energy heating reactor is always in a submerged state, which can ensure that the core is not exposed and has zero reactor melting under accident conditions[22]. The swimming pool is buried in the upper soil, and the pool wall can be a reinforced concrete upper wall or a leak-proof stainless steel wall. Earthquake, flood, wind protection and other protection measures in case of emergency are designed according to local conditions. The swimming pool type nuclear energy heating reactor adopts a three-circuit system, the parameters of the primary circuit are low (T=100 ℃, P=0.32 MPa, and the supply/return water temperature of the heating circuit is 90/60 0C, which is suitable for low-temperature heating pipe network The pressure of the secondary circuit as an isolation circuit is higher than that of the primary circuit and the heating circuit to ensure that the radioactive water does not leak into the heating network[23].



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1 cooling of swimming pool water; 2 core; 3 primary circuit; 4 secondary circuit; 5 heating network; 7 cooling water; 8 primary circuit filtration system; 9 secondary circuit filtration system; 10 waste soda water treatment system

Fig.5 Thermal schematic diagram of swimming pool type low temperature nuclear energy heating reactor

The design life of the pool-type low-temperature nuclear energy heating reactor is 4060 years, and the long life of the system makes the pool-type low-temperature nuclear energy heating reactor more economically competitive than traditional heat sources. In the initial stage, the pool-type low-temperature nuclear energy heating reactor is set up near the town, which can ensure the high safety of the heating reactor[24]. After studying the geological conditions of Shijiazhuang, Harbin, Lanzhou, Jinan, Qingdao, Hangzhou and other cities, it is proved that the foundation conditions of most Chinese cities meet the requirements of swimming pool-type low temperature nuclear energy heating reactors. Therefore, the pool-type low-temperature nuclear energy heating reactor has good site adaptability, high heat network adaptability, and no large-scale water source requirements, especially suitable for northern inland areas. In order to ensure the stable operation of the nuclear heating reactor, its design heat load should be the local basic heat load.

2.2 Characteristics of the ventilation system of nuclear power plants

In the safe use of nuclear energy around the world, in order to ensure the normal operation of nuclear power plants, the nuclear power industry has the most basic radiological safety requirements. Although different countries have different specific regulations, the relevant regulatory requirements are relatively similar. One of the main functions of the nuclear power plant ventilation system is to prevent the spread of radioactive pollution from the "dirty" area to the "clean" area. Therefore, the nuclear power plant ventilation system must ensure a certain airflow direction. And in the nuclear power plant, special methods must be used to deal with the exhaust gas with radioactive danger, and it is forbidden to discharge any radioactive waste directly to the external environment[25]. Due to the limitation of nuclear power plants and operating costs, it is also necessary to try to reduce the storage amount of radioactive waste. The ventilation system of nuclear power plants sometimes also has the function of smoke prevention and exhaust. As one of the most important safety systems, the fire and smoke exhaust system is mainly responsible for ensuring the safety of evacuation passages, corridors or stairwells during the fire phase, and evacuating personnel to the outside of the building[26]. And due to the danger of radioactive substances in some rooms of the nuclear power plant, the exhaust or smoke from the room is not allowed to be directly discharged to the outside, only the fixed ventilation system or special ventilation system is allowed to discharge the combustion gas products after the fire is extinguished.

Due to the particularity of the safety of nuclear power plants, the division of rooms in nuclear power plants is different from that of conventional rooms. Nuclear power plants are divided into two types: the first is to ensure the non-proliferation of radioactive substances, and the division is carried out according to whether there is a danger of radioactive substances in the room; the second is to ensure that the fire will not spread to the outside of the fire compartment when a fire occurs. divisions to prevent the spread of fire

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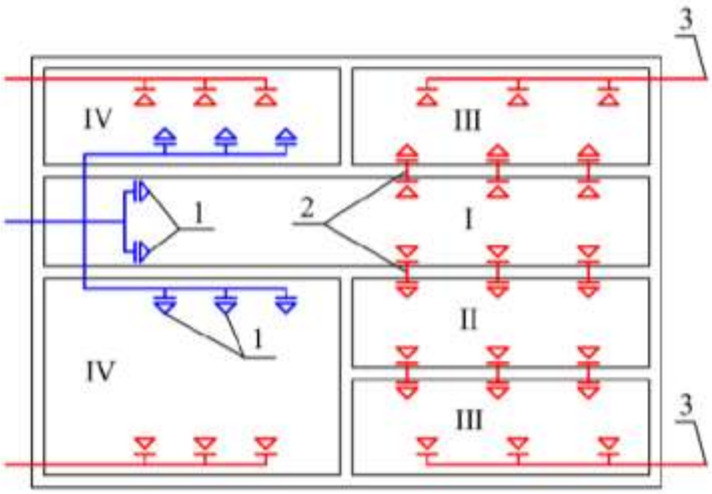
from one fire zone to another. An independent and completely isolated ventilation system should be set up in the same fire zone room. If multiple fire compartments use a ventilation system, fire dampers need to be installed on the ventilation ducts for localized fire, heat and smoke treatment. Automatic fire dampers are installed on the intake and exhaust ducts at the entrances and exits of the hazardous location and where air flows from serviceable corridors to prevent the spread of flames and smoke through the ventilation system.



1 Fresh air outlet; 2 Air duct check valve; 3 Exhaust air requiring special purification treatment; I corridor; II regular maintenance area; III.

Fig.6 Design of airflow organization in nuclear power plant

In order to maintain radiation safety, nuclear power plants are divided into two areas, restricted areas and non-restricted areas. There is no radioactive effect on the staff in the restricted area, but there is a radioactive effect on the air and walls. There is absolutely no radiological hazard in the non-restricted area[27]. Areas such as nuclear power plant reactor halls, rooms with radiant heat medium pipes and equipment are used as restricted areas. The restricted area is divided into three levels: unmanned maintenance area, where staff are prohibited from entering according to the radioactive conditions during the operation of the reactor; regular maintenance area, where the time limit for staff to be located in the area according to the radioactive conditions; conventional work area, the radiation impact does not exceed within working hours maximum allowable concentration. In order to briefly show some characteristics of the ventilation system of nuclear power plants, taking the design of China's nuclear power plants as an example, the airflow organization design of nuclear power plants is shown in Figure 6.

III BASIC HEAT LOAD ANALYSIS OF LOW TEMPERATURE NUCLEAR ENERGY HEATING REACTOR

Due to the contradiction between the operation stability characteristics of low temperature nuclear energy heating reactor and the annual heat load instability of central heating system, this chapter analyzes and studies the basic heat load ratio of low temperature nuclear energy heating reactor. First, the basic

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parameters of design and operation of low-temperature nuclear energy heating reactors are analyzed; secondly, the contradiction between supply and demand of low-temperature nuclear energy heating reactors is analyzed in combination with the small heat load of China's central heating system in summer; then, the former Soviet Union's low-temperature nuclear energy heating reactors The design of the basic heat load ratio value is used as a reference, and the method for determining the reasonable ratio of the basic heat load of the low-temperature nuclear energy heating reactor in the heating area of northern China is studied. Finally, measures to improve the thermal load factor of low-temperature nuclear energy heating reactors are proposed[28].

3.1 Basic parameters of design and operation of low temperature nuclear heating reactor

3.1.1 Basic heat load ratio of low temperature nuclear energy heating reactor

The central heating load can be divided into basic heat load and peak heat load. The basic heat load is the heat load supplied by the basic heat source, and the peak heat load is the difference heat load between the maximum heat load provided by the peak-shaving heat source and the basic heat load. The basic heat load is relatively stable throughout the year, while the peak heat load occurs for a short time, but the heat load value is large, and is generally undertaken by large, medium and small regional boiler rooms as the peak heat source[29].

In order to calculate the basic heat load of the heating system with the low temperature nuclear energy heating reactor as the basic heat source, this paper draws on the concept of thermalization coefficient of thermal power plants, and proposes the parameter of the basic heat load ratio of the low temperature nuclear energy heating reactor, which is defined as the low temperature nuclear energy heating reactor[30]. The ratio of the rated heating capacity Qn to the heating design heat load QT, namely

$$k = \frac{Q_{\mathrm{n}}}{Q_{\mathrm{T}}}$$

When the design heat load QT of the heating system is constant, the basic heat load ratio k determines the distribution of the heating capacity of the low-temperature nuclear energy heating reactor and the heating capacity of the peak-shaving heat source, thereby determining the economy of the low-temperature nuclear heating system. Therefore, , the optimization analysis of the basic heat load ratio is very important in the planning of the low temperature nuclear energy heating system[31].

3.1.2 Heat load factor of low temperature nuclear energy heating reactor

In order to evaluate the operation efficiency of low temperature nuclear energy heating reactor, this paper proposes the concept of thermal load factor of low temperature nuclear energy heating reactor according to the concept of nuclear power plant load factor[32]. The load factor of a nuclear power plant refers to the ratio of the actual power generation Wn.y of the nuclear power unit at a given time to the rated power generation Wo.y in the same period. It reflects the actual power generation utilization rate of the nuclear power unit for a period of time. Technical and economic indicators. The formula for calculating the load factor of a nuclear power plant is:

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$$F = \frac{W_{0.y}}{W_{n.y}} = \frac{W_{n.y} - W_{1.y} - W_{2.y} - W_{3.y}}{W_{n.y}}$$

The thermal load factor of the low temperature nuclear heat supply reactor can reflect the actual utilization rate of the core heat supply reactor for a period of time, and its size is related to the actual heating capacity and outage time.

3.2 Heating capacity and operating characteristics of low-temperature nuclear energy heating reactors

Since the heat load of the central heating system has the characteristics of seasonal variation, that is, the heat load in summer is significantly lower than that in winter, the heat supply of the heat source needs to be adjusted accordingly. Compared with traditional fossil fuels, nuclear fuels cannot be easily adjusted to increase or decrease fuel, so it is difficult to centrally adjust heat sources[33].

3.2.1 Analysis of power regulation range of low temperature nuclear energy heating reactor

The method of regulating the supply capacity of the nuclear reactor core is adopted in both the nuclear heating station and the nuclear power plant. Since the design and operation experience of low-temperature nuclear energy heating reactors in the world is not as rich as that of nuclear power plant reactors, and there is a lack of data or research on the regulation capability of low-temperature nuclear energy heating reactors, this section mainly discusses the regulation capability of low-temperature nuclear energy heating reactors based on the regulation capability of nuclear power plant reactors[34].

With the increasing proportion of nuclear energy in energy production, nuclear power units will not only undertake basic load operation, but also need to participate in load regulation to improve the efficiency and economy of the system. From a theoretical and technical point of view, the power of nuclear power units can vary within a certain range. Figure 7 reflects the theoretical adjustment process of the two nuclear reactors.

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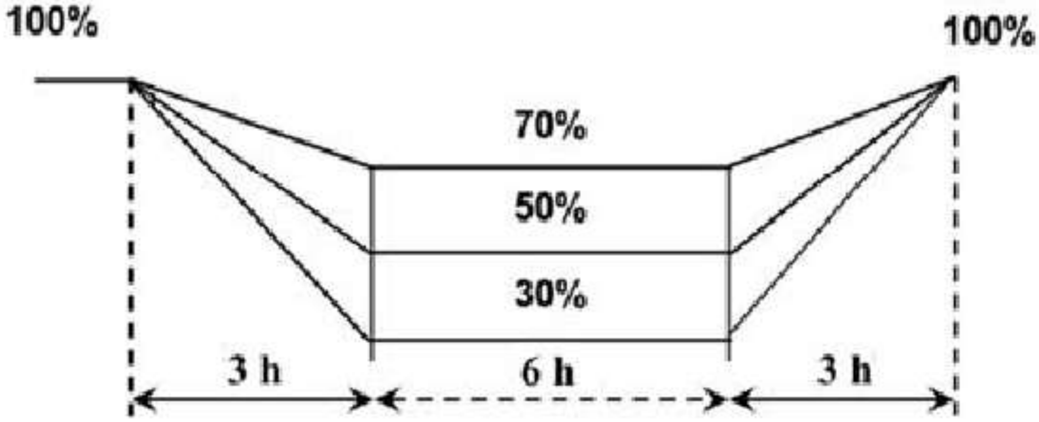

Fig.7 Theoretical adjustment process of a nuclear reactor

Although it is theoretically possible to adjust the power of the reactor, according to the actual operation experience of countries with advanced nuclear energy technology and a large proportion of nuclear energy in energy production, nuclear power units have a better ability to participate in power load regulation, but participate in heat sources[35]. There are fewer cases of centralized regulation. Taking France, which has the largest share of nuclear power in energy production in the world, as an example, as of May 2020, France was operating 57 nuclear reactors, and in 2019, nuclear power accounted for 70.58% of the country's total power generation. Figure 8 shows the annual power generation fluctuations of two nuclear power units in France. It can be seen from Figure 8 that the short-term adjustment of the power generation of some nuclear power units fluctuates greatly, but the seasonal adjustment degree of the annual average power generation does not exceed 10%[36].

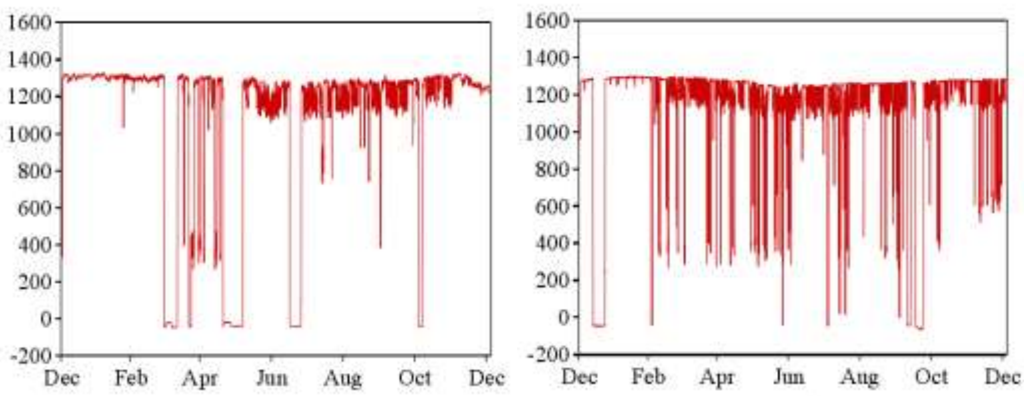

Fig.8 Annual power fluctuation of two nuclear power units in France in 2019

3.2.2 Characteristics of annual heat load variation of China's central heating system

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The heat load of the central heating system can be divided into seasonal heat load and perennial heat load according to its nature. Seasonal heat load includes the heat load of heating, ventilation, air conditioning and other systems, which is closely related to climatic conditions, and has a large change range throughout the year, while the day and night change is not large. The perennial heat load includes hot water supply and process heat load, which has little relationship with climatic conditions and is relatively stable throughout the year, while the perennial heat load varies greatly during the day and night.

3.3.3 Determination method of basic heat load of low temperature nuclear energy heating reactor in China

In order to give full play to the advantages of low-temperature nuclear energy heating reactors in clean heating and high thermal energy density, the following main conditions should be given priority when selecting the application site of low-temperature nuclear energy heating systems: serious air quality problems, long heating periods, and heating higher density.

According to the first-level division of China's building thermal design in January 2020 (as shown in Figure 8), the heating areas in China that meet the above conditions are the Northeast and Xinjiang regions. However, because the population density in Northeast China is much larger than that in Xinjiang, the following only considers Northeast China for application analysis of low-temperature nuclear energy heating reactors[37].

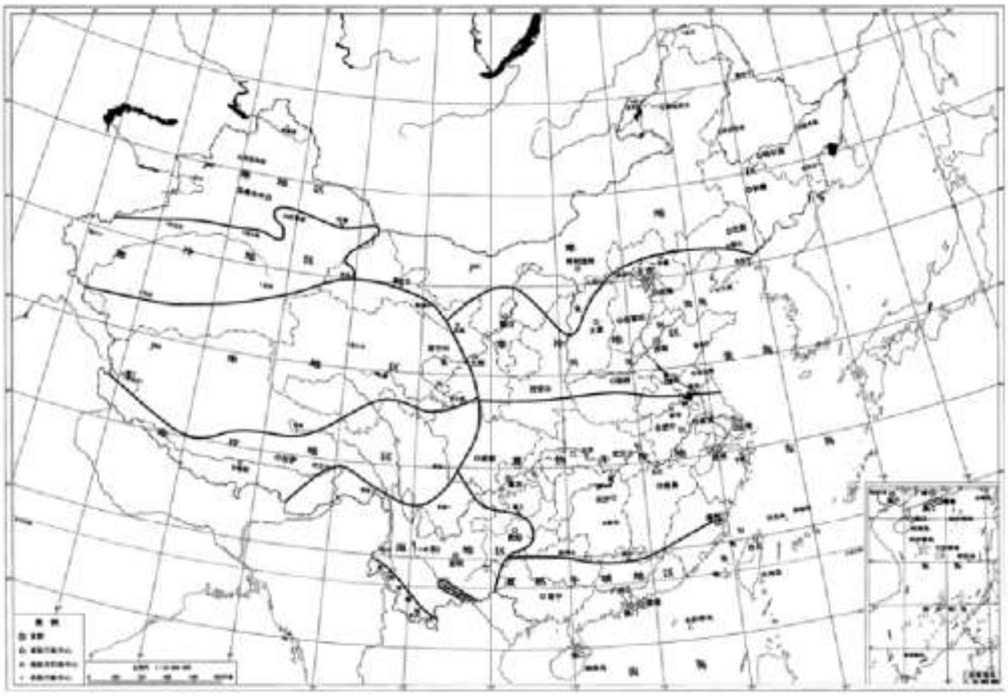

Fig.9 The first-level division of thermal engineering design of buildings in China

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IV. OPTIMIZATION OF THE THERMALIZATION COEFFICIENT OF NUCLEAR COGENERATION BASED ON THE RELATIVE SAVING RATE OF PRIMARY ENERGY

The nuclear energy cogeneration heating system belongs to a special kind of cogeneration system. The thermalization coefficient is one of the most important technical and economic parameters of the nuclear energy cogeneration system, which plays a decisive role in determining the basic heat load of the nuclear energy cogeneration system. . In this chapter, through a comprehensive analysis of the evaluation indicators of conventional thermal power plants and nuclear energy cogeneration, the maximum primary energy relative energy saving rate of the nuclear energy cogeneration system is used as the objective function, and an optimization model for the thermalization coefficient of nuclear energy cogeneration is proposed[38]. The calculation method of important parameters such as energy consumption and heat supply of the cogeneration system; the multi-factor and multi-level orthogonal test analysis of the optimal thermalization coefficient of nuclear energy cogeneration, and the determination of the optimal thermalization coefficient of nuclear energy cogeneration. Sensitivity ranking of key influencing factors was carried out, and the influence of main parameters on the optimal thermalization coefficient was analyzed.

4.1 Thermodynamic evaluation index of nuclear cogeneration

In order to evaluate the overall performance of the cogeneration system, many scholars have proposed different evaluation indicators, including thermodynamic indicators, economic indicators and environmental indicators. As a special central heating source, the research attention of nuclear energy cogeneration performance evaluation index is still lower than that of conventional thermal power plants. At present, the main evaluation indicators for the performance of nuclear cogeneration systems in China and other countries are economic indicators or environmental indicators.

4.1.1 Energy utilization efficiency of thermal and power generation system

Compared with the cogeneration system, the cogeneration system includes two independent thermal subsystems, power generation and heat supply, which provide heat and power respectively. FQ.chp and FW. chp represent the input energy of the heat supply subsystem and the power generation subsystem, respectively. Qshp.y and Wshp.y represent the heat supply and power generation respectively, which are the useful energy of the heating and power generation subsystems[39].

$$\eta_{\mathrm{Q.shp}} = \frac{Q_{\mathrm{shp.y}}}{F_{\mathrm{Q.shp}}}$$

$$\eta_{\mathrm{w.shp}} = \frac{W_{\mathrm{shp.y}}}{F_{\mathrm{w.shp}}}$$

4. 1. 2 The relative primary energy saving rate (RPES) of the cogeneration system

The above thermodynamic evaluation index of the cogeneration system can reflect the thermal efficiency of the cogeneration system, but it cannot reflect the energy saving level of the cogeneration

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system relative to the cogeneration system. In order to evaluate the energy saving level of the cogeneration system compared with the cogeneration system, scholars have proposed some energy saving evaluation parameters of the cogeneration system, and some of these parameters have been applied in the relevant standards of some countries.

Based on the first law of thermodynamics, the energy-saving evaluation parameters of the existing cogeneration system include the primary energy saving amount and the primary energy relative saving rate. Primary energy savings refers to the difference between the primary energy consumption of cogeneration and cogeneration when the heat supply and power generation of the cogeneration and cogeneration systems are the same. The ratio of the primary energy saving to the total energy consumption of the heat and power sub-production system is defined by the formula:

$$\mathrm{PES} = F_{\mathrm{shp}} - F_{\mathrm{chp}}$$

$$\mathrm{RPES} = \frac{\mathrm{PES}}{F_{\mathrm{shp}}} = 1 - \frac{F_{\mathrm{chp}}}{F_{\mathrm{shp}}}$$

4.2 Establishment of thermalization coefficient optimization model for nuclear cogeneration based on RPES

The primary energy relative saving rate RPES can directly reflect the energy saving potential of the nuclear energy cogeneration system relative to the nuclear energy cogeneration system, and is suitable for evaluating the energy saving of the nuclear energy cogeneration heat source. This section uses the primary energy relative saving rate RPES to establish the thermalization coefficient optimization model, which lays the foundation for the analysis of the optimal thermalization coefficient.

4.2.1 Total energy consumption of peak-shaving boilers

In the nuclear energy cogeneration system, the peak shaving boiler mainly meets the peak heat load of central heating. The extraction steam of the steam turbine unit of the nuclear power plant meets the basic heat load of the district heating. The combined operation of steam extraction and peak shaving boiler room of nuclear power plant can realize reasonable integration of heat sources, so that the nuclear energy cogeneration heating system and peak shaving boiler room can operate efficiently throughout the heating period. The total energy consumption of the peak-shaving boiler room is calculated according to the formula:

$$F_{\mathrm{B}} = \frac{Q_{\mathrm{peak.y}}}{\eta_{\mathrm{Q.peak}} \cdot \eta_{\mathrm{n.peak}}}$$

4.2.2 Total energy consumption of regional boilers

In the heat and power distribution system, the district boiler room is used to provide the heat for district heating. In a central heating system, several regional boiler rooms may be set up, and the energy

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consumption of the regional boiler rooms is calculated according to the formula.

$$F_{\mathrm{Q.shp}} = \frac{Q_{\mathrm{T.y}}}{\eta_{\mathrm{Q.shp}} \cdot \eta_{\mathrm{n.Q.shp}}}$$

4.2.3 Total energy consumption of nuclear cogeneration system

Since the steam extraction and heat supply of the steam turbine in the nuclear energy cogeneration system has an impact on the power generation and energy saving of the system, this paper uses the following methods to determine the influence of the steam extraction device on the performance of the steam turbine and the total energy consumption of the nuclear energy cogeneration system. The nuclear power plant steam turbine produces electricity And the energy consumption of heat energy can be determined according to the formula:

$$F_{\mathrm{chp}} = F_{\mathrm{w.w.chp}} + F_{\mathrm{Q.w.chp}}$$

4.2.4 Total energy consumption of nuclear energy thermal power generation system

Due to the error between the theoretical calculation method and the actual situation, in order to reduce the error in the model and improve the reliability of the model, this paper uses the same method as the energy consumption of nuclear cogeneration to estimate the energy consumption of cogeneration. The main difference between the cogeneration system and the cogeneration system The point is that the cogeneration system has no energy consumption for external heat, so in the case of the same input energy of the steam turbine, the pure condensing steam power generation of the cogeneration system is greater than that of the cogeneration system. The power generation principle of a condensing steam turbine with an extraction steam regenerative cycle is as follows: the steam condenses at a certain temperature in the condenser of the steam turbine, and the condensed water is heated in the regenerator by the extraction steam of the steam turbine from the outlet temperature of the condenser to feed water temperature.

4.3 Determination of key control variables for the thermalization coefficient optimization model of nuclear cogeneration

In order to calculate the relative saving rate of primary energy RPES, each control variable of the nuclear energy cogeneration and heat and power sub-generation system in formula (4.38) is analyzed and determined. The control variables include several types of parameters: thermal parameters, physical parameters, efficiency, load and Thermalization coefficient, etc. First, determine the control variables of the thermal system of the nuclear power station steam turbine unit, and establish a simple model of the control variables of the nuclear power station steam turbine unit thermal system. Second, consider meteorological parameters, pipe network transmission efficiency, peak-shaving boiler thermal efficiency and regional boiler thermal efficiency, And the determination method of important influencing factors such as steam turbine extraction power.

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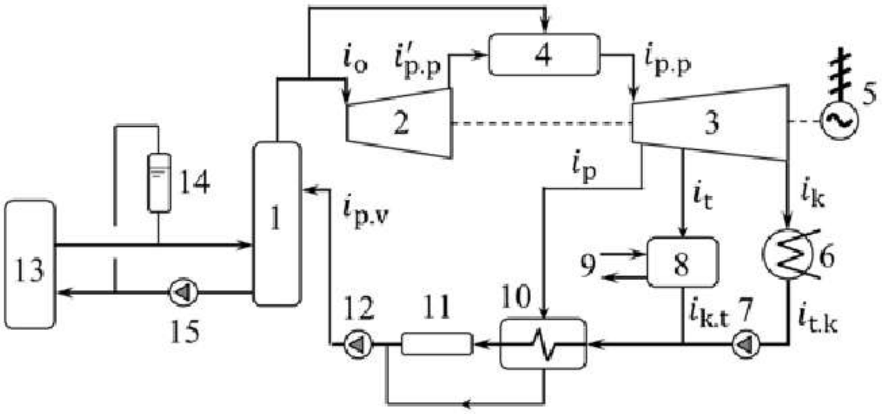
4.3.1 Control variables of nuclear energy cogeneration secondary loop thermal system

In order to study the energy-saving efficiency of converting a nuclear power station that only generates electricity into a nuclear cogeneration system, this paper takes the Hongyanhe Nuclear Power Station in Dalian, China as a case, and transforms it into a nuclear cogeneration system to analyze the thermodynamic characteristics of the secondary circuit. Based on the existing secondary circuit thermal system of Hongyanhe Nuclear Power Station, this study proposes a cogeneration system. Figure 10 shows a schematic diagram of the nuclear energy cogeneration secondary loop thermal system[40].



1 steam generator; 2 high pressure cylinder; 3 low pressure cylinder; 4 steam-water separation reheater; 5 generator; 6 condenser; 7 condensate pump; ; 11 deaerator; 12 feed water pump; 13 nuclear reactor; 14 container regulator; 15 primary circuit circulating water pump.

Fig. 10 Schematic diagram of the secondary circuit thermal system of nuclear energy cogeneration proposed in this study

In the nuclear energy cogeneration system, a heat network heat exchanger 8 is installed, and steam is extracted from the low-pressure cylinder 3 to heat the return water of the heat supply pipe network 9 (the third loop of the nuclear energy heating system) to provide heat for heat users. The condensed water formed by the condenser 6 and the heat network heat exchanger 8 enters the regenerative heater 10 to heat the feed water temperature, and then enters the steam generator through the deaerator 11.

The steam expansion process of the nuclear energy cogeneration secondary loop thermal system proposed in this study is shown in Figure 11.

4.3.2 Transmission efficiency of heating pipe network

Due to the special safety requirements of nuclear energy utilization, nuclear power plants are generally far away from cities and towns. Therefore, when considering energy-saving energy utilization of nuclear power plants, it is necessary to consider the transmission efficiency of the heating network. As the length of the heating network increases, the transmission efficiency of the heating network of the nuclear

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cogeneration system will be less than that of the regional boiler heating network of the nuclear energy cogeneration system. The long-distance heat supply network is an important feature of the nuclear energy cogeneration system, so this model cannot ignore the transmission efficiency of the long-distance heat supply network.

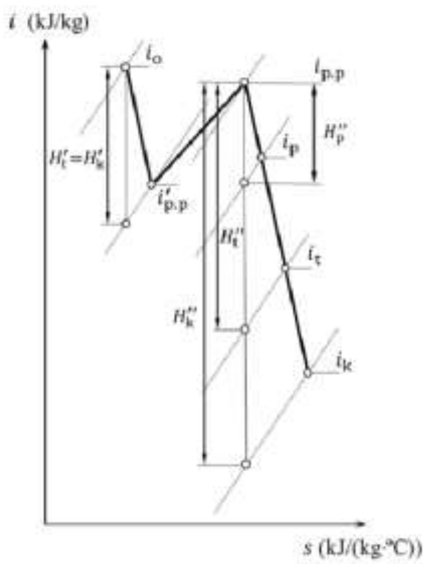

Fig. 11 Schematic diagram of the thermal process of steam expansion in the secondary circuit thermal system of nuclear energy cogeneration

V CONCLUSIONS AND PROSPECTS

(1) For the low-temperature nuclear energy heat supply reactor that only generates heat and does not generate electricity, a method for determining the basic heat load of the low-temperature nuclear energy heat supply reactor based on the reactor power adjustment range and the heat load duration map is proposed. According to the regional applicability of low-temperature nuclear energy heating reactor technology in China and the analysis of the heat load type of China's central heating system, under the condition that the power range of low-temperature nuclear energy heating reactor is 20%, it is proposed that the low-temperature nuclear energy heating reactor in typical cities in Northeast China is the best The basic heat load ratio is 0.3-0.5.

(2) Based on the relative saving rate of primary energy, an optimization model for the thermalization coefficient of nuclear energy cogeneration was established, and the orthogonal test method was used to obtain the sensitivity ranking of factors affecting the thermalization coefficient of nuclear energy cogeneration, followed by meteorological parameters, long-distance transmission and supply. Transmission efficiency of heat pipe network, thermal efficiency of boiler room, extraction steam heating power of nuclear power plant steam turbine unit and transmission efficiency of primary pipe network. It shows that compared with the nuclear power plant cogeneration system, the energy-saving performance of

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the nuclear power plant cogeneration system increases with the increase of the extraction heat power of the nuclear power plant steam turbine unit.

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