INTRODUCTION

Developing clean, low-carbon, safe, and efficient energy systems have become an essential challenge to fulfill the energy demands. Therefore, thermal power generation and District Heating (DH) based on conventional fossil energy have been gradually replaced in energy utilization. Cogeneration is an advanced energy conservation system based on the principle of energy cascade utilization. It can improve energy utilization, reduce the impact on the environment, and has characteristics of better economy and reliability. The development of cogeneration systems based on nuclear reactor as a thermal source rather than fossil fuel is becoming a promising solution to protect the environment and improving nuclear utilization efficiency.

The nuclear power cogeneration systems have been developed in Russia, Switzerland, Finland, and other countries.
since the 1970s. The Nuclear Energy Agency (NEA) launched the Nuclear Innovation 2050 (NI2050) plan to promote nuclear power cogeneration in 2015. The development of cogeneration technology is a crucial way to improve the flexibility, competitiveness, and utilization of nuclear energy. However, the distance between the Nuclear Power Plant (NPP) and the city is usually huge due to the strict siting requirements of NPPs, which makes a significant heat loss in the long-distance transportation and limits the cogeneration development with the conventional NPPs.

In Finnish, the Fortum company proposed a partial cogeneration operation at the Loviisa 3 NPP. France demonstrated the possibility of transferring heat from NPP to Lyon to carry out large-scale DH. In Switzerland, the Gösgen NPP provided a small district heating network for a nearby city. The Japan Atomic Energy Agency (JAEA) aimed to construct a first-of-a-kind commercial cogeneration plant based on the High-Temperature Engineering Test Reactor (HTTR) in 2030 and has completed the design of HTTR-GT/H2 demonstration plant in 2016 to verify the feasibility of the program. The SMART integral Pressurized Water Reactor (PWR) had been granted the standard design approval for the cogeneration applications in 2012. The Republic of Korea has signed an agreement to assess the feasibility of building cogeneration plants in Saudi Arabia for desalination cogeneration in 2015. Haiyang nuclear power in China used two AP-1000 units to provide heat for 700 000 m² in 2019.

Small Modular Reactor (SMR) is an emerging technology due to small size of core and has significant advantages such as safety, efficiency, sustainability, and feasibility. The Generation-IV (GEN-IV) International Forum (GIF) technology roadmap identified the Lead-cooled Fast Reactor (LFR) as a potential technology to meet the power supply needs in remote areas and to carry out cogeneration missions. Due to its modular construction and compact size, it can be used as Small Modular Lead-cooled Fast Reactor (SMLFR). The SMLFR can be used as a high-power energy system for DH cogeneration, small grid power supply, and ocean development. Higher security allows SMLFR cogeneration systems to be sited more flexibly and the energy supply losses can be controlled by installing the system on the site close to the city. The EU ALFRED LFR was considered for DH in the preliminary cogeneration design. Westinghouse Electric Company LLC completed the Westinghouse Lead Fast Reactor preconceptual design in 2017, which is scheduled to commercially operating in 2035 and will be used for nonelectric applications, such as cogeneration and seawater desalination. Russian Fast Reactor (FR) SVBR-100 plans to build LFR cogeneration plants near the city.

The development of the SMLFR cogeneration system is mostly focused on the preliminary concept of industrial heating, emphasizing the economy, and feasibility analysis of the system. There is no specific design study on the SMLFR cogeneration system. Wu et al. proposed a preliminary conceptual design of LFR hydrogen production system but with lower thermal efficiency. Marcin Jaskólski et al. introduced an operation mode and economic analysis method of Generation-III+ (GEN-III+) reactors NPP under partial cogeneration mode. Giorgio Locatelli et al. evaluated the different heating applications of SMR cogeneration and analyzed the economic feasibility of the SMR plant based on the Light Water Reactor (LWR) and High-Temperature Gas Reactor (HTGR).

The conventional power generation systems, including the traditional coal-fired and natural gas system, have lower thermal performance as compared to the SMLFR based cogeneration system due to lower maximum temperature and the lack of stable energy resources. SMLFR is characterized by high-temperature, long-term energy supply, and compact size, which permits better thermal efficiency in the cogeneration system. It is necessary to comprehensively study the quantity and quality of cogeneration system energy utilization with a strong focus on the high performance of the system.

A new modified conceptual design of a SMLFR cogeneration system with a better DH structure layout has been proposed along with changes in optimizing the exhaust steam/water drainage position of the system for better performance. The main factors that affecting the efficiency of SMLFR cogeneration systems have been analyzed to improve the energy utilization rate. The main components with high exergy loss have been evaluated through the thermal and exergy analysis based on a 35 MWth SMLFR cogeneration system. The parameters affecting the energy utilization rate such as steam temperature, extraction steam pressure and feedwater temperature of DH were analyzed and compared with the conventional cogeneration system. A residential district in northern China is chosen and system thermal performance under different heating demands have been compared.

## 2 DESIGN OF SMLFR COGENERATION SYSTEM

The SMLFR can be used as the ideal thermal source for the cogeneration system. China has made significant contributions to the development of LFR since 2015, especially the Institute of Nuclear Energy Safety Technology (INEST)-Chinese Academy of Sciences (CAS). INEST has proposed and carried out the concept design of 35 MWth SMLFR with the miniaturization advantages and the main parameters are listed in Table 1.

The existing nuclear power cogeneration system mainly focuses on GEN-II and GEN-III NPPs. The schematic of the conventional cogeneration system is shown in Figure 1. The design of the system based on steam Rankine cycle and the power generation system mainly includes the reactor,
High-pressure (HP) turbine, Low-pressure (LP) turbine, condenser, feedwater pumps, and generators. The regenerative and reheat system mainly include one reheater, one deaerator, three low-temperature feedwater heaters, and two high-temperature feedwater heaters. The DH system mainly extracts the steam from the end of HP turbine. The extracted steam transfers heat to water in the heat exchanger. The saturated water is transferred to the condenser for condensation.

There are some exergy destructions in the conventional nuclear reactor cogeneration system due to the high-temperature difference and pressure loss during the heat exchange between steam and water. This study proposes a modified SMLFR cogeneration system, which combines the characteristics of high outlet temperature and easy miniaturization of SMLFR to improve the thermal efficiency of the system as shown in Figure 2. Three schematic modifications were carried out in the system to reduce the exergy loss of the main components in the conventional design.

### 2.1 Schematic modification and parameter optimization

System schematic modifications and parameters optimization methods are chosen to reduce the main exergy losses based on the exergy loss analysis.

- **Schematic modification**
  - Modified the heat extraction steam for the DH system (point 5)
  - Modified the direction of DH saturated water for the condenser (point 5')
  - Modified the flow scheme of saturated water from reheater to control the temperature and flow rate (point 22')

- **Parameter optimization**
  - Optimize the outlet temperature of the steam generator ($T_{21}, T_1$)

| Parameters                                      | Value       |
|------------------------------------------------|-------------|
| Reactor thermal power, MW<sub>th</sub>        | 35          |
| Lead inlet/outlet temperature from the core, °C | 375/495     |
| Lead inlet/outlet pressure from steam generator, MPa | 0.1        |
| Maximum temperature of reactor cladding, °C   | 550         |
| Secondary cycle coolant                        | Steam       |
| Water in/steam out temperature from steam generator, °C | 340/470   |
| Secondary cycle pressure, MPa                 | 16.0        |

### Table 1 Parameters of small modular lead-cooled fast reactor

![Schematic of conventional cogeneration system](image)
2.2 | System assumptions

Thermodynamic model calculations are always based on some assumptions as follows:

- The pressure loss in the pipes and bends are not considered
- All processes are steady-state processes
- The expansion in the turbine is adiabatic and heat exchange in the heat exchanger and condenser is isentropic.

The efficiency of main components was assumed for the analysis as listed in Table 2.

3 | THERMODYNAMIC MODEL OF SMLFR COGENERATION SYSTEM

3.1 | Thermodynamic model

The computational model of the SMLFR system is based on thermodynamic laws and methods. The calculation method of the SMLFR thermodynamic calculation model is as follows.

The calculation of the turbine work power mainly includes HP and LP turbines as given below:

\[
W_{\text{HP}} = m_1 (h_1 - h_2) + (m_1 - m_2)(h_2 - h_3) + (m_1 - m_2 - m_3)(h_3 - h_4)
\]  

(1)

\[
W_{\text{LP}} = m_9 (h_9 - h_5) + (m_9 - m_5)(h_5 - h_{10}) + (m_9 - m_5 - m_{10})(h_{10} - h_{11}) + (m_9 - m_5 - m_{10} - m_{11})(h_{11} - h_{12}) + (m_9 - m_5 - m_{10} - m_{11} - m_{12})(h_{12} - h_{13})
\]  

(2)

\[
W_T = W_{\text{HP}} + W_{\text{LP}}
\]  

(3)

where, \(m \, (\text{kg s}^{-1})\) is the mass flow rate; \(h \, (\text{kJ kg}^{-1})\) is the specific enthalpy; \(W_{\text{HP}}\) and \(W_{\text{LP}}\) are the work power of HP turbine and LP turbine, and \(W_T\) is the total power of turbine.

The heating capacity of the DH system is calculated as follows:

\[
W_C = m_5 \cdot (h_5 - h_5')
\]  

(4)
The compression work of the compressors is calculated as given below, including the condenser pump, low-temperature feedwater pump and high-temperature feedwater pump.

\[
W_{CP} = m_{14} \cdot (h_{14'} - h_{14}) \quad (5)
\]

\[
W_{LFP} = m_{12} \cdot (h_{15} - h_{12'}) \quad (6)
\]

\[
W_{HFP} = m_{18} \cdot (h_{18'} - h_{18}) \quad (7)
\]

\[
W_P = W_{CP} + W_{LFP} + W_{HFP} \quad (8)
\]

The cycle net power \(W_{net}\) mainly includes the turbine work, DH power and compression work as follows:

\[
W_{net} = W_T + W_C - W_P \quad (9)
\]

The system thermal efficiency is calculated as follows:

\[
\eta_T = W_{net} / Q \quad (10)
\]

### 3.2 Exergy efficiency model

The study of thermodynamic system energy is mainly based on the thermodynamic internal energy and enthalpy. The numerical value reflects the quantity of energy rather than quality. To comprehensively reflect the quality and quantity of energy, thermodynamic exergy analysis has become a better choice. According to the second law of thermodynamics, exergy analysis comprehensively reflects the energy loss in the conversion process and the real utilization of energy by the equipment. The components with large exergy loss can be determined through the exergy loss analysis of the cogeneration system. The fundamental reason for the energy loss in the system can be explained to facilitate the energy-saving technical transformation of the system.

The main indexes of exergy analysis for the SMLFR cogeneration system include exergy loss, exergy efficiency, exergy loss rate, exergy loss coefficient. The study of relevant indexes can reflect the energy utilization of the system and the main equipment. The calculation methods of each index are as follows.

- **Exergy**

  \[
e_x = h - h_0 - T_0 (s - s_0) \quad (11)
  \]

  \[
  E_x = m \cdot e_x \quad (12)
  \]

where, \(e_x \) (kJ kg\(^{-1}\)) is the specific exergy of working fluid; \(E_x \) (kW) is the exergy of steady flow working fluid; \(T_0 \) (K) is the environment temperature; \(h_0 \) (kJ kg\(^{-1}\)) is the specific enthalpy of the environment; \(s_0 \) (kJ kg\(^{-1}\) K\(^{-1}\)) is the specific entropy of the environment.

- **Thermal exergy**

  The maximum value of the heat provided by the system \((T > T_0)\) can be converted into useful work, which is expressed as the thermal exergy of SMLFR with the environment temperature is \(T_0\) as follows:

  \[
  E_{s,Q} = (1 - T/T_0) \cdot Q \quad (13)
  \]

- **Exergy loss**

  Any irreversible process in the system is accompanied by exergy loss. The exergy loss of each component is expressed as follows:

  \[
  I_{component} = \sum E_{x,in} - \sum E_{x,out} - W \quad (14)
  \]

  where, \(E_{x,in}\) (kW) and \(E_{x,out}\) (kW) are the inlet and outlet exergies of the component; \(W\) (kW) is the work output.

- **Exergy loss rate**

  Exergy loss rate is the ratio of each component exergy loss to total exergy loss, reflecting the exergy loss proportion of each component as follows:

  \[
  \xi_{component} = \frac{I_{component}}{I_{total}} \quad (15)
  \]

  where, \(I_{total}\) is the total exergy loss in the cogeneration system as follows:

  \[
  I_{total} = \sum I_{component} \quad (16)
  \]

- **Exergy loss coefficient**

  The exergy loss coefficient refers to the ratio of exergy loss of each device to input exergy.

  \[
  \zeta_{component} = \frac{I_{component}}{E_{s,Q}} \quad (17)
  \]

  For a system consisting of multiple components, the exergy loss rate emphasizes the exergy loss percentage caused by a component to the system total exergy loss, which is analyzed from the total exergy loss. The exergy loss coefficient...
reflects the percentage of a certain component exergy loss in the total input energy and it is analyzed from the perspective of system input energy. These two parameters can reflect the distribution of exergy loss of each component in the thermodynamic system to determine the components with low energy utilization efficiency.

- System exergy efficiency

The system exergy efficiency reflects its energy utilization from the exergy analysis perspective.

\[
\eta_{\text{ex}} = 1 - \frac{I_{\text{total}}}{E_{\text{in}}} = 1 - \sum \xi_{\text{component}} \tag{18}
\]

The exergy losses of the main components in the SMLFR cogeneration schematic are mentioned in Table 3.

### RESULTS AND DISCUSSIONS

#### 4.1 Analysis of conventional SMLFR cogeneration system

Thermodynamic analysis has been carried out for the conventional SMLFR cogeneration system based on the relationship between thermodynamic internal energy and enthalpy. The boundary conditions are listed in Tables 1 and 2 with the heating steam extracted from the outlet of turbine. The temperature of the DH feedwater is 70/130°C. The main parameters of the SMLFR cogeneration system are calculated as listed in Table 4.

The thermodynamic analysis of the conventional cogeneration system based on Schematic-I show that the circulating heating capacity is 16.0 MW, the net electric power capacity is 8.55 MW and the cogeneration efficiency SMLFR is 70.13%. The SMLFR cogeneration efficiency is not high, and it can be improved by optimizing the cogeneration system parameters.

The thermal efficiency cannot accurately reflect the energy utilization of the system and the main factors affecting the efficiency of the system. To further improve the energy utilization rate and facilitate more accurate system improvement, exergy analysis of the SMLFR cogeneration system and main components were carried out based on the thermodynamic model as in Table 4.

The exergy analysis results of Schematic-I in Table 5 show that the total exergy loss of the system is 10.365 MW and the exergy efficiency is 53.57%. The components with large exergy loss are steam generator, DH exchanger, turbine, 1# high-temperature feedwater heater, and deaerator. The exergy efficiency analysis shows that although the energy efficiency of the system is 70.13% from the perspective of thermodynamic internal energy and enthalpy, the exergy efficiency of the system is only 53.57%, and there is still a large space for system change.

The main reasons behind the high exergy losses of steam generation, DH exchanger, and condenser are the maximum

| Component          | Schematic | Exergy loss                                      |
|--------------------|-----------|--------------------------------------------------|
| Steam generator    | ![Steam Generator Schematic] | \( I_{\text{SG}} = E_{x,1} + E_{x,20} - E_{x,21} \) |
| Turbine            | ![Turbine Schematic] | \( I_{\text{turbine}} = E_{x,1} - E_{x,3} - E_{x,4} - E_{x,5} - W_{\text{turbine}} \) |
| Reheater           | ![Reheater Schematic] | \( I_{\text{RH}} = E_{x,22} + E_{x,6} - E_{x,7} - E_{x,22} \) |
| Feedwater heater   | ![Feedwater Heater Schematic] | \( I_{\text{FH}} = E_{x,11} + E_{x,10'} + E_{x,15} - E_{x,16} - E_{x,11'} \) |
| Pump               | ![Pump Schematic] | \( I_{\text{pump}} = E_{x,14} + W - E_{x,14'} \) |
| Deaerator          | ![Deaerator Schematic] | \( I_{\text{dea}} = E_{x,3'} + E_{x,4'} + E_{x,5'} + E_{x,8} + E_{x,17} - E_{x,18} \) |
temperature difference between the inlet and outlet of the components and the higher irreversible energy loss. The exergy loss of the turbine is due to the change of isentropic efficiency caused by temperature and pressure difference. It is necessary to improve the efficiency of heat transfer components and modify the schematic of the cogeneration system. The cogeneration system exergy and energy performance can be optimized to reduce the heat transfer temperature difference and heat transfer loss.

4.2 | The optimized SMLFR cogeneration system

4.2.1 | The optimization analysis

- **Modification 1:**
  Extracting steam from the LP turbine according to the actual demand for heating to reduce heating steam pressure. In the conventional cogeneration system, the heating steam is extracted from the end of the HP turbine and is determined by the HP turbine exhaust parameters. There is an optimal pressure to minimize energy loss since the parameters of heating water to the user are basically fixed. The higher heating pressure would tend to enlarge the exergy loss in the heat transfer process.

- **Modification 2:**
  The flow direction of saturated water after heating is modified by changing the extraction steam position. The flow direction of saturated water is modified from condenser to deaerator (point 5’). In the schematic-I cogeneration system, the heat power of saturated water is relatively high. There is a largely irreversible loss between the water and the environment. Therefore, modifying the flow direction of saturated water is of great significance to reduce exergy loss.

- **Modification 3:**
  For the deaerator and high-temperature feedwater heater, the flow direction of saturated water from the reheater is modified to reduce the inlet and outlet temperature difference and the heat transfer loss.

4.2.2 | Parameter comparison of the cogeneration systems

The thermodynamic computation and analysis of the optimized SMLFR cogeneration system are carried out to reflect system energy utilization optimization. The boundary conditions are consistent with Schematic-I, as listed in Tables 1 and 2. The pressure of extraction steam in the optimization system is set as 0.4 MPa according to the DH feedwater

| Component                  | Exergy loss, kW | Exergy loss rate, % | Exergy loss coefficient, % |
|----------------------------|----------------|---------------------|---------------------------|
| Steam generator            | 3699.0         | 35.69               | 16.57                     |
| DH exchanger               | 2238.0         | 21.59               | 10.03                     |
| Condenser                  | 1177.0         | 11.36               | 5.27                      |
| HP turbine                 | 1153.0         | 11.12               | 5.17                      |
| LP turbine                 | 782.4          | 7.55                | 3.50                      |
| 1# High-temperature feedwater heater | 356.0     | 3.43                | 1.59                      |
| Deaerator                  | 288.8          | 2.79                | 1.29                      |
| 2# High-temperature feedwater heater | 279.5     | 2.70                | 1.25                      |
| Reheater                   | 203.8          | 1.97                | 0.91                      |
| 2# Low-temperature feedwater heater | 84.2      | 0.81                | 0.38                      |
| 1# Low-temperature feedwater heater | 54.3       | 0.52                | 0.24                      |
| 3# Low-temperature feedwater heater | 25.8      | 0.25                | 0.12                      |
| Pumps                      | 23.2           | 0.22                | 0.11                      |
| Total                      | 10 365.0       | 100                 | 46.43                     |

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parameters and the heating capacity is 16.0 MW. Based on the relationship between thermodynamic internal energy and enthalpy, the main parameters of the optimized SMLFR cogeneration system are listed in Table 6.

The thermal efficiency of the optimized SMLFR cogeneration system under the heating capacity of 16.0 MW is 73.64% with an increase of 3.51%. The system efficiency has been significantly improved, which means that the modification and optimization of schematic-II components positively affect thermal efficiency. The exergy analysis of the system is carried out from exergy efficiency to show the energy utilization and the results are mentioned in Table 7. The comparison results of the component exergy loss of the two cogeneration systems are shown in Figure 3.

Table 7 shows that the total exergy loss of the optimized cogeneration system (Schematic-II) is 9245.9 kW, which is 957.1 kW lower than that of Schematic-I with a decrease of 9.38%. The exergy efficiency of the system is 58.58%. Although the thermal efficiency of the system increases by 3.51% and the exergy efficiency increases by 4.29%. The exergy loss comparison of components under different cogeneration systems is shown in Figure 3.

It is shown that the modification of the schematic makes the exergy loss of DH exchanger, condenser, and deaerator decrease significantly and the exergy utilization of the components is improved, through the comparative analysis of the exergy and exergy losses rate of the main components of the two systems. The change of steam extraction position from the LP turbine increases the exergy loss of the LP turbine. From the perspective of exergy loss rate, the modifications in the schematics also significantly reduce the exergy loss rates of DH exchanger, condenser, and deaerator, among which the decrease of the exergy loss rate of the condenser is the most obvious from 11.36% to 2.57% with the reduction of 8.78%.

The optimized system has a significant effect on improving the thermal efficiency, energy utilization and reducing the exergy loss of components through the analysis of the thermal efficiency and exergy efficiency of the optimized SMLFR cogeneration system. The exergy loss of the steam generator and DH exchanger in the optimized schematic is still high. The parameter analysis is needed to reduce the exergy loss and improve the energy utilization rate of the system after schematic modification.

4.3 | Effects of the main cogeneration system parameters

4.3.1 Effect of the outlet temperature of steam generator on system performance

The steam generator is the most significant exergy loss component in the cogeneration system with the exergy loss rate of 36.25%. The irreversibility of the heat transfer process is higher with large exergy loss due to the large heat transfer temperature difference between the liquid metal lead and water.

The influence of temperature difference on the system exergy was analyzed by changing the steam generator’s outlet temperature. The relationship between the temperature difference and exergy loss in the steam generator heat transfer process was obtained based on the optimized cogeneration system.

The boundary conditions are as follows: The thermal power of the SMLFR cogeneration system is 35 MWth; the temperature of the steam generator in the coolant lead side is 375/495°C; the outlet pressure of the steam generator on the steam side is 16.0 MPa; the outlet temperature of the steam is 340°C; the DH power is 16.0 MW with the extraction pressure of 0.4 MPa; the temperature of the DH feedwater is 70/130°C. The outlet steam temperature of the steam generator ranges from 410°C to 480°C, and the changes of the steam generator exergy loss and exergy efficiency are analyzed.

Figure 4(A) shows that with the outlet temperature of the steam generator changes from 410°C to 480°C, the total exergy loss of the system decreases from 9053.7 kW to 9205.4 kW, with a decrease of 3.14%. The heat transfer temperature difference of the steam generator decreases gradually and the exergy loss of the steam generator drops from 3959 kW to 3653 kW, which decreases by 7.73%. Moreover, due to the decrease in temperature difference, the exergy loss rate of the steam generator is also reduced from 41.66% to 39.68%, with a reduction of 4.75%. It shows that the increase of steam generator outlet temperature significantly reduces the steam generator exergy and cogeneration system total exergy loss.

With the decrease of the steam generator exergy loss, the relevant thermodynamic properties are also improved. Figure 4(B) shows that with the increase of the outlet temperature, the system thermal efficiency increases from

| Parameters                     | Schematic-I | Schematic-II |
|-------------------------------|-------------|--------------|
| Net electric power, MW<sub>e</sub> | 8.55        | 9.77         |
| Power of cogeneration heating, MW | 16.00      | 16.00        |
| Power of pumps, MW            | 0.63        | 0.49         |
| System thermal efficiency, %  | 70.13       | 73.64        |
| Outlet temperature of steam generator, °C | 470         | 470          |
72.89% to 73.76%, and the exergy efficiency increases from 57.43% to 58.76% with an increase of 1.33%. The increase in the outlet temperature has an obvious effect on the steam generator energy utilization rate and the cogeneration system. When the temperature increases by 10°C, the cogeneration system's thermal efficiency increases by about 0.12% and the exergy efficiency increases by about 0.19%. The increased rate will gradually decrease with the increase in temperature.
With the development of high-temperature resistant materials, increasing the temperature can significantly reduce the exergy loss and make full energy use.

4.3.2 | Effect of the extraction steam pressure of DH on system performance

The extraction pressure of heating refers to the steam pressure extracted from the turbine for the DH system. The higher steam pressure enlarges the heat transfer temperature in the heat transfer, resulting in more exergy losses. The influence of extraction pressure on exergy loss of the DH heat exchanger was analyzed based on the optimized cogeneration system. The boundary conditions are that: SMLFR thermal power is 35 MW\textsubscript{th}, the steam pressure of the steam generator is 16.0 MPa, the feedwater temperature is 340\degree C and the outlet steam temperature of the steam generator is 470\degree C.

The heating power is 16.0 MW with the feedwater temperature of 70/130\degree C. The extraction pressure ranges from 0.88 MPa to 0.36 MPa was used to analyze the exergy loss of the DH exchanger and the change of system exergy efficiency.
Figure 5(A) shows that with the decreases of the extraction pressure from 0.88 MPa to 0.36 MPa, the total exergy loss of the cogeneration system decreases from 9971.4 kW to 9158.8 kW and it is reduced by 8.15%. The heat transfer temperature difference of the DH exchanger gradually decreases with the decrease of steam extraction pressure, which significantly reduces the exergy loss of the DH. The district heating exchanger exergy loss decreased from 2380.1 kW to 1395.2 kW, which decreased by 41.378% and the total exergy loss of the cogeneration system changed significantly. The exergy loss rate of the district heating exchanger decreased from 23.87% to 15.23%, and it is decreased about 8.64%.

Figure 5(B) shows that with the decrease of the extraction pressure, the system thermal efficiency increases from 71.55% to 73.89% and the thermal efficiency increases by 2.34%. The exergy efficiency also increased from 55.33% to 58.97% and the exergy efficiency increased by 3.64%, indicating that the decrease of steam extraction pressure had an
obvious effect on improving the cogeneration system energy utilization rate. The cogeneration system thermal efficiency increases by about 0.23%, and the exergy efficiency increases by about 0.35%, with the steam extraction pressure decreasing by 0.05 MPa. When the extraction pressure is close to the minimum heating extraction pressure, the DH system reaches the optimal energy utilization rate. It is of great significance to select a relatively reasonable and effective pressure of the extraction steam according to the actual heating demand for the SMLFR cogeneration system.

4.3.3 | Effect of the DH feedwater temperature on system performance

The large temperature difference mainly causes the exergy loss and the irreversible energy loss of the DH. Since the heating steam parameters at the user part are basically fixed (130°C), the feedwater temperature in the heating part is another objective of the optimization.

The influence of the heating feedwater temperature on district heating exchanger exergy loss is analyzed under other
conditions unchanged. The boundary conditions are that: SMLFR thermal power is 35 MWth, the pressure in the steam side of the steam generator is 16.0 MPa with the temperature of 470℃; the district heating power is 16.0 MW, the steam extraction pressure is 0.4 MPa and the heating temperature in DH system is 130℃. The feedwater temperature in DH ranges from 40℃ to 80℃ to analyze the exergy loss of the district heating exchanger and the exergy efficiency of the cogeneration system.

Figure 6(A) shows that with the feedwater temperature of DH changes from 40℃ to 80℃, the system exergy loss decreases from 9822.4 kW to 9068.9 kW, reduced by 7.67%. With the increase of temperature, the heat transfer temperature difference of the district heating exchanger decreases gradually, and the exergy loss of the district heating exchanger decreases from 2085.0 kW to 1331.5 kW, reduced by 36.14%. It indicates that the change of the feedwater temperature of DH has a noticeable influence on the exergy loss.

Figure 6(B) shows that the system thermal efficiency does not change with the increase of the return water temperature. Due to the decrease of the exergy loss of the system, the exergy efficiency increased from 56.00% to 59.37% and it is increased by 3.38%, indicating that the increase of the feedwater temperature of DH has an obvious effect on the improvement of the energy utilization rate of the system. The exergy efficiency of the cogeneration system increases by about 0.42% with the feedwater temperature increased by 5℃.

### 5 | THERMAL EVALUATION OF COGENERATION PLANT BASED ON HEATING DEMAND

Thermal performance and evaluation of the optimized cogeneration system with different heating areas are analyzed from the perspective of the heating demand specifically. A residential district in northern China is chosen as the research object. The boundary conditions are that: the outlet temperature of the steam generator is 470℃, the pressure of the extraction steam is 0.40 MPa, the feedwater temperature of DH is 70℃; the heating period is 150 days with the comprehensive heating index of 55 W m⁻², as listed in Table 8.

According to the actual heating demand and related energy-saving and emission reduction requirements, two
35 MW<sub>th</sub> SMLFR cogeneration systems are selected to provide regional heating for DH. There will be some different thermal performances with varying areas of heating. Therefore, this study analyzes three DH area cases of 600,000 m<sup>2</sup>, 700,000 m<sup>2</sup>, and 800,000 m<sup>2</sup>, respectively. The thermal evaluation comparisons between the two cogeneration systems are listed in Table 9.

Table 9 shows that the SMLFR cogeneration thermal performance of Schematic-II is much better than Schematic-I under the same heating demand, especially in terms of the system thermal efficiency during heating. Under the same heating area and annual heating power, the annual electricity of Schematic-II is much higher than that of Schematic-I, and the corresponding system thermal efficiency is also better as analyzed before. The cogeneration system efficiency during the heating period in Schematic-II is higher than that in Schematic-I, which is more obvious with the increase of the heating area. When the heating area is 800,000 m<sup>2</sup>, the system efficiency of Schematic-II reaches 83.51% with an increase of 5.92%. From the perspective of energy and environmental protection, the higher thermal efficiency of the optimized SMLFR cogeneration will save a considerable amount of coal than coal-fired cogeneration and reduce carbon dioxide emissions.

6 | CONCLUSIONS

The conceptual design and optimization of the cogeneration system have been proposed to reduce and control the exergy loss, which is usually encountered in the conventional cogeneration systems for a 35 MW<sub>th</sub> SMLFR. The cogeneration system components with lower energy utilization rates are evaluated by using the exergy analysis and thermodynamic calculations. Main conclusions are as follows:

- The thermal efficiency of the optimized SMLFR cogeneration system increased from 70.13% to 73.64%. The system exergy efficiency increased from 54.29% to 59.31%.
- The exergy loss in system components is obviously reduced as compared to the conventional system. The exergy loss rate of the condenser is most obviously decreased from 11.36% to 2.57% and the total exergy loss decreases 957.1 kW.
- The optimization of the main parameters such as the outlet temperature of the steam generator, suitable heating extraction steam pressure and feedwater temperature of DH can improve the energy utilization rate of the system significantly.

The DH with nuclear power as the thermal source is becoming a trend with the development of science and technology in the field of nuclear. This study can further provide a design basis for thermodynamic optimization and efficiency improvement of the SMLFR cogeneration system.

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Nomenclature

- \( e_x \) specific exergy, kJ kg<sup>-1</sup>
- \( E_x \) exergy, kW
- \( H \) specific enthalpy, kJ kg<sup>-1</sup>
- \( I \) exergy loss, kW
- \( m \) mass flow rate, kg s<sup>-1</sup>
- \( P \) pressure, Mpa
- \( Q_{cor} \) reactor thermal power, MW<sub>th</sub>
- \( S \) specific entropy, kJ kg<sup>-1</sup> K<sup>-1</sup>
- \( T \) temperature, °C
- \( W_c \) heating power, MW
- \( W_{net} \) net power, MW

Acronyms and abbreviations

CAS, Chinese Academy of Sciences; DH, District Heating; FR, Fast Reactor; GEN-II, Generation-II; GEN-III, Generation-III; GEN-IV, Generation-IV; HP, High-Pressure; INEST, Institute of Nuclear Energy Safety Technology; JAEA, Japan Atomic Energy Agency; LFR, Lead-cooled Fast Reactor; LP, Low-Pressure; NEA, Nuclear Energy Agency; NIST, National Institute of Standards and Technology; NGNP, Next Generation Nuclear Plant; NPP, Nuclear Power Plant; PWR, Pressurized Water Reactor; SMR, Small Modular Reactor; SMLFR, Small Modular Lead-cooled Fast Reactor.

Nondimensional number

- \( \eta \) efficiency
- \( \xi \) exergy loss rate
- \( \zeta \) exergy loss coefficient

Subscripts or superscripts

- \( c \) cogeneration
- \( CP \) condenser pump
- \( ex \) exergy
- \( HFP \) high-temperature feedwater pump
- \( in \) inlet
CONFLICT OF INTEREST
No conflict of interest exits in the submission of this manuscript. The manuscript was approved by all authors for publication.

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REFERENCES
1. Bamati N, Raoofi A. Development level and the impact of technological factor on renewable energy production. Renewable Energy. 2020;151:946-955.
2. Mahian O, Mirzaie MR, Kasaean A, et al. Exergy analysis in combined heat and power systems: a review. Energy Convers Manage. 2020;226:113467.
3. Kowalczyk T, Badur J, Bryk M. Energy and exergy analysis of hydrogen production combined with electric energy generation in a nuclear cogeneration cycle. Energy Convers Manage. 2019;198:111805.
4. Leurent M, Jasseraud F, Locatelli G, et al. Driving forces and obstacles to nuclear cogeneration in Europe: lessons learnt from Finland. Energy Pol. 2017;107:138-150.
5. Lipka M, Rajewski A. Regress in nuclear district heating, the need for rethinking cogeneration. Prog Nucl Energy. 2020;130:103518.
6. Magwood WD. Nuclear Innovation 2050 - An NEA initiative to accelerate R&D and market deployment of innovative nuclear fission technologies to contribute to a sustainable energy future. Nucl Energy Agency (NEA) OECD. 2019;50:14.
7. Rämä M, Leurent M, Devezeaux de Lavergne J-G. Flexible nuclear co-generation plant combined with district heating and a large-scale heat storage. Energy. 2020;193:116728.
8. Leurent M, Da Costa P, Jasseraud F, Rämä M, Persson U. Cost and climate savings through nuclear district heating in a French urban area. Energy Pol. 2018;115:616-630.
9. Welsch H, Biermann P. Measuring nuclear power plant externalities using life satisfaction data: a spatial analysis for Switzerland. Ecol Econ. 2016;126:98-111.
10. Sato H, Aoki T, Ohashi H, et al. Research and development for safety and licensing of HTGR cogeneration system. Nucl Eng Des. 2020;360:110493.
11. International Atomic Energy Agency. Guidance on Nuclear Energy Cogeneration. Vienna: International Atomic Energy Agency; 2019.
12. Chen J, Zheng W, Kong Y, Yang X, Liu Z, Xia J. Case study on combined heat and water system for nuclear district heating in Jiaodong Peninsula. Energy. 2021;218:119546.
13. Mignacca B, Locatelli G. Economics and finance of Small Modular Reactors: a systematic review and research agenda. Renew Sustain Energy Rev. 2020;118:109519.
14. Nian V. Technology perspectives from 1950 to 2100 and policy implications for the global nuclear power industry. Prog Nucl Energy. 2018;105:83-98.
15. Khan MS, Bai Y, Huang Q, et al. Conceptual design and optimization of power generation system for lead-based reactor. Appl Therm Eng. 2020;168:114714.
16. Xu C, Li Y, Jin M, et al. Preliminary design and analysis on the cogeneration system for Small Modular Lead-cooled Fast Reactor. Appl Therm Eng. 2020;174:115302.
17. Roelofs F, Boo E, Auriulli C, et al. Fast Reactors and Nuclear Cogeneration: A Market and Economic Analysis. International Conference on Fast Reactors and Related Fuel Cycles: Next Generation Nuclear Systems for Sustainable Development (FR17) Programme and Papers. 2017;49(44):1-10. https://media.super event.com/documents/20170620/2d21abde9ea75c6b8bc6fc73a36a3374/fr17-082.pdf
18. Kasilov VF, Dudolin AA, Krasheninnikov SM. Development of a thermal scheme for a cogeneration combined-cycle unit with an SVBR-100 reactor. Therm Eng. 2017;64:97-103.
19. Wang M, Huang H, Lian C, Ji X, Jiang J, Wu Y. Conceptual design of lead cooled reactor for hydrogen production. Int J Hydrogen Energy. 2015;40:15127-15131.
20. Jaskolski M, Renśki A, Minkiewicz T. Thermodynamic and economic analysis of nuclear power unit operating in partial cogeneration mode to produce electricity and district heat. Energy. 2017;141:2470-2483.
21. Locatelli G, Boarin S, Fiordaliso A, Ricotti M. Load following of Small Modular Reactors (SMR) by cogeneration of hydrogen: a techno-economic analysis. Energy. 2018;148:494-505.
22. Xu C, Kong F, Yu D, Yu J, Khan MS. Influence of non-ideal gas characteristics on working fluid properties and thermal cycle of space nuclear power generation system. Energy. 2021;3:119881.
23. Dong Z, Pan Y. A lumped-parameter dynamical model of a nuclear heating reactor cogeneration plant. Energy. 2018;145:638-656.
24. Tuomisto H. Nuclear Design Practices and the Case of Loviisa 3. Gdańsk, Poland: Third Nuclear Power School; 2010.
25. Khan MS, Bai Y, Chen Z, Huang Q, Zou X. Conceptual design and numerical assessment of compact heat exchanger for lead-based reactor. Prog Nucl Energy. 2020;124:103348.

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