

УДК 620.93: 621.039: 621.165

## **ENERGY EQUIPMENT OF NUCLEAR POWER PLANTS WITH HIGH-TEMPERATURE SMALL MODULAR REACTOR**

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<https://doi.org/10.31472/tpe.2.2025.5>

*The selection of energy equipment is a crucial task in ensuring the high efficiency of energy facilities. Generation IV Modular Multi-Purpose Reactors (MMPs) are suitable for both civilian and defense applications. High-Temperature Gas-Cooled Reactors (HTGRs) provide unprecedented safety features along with significant economic and operational advantages. Electricity generation at nuclear power plants is primarily carried out using steam turbine systems, where a considerable amount of heat is released during the condensation process. The Organic Rankine Cycle (ORC) employs various working fluids, including freons, aqueous ammonia solutions, pentane, isopentane, butane, and isobutane. In this study, calculations for the ORC were performed using R134a as the working fluid. The steam parameters at characteristic points of the cycle are determined using RefProp application. Several configurations of power systems incorporating steam turbine units were analyzed, including: a system without reheating, operating with subcritical steam; a system with reheating, utilizing both subcritical and supercritical steam; a system with a heating turbine; a turbomachinery-based system employing supercritical CO<sub>2</sub>. Among the analyzed configurations, the turbomachinery-based facility utilizing supercritical CO<sub>2</sub> demonstrated the highest energy efficiency. Additionally, the integration of the ORC significantly enhances the overall efficiency of nuclear power plants. The energy efficiency of nuclear power plants employing steam turbine systems with water vapor ranges from 27% to 34.5%, with the highest efficiency (34.5%) achieved by a system incorporating a heating turbine. In contrast, a nuclear power plant equipped with a supercritical CO<sub>2</sub> turbine attains an efficiency of 46.5%, which exceeds that of steam turbine-based systems by more than 10%. The implementation of the ORC further contributes to the overall improvement of power system efficiency.*

References 8, tables 6, figures 6.

**Keywords:** nuclear power plant, small modular reactor, steam turbine plant, Rankine cycle, turbomachine facility with supercritical CO<sub>2</sub>.

### **1 Introduction**

The significance of energy in modern society is undeniable, as it underpins electricity and heat supply across all industrial sectors and for the general population. At present, the global energy sector is undergoing a transformation, with nuclear energy playing a key role in the restructuring of energy systems in many industrialized countries. In particular, the development of nuclear energy has received substantial attention in the United States [1]. In late 2023, a congressional committee meeting addressed critical issues related to nuclear energy, concluding that it is necessary to expand both electricity generation and process heat production through nuclear power plants. Small Modular Reactors (SMRs) have been identified as a promising solution for the future of the global energy sector [2]. These reactors require lower capital investment, can compete with other cost-effective forms of electricity generation, and

offer enhanced safety features. Additionally, SMRs provide opportunities for innovative applications, such as hybrid nuclear-renewable energy systems, low-carbon industrial heat and electricity, and hydrogen production [3,4].

The selection of reactor technology for future nuclear power generation is of critical importance. Extensive research on various reactor types has been conducted in the United States, with particular interest in Generation IV reactors, specifically high-temperature gas-cooled reactors (HTGRs) utilizing helium as a coolant. These reactors, equipped with microencapsulated TRISO fuel, possess several unique safeties, economic, and operational advantages, including:

- passive safety mechanisms, ensuring the cessation of heat-generating reactions under any external impact;
- elimination of uncontrolled chain reactions, significantly enhancing reactor stability;

- structural resilience, capable of withstanding direct impacts from missiles or aircraft;
- reduced construction time, facilitating faster deployment;
- zero emissions, including carbon dioxide (CO<sub>2</sub>);
- water-free cooling system, eliminating the dependence on water resources;
- continuous year-round operation, coupled with flexible power regulation;
- extended fuel utilization period, with operational longevity reaching up to 20 years.

In recognition of the growing importance of SMRs, the European Industrial Alliance for SMR was established in 2024. The primary objective of this alliance is to support and accelerate the development, demonstration, and deployment of the first SMR projects in Europe by the early 2030s, thereby facilitating the transition of SMR technologies from conceptual stages to full-scale implementation.

## 2 Nuclear Power Plant Energy Equipment

The selection of energy equipment is a critical factor in ensuring the high efficiency of a nuclear power facility. Electricity generation at nuclear power plants is predominantly carried out using steam turbines.

A nuclear power plant is a highly complex engineering system that integrates a large number of components. The key equipment includes a steam generator, turbine, condenser, deaerator, superheaters, pumps, an electric generator, and various auxiliary systems.

To evaluate the performance of different power system configurations, several comparative calculations were conducted. A fundamental assumption in these calculations is that the steam at the turbine outlet must remain in a dry state to prevent efficiency losses and equipment degradation.

The calculations were performed for a power system incorporating a modular reactor with a capacity of 15 MW. The steam temperature at the turbine inlet was set at 550°C. The following configurations were analyzed:

- a steam turbine operating with subcritical steam;
- a steam turbine with reheating, utilizing both subcritical and supercritical steam;
- a heating turbine;
- a turbomachine system employing supercritical CO<sub>2</sub>.

The steam parameters at key points within the cycle were determined using RefProp [5], alongside calculations based on isentropic efficiency values [6].

### 2.1 Organic Rankine Cycle

The ORC enables the generation of additional electricity from low-grade heat sources. It is a thermodynamic process analogous to the conventional steam cycle but utilizes low-boiling working fluids instead of water to drive the turbine [7].

The schematic representation of the basic ORC is shown in Fig. 1. The working fluid is compressed and circulates in a closed loop with the aid of a pump. In the heat exchanger (boiler), the fluid undergoes evaporation and enters the turbine, where it expands, causing the rotor of the electric generator to rotate.

In the condenser, the vapor of the working substance condenses and enters the condensation pump.

In steam turbine plants, a significant amount of heat is removed from the steam during condensation.

Freons, an aqueous solution of ammonia, pentane, isopentane, butane, isobutane, etc. are used as working substances for the organic Rankine cycle.

Calculations of the organic Rankine cycle were performed for the working substance R134a (tetrafluoroethane, freon, CF<sub>3</sub>CFH<sub>2</sub>).

In winter, the ambient temperature drops, so the temperature at the turbine outlet can be reduced. This will provide greater turbine power, i.e. more generated electricity.

The further calculations were performed for two values of temperatures at the turbine outlet: a) 30 °C and b) 15 °C.

The organic Rankine cycles for R134a are shown in Fig. 2.

### 3 Calculation Results of Steam Turbines with Water Vapor

Steam turbine units utilizing water vapor are the most common systems for electricity generation at nuclear power plants. Calculations were performed for cases both with and without the implementation of ORC. To illustrate the process, Fig. 3 presents the steam expansion process in the turbine without reheating.

#### 3.1 A Subcritical Steam Turbine without Reheating

At the specified dryness fraction  $\chi = 1.0$ , point 2 is positioned at the intersection of the saturation curve and the isobar.

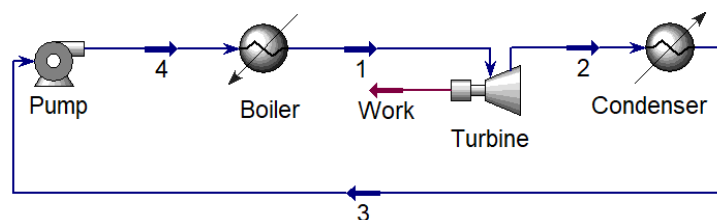


Fig. 1. Scheme of the basic ORC

A pressure of 0.05 MPa was selected for the calculations, with the enthalpy of water at the saturation line equal to 340.5 kJ/kg. The steam pressure at the turbine inlet was set to  $P = 4.85$  MPa, and the temperature to  $T = 550^\circ\text{C}$ .

The enthalpy at point 2 was determined using the following equation:

$$h_2 = h_1 - (h_1 - h_{2s}) \cdot \eta_{sT}$$

By applying this formula and utilizing RefProp, the steam parameters at the turbine inlet (point 1 in Fig. 3) were determined. The steam parameters at the key cycle points are summarized in Table 1.

The reactor heat loss to the surrounding environment was found to be approximately 1%. For the calculations, the heat flow within the heat exchanger was assumed to be 14 800 kW.

Table 1: Water: Specified state points

	Temperature °C	Pressure MPa	Density kg/m <sup>3</sup>	Enthalpy kJ/kg	Entropy kJ/kg·K
1	550.0	4.85	13.150	3552.3	7.139
2s	81.32	0.05	0.332	2484.3	7.139
2	81.32	0.05	0.316	2591.7	7.440
3 <sub>w</sub>	81.3	0.05	971.0	340.5	1.0910

The mass flow rate of water was calculated as:

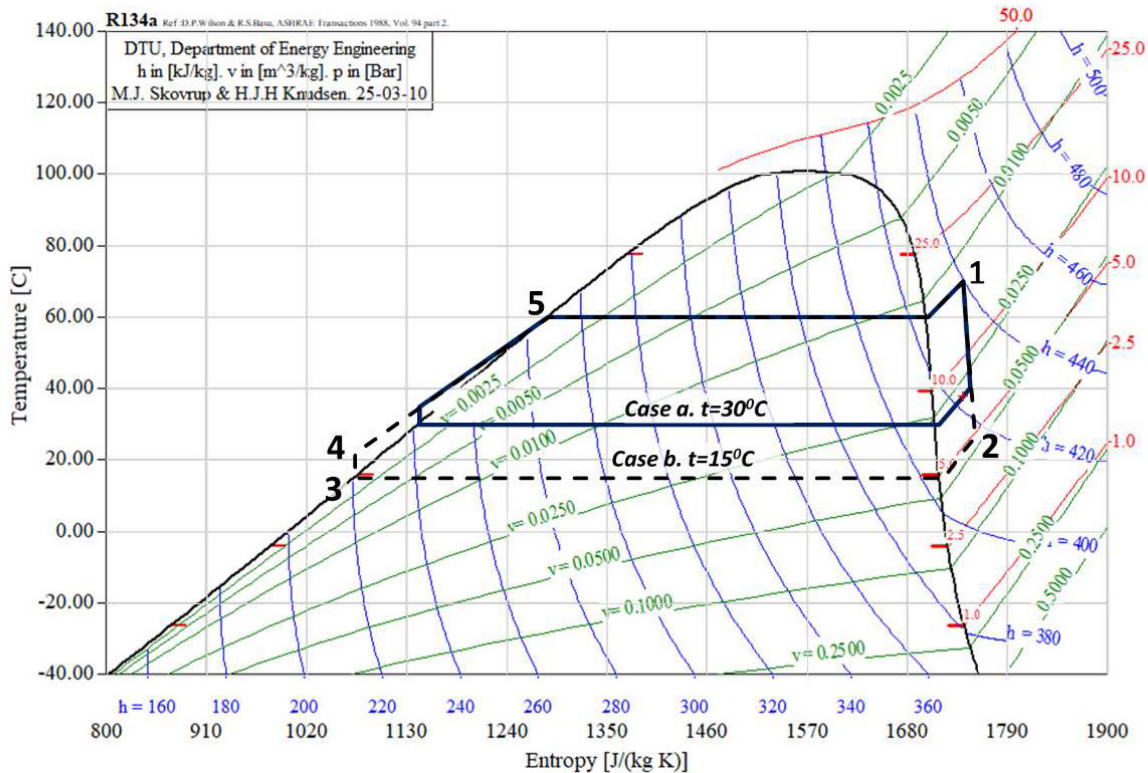
$$\dot{m}_w = \frac{\dot{Q}}{\Delta h} = \frac{14800}{(3552.3 - 340.5)} = 4.61 \text{ kg / s.}$$

The steam turbine power output was determined as:

$$N_T = \dot{m} \cdot \Delta h_{12} = 4.61 \cdot (3552.3 - 2591.7) = 4428 \text{ kW.}$$

Since the power required for the pump was negligible in comparison to the turbine output, it was not included in the calculations.

For the calculations, the mechanical efficiency of the turbine was assumed to be  $\eta_{mechT} = 0.98$ , while the efficiency of the electric generator was set to  $\eta_e = 0.98$ .



**Fig. 2. Organic Rankine cycle for R134a Freon** — 30 °C — — 15 °C  
 1–2 Expansion of vapors in the turbine; 2–3 Condensation of vapors in the condenser;  
 3–4 Pressure increase through a pump; 4–5 Heating; 5–1 Evaporation and superheating.

Finally, the overall energy efficiency of the nuclear power plant equipped with a subcritical steam turbine without reheating was determined as:

Freon R134a enters the heat exchanger at an initial temperature of either 30°C or 15°C.

The thermodynamic parameters of R134a at the saturation line and at key points of the cycle (Table 2) were determined using RefProp application.

Case a)  $t = 30^\circ\text{C}$

Freon is heated to a temperature of 70°C.

The enthalpy at the turbine outlet (point 2) is given by:

$$h_2 = h_1 - (h_1 - h_{2s}) \cdot \eta_{sT} = 439.7 - (439.7 - 423) \cdot 0.9 = 424.7 \text{ kJ/kg}.$$

The enthalpy of R134a at the saturation line is 241.7 kJ/kg.

The mass flow rate of R134a was determined as:

Table 2: R134a: Specified state points

	Temperature °C	Pressure MPa	Density kg/m <sup>3</sup>	Enthalpy kJ/kg	Entropy kJ/kg·K
1	70.0	1.68	79.76	439.7	1.741
2s	37.8	0.77	35.76	423.0	1.741
2	40.2	0.77	35.27	425.5	1.749

$$\dot{m}_{R134} = \frac{\dot{Q}}{h_1 - h_3} = \frac{10382}{(439.7 - 241.7)} = 52.4 \text{ kg/s}.$$

The power output of the ORC turbine operating with R134a was calculated as:

$$N_T = \dot{m}_{R134} \cdot \Delta h_{12} = 52.4 \cdot (439.7 - 425.5) = 744 \text{ kW}.$$

The implementation ORC enhances the energy efficiency of the steam turbine by 18%.

$$\frac{N_e \cdot \eta_{mehT} \cdot \eta_e}{N_R} = \frac{4428 \cdot 0.98 \cdot 0.98}{15000} \cdot 100 = 28.4\%.$$

### 3.1.1 A Subcritical Steam Turbine without Reheating and ORC

During condensation at  $T = 81^\circ\text{C}$ , the amount of heat removed from water steam is

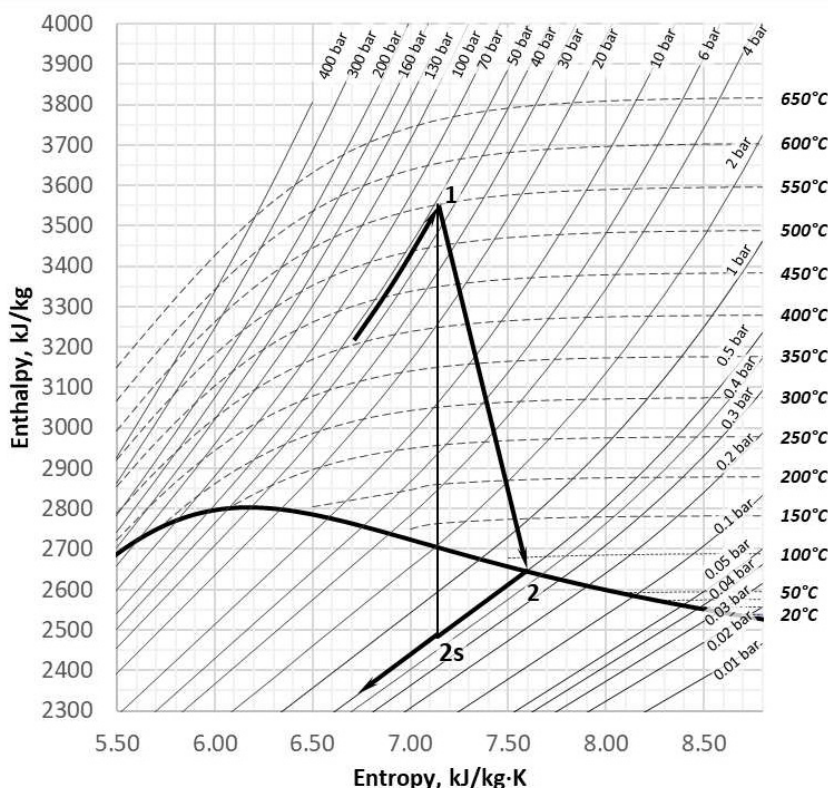


Fig. 3. Rankine cycle in the h-s diagram (enthalpy-entropy) of water

2592-340=2252 kJ/kg

The corresponding heat flow is calculated as:

$$2252 \cdot 4.61=10382 \text{ kW}$$

$$\frac{N_e \cdot \eta_{mehT} \cdot \eta_e}{N_R} = \frac{(4428 + 744) \cdot 0.98 \cdot 0.98}{15000} \cdot 100 = 33.1\%$$

The energy efficiency of a nuclear power plant equipped with a subcritical steam turbine without reheating and an ORC system is calculated as:

Incorporating the ORC results in a 5% increase in the overall energy efficiency of the nuclear power plant.

Case b)  $t = 15^\circ\text{C}$

The power output of the ORC turbine is determined as:  
1214.5 kW

For this case, the use of ORC increases the power plant's energy efficiency by 29%.

The energy efficiency of a nuclear power plant utilizing a subcritical steam turbine without reheating and an ORC system is given by:

$$\frac{N_e \cdot \eta_{mehT} \cdot \eta_e}{N_R} = \frac{(4428 + 1214.5) \cdot 0.98 \cdot 0.98}{15000} \cdot 100 = 36.1\%$$

Under these conditions, the integration of ORC leads to an overall energy efficiency improvement of 8% for the nuclear power plant.

### 3.2 Turbine with steam reheating

At the turbine inlet, the steam pressure and temperature are 28 MPa and 550 °C, respectively.

The steam expansion processes occurring within a turbine employing reheating are depicted in Fig. 4.

For an outlet turbine pressure of 0.05 MPa and a superheating temperature of 550 °C, the expansion of steam after reheating (process 3–4, Figure 4) aligns with the expansion process observed in a turbine operating without reheating (process 1–2, Figure 3).

In the high-pressure turbine section, steam expands to an intermediate pressure of 4.85 MPa.

To achieve maximum mechanical work output from the high-pressure turbine, the inlet steam pressure must be no less than 25 MPa.

The critical parameters for water are as follows: critical pressure of 22.1 MPa, critical temperature of 374.15 °C, and critical density of 303 kg/m<sup>3</sup>.

Utilizing RefProp software, steam parameters at designated points 1, 2s, and 2 were calculated for the inlet conditions of 28 MPa and 550 °C (Table 3).

The total heat required for the cycle with reheating is the sum of the initial water heating and reheating components:

$$h_1 - h_w = 3304 - 340.5 = 2963.5 \text{ kJ / kg.}$$

$$h_3 - h_2 = 3552.3 - 2900 = 652.3 \text{ kJ / kg.}$$

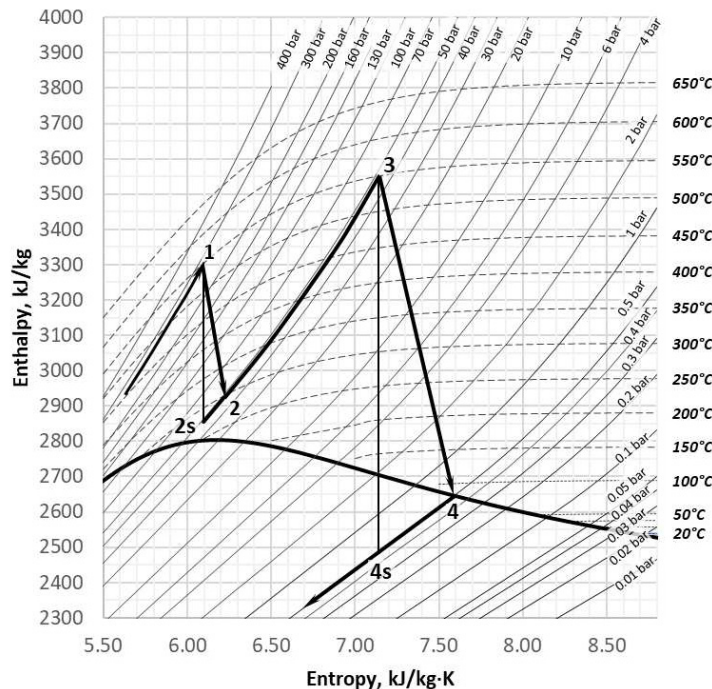


Fig. 4. Rankine cycle in the h-s diagram of water for a turbine with reheating

Table 3: Water: Specified state points

	Temperature °C	Pressure MPa	Density kg/m <sup>3</sup>	Enthalpy kJ/kg	Entropy kJ/kg·K
1	550.0	28.000	90.171	3304	6.095
2s	276.9	4.850	23.037	2854	6.095
2	290.2	4.850	21.95	2900	6.179

Thus, the overall heat added to the cycle is

$$\Delta h_q = 2963.5 + 652.3 = 3616 \text{ kJ/kg.}$$

The mass flow rate of water through the cycle is calculated by the formula:

$$\dot{m}_w = \frac{\dot{Q}}{\Delta h_q} = \frac{14800}{3616} = 4.09 \text{ kg/s.}$$

The enthalpy at point 2 is calculated by the following relation:

$$h_2 = h_1 - (h_1 - h_{2s}) \cdot \eta_{sT} = 3304 - (3304 - 2854) \cdot 0.9 = 2900 \text{ kJ/kg.}$$

Consequently, the steam turbine power output is determined as follows:

$$N = \dot{m} \cdot \Delta h_T = \dot{m} \cdot [(h_1 - h_2) + (h_3 - h_4)] = 4.09 \cdot [(3304 - 2900) + (3552.3 - 2592)] = 5579 \text{ kW.}$$

Implementing reheating significantly enhances turbine performance, increasing the turbine power output by approximately 12% compared to non-reheated cycles.

The calculated energy efficiency of a nuclear power plant utilizing a reheating steam turbine is:

$$\frac{N_e \cdot \eta_{mehT} \cdot \eta_{ez}}{N_R} = \frac{5579 \cdot 0.98 \cdot 0.98}{15000} \cdot 100 = 35.7\%.$$

Reducing the turbine inlet pressure to 20 MPa results in a decrease of approximately 5% in electrical generator output power.

### 3.2.1 Turbine with reheating and ORC

The amount of heat removed from steam during condensation at  $T = 81^\circ\text{C}$  is 2305 kJ/kg.

The total heat flow is calculated as

$$2305 \cdot 4.09 = 9427 \text{ kW.}$$

The thermodynamic parameters of R134a refrigerant at the saturation line and key cycle points are determined using RefProp.

Case a)  $T = 30^\circ\text{C}$

The mass flow rate of R134a is computed as:

$$\dot{m}_{R134} = \frac{\dot{Q}}{h_1 - h_3} = \frac{9427}{(439.7 - 241.7)} = 47.6 \text{ kg/s.}$$

The power output of ORC turbine operating with R134a is

$$N_T = \dot{m}_{R134} \cdot \Delta h_{12} = 47.6 \cdot (439.7 - 425.5) = 676 \text{ kW.}$$

The overall energy efficiency of a nuclear power plant incorporating a subcritical steam turbine with reheating and ORC is calculated as:

$$\frac{N_e \cdot \eta_{mehT} \cdot \eta_{ez}}{N_R} = \frac{(5579 + 676) \cdot 0.98 \cdot 0.98}{15000} \cdot 100 = 40\%.$$

Case b)  $T = 15^\circ\text{C}$

For this case, the ORC turbine power is determined as:

The inclusion of ORC in this configuration leads to a 19% increase in turbine energy efficiency.

The overall energy efficiency of the nuclear power plant, considering the subcritical steam turbine with reheating and ORC, is:

$$\frac{N_e \cdot \eta_{mehT} \cdot \eta_{ez}}{N_R} = \frac{(5579 + 1010) \cdot 0.98 \cdot 0.98}{15000} \cdot 100 = 42.2\%.$$

### 3.3 Heating turbine

At the turbine inlet, the steam pressure and temperature are  $P = 28 \text{ MPa}$  and  $T = 550^\circ\text{C}$ , respectively. The steam expansion processes in a heating turbine with intermediate reheating are illustrated in Fig. 5.

Thus, process 1-2 is similar to a similar process in a turbine with intermediate overheating (Fig. 4).

To heat water in the heating system, the temperature of the steam at the exit from the turbine must be at least 150 °C. To ensure this temperature, the steam in the low-pressure cylinder of the turbine expands to 0.15 MPa.

At the turbine outlet, the steam temperature reaches 160°C, making it suitable for heating water to temperatures ranging from 100°C to 130°C. After passing through the heat exchanger, the steam temperature decreases to 112°C.

The enthalpy at point 4 is determined by the formula:

$$h_4 = h_3 - (h_3 - h_{4s}) \cdot \eta_{sT} = 3552 - (3552 - 2661) \cdot 0.9 = 2750 \text{ kJ/kg}.$$

$$h_1 - h_w = 3304 - 473 = 2831 \text{ kJ/kg}.$$

Table 4: Water: Specified state points

	Temperature °C	Pressure MPa	Density kg/m <sup>3</sup>	Enthalpy kJ/kg	Entropy kJ/kg·K
1	550.0	28.000	90.171	3304	6.095
2s	276.9	4.850	23.037	2854	6.095
2	290.2	4.850	21.95	2900	6.179
3	550.0	4.850	13.15	3552	7.139
4s	111.4	0.150	0.875	2661	7.139
4	160.5	0.150	0.758	2794	7.47
5 <sub>w</sub>	112.0	4.850	951.7	473.3	1.44

$$h_3 - h_2 = 3552.3 - 2900 = 652.3 \text{ kJ/kg}.$$

That's all

$$\Delta h_q = 2841 + 652.3 = 3493.3 \text{ kJ/kg}.$$

Mass flow of water

$$\dot{m}_e = \frac{\dot{Q}}{\Delta h_q} = \frac{14800}{3493.3} = 4.24 \text{ kg/s}.$$

Steam turbine power

$$N_T = \dot{m} \cdot \Delta h_T = 4.24 \cdot \left[ (3304 - 2900) + (3552.3 - 2794) \right] = 4928 \text{ kW}.$$

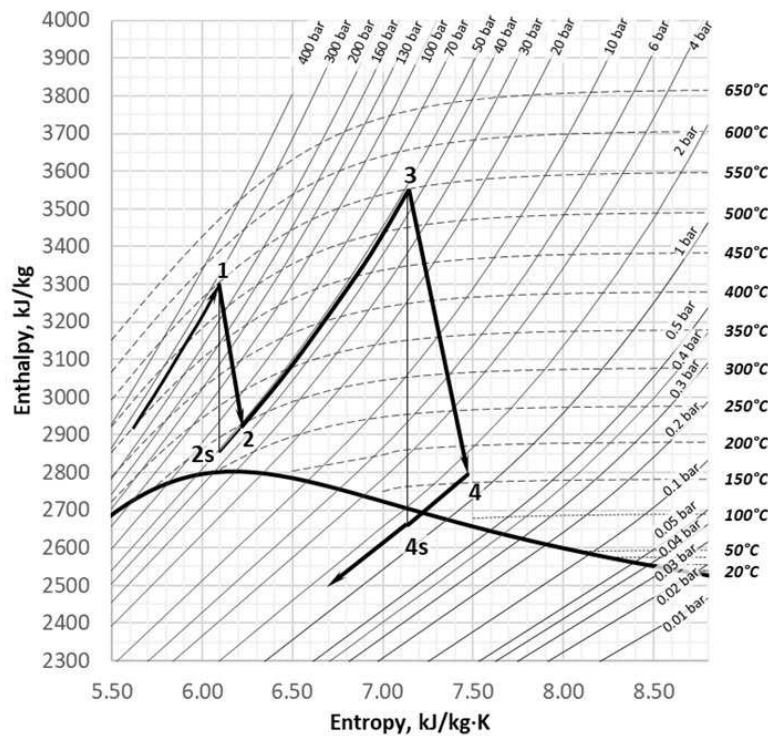


Fig. 5. Rankine cycle in the h-s diagram for a heating turbine

The thermal power output of the water heater for  $\Delta T = 48^\circ\text{C}$  is calculated as:  $\dot{Q} = 794\text{ kW}$ . Thus, the total available power is

$$4928 + 794 = 5722\text{ kW}$$

The energy efficiency of a nuclear power plant with heating turbine with intermediate superheat is equal to

$$\frac{N_e \cdot \eta_{mehT} \cdot \eta_e}{N_R} = \frac{5722 \cdot 0.98 \cdot 0.98}{15000} \cdot 100 = 36.6\%$$

### 3.3.1 Heating turbine and ORC

The amount of heat removed from steam during condensation at  $T = 112^\circ\text{C}$  is 2286 kJ/kg.

The total heat flow is calculated as

Case a)  $T = 30^\circ\text{C}$

Freon R134a enters the heat exchanger at an initial temperature of  $30^\circ\text{C}$  and is heated to  $90^\circ\text{C}$ .

The thermodynamic parameters of R134a key cycle points are determined using RefProp (Table 5).

The enthalpy at the exit from the turbine (point 2) is equal to

$$h_2 = h_1 - (h_1 - h_{2s}) \cdot \eta_{sT} = 446 - (446 - 420.5) \cdot 0.9 = 423\text{ kJ/kg}$$

Mass flow of R134a

$$\dot{m}_{R134} = \frac{\dot{Q}}{h_1 - h_3} = \frac{9693}{(446 - 241.7)} = 47.5\text{ kg/s}$$

Steam turbine power

$$N_T = \dot{m}_{R134} \cdot \Delta h_{12} = 47.5 \cdot (446 - 424.3) = 1031\text{ kW}$$

The overall energy efficiency of a nuclear power plant equipped with a CHP system and ORC is calculated as follows:

$$\frac{N_e \cdot \eta_{mehT} \cdot \eta_e}{N_R} = \frac{(5722 + 1031) \cdot 0.98 \cdot 0.98}{15000} \cdot 100 = 43.2\%$$

Table 5: R134a: Specified state points

	Temperature °C	Pressure MPa	Density kg/m <sup>3</sup>	Enthalpy kJ/kg	Entropy kJ/kg·K
1	90.0	2.63	134.1	446	1.733
2s	35.4	0.77	36.3	420.5	1.733
2	39.1	0.77	35.5	424.3	1.745

Thus, the integration of ORC technology results in 6% overall increase in the nuclear power plant's energy efficiency.

Case b)  $T = 15^\circ\text{C}$

For this case, the power output of the ORC turbine is  $N_T = 1326\text{ kW}$ .

The total energy efficiency of a nuclear power plant incorporating CHP and ORC is:

$$\frac{N_e \cdot \eta_{mehT} \cdot \eta_e}{N_R} = \frac{(5722 + 1326) \cdot 0.98 \cdot 0.98}{15000} \cdot 100 = 45.1\%$$

As a result, using ORC leads to an overall 7% increase in the nuclear power plant's efficiency.

### 3.4 Supercritical CO<sub>2</sub> turbomachine facility

The supercritical CO<sub>2</sub> (s-CO<sub>2</sub>) Brayton cycle has recently gained significant attention for next-generation nuclear reactor applications. The primary advantages of the s-CO<sub>2</sub> cycle include high thermal efficiency in the moderate turbine inlet temperature range, compact system layout, and smaller turbomachinery and heat exchangers. Various heat sources, such as nuclear energy, fossil fuels, waste heat, and renewable sources like solar energy or fuel cells, can serve as inputs for the s-CO<sub>2</sub> cycle [8].

The s-CO<sub>2</sub> power cycle is particularly well suited for Gen IV nuclear reactors, offering enhanced efficiency and better stability with conventional structural materials.

Critical CO<sub>2</sub> parameters: pressure 7.4 MPa; temperature  $31^\circ\text{C}$ ; density 468 kg/m<sup>3</sup>.

The following calculations are based on turbine inlet conditions of  $550^\circ\text{C}$  and 18 MPa.

The T-s diagram for the s-CO<sub>2</sub> Brayton cycle is illustrated in Fig. 6.

The enthalpy at the turbine outlet (point 2) is calculated as:

$$h_2 = h_1 - (h_1 - h_{2s}) \cdot \eta_{sT} = 1036.6 - (1036.6 - 908.5) \cdot 0.9 = 921.3\text{ kJ/kg}$$

The pressure at the inlet compressor is 7.5 MPa, the temperature is  $35^\circ\text{C}$ . The output pressure is 18 MPa.

The temperature at point 5 is  $97^\circ\text{C}$ .

Due to regenerative heat exchange, the CO<sub>2</sub> temperature can be increased to 380°C.

The properties of CO<sub>2</sub> at 18 MPa and 380°C are determined using RefProp.

To achieve the enthalpy value at the turbine inlet of 1037 kJ/kg, it is necessary to increase the enthalpy by 207.5 kJ/kg (1037-829.5=207.5).

CO<sub>2</sub> mass flow rate:

$$\dot{m}_{CO_2} = \frac{\dot{Q}}{\Delta h} = \frac{14800}{207.5} = 71.3 \text{ kg/s.}$$

Thus, the enthalpy difference is:

$$\Delta h_{12} = h_1 - h_2 = 1036.6 - 921.3 = 115.3 \text{ kJ/kg}$$

Turbine power output:

$$N_T = \dot{m} \cdot \Delta h_{12} = 71.3 \cdot 115.3 = 8221 \text{ kW.}$$

The enthalpy at the compressor outlet (point 5) is:

$$h_5 = h_4 + \frac{(h_{5s} - h_4)}{\eta_{sc}} = 397.7 + \frac{(426 - 397.7)}{0.85} = 431 \text{ kJ/kg}$$

Table 6: carbon dioxide: Specified state points

	Temperature °C	Pressure MPa	Density kg/m <sup>3</sup>	Enthalpy kJ/kg	Entropy kJ/kg·K
1	550.0	18.0	112.4	1036.6	2.763
2s	434.7	7.5	56.01	908.5	2.763
2	445.7	7.5	55.1	921.3	2.78
3	100	7.5	130.4	523.7	2.03
4	35	7.5	273.0	397.7	1.65
5s	94.8	18.0	449.8	426.4	1.65
5	96.9	18.0	439.5	431.4	1.661
6	380.2	18.0	146.2	829.1	2.48

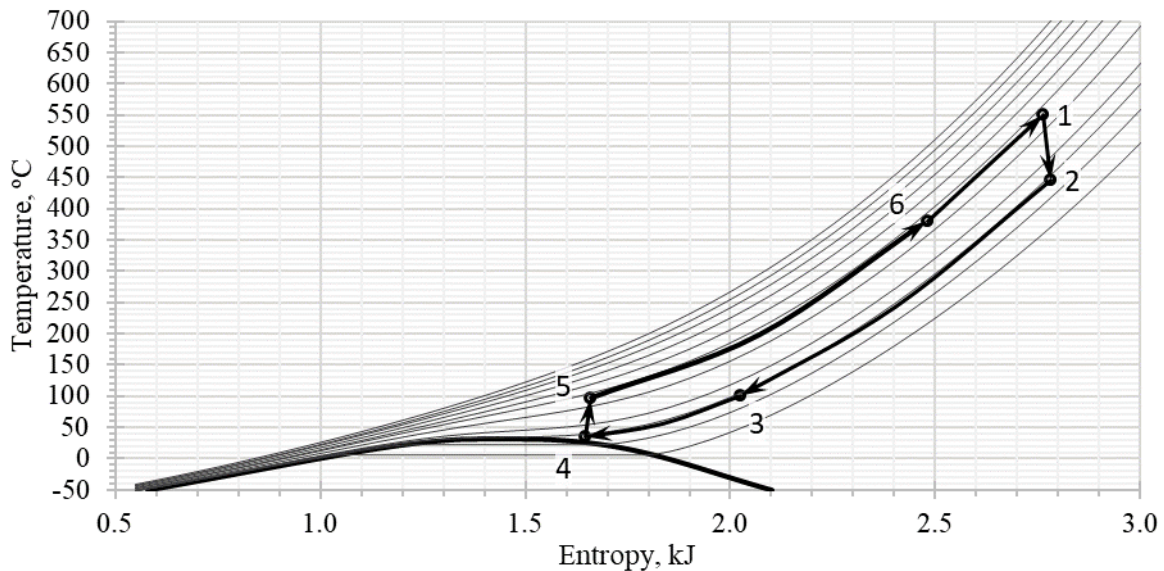


Fig. 6. Supercritical Brayton cycle in the T-s diagram for turbomachine facility with supercritical CO<sub>2</sub>

- 1-2 steam expansion process in the turbine;
- 2-3 process of heat transfer in a recuperative heat exchanger;
- 3-4 heat removal process in the cooler;
- 4-5 process of compression of CO<sub>2</sub> in the compressor;
- 5-6 CO<sub>2</sub> heating process in a recuperative heat exchanger;
- 6-1 process of supplying heat from the reactor to CO<sub>2</sub>

Compressor power requirement:

$$N_c = \dot{m} \cdot \Delta h_{54} = 71.3 \cdot 22.7 = 2407 \text{ kW}.$$

Net electric power output:

$$N_e = N_T - N_c = 8221 - 2407 = 5813 \text{ kW}$$

$$\frac{N_e \cdot \eta_{mechT} \cdot \eta_{ez}}{N_R} = \frac{5813 \cdot 0.99 \cdot 0.99}{15000} \cdot 100 = 38\%$$

### 3.4.1 Supercritical CO<sub>2</sub> turbomachine facility and ORC

Heat from the CO<sub>2</sub> cycle is transferred to the working substance of the ORC cycle in the heat exchanger. At temperature of CO<sub>2</sub> at the inlet to the heat exchanger T<sub>3</sub>=100 °C and at the outlet T<sub>5</sub>=35 °C heat flow in the section of cycle 3-4 is equal to 9010 kW.

Freon enters the heat exchanger at a temperature of 30 °C and is heated to a temperature of 90 °C.

Mass flow of R134a

$$\dot{m}_{R134} = \frac{\dot{Q}}{\Delta h_q} = \frac{9010}{(446 - 241.7)} = 44.1 \text{ kg/s}.$$

Steam turbine power

$$N_T = \dot{m}_{R134} \cdot \Delta h_{12} = 44.1 \cdot (446 - 424.3) = 957 \text{ kW}.$$

Energy efficiency of a nuclear power plant with turbomachine facility with supercritical CO<sub>2</sub>

$$\frac{N_e \cdot \eta_{mechT} \cdot \eta_e}{N_R} = \frac{(5813 + 957) \cdot 0.99 \cdot 0.99}{15000} \cdot 100 = 44\%.$$

The ORC increases the energy efficiency of the nuclear power plant by 6 %.

### 4. Summary

Steam turbine-based nuclear power plants typically exhibit energy efficiency in the range of 28% to 36.5%. The highest efficiency for a heating turbine system is 36.5%.

The energy efficiency of a nuclear power plant with turbomachine facility with supercritical CO<sub>2</sub> is the highest – 38 %.

The ORC provides a notable efficiency boost of approximately 5%. In winter conditions, ORC contributes a larger increase in nuclear power plant efficiency compared to summer conditions.

Increasing the temperature and pressure of supercritical CO<sub>2</sub> makes it possible to achieve an efficiency of more than 50%.

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УДК 620.93: 621.039: 621.165

**ЕНЕРГЕТИЧНЕ ОБЛАДНАННЯ  
АТОМНИХ ЕЛЕКТРОСТАНЦІЙ З  
ВИСОКОТЕМПЕРАТУРНИМ МАЛИМ  
МОДУЛЬНИМ РЕАКТОРОМТ**

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<https://doi.org/10.31472/ttpe.2.2025.5>

Важливість енергії в сучасному суспільстві є незаперечною, оскільки вона лежить в основі електро- та тепlopостачання в усіх галузях промисловості та для населення загалом. Зараз глобальний енергетичний сектор переживає трансформацію, і ядерна енергетика відіграє ключову роль у реструктуризації енергетичних систем у багатьох промислово розвинених країнах. Зокрема, розвитку ядерної енергетики приділено значну увагу в США. Наприкінці 2023 року комітет Конгресу розглянув критичні питання, пов'язані з ядерною енергетикою, дійшовши висновку, що необхідно розширити як виробництво електроенергії, так і виробництво технологічного тепла за допомогою атомних електростанцій. Малі модульні реактори були визначені як перспективне рішення для майбутнього глобального енергетичного сектора. Ці реактори потребують менших капіталовкладень, здатні конкурувати з іншими економічно ефективними формами виробництва електроенергії та пропонують покращені характеристики безпеки. Крім того, SMR надають можливості для інноваційних застосувань, таких як гібридні ядерно-відновлювані енергетичні системи, низьковуглецеве промислове тепло та електроенергія, а також виробництво водню.

Вибір реакторної технології для майбутнього виробництва ядерної енергії має вирішальне значення. Великі дослідження різних типів реакторів були

проведені в Сполучених Штатах, з особливим інтересом до реакторів покоління IV, зокрема до високотемпературних газоохолоджуваних реакторів (HTGR), які використовують гелій як теплоносії. Ці реактори, оснащені мікрокапсульованим паливом TRISO, мають декілька унікальних переваг у сфері безпеки, економічних та експлуатаційних переваг. Малі модульні реактори придатні для експлуатації на цивільних і оборонних об'єктах.

Вибір енергетичного обладнання є важливим завданням для забезпечення високої ефективності енергетичного об'єкта. Виробництво електроенергії на атомних електростанціях найчастіше здійснюється за допомогою паротурбінних установок. Надкритичний CO<sub>2</sub> (s-CO<sub>2</sub>) цикл Брайтона нещодавно привернув значну увагу для ядерних реакторів нового покоління. Основні переваги циклу s-CO<sub>2</sub> включають високу термічну ефективність у помірному діапазоні температур на вході в турбіну, компактне розташування системи та менші турбомашини та теплообмінники. Різні джерела тепла, такі як атомна енергія, викопне паливо, відпрацьоване тепло та відновлювані джерела, такі як сонячна енергія або паливні елементи, можуть служити вхідними речовинами для циклу s-CO<sub>2</sub>.

Виконані розрахунки різних варіантів енергосистем з паротурбінною установкою: без проміжного перегріву з докритичною парою; із проміжним перегрівом з докритичною та надкритичною парою; з теплофікаційною турбіною. Виконані розрахунки турбоустановки з надкритичним CO<sub>2</sub>. Найбільш енергетично ефективною є енергосистема з турбоустановкою з надкритичним CO<sub>2</sub>. Використання органічного циклу Ренкіна суттєво підвищує ефективність атомних станцій. Розрахунки органічного циклу Ренкіна проводили для робочої речовини R134a. Параметри пари в характерних точках циклу визначаються за допомогою RefProp.

Енергоефективність атомних електростанцій з паротурбінною установкою з водяною парою перебуває в межах 28-36,5%. Енергоефективність атомної електростанції з надкритичною CO<sub>2</sub> турбіною становить 38 %. Підвищення температури і тиску надкритичного CO<sub>2</sub> дозволяє досягти ККД більшим за 50%.

Використання органічного циклу Ренкіна (ORC) суттєво підвищує ефективність енергосистеми.

**Ключові слова:** атомна електростанція, малий модульний реактор, паротурбінна установка, цикл Ренкіна, турбоустановка з надкритичним CO<sub>2</sub>.

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Отримано 02.04.2025

Received 02.04.2025

Прийнято до друку 10.05.2025  
Accepted for publication 10.05.2025