

The use of heat from the CO₂ compression system for production of system heat

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Abstract. The study presents the concept and computations of the CO₂ compression for the purposes of transport and underground storage of the gas. Cooling between individual stages is needed to reduce the power needed for CO₂ compression. Heat obtained from the cooling process can be used to provide heat to the municipal heat power systems. A design of a heat accumulator for storage of excess heat was proposed in order to improve heat supply safety. The solution proposed in the study allows for heating condensing power units using waste heat from the CO₂ cooling process.

1 Introduction

In many countries, including Poland, combustion of fossil fuels have been used to generate electricity and heat. Fossil fuel combustion processes contribute to degradation of the natural environment and climate changes through emissions of combustion products to the atmosphere, including: CO₂, SO₂, NO_x, dusts, and heavy metals, including Hg. Modern technologies of flue gas treatment allow for a substantial limitation of emissions of SO₂, NO_x and dusts. Technologies of Hg emissions limitation and other heavy metals have been developed [1–3]. The problem of CO₂ emissions to the atmosphere has not been solved yet. The regulations known as climate package require limitations of CO₂ emissions by 20%, the increase in the use of renewable energy sources to 20% and the increase in energy efficiency to 20% compared to prognoses for 2020. In the development of renewable energy sources, it is mainly the energy sector that uses wind force which helps meet the requirement of 20% energy production from renewable sources. The percentage of electricity generated from renewable sources in Germany increased from 6.3% in 2000 to ca. 41% in 2018, which is double the value of the assumed level of 20% [4]. One should expect further dynamic increase in renewable energy in other countries of the European Union. The studies have been conducted in recent years to improve efficiency of energy generation in power plants and combined heat and power plants [5–7]. Ultra-supercritical power unit technologies are being developed in order to exceed the level of efficiency of 50%. The increase in the use of fossil fuel energy can be achieved by the combined generation of electricity and heat and construction of gas and steam systems. Limitation of CO₂ emissions to the atmosphere can be achieved by its capture from flue gas, followed by storage [8]. The process of CO₂ capture from flue gas can be performed using various technologies:

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adsorption, absorption, membrane, and cryogenic. Carbon dioxide isolated from flue gas should be then transported to places where it can be permanently stored.

The study presents a proposal for the use of heat from the CO₂ combustion process for the purposes of supplying heat to the steam power unit. Furthermore, the opportunities for storing the heat using a heat accumulator were also discussed.

2 Conventional energy generation

As mentioned in the Introduction section, processes of combustion of fossil fuels for the purposes of electricity and heat generation contribute to emissions of various pollutants, including CO₂. All the newly built power plants have to be prepared for construction of installations of CO₂ capture and separation. With the already existing energy installations, one should take into consideration the increase in unit costs of electricity and heat generation connected with buying permits for CO₂ emissions to the atmosphere or the necessity to install CO₂ capture and separation systems.

The conventional energy sector can limit CO₂ emissions through [8]:

- CO₂ capture from flue gas. Nowadays, it is possible to use absorption or adsorption technologies;
- Oxygen combustion. In this case, flue gas contains 90–95% CO₂;
- CO₂ capture before combustion.

Regardless of the method of limitation of CO₂ emissions, it is necessary to compress the gas in order to transport it and store underground. In order to demonstrate the scale of the problem, one can use the following example of newly built power units. Depending on the fuel burnt, a power unit with a capacity of 900 MW_e emits around 175 kg CO₂/s (hard coal), 225 kg CO₂/s (brown coal).

The major task of power units in industrial power plants is to generate electricity. Depending on the location (power plant near a big city) and local infrastructure (presence of heat power systems), power units may, besides their main function of electricity generation, be a source of heat needed for municipal heat power system.

In the case of big power objects (with condensing turbines), the opportunities for generating additional heat is connected with collecting the steam from the turbine outlet and transfer of the steam to heat exchanger where the water for the network is heated while steam collected from the turbine outlet is condensed. This solution is popular in steam power units and allows for generation of the required amount of heat. This system allows for improving the efficiency of electricity and heat generation. A drawback of this solution is a decline in electricity generation with the increase in heat generation, related to the increased stream of steam transferred to the heat exchanger. Another method to provide heat for power unit is to use waste heat contained in flue gas or water that cools the turbine condenser.

The efficiency of power units depends on several factors, such as power, combustion technology (pulverized coal-fired boiler, fluidized-bed boiler) and parameters of generated steam or water. However, the biggest effect on energy boiler efficiency is from the fuel and its water content. The most advanced brown coal-fired power boilers reach the efficiency of ca. 88%, whereas those hard coal-fired have an efficiency of even 95% [9]. Despite such high efficiency, the amount of heat contained in flue gas, especially in boilers fired by brown coal or biomass with high water content is sufficient for heat production [10] or using it for other purposes, e.g. preparation of flue gas for CO₂ separation using adsorption methods [11]. In this case, the amount of heat generated is proportional to boiler power and, therefore, the capacity of steam power unit. Using this solution, there is a necessity to install a peak heat exchanger that allows for reaching required parameters (temperature, power) of the water in the network.

Another method to provide heat to the steam power unit is to install an absorption heat pump which is fuelled by steam from the turbine outlet and allows for using a low-temperature heat contained in the water that cools the condenser [12]. Compared to a conventional steam-fuelled heat exchanger, this solution allows electrical power of the steam power unit to be reduced at similar heat generation. Providing heat to a steam power unit using an absorption heat pump helps prepare water with maximal temperature of up to 95°C but it requires installation of a peak heat exchanger for ensuring the required parameters of the network water and heat supply safety.

The presented methods to provide heat to condensing steam power units allow first and foremost to improve the efficiency of the combined electricity and heat generation. However, they require additional investment expenditure for building installations of heat exchangers or installations of absorption heat pumps. In order to limit costs of these installations (reduction of installed capacity) and their negative effect on operation of a steam power unit (reduction in electrical power), it is necessary to store heat generated. Installation of the system of heat storage helps make electricity and heat generation process independent in the steam power unit. Therefore, it is possible to ensure optimal electricity and heat generation at higher thermodynamic and economic efficiency.

Heat supplies to heat networks and next to receivers require ensuring adequate parameters (temperature, mass flux) of the heat carrier (water). Parameters of heat network operation are contained in the regulation tables which are prepared individually for each heat network and heat consumer. An example of a regulation table is presented in Table 1. From the standpoint of work and installed capacity of the heat source, in addition to the required temperature of network water, important factors also include durations of individual values of external temperatures. Fig. 1 presents an example diagram of external temperatures and the number of hours these temperatures are observed [13].

Table 1. Regulation table [10].

| Nº | Air temp. [°C] | Feed water temp. [°C] | Return water temp [°C] |
|----|----------------|-----------------------|------------------------|
| 1 | -16 | 125 | 66 |
| 2 | -15 | 123 | 65 |
| 3 | -14 | 121 | 64 |
| 4 | -13 | 118 | 63 |
| 5 | -12 | 115 | 62 |
| 6 | -11 | 113 | 61 |
| 7 | -10 | 111 | 60 |
| 8 | -9 | 108 | 59 |
| 9 | -8 | 105 | 58 |
| 10 | -7 | 102 | 57 |
| 11 | -6 | 99 | 56 |
| 12 | -5 | 97 | 55 |
| 13 | -4 | 95 | 54 |
| 14 | -3 | 93 | 53 |
| 15 | -2 | 91 | 52 |
| 16 | -1 | 88 | 51 |
| 17 | 0 | 86 | 50 |
| 18 | 1 | 84 | 49 |
| 19 | 2 | 81 | 48 |
| 20 | 3 | 79 | 47 |
| 21 | 4 | 76 | 46 |
| 22 | 5 | 72 | 45 |
| 23 | 6 | 69 | 44 |
| 24 | 7 | 66 | 43 |
| 25 | 8 | 63 | 42 |
| 26 | 9 | 59 | 41 |
| 27 | 10 | 56 | 40 |
| 28 | 11 | 53 | 39 |
| 29 | -12 | 115 | 62 |

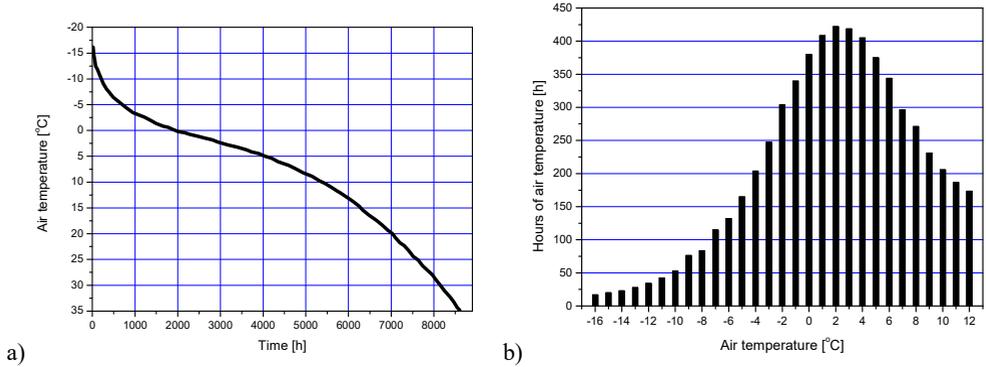


Fig. 1. The structured graph of outer air temperature for location of a dedicated heat recipient a), hours of presence of external air temperature during the central heating season b) [13].

3 Storing heat

Due to substantial capacities of heat power systems, storage of heat requires the equipment and installations which allow for storing huge amounts of heat. There is a number of heat storing methods [14]. However, for technical reasons, the best solution is to store heat in hot water in heat accumulators. Heat accumulators are mostly built near combined heat and power units, which allows for separation of electricity and heat generation.

A heat accumulator is a tank which accumulates heat contained in hot water. The accumulator ensures smooth operation of the unit between night and day, allowing for switching the generation to more efficient units and increasing production in co-generation. The heat is collected when the demand for heat is lower and returned when its consumption increases (in the mornings and evenings). Heat accumulator capacities have to be chosen based on the analyses of heat demand and opportunities for operation with the generating unit and heat network and economic analysis connected with investment costs.

A heat accumulator is usually an unpressurised water tank included in the heat power system. During "charging" the accumulator (Fig. 2a), hot water is supplied to the upper part of the tank, whereas cold water is received from its bottom part. Therefore, the intermediate layer between the hot and cold water is moved to the lower part of the tank, while the amount of heat collected in the accumulator is increased (level of water in the tank is virtually unchanged). The accumulator is discharged (Fig. 2b) by reception of the hot water

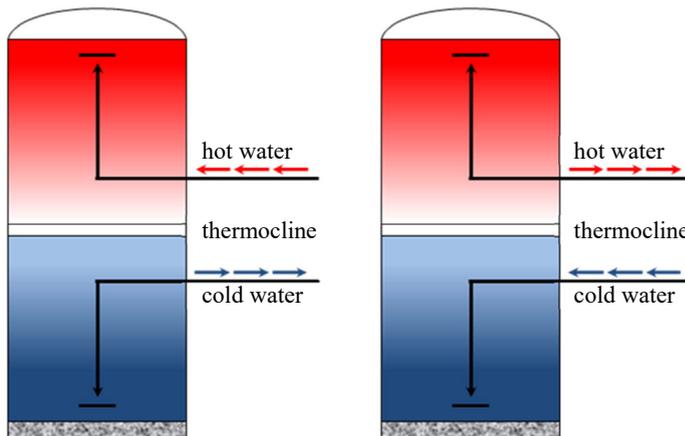


Fig. 2. Processes of (a) charging and (b) discharging of a heat accumulator.

from the upper part of the tank and supply of the cooled water to its lower part. A direct layer is moved towards the upper part of the container. For economic and constructional reasons, heat accumulators are unpressurised tanks, and, consequently, maximal temperature of the water stored cannot exceed 100°C.

The upper part of the heat accumulator contains hot water with the temperature of the heat network feed, whereas the lower part of the tank is filled with water with the return temperature. There is also a mixture of both types of water between each other, termed thermocline. The difference between temperature of hot and cold water in unpressurised tanks ranges from 30–40°C. The phenomenon of thermal stratification of water is demanded in heat accumulators. In properly designed containers, this phenomenon occurs independently through gravitational forces (differences in hot water and cold water densities). For functional reasons, the heat accumulator should be smooth. The optimal height-to-diameter ratio of heat accumulator ranges from 3 to 4 [15]. The Polish energy system uses heat accumulators with capacities from 12,000 to over 30,000 m³. The heat accumulator installed in Elektrociepłownia Siekierki has capacity of 30,400 m³, with tank diameter of 30 m and height of 47 m. Heat capacity of the accumulator is 1,600 MWh whereas its heat power is 300 MW_t.

4 Compression of CO₂

The CO₂ separated from flue gas, with pressure and temperature similar to conditions of the environment has to be compressed to the pressure of 12–15 MPa and cooled to the temperature of 10–25°C that ensures its transport in the liquid phase.

The process of CO₂ compression can be performed by means of positive displacement compressors and flow compressors. However, due to substantial fluxes of the compressed CO₂, the flow compressors are more often used. The thermodynamic fundamentals of the multi-step CO₂ compression were presented in a study [16]. The work [J/(kg CO₂)] of the polytropic compression which is actually performed is given by (1):

$$L_t = R \cdot T_0 \cdot \frac{m}{m-1} \cdot \left[\left(\frac{p}{p_0} \right)^{\frac{m-1}{m}} - 1 \right] \quad (1)$$

R – individual gas constant;

*T*₀ – initial suction temperature;

*p*₀ – initial pressure (suction);

p – final pressure (pumping);

m – polytropic exponent, has value from 1.4 to 1.

A multi-stage compression process with cooling between stages is used to limit the demand for power for compression of CO₂ stream. This solution substantially limits the power needed to drive compressors and allows for the reduction of their size and helps use the heat stream obtained in inter-stage coolers in e.g. the system of boiler water regeneration for heating purposes or supplying heat to a cooler or absorption coolers for cold generation. The increase in the number of compression stages with cooling between stages allows for a reduction in the demand for power while reducing gas temperature following the compression process, which directly impacts maximal temperature of the cooling medium at the outlet from the inter-stage cooler.

The demand for work [J/(kg CO₂)] at multi-stage adiabatic compression with *n* degrees is described by the relationship (2):

$$L_t = R \cdot T_0 \cdot \frac{\kappa}{\kappa - 1} \cdot n \cdot \left[\left(\sqrt[n]{\frac{P}{P_0}} \right)^{\kappa} - 1 \right] \quad (2)$$

κ – adiabatic exponent;
 n – number of compression stages.

The most popular compression systems are those with 3 to 6 compression degrees with cooling between stages, whereas the use of a higher number of compression stages does not produce substantial thermodynamic effects [16] and significantly improves the costs of installation and reduces its efficiency. In the case of multi-stage systems, adequate division of pressures between individual compression stages is critical to minimize compression. It is necessary to conduct multi-dimensional optimization, with optimization criterion being minimization of power necessary for CO₂ stream compression.

The CO₂ obtained from flue gas during separation has to be compressed to reach the parameters that allow for its transport in the liquid phase. With the necessity of supplying the compressed gas to more remote destinations (200 to 300 km), it is critical to obtain high initial pressure which allows for overcoming CO₂ flow resistance in the piping and ensures minimal pressure in the pipeline which is not lower than 8 MPa. Therefore, for the purposes of computations presented in the study, the initial CO₂ pressure of 15 MPa was adopted, with temperature of 20°C.

Computation of the multi-stage compression with cooling between stages was performed for the 900 MW_e power unit fired with hard coal (emits CO₂ around 175 kg/s) using the dedicated computation software where necessary physical parameters of CO₂ were implemented based on the studies [17, 18].

The process of multi-stage CO₂ compression is performed near the steam power unit that generates power necessary for driving the compressors (6 to 8% of the power unit capacity) [8]. Depending on the parameters, the heat obtained during cooling in inter-stage coolers can be used in the system for regeneration of water that fuels the steam water, in ORC cycle, and system heat generation or for the purposes of cold generation.

The process of multi-stage compression with cooling between stages was performed for the systems containing from 4 to 7 compression stages in the 900 MW_e power unit. A diagram of an example structure of a 7-stage compression system with cooling between steps is presented in Fig. 3. The system is composed of seven compressors denoted with symbols of C1 to C7, with heat exchangers between each other, marked HE1 to HE7. The HE0 heat exchanger is installed before the first compression stage. The temperature of the compressed CO₂ after each heat exchanger and before the next compression stage is 60°C. Adoption of this value results from the assumption of the network water temperature of 55°C for the ambient temperature of -5°C (Table 1).

It was assumed that polytropic efficiency for the first compressor is 85% and it is gradually reduced to 70% in the last compression stage. This assumption was adopted for all the analysed multi-stage compression systems.

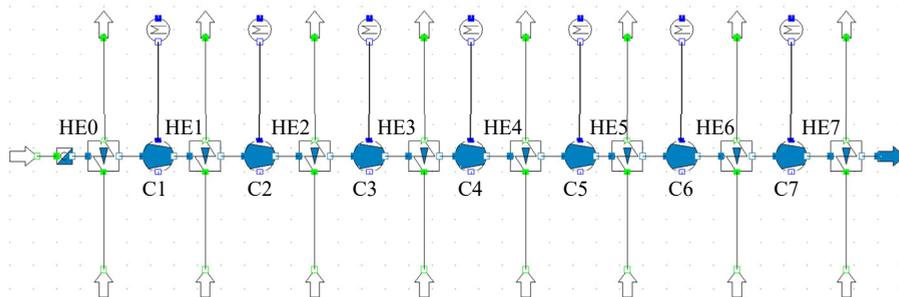


Fig. 3. The system structure for seven-stage compression process with cooling between stages.

For this complex system, a comprehensive optimization analysis of pressures of inter-stage compression p_i was performed, with its criterion being a minimal demand for compression power P . The result of the optimization process (minimum power necessary to carry out the compression of CO₂ process, mass flow equal to 175 kg/s) are optimal inter-stage pressure values $p_{i\ opt}$. Details of the optimization procedure can be found in [16].

$$\min\{P = f(p_i)\} \Rightarrow p_{i\ opt} \tag{3}$$

The results of computations for four computational cases for complete optimization, from seven-stage compression to four-stage compression are presented in Figs. 4 to 8.

Fig. 4 presents the values of inter-stage pressures for four analysed cases. Figure 5 presents values of CO₂ temperature following the compression stages for the four analysed cases. It can be observed that for the system composed of four compression degrees, maximal gas temperature exceeds the level of 190°C, and reduces following individual stages, eventually reaching 150°C following the fourth compression stage. Analysis of the results for greater number of compression stages (5, 6, 7) reveals a reduction in CO₂ temperatures after compression. In the case of seven compression degrees, CO₂ temperature following the last stage is ca. 95°C. Fig. 6 presents the values of heat flux which should be received in coolers between stages from the compressed CO₂ in order to reduce its temperature to 60°C. Figure 7 presents the values of compression power at individual stages depending on the number of compression stages. It can be observed that the increase in the number of compression stages reduces the power of individual stages. Fig. 8 illustrates the demand for power for CO₂ compression and total heat flux which should be received in the process of CO₂ cooling. It is noticeable that the increase in the number of compression stages leads to the reduction in the demand for power and heat flux from the process of CO₂ cooling.

Assuming the temperature in the heat accumulator at the level of 97°C, it is possible to use heat from systems composed of 4, 5 or 6 compression stages due to the temperature of CO₂ after the compression process following individual stages (Fig. 5). From the standpoint of the demand for power for driving compressors, the best solution is the system composed of 6 compression stages. The demand for power for compression is ca. 65.6 MW, whereas heat flux from CO₂ cooling is ca. 98.8 MW. The heat obtained from the compression process can be directly used in the heat network or be stored in the heat accumulator.

Assuming the operation of the power unit at maximal power output for 16 hours and minimal power output (40%) for 8 hours over the day, it is necessary to collect 6,829 GJ (1897 MWh) from the compressed CO₂ for a system with 6 compression stages. In order to store this amount of heat in the heat accumulator, the required capacity of 41,000 m³ of water is needed assuming the difference between water temperatures (of hot and cold water) of 40°C. Due to the variable demand for heat in the heating season and opportunity

of storing heat from the CO₂ cooling process, it is advisable to increase the accumulator capacity to ca. 50,000 m³.

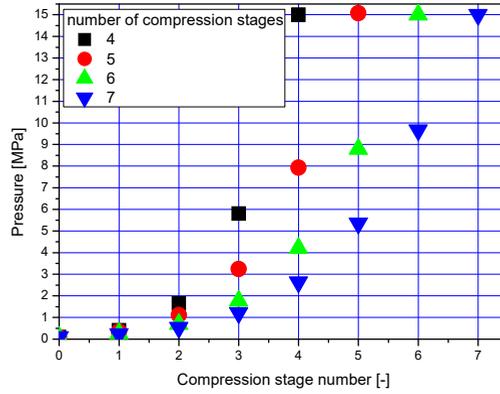


Fig. 4. Distributions of pressure between stages for the analysed four structures of the compression system.

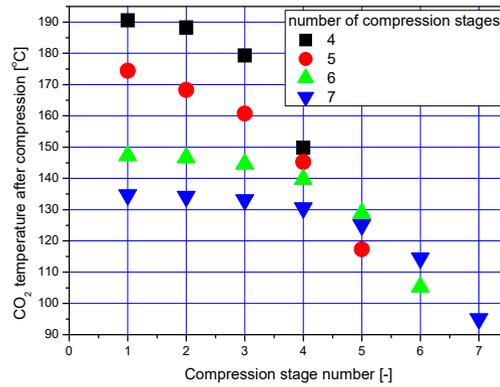


Fig. 5. Distributions of temperatures between stages for the analysed four structures of the compression system.

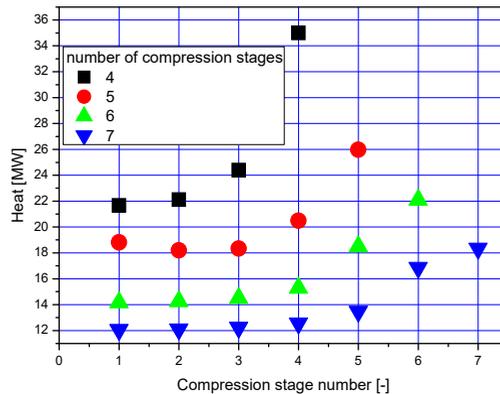


Fig. 6. Values of CO₂ cooling at individual stages depending on the number of compression stages.

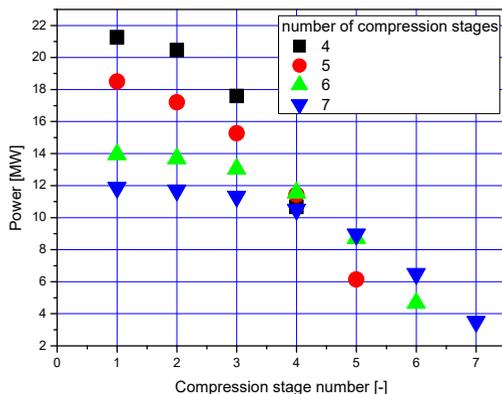


Fig. 7. Values of compression power at individual stages depending on the number of compression stages.

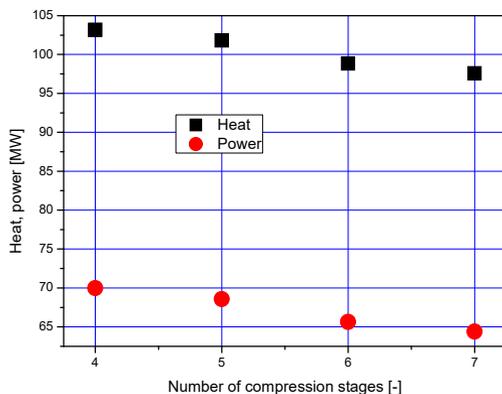


Fig. 8. Demand for power for compression, total heat flux from CO₂ cooling between steps.

5 Conclusion

The computations of the CO₂ compression process for the purposes of transport and underground storage presented in this study demonstrated the opportunities for the use of heat from the CO₂ cooling system for the municipal heat network. The choice of optimal compression system should take into consideration the parameters of heat network operation, temperatures and opportunities for storing heat and minimal power needed for the CO₂ compression system. The system composed of 6 compression stages seems to be an optimal solution for the analysed case. It allows for reaching the heat power at the level of 98.8 MW_t. Assuming variability of the load to the steam power unit, it is possible to reach daily heat generation from the compression system of 6829 GJ. In order to store this amount of heat it is necessary to use a heat accumulator with a water capacity of at least 41,000 m³.

If power unit had to be performed, the process of CO₂ capture and compression for the purposes of transport and storage, this solution would allow for the use of waste heat from the compression process for heating the condensing steam power units.

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