

A New Concept to Designing a Combined Cycle Cogeneration Power Plant

Dr. Leonid Moroz, Dr. Boris Frolov, Dr. Maksym Burlaka

SoftInWay Inc.

15 New England Executive Park Burlington, MA 01803, USA

Email: l.moroz@softinway.com, boris.frolov@softinway.com, m.burlaka@softinway.com,

Abstract

Cogeneration, or combined heat and power (CHP), is the use of a heat engine or power station to simultaneously generate electricity and useful heat. Cogeneration is considered as a thermodynamically efficient use of fuel. In separate production of electricity, some energy must be discarded as waste heat, but in cogeneration, this thermal energy is almost completely or partially put to use. Usually, the CHP plant uses steam as a working fluid and has a flexible ratio of cogeneration, which depends on the season.

During the cold seasons, when heat production is required, the low-pressure part of a steam turbine is not loaded. It consumes power and reduces the efficiency of the turbine, and therefore the cycle. It should be noted that some technologies exist which help to reduce the negative effect, but which still have some drawbacks.

This paper considers a new concept for combined heat and power generation: the combination of Rankine Steam and Brayton Supercritical CO₂(S-CO₂) cycles. The principles and features of combined Steam/S-CO₂ cycles are presented and performances of the combined Steam/S-CO₂ cycles at different ratios of cogeneration are studied. The influence of such an approach on a turbine unit footprint and an estimation of the specific quantity of metals are also examined.

Introduction

CHP is the concurrent production of electricity or mechanical power and useful thermal energy from a single source of energy. CHP is a type of distributed generation, which, unlike central station generation, is located at or near the point of consumption. Instead of purchasing electricity from a local utility and then burning fuel in a furnace or boiler to produce thermal energy, consumers use CHP to improve efficiency and reduce greenhouse gas (GHG) emissions.

The reports [1], [12] and [13] about the state and trends of combined heat and power in the U.S. and Europe showed that CHP is very prospective especially when taking the increase in price of energy sources and other aspects into account. For example, it is stated in report [12] that: “A number of states have developed innovative approaches to increase the deployment of CHP to the benefit of users, utilities and ratepayers. CHP is being looked at as a productive investment by some companies facing significant costs to upgrade outdated coal and oil-fired boilers. In addition, CHP can provide a cost-effective source of highly-efficient new generating capacity. Finally, the economics of CHP are improving as a result of the changing outlook in the long-term supply and price of North American natural gas — a preferred fuel for many CHP applications”.

In turn, Supercritical CO₂ operating in a closed-loop recompression Brayton cycle has the potential of an equivalent or slightly higher cycle efficiency compared to supercritical or

superheated steam cycles at similar temperatures [2]. The current applications of the Supercritical CO₂ Brayton cycle are intended for electricity production only, and the questions related to the building of CHP plants based on Supercritical CO₂ technology were not considered yet.

Considering the benefits of CHP plants and the high potential of the Supercritical CO₂ technology, the latter should be used as the basis of future CHP plants. A comparison with traditional Steam-based CHP plants should also be performed.

The study of CHP plant concepts were performed using the heat balance calculation tool AxCYCLE™ [3] and presented in paper [7].

Conventional Steam Cogeneration Plant

Typical Steam Rankine cycle CHP plants are based on a condensation steam power cycle. In such a cycle, the cogeneration is implemented by the adjustable steam extraction for heat production. In correspondence with the useful heat purposes, the extraction, as well as the heated water, may have different parameters. For urban center or campus heating, the typical steam pressure of the extraction is about 0.2 MPa due to the value of the condensation temperature at this pressure (120.21 °C). Steam from this extraction heats the water for the consumers. The temperature of backwater from consumers may vary from 30 to 70 °C depending on the heating network peculiarities, heat load and other aspects. After the heating, the water usually has a temperature of around 100 °C. The typical pressure of the water for the consumers is about 1 MPa. These parameters were used as a basis in this study. For simplicity, the temperature of backwater was made constant at 30 °C. Another backwater temperature may result in a different performance.

The cogeneration steam turbine unit T-250/300-23.5 was taken as a basis for the comparison. The T250/300-23.5 has a live steam temperature of 540 °C and a live steam pressure of 23.5 MPa. The schematic flow diagram is shown in Figure 1. As can be seen from the Figure 1 turbine unit has 4 turbine cylinders (HPC – High Pressure Cylinder; IPC-1 – Intermediate Pressure Cylinder #1; IPC-2 – Intermediate Pressure Cylinder #2; LPC – Low Pressure Cylinder), steam reheat after HPC, and an advanced regenerative system (which includes 3 High Pressure (HP) Heaters, Deaerator and 5 Low Pressure (LP) Heaters). The water for consumers is heated by controllable steam extractions.

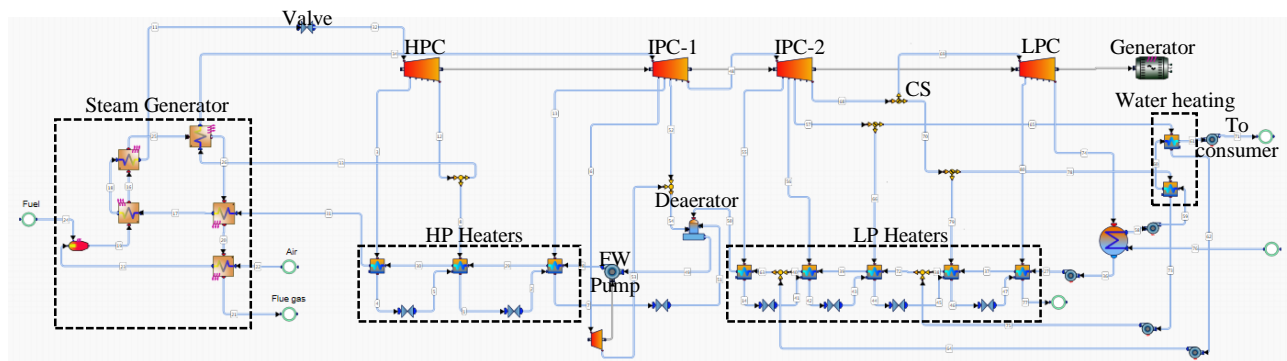


Figure 1. Schematic Flow Diagram of T-250/300-23.5

Adjustable steam extraction for water heating potentially leads to the LPC operating at significantly different mass flow rates. That is why the LPC of the cogeneration turbine unit is essentially a single turbine with specific construction. The LPC turbine has a control stage and a small number of subsequent stages. The turning control diaphragm determines the partial admission of the control stage. Inlet and outlet steam conditions of LPC are changing with variations in the cogeneration turbine operation mode. Mass flow rate through the LPC can vary from very small (at

almost closed Control Splitter (CS)) to a nominal value at a condensing mode of maximum electricity production. This CHP plant gives 250 MW of electrical power and 384.1 MW of useful heat at the maximum heat load mode and only 300 MW of electrical power at condensate mode. I.e. at cogeneration mode, this plant has a Heat Utilization Factor (HUF – the ratio of the sum of Net Electrical Power and Useful Heat to Total Heat Consumption) of 0.803.

The most significant drawback of such a cogeneration scheme is that, at high heat load, the LPC operates at low mass flow rates. With the reduction of the mass flow rate and volumetric flow rate the heat drops, other parameters of LPC stages deviate from an optimum, and the efficiency of the LPC decreases. At some mass flow rate, the strong flow separation near the hub and separation near the tip appear in the LPC (Figure 2). Such a flow separation consumes some useful energy from the main flow and some from the shaft mechanical energy. Useful power of these stages may even become negative due to the useful energy consumption. Besides this, the captured energy dissipates into heat, which, in turn, increases the temperature of the LPC flow path. Such an increase in the flow path temperature requires a lot of effort and intervention to avoid damaging the blades and weakening the landing of rotor discs, exhaust pipe heating, etc.

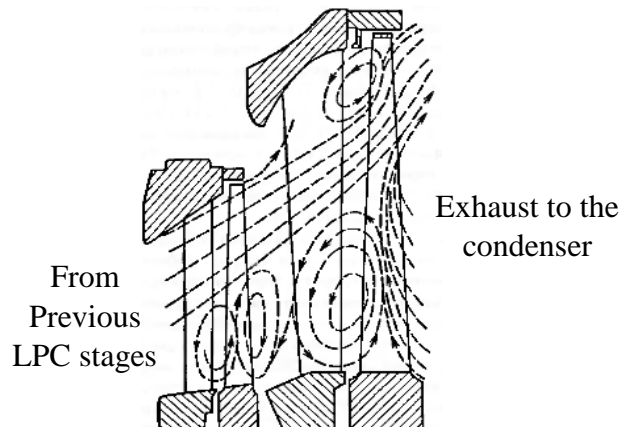


Figure 2. Flow Structure in the Last LPC Stages at Low Volumetric Flow Rate

The previous explanation allows the conclusion that the low mass flow rate operation mode of LPC (maximum heat load) complicates its design and operation and significantly reduces the turbine efficiency. This is an additional reason to synthesize the S-CO₂ technology with combined heat and power principles. We must also try to avoid the previously mentioned drawbacks and increase the effectiveness of the CHP plant.

Synthesis of the S-CO₂ technology with CHP principles

In order to accommodate Supercritical CO₂ technology for CHP conception, a lot of configurations and approaches were considered. The following two approaches, each with two embodiments, were selected as the most interesting:

- 1. Steam Rankine cycle CHP plant with bottoming Supercritical CO₂ cycle**
 - Embodiment a. Combined Complex Steam-S-CO₂ CHP Plant
 - Embodiment b. Combined Simple Steam-S-CO₂ CHP Plant
- 2. CHP plant with single Supercritical CO₂ working fluid**
 - Embodiment a. Cascaded Supercritical CO₂ CHP Plant
 - Embodiment b. Single Supercritical CO₂ CHP Plant

In order to accurately compare the proposed concepts of S-CO₂-based CHP plants with the ordinary CHP unit, we use the same total heat consumption and live steam conditions for the combined Steam-S-CO₂ schemes. However, for the S-CO₂ schemes, the live pressure of S-CO₂ was optimized and was consequently different. The efficiency of the steam turbine cylinders as well as the CO₂ turbine and the compressor were determined at 90 %. The efficiency of the alternators was set at 98% and the heat losses for the regenerative heaters of the Steam cycle part as well as for the S-CO₂ recuperators were 1 % of the transferred heat total.

Thermodynamic analysis and comparison of the above concepts with the conventional steam CHP plant are presented in paper [7]. The results of the thermodynamic study are shown in Table 1. It can be seen from the table that in terms of maximum Heat Utilization Factor (HUF), the best embodiment is 1.b “Combined Simple Steam-SCO₂ CHP Plant.” However, taking into account the negligibly small difference in the HUF magnitudes and the fact that the electrical power is more valuable than the heat, 1.a “Combined Complex Steam-SCO₂ CHP Plant” and 2.a “Cascaded Supercritical CO₂ CHP Plant” are preferable. In order to make a choice between these embodiments, the dimensions, footprint and value of capital costs should be also compared with T-250/300-23.5. The current paper focuses on the consideration of 1.a (Combined Complex Steam-S-CO₂ CHP Plant) and 2.a (Cascaded Supercritical CO₂ CHP Plant) cycles and their comparison with the T-250/300-23.5 power unit in terms of dimensions, approximate 3D layout, and total volume of the components.

Table 1. Performances of the considered CHP plants

Parameter	Embodiment 1.a		Embodiment 1.b		Embodiment 2.a		Embodiment 2.b		T-250/300	
Heat load, %	0	100	0	100	0	100	0	100	0	100
Heat consumption, MW	789.998									
Net electrical power, MW	304.4	252.2	266.6	140.4	311.6	311.6	297.7	297.7	300	250
Useful heat, MW	-	494.6	-	607.6	-	421.0	-	436.2	-	384.1
Electrical efficiency, %	38.53	31.93	33.76	17.77	39.44	39.4	37.68	37.68	37.97	31.65
Heat utilization factor	0.385	0.945	0.338	0.947	0.394	0.927	0.364	0.929	0.380	0.803
Potential of Useful heat, MW	-	-	-	-	421.0	-	436.2	-	-	-

It should be noted that such an advantage of S-CO₂ CHP plants was obtained at the same temperature 540 °C but usually the advantage of S-CO₂ cycles over the ordinary steam cycles takes place at higher temperatures [2]. This provides evidence that the synthesis of the S-CO₂ and CHP technologies is more beneficial than pure electricity production S-CO₂ examples at the same live fluid temperatures. Therefore, it is not necessary to increase the live temperature for S-CO₂ CHP plants to obtain significant gains in efficiency. In turn, the development of the effective S-CO₂ CHP plant at 540 °C seems to be much simpler than the development of high efficiency S-CO₂ pure electricity production units at higher temperatures.

All evaluative design steps of turbines and compressors, thermo/aerodynamic and structural analyses were performed within the AxSTREAMTM turbomachinery design & optimization tool [8, 9, 10, 11].

Throughout this study, the 1D meanline codes (direct task and inverse task [9, 10]) were used for thermodynamic calculations. Beam theory was applied as the structural calculation method.

Heat exchanger evaluative design was performed according to the methods and approaches described in [14] and [15].

It should be noted that, for turbines and compressors, the flow path dimensions were evaluated without casings, but for heat exchangers, the dimensions were estimated including casings.

Combined Complex Steam-S-CO₂ CHP Plant Analysis

The scheme of the combined Simple Steam-S-CO₂ CHP Plant is presented in Figure 3.

In the current embodiment, instead of the adjustable extraction, we fully exclude the Low Pressure Cylinder (LPC) and second Intermediate Pressure Cylinder (IPC-2) of the turbine so the steam after the first Intermediate Pressure Cylinder (IPC-1) is directed to the Control Splitter (CS), which divides the main flow into two parts. Heat load control is implemented through the adjustment of CS, i.e. without heat load, all steam after IPC goes to the condenser where all of the heat is transferred to the S-CO₂. At maximum heat load mode, all steam goes to IHX where heat is transferred to the water for the consumer. At the latter operation mode, the bottoming S-CO₂ cycle can be turned off. At intermediate combined heat and power modes of operation, the bottoming S-CO₂ cycle operates at partial mass flow rate which is determined by the amount of heat received from steam in the condenser.

The bottoming Supercritical CO₂ cycle is quite simple and corresponds to a simple closed recuperated Brayton cycle [6]. The scheme consists of a turbine, a compressor, a recuperator and a cooler. The Supercritical CO₂ is heated by steam in the condenser up to 120°C. The bottoming Supercritical CO₂ cycle has a lower pressure of 7.7 MPa and a compressor outlet pressure of 15 MPa. The temperature of the Supercritical CO₂ after the cooler was 32°C.

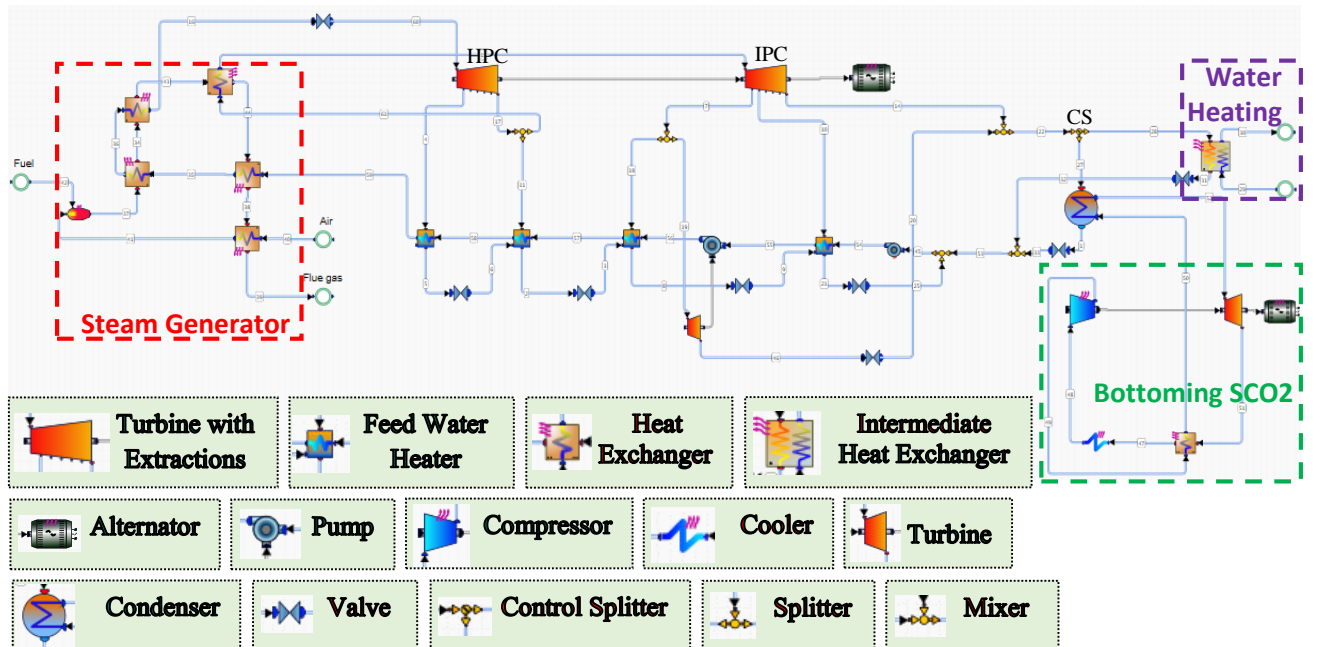


Figure 3. Combined Complex Steam-S-CO₂ CHP Plant

In such a scheme, the steam turbine constantly produces 252.3 MW of net electrical power with any heat load values, when all other conditions are kept constant. However, the electrical power produced by the CO₂ turbine varies depending on the heat load. It is obvious that when we direct more steam to the CO₂ heating loop we produce more electricity and less heat, and vice versa. At the mode of the maximum heat load, this CHP gives 252.3 MW of electrical power, 494.6 MW of useful heat, and 304.4 MW of electrical power only at the mode without heat load. At the maximum heat load, this CHP plant has a HUF of 0.945. Therefore, this CHP exceeds the performance of the convenient T-250/300-23.5 unit at both modes of operation (Table 1). However, partial modes of operation of the bottoming S-CO₂ cycle should be studied separately.

The obvious advantage of such a CHP plant concept is that the steam generator remains the same so it is not necessary to design a new one for the S-CO₂ implementation, a task that can be quite challenging. The HP and IP steam turbine cylinders also remain the same, along with the HP and LP heaters of the steam turbine unit regeneration system, while featuring the absence of a volumetrically imposing LP cylinder. The bottoming S-CO₂ cycle is extremely simple due to the low temperature of the live CO₂, the single recuperator scheme, and the low temperature gradient at the recuperator.

The dimensions are estimated for the following S-CO₂ cycle components at no heat load mode: compressor, turbine, recuperator and cooler. The dimensions of the new condenser, which uses the S-CO₂ instead of water, are also evaluated. The rest of the steam cycle components are not changed and therefore their dimensions estimations are not required.

The type of component significantly affects component dimensions. Therefore, when we performed the component performance estimation, we also compared respective component types. Namely for turbines we compared impulse and reaction types, for compressors we compared centrifugal and axial types. The shell&tube type was used for all heat exchangers. The cold fluid of bottoming S-CO₂ cycle cooler is water. The main criterions for the type selection were maximum efficiency and minimum dimensions.

The estimated dimensions and volume of the bottoming S-CO₂ cycle components are presented in Table 2.

Table 2. Combined Complex Steam-SCO₂ CHP Plant Dimentions: Bottoming S-CO₂ cycle components

Parameter	Turbine	Compressor	Recuperator	Cooler	Condenser
Type	Reaction	Centrifugal	Shell&tube	Shell&tube	Shell&tube
Estimated dimensions, m	D1.4*L1.4	D2.4*L0.5	D3.3*L12.8	D2.7*L11.9	D2.5*L9.3
Volume, m ³	2.2	2.3	109.5	68.1	45.7
Total volume, m ³	227.7				

It should be noted that the presented estimations are a first approach to cycle component dimensions and volume, so after a detailed comprehensive design of the components, the dimensions may deviate from the data in Table 2. In addition, we used a total volume parameter which is the sum of the component volumes. This parameter was used as a final general criterion for the comparison of the considered cycle's components sizes.

As we can see from Table 2 the heat exchanger values are significantly larger than the turbine and compressor values. The largest heat exchanger in this scheme is the recuperator. This

recuperator is even larger than the new condenser. Total volume of the bottoming cycle components, including new condenser, is 227.7 m³.

Cascaded Supercritical CO₂ CHP Plant Analysis

The scheme of the cascaded Supercritical CO₂ CHP Plant is presented in Figure 4. This concept is based on the cascaded Supercritical CO₂ approach [4] in the context of CHP technology (cf. Figure 4. The designations are the same as on Figure 3). According to the approach, the cascade of Supercritical CO₂ recompression cycles [2] is used for an electrical power production. The cascade of Supercritical CO₂ cycles is reasonable because of the small temperature difference in the IHX due to the high degree of Supercritical CO₂ cycle heat recuperation and it allows the utilization of heat from the burning of fossil fuel more effectively.

The temperature of the live carbon dioxide in the HT cycle of the cascade was equal to 540°C while it was equal to 300°C for the LT cycle. The lower pressure magnitude of both cycles was assigned as 7.7 MPa while the compressor outlet pressure magnitudes were optimized and defined as 21 MPa and 20 MPa for the HT and LT cycles, respectively.

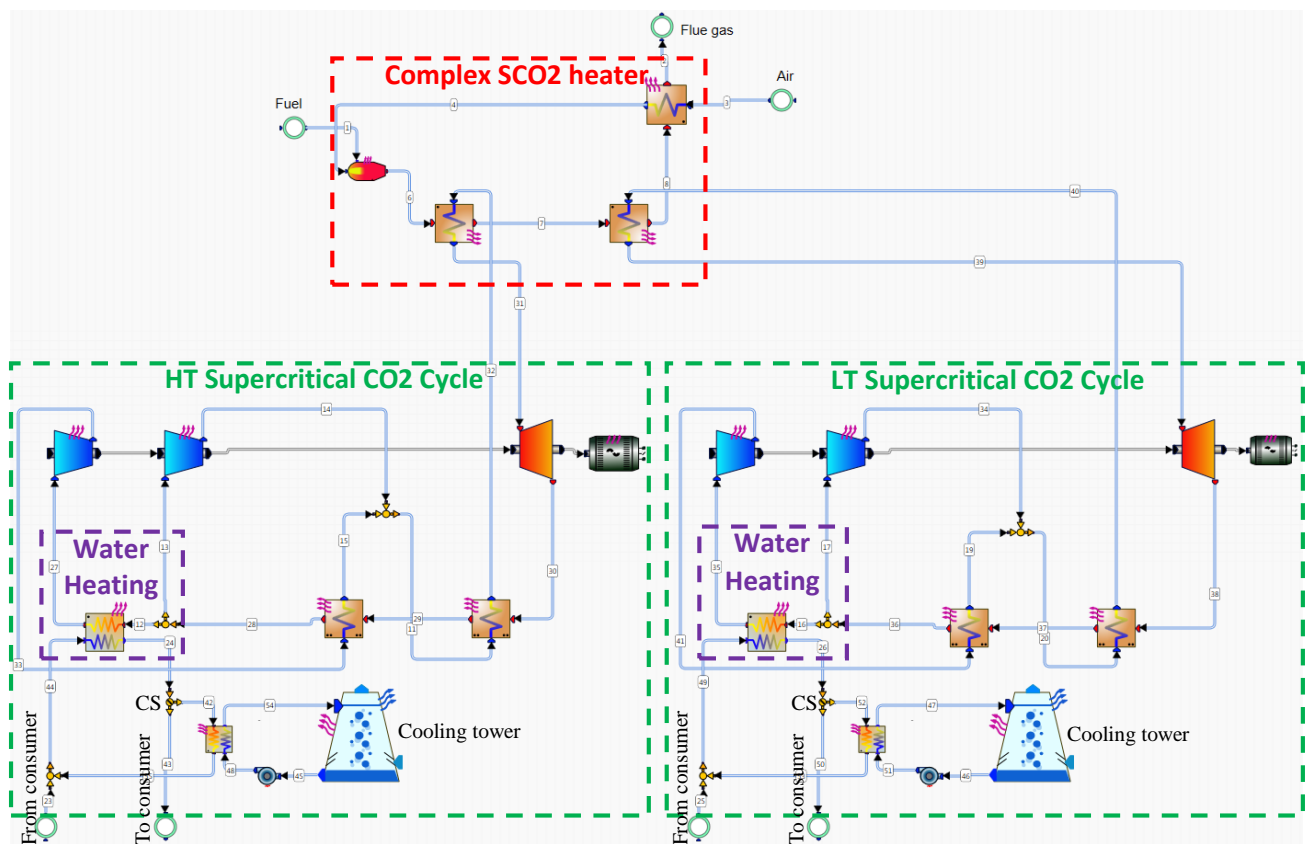


Figure 4. Cascaded Supercritical CO₂ CHP Plant

In order to heat the water for the consumers to 100°C, the ratio of mass flow rates between the main compressor and the recompressor was optimized for both the HT and LT cycles of the cascade, to finally obtain a temperature of carbon dioxide after the LT recuperator equal to 115°C. In addition, the temperature of the Supercritical CO₂ after the cooler was increased from 32 °C to 37 °C. It was done because at 32 °C it was impossible to transfer all of the heat from CO₂ to the water

due to the negative pinch on the cooler. Negative pinch occurs due to the significant S-CO₂-specific heat capacity varying near the critical point. New conditions allow the avoidance of the negative pinch on the water heater.

The heat load in such a CHP plant can be adjusted by dividing the cooling water into two parts on CS. One part is directed to the consumers while the other one goes to the IHX with the secondary water circuit with cooling tower in Figure 4. The total amount of cooling water must be the same to preserve the power production.

In such a scheme, both turbines together constantly produce 311.6 MW of net electrical power with any heat load values, with all other conditions kept constant. This is an obvious advantage of the Cascaded Supercritical CO₂ CHP Plant when compared to T-250/300-23.5, where LPC operates at partial mass flow rates and Combined Complex Steam-S-CO₂ CHP Plant, where the whole bottoming cycle operates at partial mass flow rates. It should be noted that in addition to the electrical power, this plant constantly produces 421 MW of useful heat. This CHP plant may have a constant HUF of 0.927. Therefore this plant has superior performance to T-250/300-23.5 as per electrical power and useful heat at any mode of operation, and it does not have the problems with partial mass flow rates while heat load adjusting.

The dimensions are estimated for both High Temperature (HT) and Low Temperature (LT) S-CO₂ cycle components (a turbine, a main compressor, a recompressor, an HT recuperator, an LT recuperator, and a water heater). The dimensions of the heat exchanger in the Complex SCO₂ heater are not estimated because it is assumed that it will be close to those in a conventional steam generator.

The estimated dimensions and volumes of Cascaded S-CO₂ cycle components are presented in Table 3 and Table 4.

Table 3. HT Cycle of the Cascaded Supercritical CO₂ CHP Plant Dimentions

Parameter	Turbine	Main Compressor	Recompressor	High temperature recuperator	Low temperature recuperator	Water heater
Type	Reaction type	Centrifugal	Centrifugal	Shell &tube	Shell &tube	Shell &tube
Estimated dimensions, m	D1.6*L4.0	D2.5*L0.5	D5.0*L0.8	D3.5*L13.2	D3.3*L11.9	D2.2 *L10.9
Volume, m ³	8.0	2.5	15.7	127.0	101.8	41.4
Total volume, m ³	296.4					

As we can see from these tables, the heat exchanger values are significantly larger than the turbine and compressor values. The largest heat exchanger value in this scheme is the high temperature recuperator in HT cycle. Total volume of the cascaded S-CO₂ CHP plant components is 347 m³.

Table 4. LT Cycle of the Cascaded Supercritical CO₂ CHP Plant Dimentions

Parameter	Turbine	Main Compressor	Recompressor	High temperature recuperator	Low temperature recuperator	Water heater
Type	Impulse type	Axial	Axial	Shell & tube	Shell & tube	Shell & tube
Estimated dimensions, m	D0.7*L1.6	D0.5*L0.5	D0.8*L0.8	D1.3*L8.5	D1.9*L9.1	D1.3*L9.3
Volume, m ³	0.6	0.1	0.3	11.3	25.8	12.2
Total volume, m ³	50.5					

Total dimension difference comparison

It is known that at the similar parameters of live fluid (pressure, temperature) the cost of plant components is directly related to metal consumption, which in turn, is directly related to dimensions of the key components. Thus, the comparison of the dimensions of the key CHP plant components allows the approximate estimation of the difference in relative costs of turbine units.

In order to compare the dimensions, we created the illustrative 3D layouts of the components of Combined Complex Steam-S-CO₂ CHP Plant and substituted components from the T-250/300-23.5 (Figure 5).

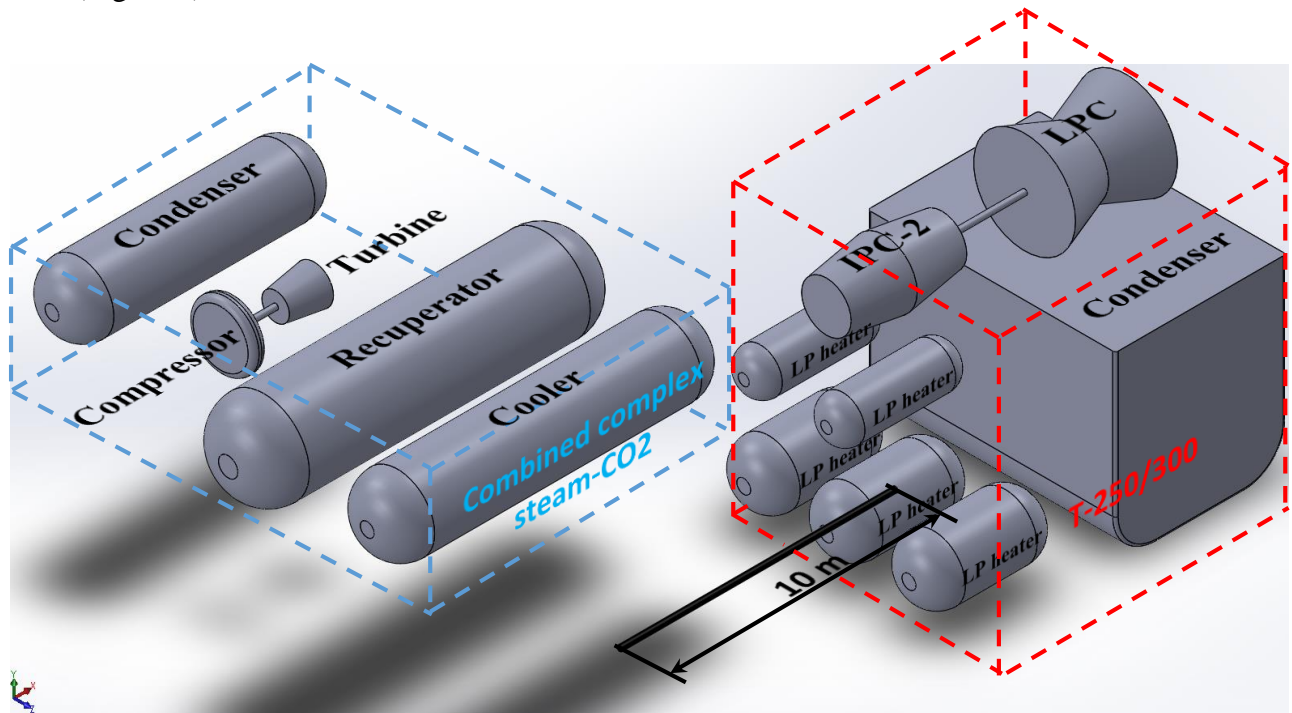


Figure 5. Comparison of the interchangeable components dimensions between the Combined Complex Steam-SCO₂ and the T-250/300

The components in Figure 5 have the same scale so the layouts allow a visual comparison. It should be noted that in the 3D layout of the Combined Complex Steam S-CO₂ the steam cycle part components are not shown, (except for a new condenser) as well as the steam generator and other

auxiliary components. On the 3D layout of the T-250/300-23.5 the only removed parts are shown. Total volume of the removed parts from the T-250/300-23.5 is 506 m^3 . It is obvious that the highest volume component is the condenser with a volume of about 374 m^3 . Comparing the total volumes of the interchangeable components showed in Figure 5 demonstrates that new components have 2.2 times less total volume ($506 \text{ m}^3 / 227.7 \text{ m}^3$).

In order to compare the Cascaded S-CO₂ CHP plant, the respective 3D layout was made (Figure 6). Thus, this CHP plant is a new standalone unit we must compare with the complete unit T-250/300-23.5. The complete T-250/300-23.5 unit is also shown in Figure 6 in the same scale as the Cascaded S-CO₂ CHP plant. Steam generator and complex S-CO₂ heater are not shown because it is assumed that they have comparable dimensions. The auxiliaries are not present for either unit. Complete T-250/300-23.5 unit has a total volume of about 798 m^3 . In turn, Cascaded S-CO₂ CHP unit has total volume 347 m^3 . Therefore, this one has 2.3 times less volume.

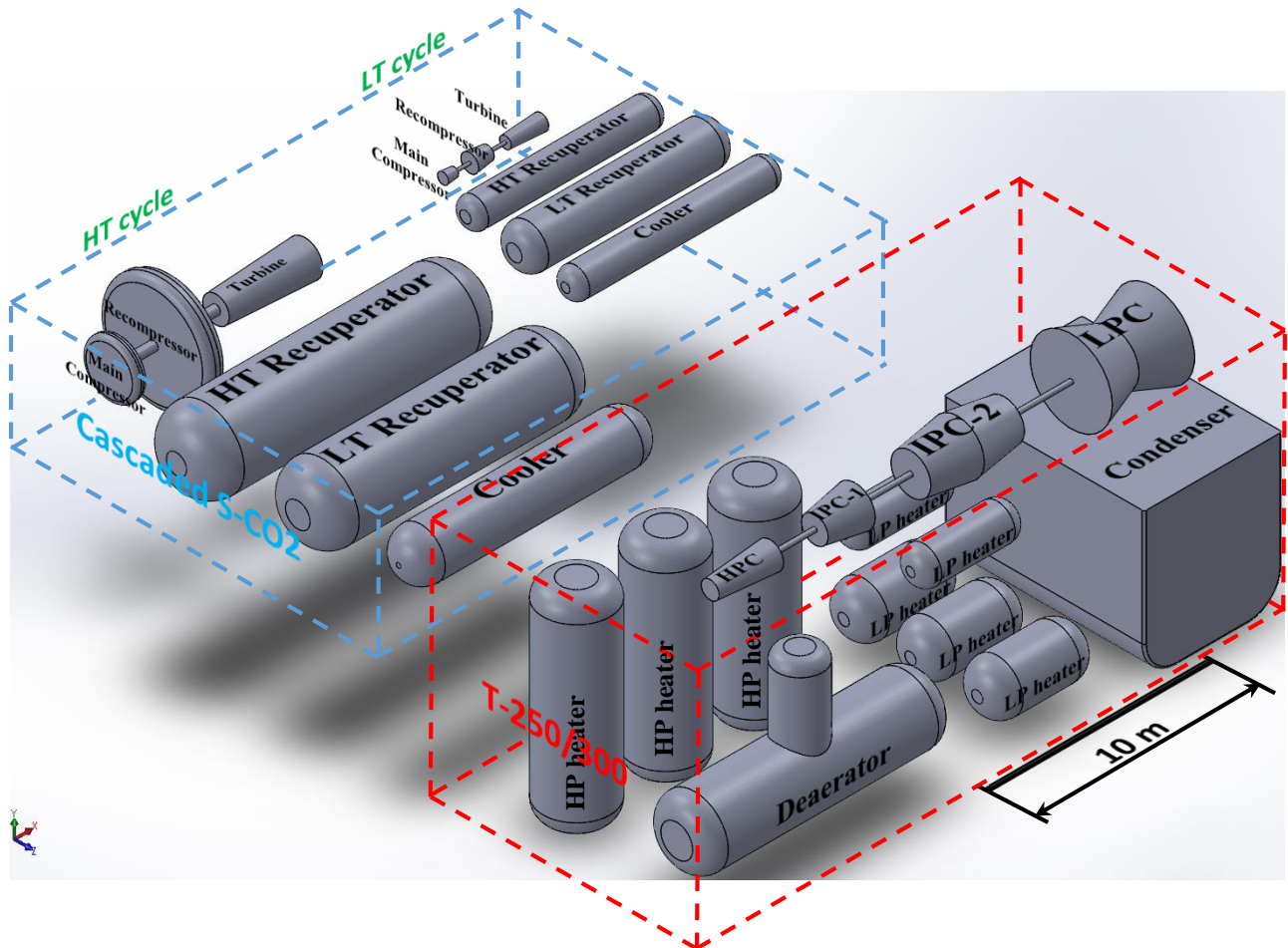


Figure 6. Comparison of the Cascaded S-CO₂ CHP plant 3D layout with the T-250/300 CHP plant 3D layout

In terms of cost, it is reasonable to say that the temperatures, and particularly the pressures, are comparable for ordinary steam CHP plant and for Cascaded S-CO₂ CHP plant. The ratio of total volumes can be treated as an approximate estimation of the units-cost ratio. The creation of turbines and compressors, as well as recuperators and other heat exchangers, for S-CO₂ is quite challenging and expensive and it may increase the initial investments in this technological development. However, future benefits look quite profitable, especially for CHP. It should be noted that the cost of

general facilities is higher than the turbine unit cost [16]. For example, the 300 MW U.S. Pulverized Coal Power Plant earthwork/civil cost is \$52.6 million, steam turbine cost is \$40.2 million and general facilities cost is \$130.4 million. A reduction of the general facilities field and earthwork for the Cascaded S-CO₂ CHP plant may be also significant because this CHP plant does not require a cellar for the huge condenser and other equipment. I.e. the plant may be arranged at one level. Thus, it is an important additional benefit of the Cascaded S-CO₂ CHP plant.

As a result, taking into account the effectiveness of Cascaded S-CO₂ CHP plant and its 2.3 times less total unit volume than ordinary steam CHP, it must be considered a promising CHP plant concept. The scheme with bottoming S-CO₂ cycle may also be reasonable, but partial modes of operation remain to be studied.

It is obvious that there are still a lot of problems and concerns, which are to be solved before the commercialization of the S-CO₂ CHP technology but the present paper shows one perspective of the future of power plant development.

Conclusions

- Taking into account the benefits of CHP plants and the high potential of the Supercritical CO₂ technology, the latter should also be considered as the basis for future CHP plants. The comparison with traditional Steam based CHP plants should be performed.
- The most significant drawback of the convenient steam CHP plants scheme is that at a high heat load, the LPC operates at low mass flow rates. At partial mass flow rate modes the LPC may consume the power from the shaft which may lead to an unwanted flow path temperature increase and all the consequent problems.
- Two new embodiments of the S-CO₂ CHP plant (Combined Complex Steam-S-CO₂ CHP Plant and Cascaded Supercritical CO₂ CHP Plant) are considered and compared with the conventional steam CHP plant in terms of components' total sizes.
- Comparisons of the total volumes of the Combined Complex Steam-SCO₂ and the T-250/300 of the interchangeable components showed that new CO₂ components have 2.2 times less total volume (506 m³/ 227.7 m³).
- Cascaded S-CO₂ CHP unit has a total volume of 347 m³. This is 2.3 times less than T-250/300-23.5 unit total volume.
- Taking into account the high effectiveness of Cascaded S-CO₂ CHP plant (311.6 MW of net electrical power and 421 MW of useful heat) at any heat load mode and relatively small total volume, it must be considered a promising CHP plant concept.
- The embodiment with the bottoming S-CO₂ cycle may also be reasonable in terms of effectiveness and footprint but partial modes of operation remain to be studied.

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