A New Combined Joule – Supercritical Rankine Cycle Exergetic Analysis and Optimization

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1. Abstract – The application of a supercritical Rankine cycle in combined cycles does not happen in today's thermoelectric power stations. Nevertheless, the most recent development in gas turbines, that allows a high efficiency and high exhaust gases temperatures, and the improvement of high pressure and temperature alloys, makes this cycle possible.

This study's intent is to prove the viability of this combined cycle, since it can break the 60% efficiency barrier, which is the *plafond* in actual power stations.

To attain this target, several configurations for this cycle have been simulated, optimized and analyzed [1]. The simulations were done with the computational program IPSEpro [2] and the optimizations were effectuated with software developed for the effect, using the DFP method [3]. In parallel with the optimization that claims the cycle's efficiency maximization, an exergetic analysis was also made [4] to all the cycle components.

In opposite to what happens in subcritical combined cycles, it was demonstrated that in supercritical combined cycles the higher efficiency takes place with a single steam pressure in the heat recovery steam generator (HRSG).

2. Introduction – The study of thermodynamic cycles applied to power stations is of great importance due to the increasing energy consumption, the opening of electricity markets and the rising environmental restrictions, specifically in the carbon dioxide emissions issue.

Today, the modern combined cycle power stations operate with a HRSG with triple pressure and steam reheat after a first expansion in the steam turbine. This configuration offers higher thermal cycle efficiency when compared with a HRSG that produces steam in one or two pressures. In subcritical combined cycle it is proved [1] that the performance in the HRSG improves with the increase of the number of pressures in which the steam is produced. This is obtained reducing exergetic losses due to the decrease in the difference between temperatures in the water/exhaust gases circuit [1].

In supercritical steam cycles the exergetic losses diminish, since the evaporation doesn't take place at constant temperature. However, maintaining the steam temperature at boiler supercritical exit, leads to the decrease in steam quality at steam turbine exhaust, compromising turbine's integrity.

This study starts with an exergetic analysis to a subcritical triple pressure combined cycle with reheat, configuration A, and proceeds with solutions to overcome problems inherent to the application of a supercritical pressure, configuration B to E.

The study ends with a new configuration proposal to the HRSG for the supercritical combined cycle, that being simple guaranties high cycle efficiency, configuration F.

All the simulations were done via the commercial computer program IPSEpro 3.0 [2]. Since this program does not effectuate exergetic analysis [4], routines were developed for the effect. The version 3.0 does not allow cycle parameters optimization either. So, using the possibility of connecting the IPSEpro program to EXCEL the DFP optimization method programmed in EXCEL macros was used.

3. Development – This section presents the cycle's configuration from A to F, their optimal operation conditions and the respective cycle efficiency. At the end a table is presented with the resume of the main results from exergetic analysis and cycles performance. Since the exergetic theory [4] and the optimization model [3] are well known only the study results are exposed.

Configuration A – This work begins with an exergetic analysis of a combined cycle Joule – Subcritical Rankine with a triple – pressure HRSG with steam reheat, since this is the technological solution used in the modern combined cycles power stations that claims higher efficiency [5], [6]. This configuration is the starting point, and a comparison mark to the next presented configurations.

In the exergetic analysis is demonstrated that although the higher exergetic losses in the combined cycle happen in the gas turbine, namely in the combustion chamber, the exergetic losses in the steam circuit aren't negligible. From the exergetic value of the fuel, 4.48% is loss in the heat exchange in HRSG and stack and 2.88% is loss in the rest of the steam cycle (table1). In the next configurations solutions are presented to reduce this energy degradation.

Configuration B – Known the performance of the supercritical steam cycles, which offer an efficiency increase compared to the subcritical steam cycles, this solution was applied in a combined cycle. Since in subcritical combined cycles, the higher efficiency is obtained with a triple pressure HRSG, the first supercritical combined cycle was simulated using this configuration, being the high pressure supercritical, 300 bar.

Considering similar values for minimum temperature differences and pressure drops in HRSG, was achieved a 56.96% efficiency. This corresponds to optimal operation conditions, being produced 8.6% of the steam at 3.7 bar and 14.7% at 35 bar. The lasting 76% are generated at 300 bar and 525 ºC.

The results, table 1, show that although the exergetic losses in HRSG have been reduced, the cycle efficiency had no significant increase compared with configuration A.

The high pressure increase leads to a low steam quality in the steam turbine exhaust, decreasing from 0.9 in configuration A to 0.75, which is a value that compromises the turbine integrity.

Configuration C – The obvious solution to solve the low steam quality problem in configuration B is to increase the supercritical steam temperature. To do this, a gas turbine with a combustion chamber temperature of 1312 ºC that delivers an exhaust gases temperature of 620 ºC was considered. In this simulation, the supercritical temperature is 597 ºC.

Using the same HRSG arrangement, after optimization, a cycle efficiency of 59.27% was reached, but the increase in steam quality at the exhaust steam turbine was only to 0.78.

The increase in gas turbine exhaust temperature offers more energy to produce steam at supercritical pressure. Increasing the supercritical steam mass flow, the exhaust gases energy at low temperature available to produce steam at medium and low pressure is small, since more energy is consumed in the high pressure economizer. Consequently, the steam mass flow at medium and low pressures decreases to 5.8% and 7.8% respectively. This decrease can be easily observed in figure 1 and 2 by the energy dispended in evaporation section.

The optimal medium and low pressures are 35 bar and 4.5 bar respectively.

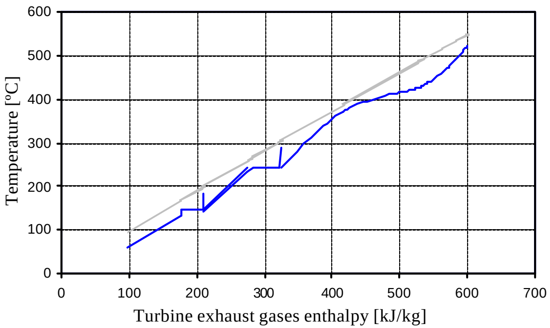


Figure 1 – Temperature – Enthalpy diagram for gases and water circuits in the HRSG in a triple steam pressure Joule – supercritical Rankine combined cycle with gas turbine exhaust gases of 548 ºC.

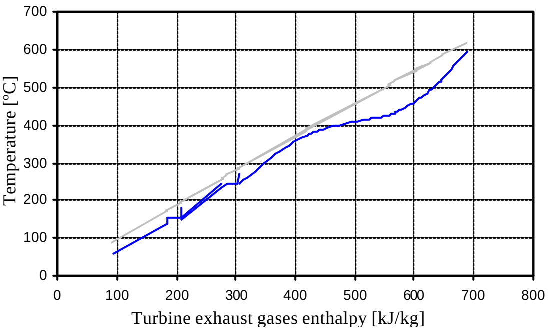


Figure 2 – Temperature – Enthalpy diagram for gases and water circuits in the HRSG in a triple steam pressure Joule – supercritical Rankine combined cycle with gas turbine exhaust gases of 620 ºC.

Configuration D – The decrease in subcritical pressures steam flow, motivated by high exhaust gases temperature, point to the use of a single subcritical pressure in HRSG. In doing so, and comparing the results with configurations B and C, the configuration D suffers an efficiency penalization of 1.06% and 0.65% respectively. This proves that the penalization in cycle efficiency, resulting from less steam production pressures in HRSG, decreases with the increase in gas turbine exhaust gases temperature.

In this configuration the low steam quality in the last steam turbine stage remains, taking the same value as in configuration C (table 1).

Configuration E – Considering the result from the last configuration, a typical solution to increase the quality in steam turbine exit is to reheat the steam after a first expansion, but using a single reheat within the superheater section does not increase the cycle efficiency as it does in subcritical cycles. Nevertheless, it points to another solution: reheat the steam within the high pressure economizer.

It was verified, by simulating the above proposed solution, that the optimal low pressure steam flow should only be the necessary to operate the deaerator. This result indicates the utilization of HRSG with a single high pressure steam production.

Depending on the gas turbine exhaust gases temperature, after the steam production, the energy available to reheat is variable, leading to high temperature differences in the reheater circuits followed by increases in exergy losses. The solution encountered to minimize this problem is to adjust the reheat steam flow using a by-pass circuit. With this configuration, can be always achieved a minimum temperature difference in the reheater, independent from the gas turbine exhaust gases temperature.

In this combined cycle configuration was obtained a 59.6% efficiency, corresponding to the reheat pressure of 4.8 bar and to a 36.6 % bypass. With this configuration, the reheat utilization increases the steam quality in steam turbine exhaust. The value obtained was 0.9.

Configuration F – The more efficient solution to the HRSG configuration, when the gas turbine exhaust gases temperature is high, is to reheat at high and low pressure. With this configuration, the steam generation flow can be adjusted with high pressure reheat. With the correct reheater heat exchangers adjustments, the necessary energy in each HRSG component can be regulated to promote minimum exergy losses in the economizer and in the low pressure reheater. It can even guaranty the same temperature difference along all economizer and low reheater heat exchangers. This is observed in figure 4 between the exhaust gases enthalpy of 170 and 420 kJ/kg. In this part, the lines that represent the steam/water circuits and the gas turbine exhaust gases temperature are parallel.

The high pressure reheat is effectuated within the superheater section and the low pressure reheat is done within the high economizer.

After optimization, it was obtained a cycle efficiency of 60.09% and a steam quality at the exhaust of steam turbine of 0.95. The operation pressures at optimum conditions are 300 bar for the supercritical steam, 231 bar for the high pressure reheat and 3.9 bar for the low pressure reheat.

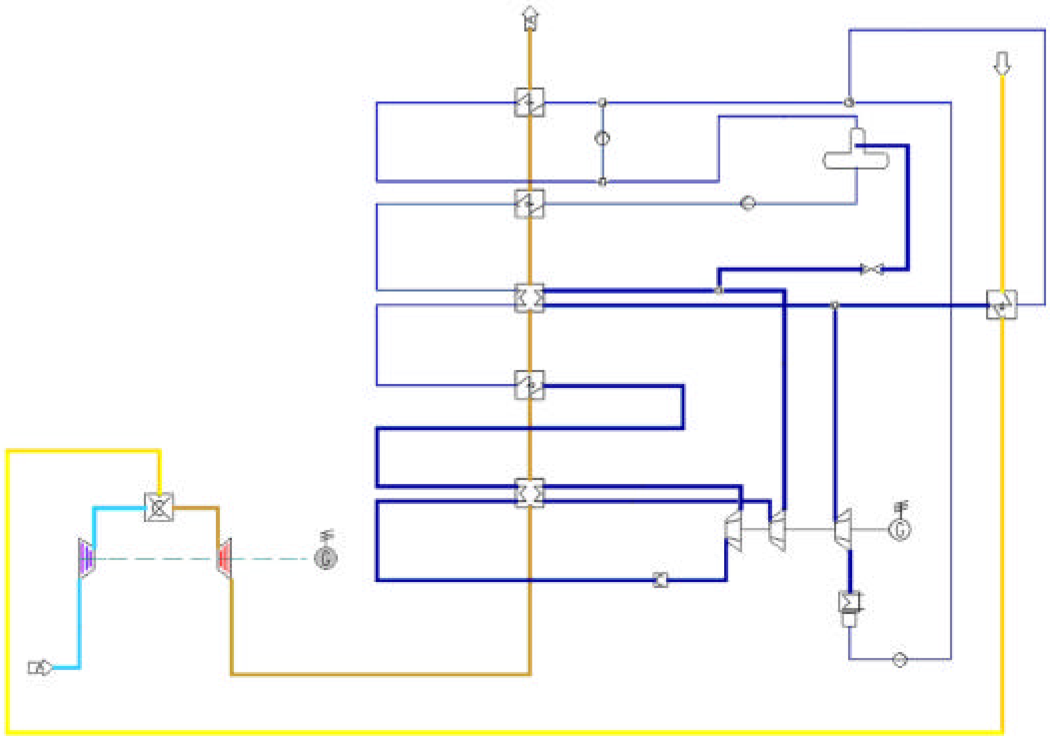
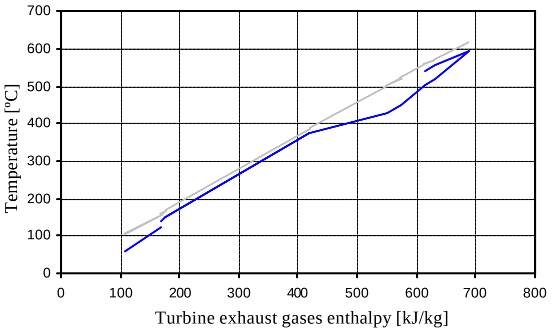


Figure 3 – Joule – supercritical Rankine Cycle combined cycle with low and high pressure reheating, configuration F.



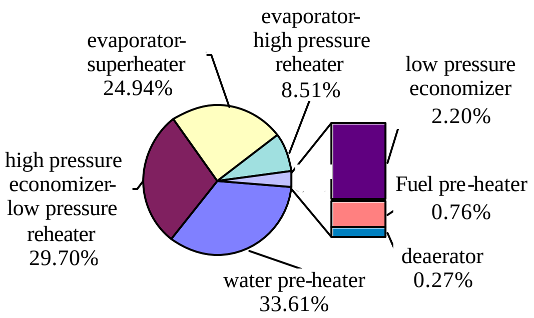


Figure 4 – Temperature – Enthalpy diagram for gases and water circuits in the HRSG for the combined cycle in figure 3, configuration F.

Figure 5 – Exergetic losses in the HRSG in a single steam pressure Joule – supercritical Rankine combined cycle.

Table1 – Exergetic and energetic performance for the studies effectuated through configurations A to F.

		A	B	C	D	E	F
exergetic losses [%]	**compressor**	2,83	2,81	2,42	2,41	2,47	2,47
	combustion chamber	31,06	30,91	29,82	29,83	29,23	29,15
	turbine	3,61	3,59	3,16	3,14	3,22	3,21
	electric generator	1,46	1,5	1,58	1,56	1,58	1,59
	HRSG	3,22	2,43	2,26	2,48	2	1,85
	exhaust	1,26	0,94	0,7	0,69	0,84	0,95
	steam turbines	1,48	1,64	1,74	1,83	1,82	1,83
	condenser	1,36	1,38	1,36	1,38	1,31	1,27
	auxiliaries	0,04	0,2	0,2	0,21	0,22	0,18
thermal efficiency [%]		56,19	56,96	59,27	58,89	59,6	60,04
steam quality in exhaust steam turbine		0,9	0,75	0,78	0,78	0,9	0,95
gas turbine combustion chamber temperature [ºC]		1200	1200	1312	1312	1312	1312
net power fraction in steam cycle		0,32	0,34	0,35	0,35	0,34	0,35

4. Conclusions – The last proposed cycle, configuration F, demonstrate the potentiality of the Joule – supercritical Rankine cycles. In opposite to what occurs in subcritical combined cycles, it was demonstrated that in supercritical combined cycles the higher efficiency takes place generating steam with a single pressure in the HRSG.

With three steam pressures, the efficiency is similar in both subcritical and supercritical cycles, being the last one penalized by low steam quality in the exhaust of the steam turbine.

Through the configuration F, proposed in this study, the application of reheat at low and high pressures promote the minimum temperature difference in the economizer and reheaters at the HRSG. This enables the decrease in exergy losses in these components. As observed in figure 5, the exergetic losses in these components represent the major exergy losses in HRSG heat exchange, and so, justify their study and optimization. Another component that should be analyzed in these configurations with more detail is the water pre-heater.

The advances in gas turbines, which allow high exhaust gases temperatures, and the new advances in alloys that resist to high pressures and temperatures, give reason for studies in new combined cycle configurations.

This proposal requires high resistant materials and advanced metallurgical techniques, but the HRSG configuration is quite simple and provide high cycle efficiency. Nevertheless, being an innovative proposal, it requires a detailed technical and economical analysis.

5. References

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