COMPARISON CONCERNING TO THE COGENERATION SYSTEMS DEVELOPMENT

Radu Cristian DINU, Ion MIRCEA, Emilia Marinela DINU

niversity of Craiova, Faculty of Electrotechnique, Electroputere S.A., Craiova
rcdinu elth.ucv.ro, imircea elth.ucv.ro, cremit2004 yahoo.com

Abstract − **In view of the constant growth of electricity usage and public pressure to reduce the dependence on nuclear power plants in the energy supply, solutions are sought to increase the capacity of power plants using fossil fuels. Highly efficient cycles are available gas turbine combined with waste heat boilers and steam cycles are able to achieve efficiencies above 50 55 . Alternative proposals are based on upgrades of existing plants capital savings are expected by reusing part of the facilities. In the present study, three parallel proposals are compared on the basis energy efficiency cost of investments and flexibility of operation are also discussed. They are compared with classical Rankine cycle and state of the art combined cycles.**

Keywords cogeneration, power plants, exergy efficiency.

1. INTRODUCTION

Improvements of steam and gas turbine technology lead to some economical potential in capacity and efficiency increase of existing power plants. Depending on age, size and configuration of the existing plant, a number of rehabilitation concepts can be compared. The simplest way to increase the power of an existing plant is to install additional generators and prime movers in parallel to the existing equipment.

Combining a steam and a gas cycle is known to improve considerably the efficiency of work production, and many combined cycle plants have recently been put in operation. However the conversion of existing large steam power plants with reheat to combine cycle power plants is a rather new concept [3], [4].

In the following, one will evaluate the potential for a capacity increase in the order of 15…20% of the existing Rankine cycle.

2. CONCEPTS OF COGENERATION

In order to provide a uniform framework for all subsequent comparisons, a somewhat simplified model of a classical power generation cycles. The reference is a Rankine cycle with steam reheat and water preheating using extracted steam, and is illustrated in figure 1.

Fuel is natural gas (84%CH_4, 11,9%C_2H_6, 3,5%N_2, 0,6%CO_2) available at 35 bar. Superheated steam is produced at 810 K, 180 bar. After first expansion, a part of it ($\approx$20%) is extracted to preheat boiler feed water, and the rest is reheated to 808K. After a second expansion to 5,5 bar, some more steam is extracted to heat the feed drum. A third extraction occurs after expansion to 0,8 bar. The condenser nominal presuure is 0,065 bar.

Figure 1: Reference cycle – Rankine with steam reheat and 3-level extraction.

Fuel is natural gas (84%CH_4, 11,9%C_2H_6, 3,5%N_2, 0,6%CO_2) available at 35 bar. Superheated steam is produced at 810 K, 180 bar. After first expansion, a part of it ($\approx$20%) is extracted to preheat boiler feed water, and the rest is reheated to 808K. After a second expansion to 5,5 bar, some more steam is extracted to

heat the feed drum. A third extraction occurs after expansion to 0,8 bar. The condenser nominal presuure is 0,065 bar.
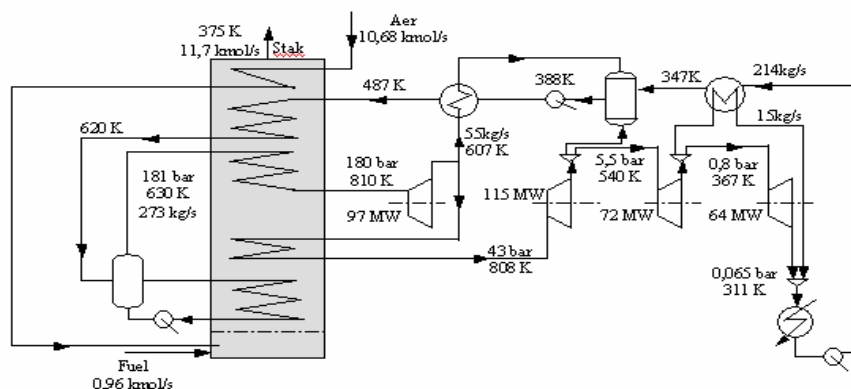
Net power generated is 340 MW, thus calculated thermal efficiency is 41,9%, and exergy efficiency is 40%. In all the models used in this study, heat losses to the environment, mechanical and transformation losses have been neglected.

Even if dome simplifications have been introduced in the model (namely the number of extraction stages is usually larger), such a cycle is representative of currently operating plants.

3. COMBINED CYCLE

A waste heat boiler can be designed to recover efficiently the energy in the exhaust of a gas turbine. The flowsheet of a typical combined cycle plant is presented on figure 2. Since the hot gas temperature (550°C) is much lower than the temperature in the combustion chamber of a fired steam generator (above 1500°C), matching the cooling curve of the gas with the heating curve of water and steam requires a complex design. Production of steam at several pressure levels (2 and even 3 in recent designs) is needed for enhanced heat recovery. Extended heat transfer area is needed to compensate for the lower temperature difference (less than 10°C at pinch points) and for the absence of radiative transfer.

Due to the clever arrangement of the heat recovery system, combined cycles can achieve a good efficiency and be used for base load production. Heavy duty turbines used in these applications differ from aeroderivative lightweight machines, and deliver up to 150…200 MW. For the cycle illustrated in figure 2, gas flow rate is 0,527 kmol/s, air flow rate 17,2 kmol/s, and fumes production is 17,8 kmol/s (505 kg/s). Stack temperature is below 100°C. The net power production is 235 MW, and overall cycle exergy efficiency is 50,6%, compared to 31,0% for the gas turbine alone.

Figure 2: Combined cycle with 2 pressure levels: 1 – gas turbines; 2 – combustion chamber; 3 – generator unit; 4 – tanks; 5 – recovery boiler; 6 – steam turbines; 7 – steam turbines condenser

4. REPOWERING A RANKINE CYCLE BY TOPPING WITH A GAS TURBINE

In view of such a high efficiency, one maz wonder whwther the adjunction of a gas turbine to an existing power plant would improve the efficiency and the troughput of the cycle. One should note however that such a modification will induce many changes in the process operating conditions.

The exhaust of the gas turbine still contains a large amount of oxygen and its temperatures is relatively high: the machine, while generating additional shaft power, may also be viewed as an air preheater. However the practical implementation of such a scheme implies significant modification of the boiler steam generator and water circuits, as shown on figure 3. The existing air preheater can no longer be used, since the gas turbine already delivers oxidising gas at a temperature higher than the classical air preheater.

Removing the air preheater from the flue gas channel would result in a large increase of the stack temperature. Such a waste of energy can be avoided by heating a cold stream, such as boiler feed water. In fact, the duty of the air preheater corresponds roughly to 2/3 of the enthalpy needed to raise the condensates to the inlet temperature of the economiser. However this means that the amount of steam extracted from the turbines for such a usage is to be reduced. The total steam bleed flow rate corresponds approximately to 25% of the boiler production.

Reducing the bleeds will thus put turbine line out of balance, since the LP turbine and condeser are not likely to be able to accept a 33% increase of capacity. Thus the inlet flow rate of the turboset, and thus the power generated by the original machines will decrease: in the following study, calculations have

been performed by holding the pressure profile constant, and by reducing the steam flow rate to keep the power generated by the lowest pressure turbine at it original value. The gas turbine capacity has been fixed by an oxygen balance. Air and fuell gas flow rates are adjusted to keep the oxygen content it the stack gas equal to its original value. Since the gas turbine exhaust contains less oxygen than air, the ratio of flue gas to fuel has to increase.
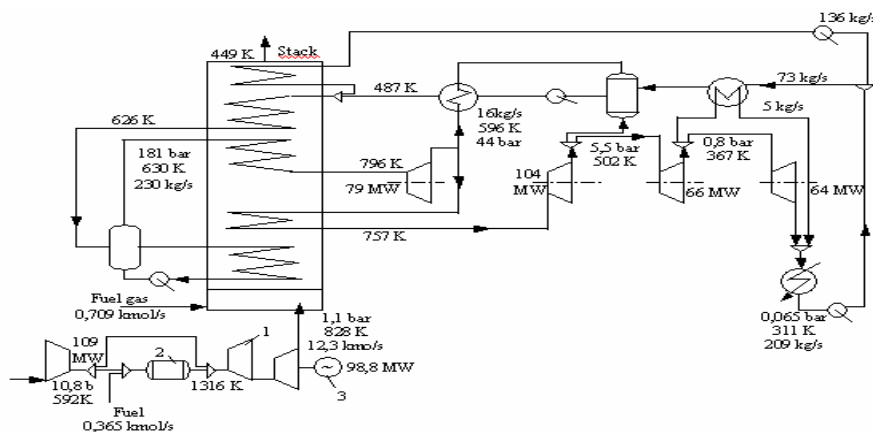

Figure 3: Topping the Rankine cycle with a gas turbine: 1 – gas turbine; 2 – combustion chamber ; 3 – steam turbine.

Nr. crt.	Parameters	Reference cycle	Topping with gas turbine	Topping with partial oxidation
1.	Gas turbine, net power, [kW]	-	98856	73941
2.	HP steam turbine, [kW]	96661	79351	97907
3.	IP steam turbine, [kW]	115020	104380	114970
4.	LP1 steam turbine, [kW]	71623	65749	71712
5.	LP2 steam turbine, [kW]	63724	63759	64377
6.	Pumps, power required, [kW]	-7055	-5836	-7079
7.	Net useful power, [kW]	339973	406259	415828
8.	Exergy of NG for gas turbine, [kW]	-	322840	91729
9.	Exergy of NG for steam generator, [kW]	848630	626640	874000
10.	Total exergy of NG, [kW]	848630	949480	965729
11.	Exergy efficiency	0,400	0,428	0,431
12.	Thermal efficiency (based on fuel LHV)	0,419	0,448	0,451

Table 1: Shaft power distribution and exergy efficiency. Partial oxidation vs. standard gas turbine and base case

The fume flow rate is increased from 11,69…13,19 kmol/s; the air preheat temperature raises also (outlet of gas turbines is 817K, compared to 637K with air preheater). The adiabatic combustion temperature decreases from 2395…1973 K. An energy balance around the combustion chamber and the vaporiser indicates that the fumes temperature entering the superheater decreases from 1940 to 1660K. This corresponds also to the average temperature in the combustion chamber. Knowing that the temperature of the vaporising steam remains the same, and that the energy transferred by radiation involves differences of terms in T^{-4}, one can estimate that the vaporiser capacity is reduced by approximately 45%; a detailed calculation, beyond the scope of the simplified model used here, should be performed to redesign the vaporiser, taking also into account that the expected decrease in steam production (from 272 to 230 kg/s) brings some compensation.

Table 1 summarises the result to be expected from such a process modification [6]. Net power from the gas turbine is 99 MW, but limitations in the steam

flow rate reduce the power from the steam turbines by 32 MW. Thus the net capacity increase is 66 MW or 19,5%. Fuel usage increases by 11,9% and thus the plant exergy efficincy raises from 40,00 to 42,80%.

However the plant modifications are complex: air preheater has to be replaced by a new economiser (in case of regenerative preheater, it cannot be reused), which required significant work and a long shut down of the power plant (8 months) [4]. The heat exchanger used to preheat feed water with bleed steam become over designed, which may lead to operation problems. The turbine operating conditions are also modified, which may require retrofit of the machines. The investment needed for such a revamp is lower than for building a new facility with the same additional capacity; however the long shut down period needed for the modification makes this scheme unattractive.

5. REPOWERING A RANKINE CYCLE TOPPING WITH A PARTIAL OXIDATION GAS TURBINE

Another alternative can be proposed, based on partial oxidation of the fuel [1], [2]. In convenational gas turbines, the major portion of air is addes to dilute the combustion products, avoiding too high a temperature, but it must nevertheless be compressed and expanded. These operations are irreversible processes, and introduce losses proportional to the total gas flow rate. Another way to avoid high temperatures is to react the fuel with air below stoichiometric proportions. Figure 4 shows how the adiabatic combustion temperature of gas varies with the air to gas ratio, assuming chemical equilibrium is achieved after reaction.
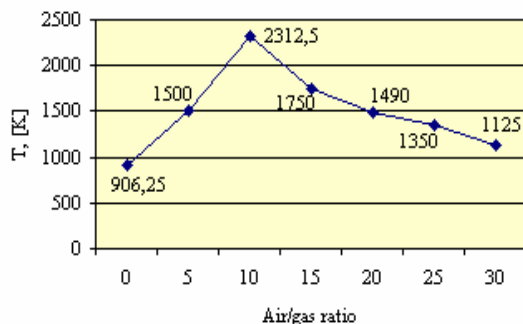

Figure 4: Adiabatic combustion temperature vs. air/gas ratio

The components of a partial oxidation gas turbine are shown in figure 5.
An aeroderivative gas turbine is used to generate the high temperature pressurised stream containing oxygen. This oxidising gas is mixed with the fuel and some steam; it reacts in the partial oxidation reactor in presence of a solid catalyst. The reactor exhaust is a high temperature gas, rich in CO and H_2. The stoichiometry of the reaction is such that molar flow rate increase during reaction.
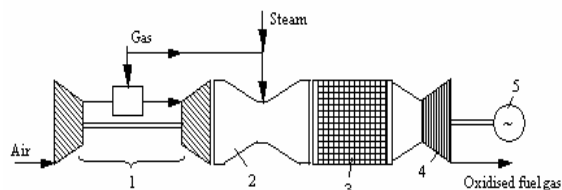

Figure 5: A partial oxidation gas turbine: 1-hot gas generator (gas turbine); 2-mixer; 3-partial oxidation catalytic reactor; 4-power tubine; 5-generator unit

The air/fuel ratio is adjusted to limit the temperature of the reaction product, which is expanded in a second turbine and produces useful power. Finally, the turbine exhaust gas is used as fuel in a conventional steam generator.
A much lower amount of air is needed, and the gas turbine exhaust contains CO, H_2 and some unburned fuel. Some compression power is saved, since the molar flow rate of the exhaust gas is significantly higher than the flow rate, which is not the case for a standard gas turbine.
The flowsheet of a process combining a conventional Rankine cycle with a partial oxidation gas turbine is illustrated in figure 6.
We note that the gas turbine needed to implement the partial oxidation systems is smaller than the one needed for a topping cycle: air flow rate is reduced from 11,9 to 4,2 kmol/s. The modified process has been modelled assuming that an aeroderivative gas turbine was used to generate the hot compressed air needed for the partial oxidation reactor. Pressure ratio and turbine inlet temperature of the first expansion stage match those found in commerciall available machines. In the previous case, the power required was beyond the range of currently available aeroderivative engines.
Compared to the previous case, compression power is reduced from 109 to 60 MW (even if the compression ratio has been raised from 10 to 23). The ratio of useful work to compression work is 1,23 for the partial oxidation system, compared to 0,9 for the gas turbine [5], [6]. The air and gas flow rate have been adjusted to provide the steam generator with the required amount of fuel gas. Oxygen content in the fumes is similar to the base case value. In practice, in case no machine matching the required duty can be found in the supplier catalogue, a smaller gas turbine may be selected and the missing fuel can be replaced by natural gas. Compared to natural gas, the oxidised fuel gas has a lower calorific value, and it must be supplied in larger amount. In the model, the oxygen content of the fumes is kept to the same value as for the base case. Since part of the combustion air comes through the gas turbine, the load of the air preheater

is decreased: fresh air flow rate to be preheated drops from 10,68 to 7,56 kmol/s. This leaves energy to preheat the natural gas to be fed to the partial oxidation reactor. Even so, heat recovery from the fumes is not complete, and stack temperature raises to 440K. Steam to be injected in the reactor can be obtained from the high pressure turbine bleed. Since

the fue gas has a lower calorific value, combustion temperature is lower than in the refecence case. This is somewhat compensated by a higher preheat air temperature, and the fume temperature at the superheater inlet is only decreased by 50K (from 1940 to 1890K).

Figure 6: Topping the Rankine cycle with a partial oxidation gas turbine: 1-gas turbine; 2-combustion chamber; 3-generator unit; 4-recovery boiler; 5-tanks; 6-steam turbines CHP; 7-steam turbines CMP; 8-steam turbines CLP; 9- steam turbines condenser

Using the same resoning as for the previous case, we estimate that the vaporiser capacity is not reduced by more than 10%. For all heat exchanger in the convection section, heat exchange should be improved since the fume flow rate is 10% higher than in the base case (13 kmol/s compared to 11,7 kmol/s). The only significant procedd modifications are the addition of the gas preheater and the redirection of a small part of the high-pressure steam bleed to feed the oxidation reactor. Gas burners must also be adapted to the modified fuel: flow rate is larger and temperature is higher. Table 1 shows what can be expected from such a process modification: the power delivered by the steam turbines remains unchanged, and the expansion of the oxidation reactor effluent allows to recover 74 MW (+22,2%). Exergy content of the additional fuel gas is 117 MW (+13,8%).

The overall exergy efficiency of the cycle is raised to 0,431. While this is still below what can be achieved with a new combined cycle, whose structure is optimised and whose equipment is designed accordingly, the addition of a partial oxidation stage to an existing power plant appears to be sensible way to improve both is efficiency and production at a moderate investment cost. Furthermore, since combustion temperature is lower than in the reference steam generator, this has a favourable impact on emission of pollutants (NO_x), that can be kept easily below existing norms.

. EXERGY EFFICIENCY

Table 2 shows where the exergy losses ocur [5], [6]. It allows to compare the factore that influences the exergy efficiency of both processes. Comparing absolute figure, we notice that exergy loss in heat exchangers is similar for the reference cycle and for the partial oxidation modification. Since the steam system is almost the same in both cases, one can conclude that modification does not degrade significantly the heat exchange train. The losses in heat exchangers appear lower when using a gas turbine; however, this is explained when we consider the relative power generated by the steam system (308 MW vs. 340 MW). A lower power is generated using the same heat exchanger area, and this justifies lower irreversible transmission losses. Stack losses are higher in both modified plants: the heat exchanger network has not been optmised. The most significant remark deals with the losses due to reaction irreversibility: they are reduced with the partial oxidation scheme. In fact, some of the reactions involved in the partial oxidation are reversible; alternating heat release by stepwise oxidation with work production seems to improve the exergy efficiency of the process. Higher yields can be expected in systems that could be designed from scratch and optimised to carry out this reaction scheme. We estimate that power production could be increased by 5...7% if heat exchangers are redesigned

and if limitations on steam flow rate in turbines are relaxed

Parameters	Reference cycle		Topping with gas turbine		Topping with partial oxidation	
	[kW]	%	[kW]	%	[kW]	%
Lost to stack	24036	2,83	39040	4,11	36413	3,77
Lost to condenser	22399	2,64	22789	2,40	23184	2,40
Net power	339973	40,06	406259	42,79	415828	43,06
Reaction irreversibility	195490	23,04	242382	25,53	198019	20,51
Mixing irreversibility	5363	0,63	10267	1,08	15381	1,58
Loss in pumps and compressors	1300	0,15	6937	0,73	5139	0,53
Loss in turbines	30724	3,62	39480	4,16	41247	4,27
Loss in heat exchangers	229350	27,03	182329	19,20	230618	23,88
Exergy of total fuel, [kW]	848635	100	949483	100	965729	100

Table 2: Exergy balances. Partial oxidation vs. standard gas turbine and base case

. CONCLUSIONS

Repowering an existing steam cycle either by topping with a gas turbine or by using a partial oxidation reactor appear both to be alternatives that deserve a closer look. The preliminary study described here provides order of magnitude of the potential for extra power generation, and indications on the bottlenecks and the technological constraints. Any detailed analysis should be based on existing machines that can be offered by suppliers, and take into account their characteristics. A complete model of the existing plant, including detailed calculation of heat transfer, pressure drops and efficiency curves of the turbines must also be developed for each specific case: a general proposal for modification cannot be issued, and case by case analysis is necessary.

The partial oxidation technology for repowering an existind steam cycle relies on standard equipment available at moderate cost: aeroderivative gas turbines. Compared to topping with a conventional gas turbine, it does not require heavy modifications of the existing steam generator, since air circuits are kept the same: mainly the fuel delivery and burners must be modified. It allows a significant increase of the power generation capacity, while improving the overall cycle efficiency. Since combustion temperature is lower than for the original burner, the impact of emission of pollutants (NO_x) is favourable, which eases the adaptation of the process to satisfy new pollution abatement constraints.

The partial oxidation gas turbine compares favourably with the conventional gas turbine: the compression work is much smaller fraction of the expansion work, and the overall efficiency is thus less sensitive to performance degradation of the machines. A smaller compressor is thus needed to buil a system able to deliver the same useful net power.

Partial oxidation gas turbines could be integrated into the design of new power cycles. By combining turbomachines speciffically built for such operation with optimised steam cycle, we expect to raise the cycle efficiency beyond 0,60.

. REFERENCES

[1] J., Ribesse, *Cycle de turbine ga comportant un r acteur d oxydation partielle catalytique de ga naturel, son application dans des syst mes nergie-chaleur*, Proceedings of 8th World Energy Conference, paper 3. 1-30, Bucharest, 1971.

[2] J., Ribesse, *The isotherm partial oxidation gas turbine,* European Journal M 36 (1), paper 27-32, 1991.

[3] H., Kotschenreuther, *Improvement of existing large steam power plant by conversion to combined cycle plant,* Proceedings of International Conference on Assessment and Extension of the Residual Lifetime of Fossil-Fired Power Plants, Moscow, May, 16-20, 1994.

[4] S.A., Belsim, *SIM II users guide*, Belsim, Allée des Noisetiers, 1, B-4031 Angleur Belgium, 1995.

[5] G., Heyan, B., Kalitventzeff, *A comparison of advanced thermal cycles suitable for upgrading existing power plant,* Applied Thermal Engineering, no.19, pp. 227-237, 1999.

[6] R.,C., Dinu, *The study of the cogeneration energetic systems in variable duty,* Doctor's degree Paper, Faculty of Installation, Constructions Technical University, Bucharest, 2006.