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Gas turbine selection for feedwater repowering

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Abstract

The paper presents the concept of using hot exhaust gases from gas turbines with different power output to heat up feedwater in a supercritical power plant unit. The gas turbine is connected to the system, bypassing a high pressure regenerative heat exchanger. The benefits of this solution are discussed and the factors to be taken into account are listed. The criteria to be met by the gas turbine to ensure safe and optimal connection to the steam system are discussed. A reference unit model with 800 MW electric power (an existing super-critical power unit in Poland—Belchatow II) was created and presented in a previous paper by the same authors. This model was later supplemented with a gas turbine (three different models with different levels of power production are taken into consideration). The system with a gas turbine enjoys greater power and efficiency over the steam cycle alone. The power increase is due to the extra power generated by the gas turbine and the higher output of the steam system caused by increasing the steam flow through the turbine (closed extraction to the "bypassed" high-pressure heat exchanger). System power is changed linearly with the steam flow and reaches the nominal point 40..50% higher than without an added gas turbine (depending on gas turbine power and efficiency). The efficiency characteristics of the whole system are flatter, with higher values.

Keywords: gas turbine, steam turbine power plant, feedwater repowering

1. Introduction

The concept of a steam and gas turbine co-operating in a common system essentially arises directly from a review of the main advantages and disadvantages of steam and gas systems treated separately.

The advantage of the steam turbine is its very low ratio of compression work to expansion work (due to water condensation which runs at a constant temperature, only slightly higher, 5..7°C, than ambient temperature). The disadvantage of this system is the process of heat supply, implemented through a metal wall, mechanically and thermal loaded. Substantial heat transfer surfaces are needed, forcing a reduction in the temperature used in the live steam to below about 570°C.

The most efficient solution from the viewpoint of the efficiency of the system is the classical Gas Turbine Combined Cycle (GTCC) [1–3], in which several gas turbines supply waste heat to the Heat Regeneration Steam Generator (HRSG) which works with one steam turbine. The efficiency obtained this way is about 30..40% higher than the steam-only unit, and the power achievable can be as much as 200% compared to Coal-Fired Power Plants (CFPP).

Another possible solution is to discharge gas turbine exhaust to the coal-fired boiler as an oxidant (as the gas turbine exhaust gases have a considerable amount of oxygen) [4]. This solution can increase efficiency by 5..15%, and power by 30..40% [5].

Another possibility for steam cycle repowering is to use the hot exhaust of the gas turbine, not of the steam turbine, to raise the temperature of the feedwater. This is

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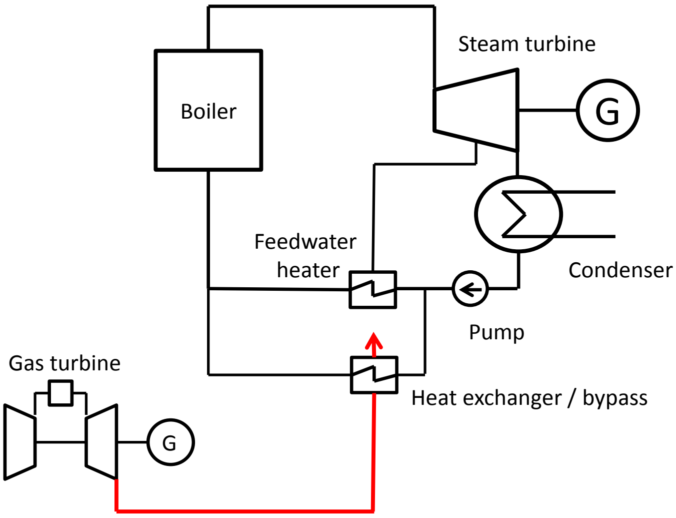

Figure 1: Schematic diagram of using a gas turbine to repower a coal fired power plant to cover peak loads

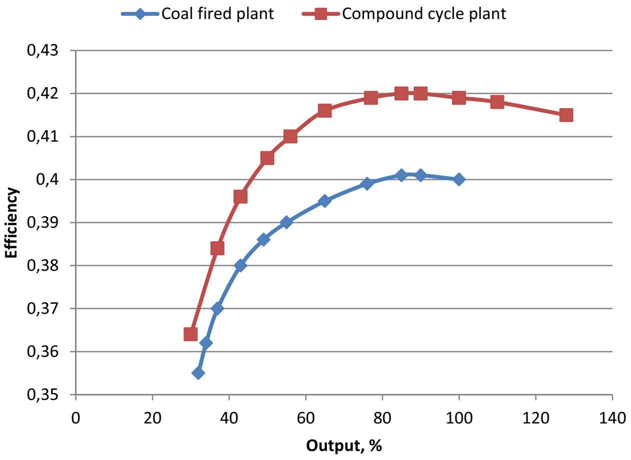

Figure 2: Use of feedwater repowering to increase the efficiency of the steam turbine cycle

called feedwater repowering. The benefits of this solution depend on the amount of "energy saved"; the achievable increase in power here is 30..40% and in efficiency of 5..10%, limited by the nominal capacity of the steam turbine. The actual values are 2% for improving efficiency and 20% for power, respectively. The layout of this type is used to cover peak loads, as shown in Fig. 1.

The steam cycle has the typical layout of an existing primary system and the gas turbine sub-system is the typical peak system. Both cycles work only at times of peak load and are connected by the feedwater heater, which is fed by a gas turbine outlet. Peak power grows by forcing steam turbine power through the regenerative heater, which is disconnected. This is done without compromising performance by including heat recovery from the gas turbine in place of steam turbine regeneration.

Feedwater is heated up by bypassing the original regenerative heat exchanger and directing it to the gas/water heat exchanger. In this case, the bypassed regenerative heat exchanger does not take steam from the steam turbine, which increases power. Additional power is generated by the added gas turbine. This system has considerable flexibility: the gas turbine can operate even if the steam cycle is out of operation, and vice versa.

Increasing the capacity of existing installations is a serious alternative to constructing new facilities and can achieve several objectives:

1. reduction of specific fuel consumption (efficiency gains of around 2%),
2. reduction in unit operating costs,
3. reduced emissions (including CO_2 [6, 7]),
4. lower cost of growing existing installed capacity,
5. minimization of investment costs,
6. fuel flexibility—hydrogen [8], natural gas [9] and coal can be used,
7. keeps coal as the main fuel, reducing natural gas dependence.

Leaving the regenerative heat exchangers enables the steam turbine system to function independently if the gas turbine is not in operation (e.g. due to maintenance).

The efficiency of the gas turbine system itself is 35.1% at rated power (60 MW). The efficiency of the steam turbine cycle at its maximum power is 39.9%. With simultaneous operation of both uncoupled systems, their average efficiency is 39.1%, while combining the system into one gives efficiency of 41.5% (5.5% increase compared to the nominal value—see Fig. 2).

The power needed to cover the peak load is generated at a very low natural gas consumption rate because: (i) part of this power comes from the steam turbine and (ii) the entire system enjoys relatively high efficiency—of up to 50%.

Nevertheless, it should be remembered that this solution will always have lower efficiency than the classic GTCC, as it is associated with non-optimal parameters such as:

1. steam pressure,
2. quantity and pressure level of steam in Heat Recovery Steam Generator,

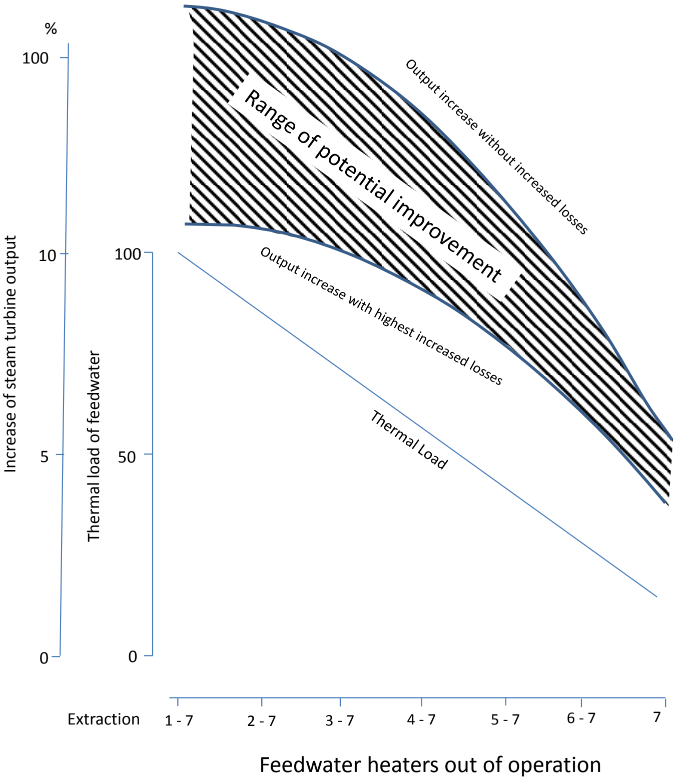

Figure 3: Effect of replacing selected regenerative heat exchangers to increase the power of a steam turbine [4]

3. LP turbine capacity,
4. steam turbine outlet pressure.

On the other hand, upgrading the existing structure of the steam turbine, for example by replacing the LP part of the steam turbine, can offset the above-mentioned shortcomings.

The most important feature of incorporating a gas turbine in a steam turbine system is selecting the right gas turbine unit, so that heat can be supplied at as high a temperature as possible. An example of a gas turbine selected for this end is shown in Fig. 3. For the same temperature increase in each of the heat exchangers, the heat load is reduced by 15% between the first and last regenerative heat exchanger. The largest increase in steam turbine power is gained by replacing the regenerative heat exchanger employed in the first extraction of the steam turbine. Bypassing the low pressure exchanger regeneration produces very little effect in terms of the increase in power of the steam turbine (e.g. bypassing the last three regenerative heat exchangers gives only a 1% increase in power).

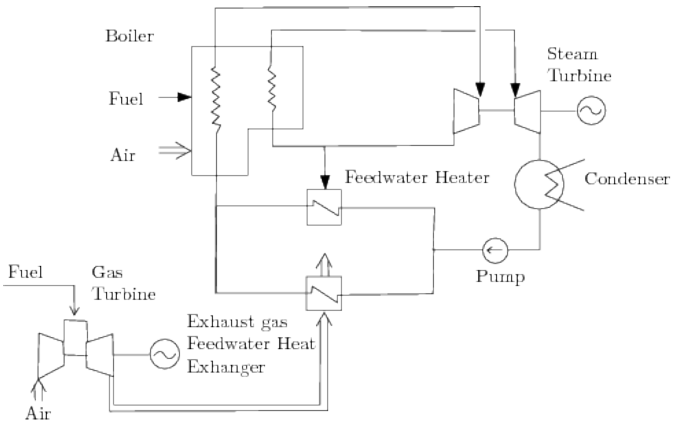

Figure 4: Example of use of a gas turbine to regenerate coal boiler feedwater [5, 10, 11]

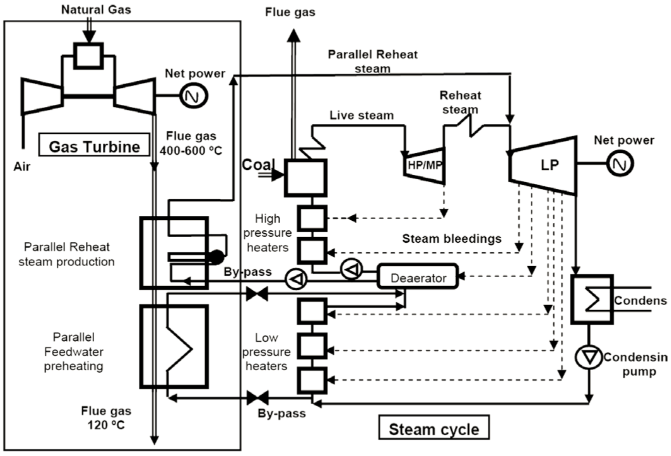

Figure 5: Superstructure of parallel repowering option [12]

Systems designed as GTCC achieve efficiency levels of up to about 60%; feedwater repowering enables enhanced efficiency to a lesser extent, for example, the supercritical steam cycle has efficiency levels of 42..46% and after repowering efficiency can be 45..49%.

On average, it can be assumed that the power of a gas turbine should be approximately one quarter of the power of the steam turbine to which the gas turbine is connected. The use of a larger gas turbine for feedwater repowering can be considered for a plant which has more than one steam turbine unit. Parallel repowering (reheat steam yielding in parallel to the coal boiler) would be another option [12] (see Fig. 5). Integrating waste heat in other arrangements including CO_2 post-combustion capture systems could be yet another way to improving cycle performance.

Such solutions have been used before, a typical example is the unit shown in Fig. 4, in which 370 MW is generated through a base steam turbine cycle. An additional 85 MW is delivered though the installation of a 60 MW gas turbine system for feedwater repowering.

Table 1: GE plants that use feedwater repowering [13]

In operation	Owner	Place	Gas turbine	Total power, MW
1949	Oklahoma Gas & Electric	Belle Isle	MS3001	40
1952	Oklahoma Gas & Electric	Belle Isle	MS3001	40
1961	Wester Power	Liberal, KS	MS5001	65
1998	Electrabel	Langerlo, Belgium	LM6000	271
2002	SK Power	Avedore, Denmark	LM6000	390

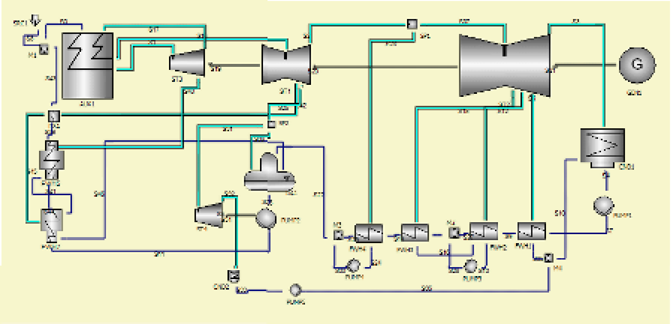

Figure 6: Steam cycle before retrofit/repowering [14]

The use of regenerative heat exchangers leads to lower steam consumption, causing an increase in the power of the steam turbine from 370 to 395 MW [4].

Other examples where this solution was implemented are GE plants (e.g. Oklahoma Gas & Electric—Belle Isle and Western Power—Liberal, KS), see Table. 1.

The capital costs of adding a gas turbine to heat up feedwater are estimated at $90..110/kW for smaller units and $75..80/kW for larger units. New gas turbine units can be installed in less than eight weeks.

The installation costs comprise the following main elements:

1. installation of a gas turbine,
2. exhaust duct assembly,
3. installation of a hot stack for a gas turbine,
4. construction of a heat exchanger gas/water supply.

2. Specification of the reference power plant unit and mathematical model of the system

Most of the parameters necessary for reference unit calculations have been adopted from the supercritical power plant unit Belchatow II and literature data. A simple layout of the steam cycle before retrofit/repowering is shown in fig. 6. Parameters that are not clearly identified in the source material were established on the basis of data taken from the world's most advanced facilities of that class (in particular low-emission coal-fired power plants in Germany) and based on the experience of the authors of this paper. The whole specification of the reference power plant is presented in [14].

All calculations were performed using commercial software [15, 16]. The method used to determine the efficiency of modeled steam turbines is based on experimental data and the SCC theoretical approach (creators: Spencer, Cotton, Cannon [17]). This method is recommended by the American Society of Mechanical Engineering to calculate the working efficiency of turbines in conventional power plants. A description of the mathematical model of the system can be found in [14].

3. Effect of feedwater repowering on steam power plant characteristics

Fig. 4 shows how to connect the gas turbine and bypass the regenerative heat exchanger. Theoretically, a gas turbine can operate independently of the steam system (even when the steam unit is completely off). Placed between the regenerative heat exchanger and the boiler is the steam cooler which, at the nominal point, is supplied with water at a temperature of 270°C. During the simulation, appropriate gas turbine operation parameters were chosen so that the water temperature before the steam cooler is still at the nominal point.

The analysis were provided for three different Gas Turbines (three different levels of power production):

- GE PG 7241 (FA): 168 MW
- GE PG 9351 (FA): 250 MW
- SIEMENS Energy SGT5-4000F SC: 287 MW

The water temperature after the bypassed heat exchanger is constant, whereas the water temperature before the heat exchanger varies according to the characteristics of the unit. This is due to the gas turbine power being adjusted to keep the temperature constant and equal to the temperature after the bypassed heat exchanger, as for operation without the gas turbine at

Table 2: Basic parameters of investigating cases

Parameter	Without gas turbine	With GE PG 7241 (FA)	With GE PG 9351 (FA)	With SIEMENS SGT5
Live steam mass flow, kg/s	644	644	644	644
Reheated steam mass flow (intermediate pressure), kg/s	583	644	644	644
LP turbine steam inlet mass flow, kg/s	406	503	503	503
Live steam pressure, bar	252	252	252	252
Feedwater temp. at boiler inlet, °C	279	271	271	271
Feedwater temp. before bypassed heat exchangers, °C	191	191	191	191
GT exhaust gases temp. after the feedwater heat exchanger	–	191	280	256
GT exhaust gases temperature, °C	–	564	611	562

the nominal point (272°C). This restriction was introduced to avoid overheating after the regenerative heat exchanger (steam cooler). Fig. 7 presents the characteristics of the heat exchanger outlet temperature depending on live steam mass flow. The curve indicated as Without GT shows the temperature increasing from about 180 to 272°C (nominal point). Other characteristics are flat due to the restriction which keeps the temperature not higher than that at the nominal point. On two curves: GE PG 7241 (FA) and SIEMENS SGT5-4000F the heat exchanger outlet temperature falls after a specific point. This is the point where the gas turbines reach their nominal power but feedwater mass flow is increasing. The exhaust gases cannot maintain a constant feedwater temperature.

In figure 8 the total power of the system during off-design operation is presented. As the figure shows, the highest total power can be achieved for the system with the biggest gas turbine—SIEMENS SGT5-4000F. System power changes linearly with the steam flow and reaches the nominal point 40–50% higher than it does without the addition of the gas turbine.

Fig. 9 shows the efficiency of the system during off-design operation. The efficiency is higher for all repowered systems compared to the system without GT. For two of the gas turbines the efficiency reaches the maximum point for live steam mass flow lower than nominal for the steam cycle.

In figure 10 the power of all gas turbines is presented. Two of them: GE PG 7241 (FA) and SIEMENS SGT5-4000F reach their nominal power (point 1 at fig. 10) and keep it constant even when live steam mass flow is increasing (the gas turbines cannot be overloaded).

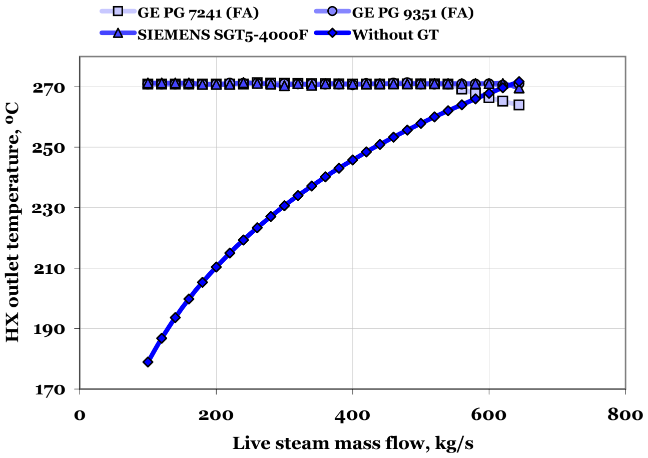

Figure 7: Heat exchanger outlet temperature depending on live steam mass flow for 3 different GT repowered systems and pure Steam Cycle

4. Discussion and conclusions

The paper sets out the concept of using hot exhaust gases from the gas turbine—instead of steam turbine extraction—to raise the temperature of feedwater. The benefits of this solution over the construction of new generating capacity are discussed and the factors affecting the lower efficiency of this solution compared to traditional GTCC are identified. The paper discusses the detailed criteria to be met by the gas turbine for safe and optimal connection to the steam system. The model of the reference case of the steam turbine was

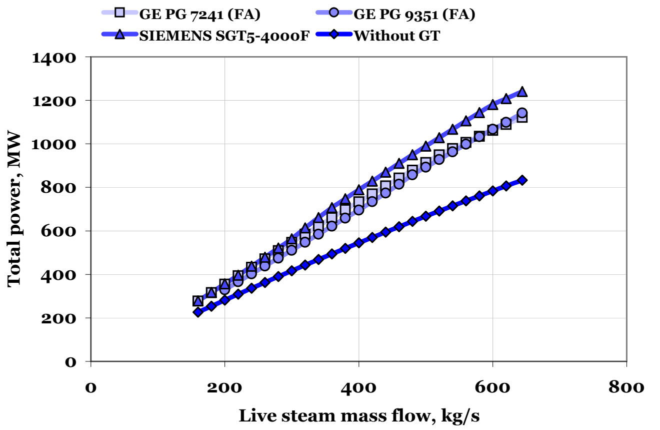

Figure 8: Total power of 3 different GT repowered systems and pure steam cycle

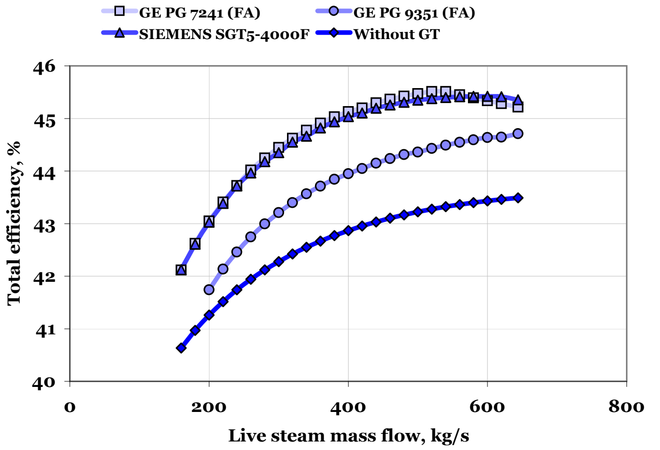

Figure 9: Efficiency of 3 different GT repowered systems and pure steam cycle

built and was later supplemented with a gas turbine.

The repowered steam cycle enjoys greater power and efficiency than the reference system. The power increase is due to the extra power generated by both the gas turbine and steam turbine (higher power achieved by increasing the flow of steam through the turbine—closed extraction to the bypassed high-pressure regeneration heat exchanger). System power changes linearly with the steam flow and reaches the nominal point 40..50% higher (for the biggest GT) than without the addition of the gas turbine.

Fig. 9 presents a comparison of the two systems' efficiency (reference and after repowering). It can be seen that the efficiency of the repowered system is higher across the whole range. In the nominal point the difference is about 2% and rises from 43.5% to about 44.8% for GE PG 9351 (FA) and to about 45.2% for GE PG 7241 (FA) and 45.3% for SIEMENS SGT5-4000F.

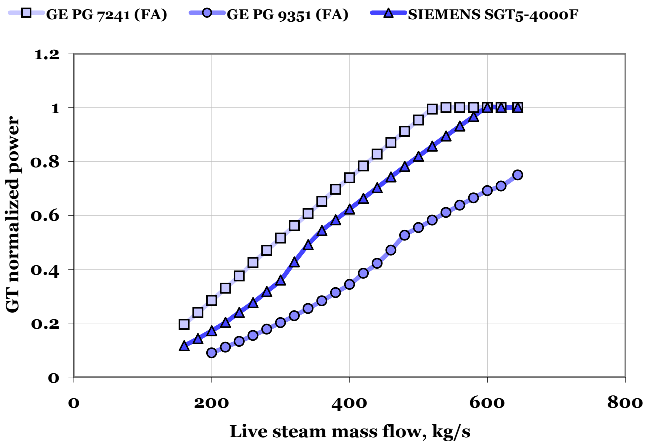

Figure 10: Gas Turbines power

The investment costs of steam cycle repowering are provided based on the reviewed installation of General Electric. An economic analysis lay outside the objectives of this work and will form the subject of further studies.

A review of the literature suggests that a 5% increase in efficiency is achievable, but this study failed to confirm it. This may be due to the fact that the gas turbine has relatively low efficiency.

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