GAS TURBINE OPERATING IN COMBINED AND REGENERATIVE CYCLES USING LIQUID METAL HEAT EXCHANGERS

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ABSTRACT

Liquid metal technology for heat transfer was developed for use in nuclear power stations. Applied to a gas turbine regenerative cycle plant, it makes high heat exchange rates in the regenerator, and low pressure losses as well as on the air side as on the exhaust side economically possible. Its application permits combined cycle as well as regenerative cycle operation of the same gas turbine. Mixed operation in any ratio is also easily accomplished, so that the ratio of heat and electricity produced by the gas turbine plant is variable within a wide range.

This paper presents the results of thermodynamic calculations for such plants and describes the optimization of design parameters. Influences of the individual parameters of the regenerative cycle on the power output and efficiency of the plant are examined, and the reasonable limits for this application are outlined.

The advantages of applying liquid metal technology to gas turbines, such as a virtually pressureless liquid metal system, flexible operation, and separate optimization of the heat exchange coefficients for the air and exhaust flows are discussed.

Reference is also made to emissions, which are more complicated than those for combined or regenerative cycles because the plant is operated in both modes.

1. INTRODUCTION

Only recently have a few gas turbines been designed for the regenerative cycle operation. This is attributed to the enormous advances in gas turbines development and the difficulties involved with operating a plant with classic tube or plate recuperators.

Gas turbines today are designed with a compression ratio, which is either close to the specific work optimum or close to the efficiency optimum (see Figure 1). With such compression ratios, the use of recuperation only slightly increases the efficiency of the gas turbine plant, if at all (see Figure 2). From a certain compression ratio upwards, recuperation is no longer possible (Figure 3).

![Figure 1: Plant efficiency and specific power output optimum for given design parameters](image-url)

Classic recuperators are extremely sensitive to a rapid load changes. Thermal stresses occurring in the recuperator often cause cracking, and in turn leakage, which reduces the efficiency increases achieved by using the recuperator.

Only the use of a more effective and flexible heat exchanger system will make the design of the gas turbine at low compression ratios meaningful, provided that it at least has the efficiency of an optimized gas turbine plant.

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Adapting liquid metal technology developed for use in nuclear power stations offers new opportunities for the gas turbine with recuperation. The main advantages of this technology are:

- Higher heat exchange ratios at lower pressure losses.
- The heat exchanger system is virtually pressureless.
- Pumping and/or bypassing of the liquid metal permits flexible operation of the gas turbine in combined and regenerative cycles.
- Mixed operation and variation of the electrical energy and usable heat ratios is possible within wide limits.

Further advantages are:

- High combustion air preheating.
- The possibility of separate optimisation of heat exchangers for the air and exhaust flow and
- Simplification of the ducting for the high volume flow of compressed combustion air and exhaust gas flow.

Since gas turbines with compression ratios for optimal recuperation are not readily available on the market today, and if, then would not be designed for the usual turbine inlet temperatures, a study was carried out covering three development stages:

- A standard gas turbine with an acceptable compression ratio was equipped with the liquid metal system.
- Optimizing of the compression ratio of this gas turbine was performed.
- The turbine inlet temperature was increased to the values of modern gas turbines, but with the optimum compression ratio for recuperation.

The result of this study shows that already the first developmental stage meets the above efficiency requirements and offers all of the mentioned advantages.

2. PLANT DESCRIPTION

Figure 4 shows the gas turbine plant with recuperation according to the proposed principle. Integrated into the exhaust duct of the gas turbine is a heat exchanger (HE1) in which the hot exhaust gases transmit heat to the liquid metal. This is pumped (P) through a virtually pressureless pipe system to a heat exchanger (HE2), through which the compressed combustion air flows. The compressed air is heated prior to entry into the combustion chamber, which saves part of the fuel. Via a branch pipe in the liquid metal system,
the heat of the exhaust gases can also be passed to the fuel to increase its enthalpy (HE3).

If a waste-heat boiler (WHB) is installed in the waste gas duct, the plant can be operated in a combined and regenerative cycle. Simple regulation of the liquid metal flow also permits mixed operation, so that part of the waste heat is transferred to the combustion air (HE2) and fuel (HE3), and the remainder to the water and steam (WHS).

The heat exchanger in the exhaust duct and waste heat boiler can be integrated into one unit and regulation of the exhaust flow can be carried out in a relatively simple manner using dampers and sliding elements.

The steam produced in the waste heat boiler can also be passed to a steam turbine (which corresponds to the combined cycle), although using this steam for other purposes (e.g. process and district heating) may be preferred.

- Maximum heat generation (e.g. winter operation):

The liquid metal cycle is bypassed, the total waste heat is transferred to the water and steam and discharged outside the plant for utilization.

The lack of heat in the combustion chambers in this case must be compensated for with additional fuel if the plant is to produce the full amount of electricity.

If required, any stage of the mixing operation can be adjusted, so that the operational mode of the gas turbine can be adjusted within a wide range to meet electricity and district heating system requirements.

4. CYCLE CALCULATIONS

Cycle calculations were made on the basis of a suitable gas turbine available on the market. Its parameters were selected as reference quantities for illustrative purposes. The following steps were considered separately:

- Introduction of recuperation
- Optimization of the compression ratio
- Increasing the turbine inlet temperature

Figure 5 shows the achievable increase of the plant efficiency when the gas turbine operating in a simple cycle is equipped with the regenerative system. The conversion rates of the system were selected so that a classic plant, after extended operation (possibly leakage), as well as a new plant, according to the proposed principle, are covered. All other parameters were maintained at constant values.
It can be clearly seen that at lower compression ratios a considerable increase in plant efficiency can be achieved by the introduction of recuperation, and further enlarged by optimizing the compression ratio. Figure 6 shows the respective fuel saving for the same cases.

If the third step is carried out, the ratios change substantially. If reduction of the compression ratio is necessary in the case of the original turbine inlet temperature, the compression ratio would have to be increased at higher turbine inlet temperatures to achieve the efficiency optimum (see Figure 7).

5. INFLUENCE OF PARAMETERS

During cycle calculation compression ratio, turbine inlet temperature and the heat exchange rate have a significant influence on the result, as well as the following parameters:

- Compressor efficiency
- Turbine efficiency
- Combustion efficiency (including heat radiation losses)
- Cooling air flow for the turbine, extraction flows
- Pressure losses of the heat exchanger system on the air and exhaust sides

Figures 10, 11 and 12 show the influences of the parameters of the heat exchanger system (regenerator effectiveness, pressure losses on the exhaust side and pressure losses on the air side) on the effective power output, efficiency and heat consumption of the plant. The influence of the remaining parameters (compressor, turbine, combustion and cooling) has already been discussed on other occasions and does not need to be mentioned here.
Figure 10: The influence of regenerator effectiveness on plant efficiency, power output and heat consumption

Figure 11: The influence of exhaust side pressure losses in a regenerative system on plant efficiency, power output and heat consumption

Figure 12: The influence of air side pressure losses in a regenerative system on plant efficiency, power output and heat consumption

Allillustrated quantities are based on the respective value of the original gas turbine operating in simple cycle.
6. EMISSIONS

If the emissions of a gas turbine modified according to the above described principles and operating in variation from the normal case are considered, it can be seen from the NOx emissions example that a completely new situation is created. As great as the desire is for plant flexibility, it should not be forgotten that a different combustion chamber is normally required for a gas turbine in combined cycle operation, in contrast to one in regenerative cycle operation. The temperature of the combustion air is 150 to 250°C higher in regenerative cycle operation as compared to combined cycle operation.

In order to fully exploit the advantages of the heat exchanger system, a combustion chamber must cover both operational modes and all combinations, and should also be extremely flexible with respect to emissions.

The recently developed dry low NOx systems feature exact air-fuel ratios for the diffusion flame and tightly defined mixing ratios for premixing operation. They function only within relatively tight limits.

Reference is therefore not made to the dry systems when using the gas turbine according to the above described principles where the air-fuel ratio varies widely, but steam and water injection, or in exceptional cases, catalytic reduction is necessary. Dry NOx reduction for a gas turbine in such operation has yet to be developed.

Despite its conventional design and steam injection, the combustion chamber of a gas turbine used in this way must be carefully redesigned and the correlations mentioned below must be taken into account. The development of such combustion systems is not described here, although several thoughts on this subject are presented.

From the relevant literature, very different information on the influence of the combustion air temperature on NOx production is known (see Figure 13). Even if the lowest dependence is assumed, approximately 60% higher NOx emissions can be expected if the temperature of the combustion air increases from 300°C to 500°C.

Figure 14 shows the influence of the air-fuel ratio in the primary zone of the combustion chamber. The ratio for an application can now normally be selected in such a way that the full-load point remains as high on the slope of the curve as needed in order that the no-load point is still located in the stable range on the lower part of the curve.
If a combustion chamber designed in this way is used in a different operational mode, the situation occurs as shown graphically in Figure 15. Optimization of the design can be made for either recuperative or combined operation of the gas turbine. It is clear that in the first case, the full-load point is located in the rich combustion zone (which is to be avoided), while in the second case, problems with flame stability will occur.

The final design of the system will be carried out, taking test results into account which have to be carried out for this purpose, and which will represent a compromise between both optimisation methods.

7. SUMMARY

New possibilities are opening up for applying gas turbines in the regenerative cycle by using effective and flexible heat exchanger systems, such as liquid metal heat exchangers. The gas turbine with recuperator, which has been forgotten in the past decade, can be revived and, besides increasing its efficiency, can achieve the ability to be operated in both combined and regenerative cycles.

The known disadvantages of gas turbine plants with classic recuperators can be avoided to a large extent. If optimisation of the compression ratio with a simultaneous increase of the turbine inlet temperature to the maximum values of current technology is carried out, otherwise unachievable levels of efficiency are possible.

The NOx emissions can be maintained within the required limits even in the case that one combustion system is operating in both combined and regenerative cycles. However, the steam or water injection must be applied presently while dry low NOx systems still being developed.

References:

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