THE AMERICAN SOCIETY OF MECHANICAL ENGINEERS
345 E. 47th St., New York, N.Y. 10017

97-GT-44

USE OF THERMOCHEMICAL RECUPERATION IN COMBUSTION TURBINE POWER SYSTEMS

Richard A. Newby and Wen-Ching Yang
Westinghouse Science & Technology Center
Pittsburgh, PA 15235

Ronald L. Bannister
Westinghouse Electric Corporation
Orlando, FL 32826-2399

ABSTRACT

The performance and practicality of heavy duty combustion turbine power systems incorporating thermochemical recuperation (TCR) of natural gas has been estimated to assess the potential merits of this technology. Process models of TCR combustion turbine power systems based on the Westinghouse 501F combustion turbine were developed to conduct the performance evaluation. Two TCR schemes were assessed - Steam-TCR and Flue Gas-TCR. Compared to conventional combustion turbine power cycles, the TCR power cycles show the potential for significant plant heat rate improvements, but their practicality is an issue. Significant development remains to verify and commercialize TCR for combustion turbine power systems.

INTRODUCTION

Numerous approaches for improving the thermodynamic performance of combustion turbine power generation cycles have been proposed since the early 1950s when combustion turbines were first applied for stationary power generation (Scalzo et al., 1996). Some of those approaches have been put into practice to reach the current level of performance that combustion turbine power generation has evolved to today (Briesch et al., 1995). Combined cycle power generation with clean turbine fuels, such as natural gas, can now achieve 58% (LHV) net efficiency using "G" technology, and is expected to exceed 60% (LHV) net efficiency by the beginning of the twenty-first century (Bannister et al., 1995).

Many proposed approaches for advanced combustion turbine power cycles have either been rejected as being unworkable or uneconomical, and some have not yet been developed sufficiently to be verified, demonstrated and commercialized. Thermochemical recuperation (TCR), also known as chemical recuperation, is one proposed technique that has been under evaluation for several years as a promising approach to increase power generation efficiencies. Several evaluations of the TCR technique applied to both heavy duty turbines and aeroderivative turbines have been reported in the literature (Kesser et al., 1994; Ottarsson, 1991; Rao, 1993; Janes, 1990). These evaluations provide conflicting points of view on the effectiveness, feasibility, and practicality of TCR techniques.

Westinghouse, working with the Institute of Gas Technology (IGT), has been supported by the US Department of Energy (DOE) to assess TCR techniques based partly on recent reformer information available from the former Soviet Union (Rabovitser et al., 1996). The objectives of the evaluation were to:

- assess TCR cycle options and their performance potential compared to current technology for heavy duty combustion turbines,
- identify the required modifications to the combustion turbine and the conventional power cycle components,
- assess the practicality of the TCR cycle (complexity, availability, cost)
- determine what development activities are required to bring the TCR technology to commercial readiness.

Preliminary findings on the potential performance and practicality of TCR cycles from the Westinghouse evaluation are provided in this paper.

TCR CONCEPTS

The reforming of hydrocarbons catalytically with steam to generate hydrogen-rich syngas streams is a mature technology that is applied widely in the chemical process industries and in petroleum refining. Fuel reforming has been proposed in the past as a means to improve the performance of combustion turbine power cycles, enhancing the performance of thermal recuperation with the endothermic fuel reforming reactions. Two general TCR cycle concepts have been proposed for combustion turbine applications: Steam-TCR and Flue Gas-TCR.

Steam-TCR

The Steam-TCR conceptual power cycle is illustrated in Figure 1. The figure shows the exhaust gas from the

Presented at the International Gas Turbine & Aeroengine Congress & Exhibition
Orlando, Florida — June 2–June 5, 1997

combustion turbine passing through a TCR vessel to provide the energy required to heat the fuel-steam mixture and to conduct the endothermic fuel conversion reactions.

Major reactions involved in the thermochemical recuperator are well known. The overall reaction for a general hydrocarbon fuel, C_nH_m, is:

$$C_nH_m + n\,H_2O \Rightarrow n\,CO + (n+m/2)\,H_2$$

Other reactions also enter into the reforming process, such as the water-shift reaction,

$$CO + H_2O \Leftrightarrow CO_2 + H_2$$

and the Boudouard reaction,

$$2\,CO \Leftrightarrow C(solid) + CO_2.$$

The basis of the TCR concept is that the overall endothermic nature of the reforming chemical reactions, and the formation of a low-thermal-value fuel gas replacing high-thermal-value fuel, contribute to improved efficiency in the power cycle (Vakil, 1983). The resulting fuel gas may also have improved combustion stability characteristics compared to the fuel-steam mixture resulting with the steam injection cycle. An added benefit of the hydrogen-rich reformer gas is potentially lower NOx formation in the combustor. Formation of carbon, however, must be minimized in the operation of the reformer.

The TCR vessel must be designed as an effective catalytic reactor and heat exchanger. In combustion turbine applications, the fuel reforming reactions are limited by the reaction temperature that can be reached by heat exchange with the turbine exhaust gas. The fuel conversion will only proceed to partial completion. In contrast, industrial chemical reforming application conditions are tailored for high conversion efficiency. In industrial applications reforming reactions are performed at higher temperatures (about 1470°F [800°C]) than can be achieved in combustion turbine applications using high-temperature combustion products as the heat source. The firing of the TCR vessel has been proposed in the past as a means to achieve higher fuel reformation conversions (Homer and Hines, 1992).

Note that the Steam-TCR cycle eliminates the steam turbine bottoming cycle, and is comparable in many aspects to the steam-injected turbine cycle shown in Figure 2. Because of this similarity, it is meaningful to compare the performance of Steam-TCR with a steam-injected turbine. The use of Steam-TCR also has some influences on the design of the air compressor, the combustors, the turbine expander, and the HRSG.

Flue Gas-TCR

The Flue Gas-TCR concept is an alternative to Steam-TCR. The reactions involve partial combustion resulting from the flue gas excess oxygen content, steam reforming and carbon dioxide reforming:

$$C_nH_m + n\,CO_2 \Rightarrow 2n\,CO + m/2\,H_2$$

$$C_nH_m + n\,H_2O \Rightarrow n\,CO + (n+m/2)\,H_2$$

$$C_nH_m + n\,O_2 \Rightarrow (n+m/2)/2\;CO + m/2\,H_2O$$

$$CO + H_2O \Leftrightarrow CO_2 + H_2$$

A Flue Gas-TCR cycle concept is shown in Figure 3. In this process, flue gas is recycled from a point before the stack, and is used both for fuel reforming and for turbine cooling. Because of the presence of oxygen in the flue gas, the cycle must be arranged so that the excess oxygen level in the flue gas is small (about 1-2 vol. %). The flue gas is cooled by inlet air prior to its compression. Part of the compressed flue gas is distributed to the turbine expander for airfoil cooling. The remainder of the flue gas is mixed with fuel within the thermochemical recuperator vessel, raising the temperature of the mixture slightly before the mixture enters the catalytic conversion and heat exchanger section. The reformed fuel is sent to the turbine combustor, and the combustion products are expanded. The turbine exhaust gas is first partially cooled as it passes through the thermochemical recuperator. It can then be used to raise steam for a steam bottoming cycle, such that the plant is a combined cycle. Alternatively, the turbine exhaust gas can be released to the stack as in a simple cycle. In this case the recycle flue gas is water-cooled before it is compressed.

Flue Gas-TCR requires several significant modifications to the combustion turbine and power plant arrangement due to the recycling of a significant portion of the plant flue gas. The air compressor is greatly reduced in capacity, and the turbine cooling must be adapted to recycle flue gas as cooling medium. Flue gas recycle compressors must be added, and these may need to be intercooled to be efficient. The steam bottoming cycle and HRSG are modified substantially.

EVALUATION BASIS

Using a Westinghouse 501F combustion turbine, steam-TCR and Fuel Gas-TCR thermal cycle performance has been evaluated on the following basis:

- Fuel: natural gas (desulfurized),
- Conditions: ISO, base load,
- Reforming reaction conversion performance estimated by three methods:
    - equilibrium conversion,
    - IGT conversion correlations,
    - partial conversion based on Kesser's paper (Kesser et al., 1994),
- Heat recovery steam generator pinch point temperature: 18°F (10°C),
- TCR vessel outlet temperature approach: 68°F (20°C),
- TCR vessel pressure drop (bar): 0.3.

Standard assumptions used in Westinghouse commercial cycle estimates for power island component heat losses, pressure drops, mechanical losses, efficiency factors and auxiliary losses have been applied.

The 501F engine is a 3600-rpm heavy duty combustion turbine designed to serve the 60-Hz power generation needs. Rated at 168 MW, tha technologically advanced engine represents one of the latest in the evolutionary cycle that continues a long line of large single-shaft, heavy duty combustion turbines (Scalzo et al., 1989). The 701F is a 240 MWe-class heavy duty gas turbine for 50-Hz markets. Some major 501F characteristics are:

• Air flow, lb/s (kg/s):	961 (436)
• Number of compressor stages:	16
• Compression ratio:	14.6
• Number of combustor cans:	16
• Turbine exhaust gas flow, lb/s (kg/s):	981 (445)
• Rotor inlet temperature, °F (°C):	2400 (1316)
• Exhaust temperature, °F (°C):	1125 (607)
• Number of stages:	4
• Number of cooled rows:	6

To date, 60 of the 501F/701F machines have been sold. The 22 units currently operating have accumulated over 215,000 hours of operating hours. The longest operating 501Fs are located at the FPL Lauderdale plant. With over 120,000 cummulative hours of operation their availability is over 94%.

The process flow diagrams and cycles have been evaluated using the ASPEN Plus™ process simulator which is well adapted to handling power cycles with nonstandard chemical conversions. A detailed stage-by-stage model of the 501F was incorporated into the process simulator. The thermochemical recuperator was modeled as a countercurrent heat exchanger. Detailed designs were not conducted of the reformer, looking only at its thermodynamic potential.

The sensitivity of nickle-based catalysts to sulfur species requires that the fuel be desulfurized to very low sulfur leves using commercial technology. The nickel-based catalysts become active at temperatures greater than 300°C, and with appropriate catalysts and operating conditions the methane reforming reactions are expected to proceed almost to equilibrium. Experimental correlations for methane reforming conversion in steam and steam-carbon dioxide mixtures have been developed by IGT based on recent information collected from the former USSR, and these confirm a close approach to equilibrium. A recent paper (Kesser et al., 1994) reported an estimation technique for the chemical equilibrium approach difference:

$$\Delta T_{eq} = 0 \quad \text{for } T_r > 650°C$$

$$\Delta T_{eq} = 43.33 \times (1.0 - T_r / 650) \quad \text{for } T_r < 650°C$$

where ΔT_{eq} is the chemical equilibrium approach temperature difference, and T_r is the reformer operating temperature.

In addition to the TCR cycles, simple cycle, combined cycle and steam injected cycle performance have been estimated for comparison with the TCR cycles. The process flow diagrams and cycle results have been assessed with respect to the performance merits of the TCR cycles as well as their impact on required combustion turbine modifications, and the general practicality of the cycles.

STEAM-TCR POWER CYCLE

The major components in the Steam-TCR cycle are the air compressor system, the combustors, the turbine expander, the HRSG, and the thermochemical recuperator. Two major factors in the cycle are the reformed fuel gas temperature that can be achieved and the natural gas conversion that can result. In the Steam-TCR cycle studied, the values achieved were:

• reformed fuel temperature °F (°C):	1075 (579)
• natural gas reformer conversion (%):	38

If the Kesser equation is used, the approach temperature to equilibrium is about 9°F (5°C), and the influence on the conversion and the plant efficiency is very small. Even with this level of fuel conversion the benefits of thermochemical recuperation are evident.

The main process parameters of interest to the cycle performance, listed in Table 1, are compared to the performance of the simple cycle, the combined cycle and the steam injected cycle. The predicted efficiency of the Steam-TCR plant is significantly less than that of the conventional combined cycle, and is substantially higher than that of the conventional simple cycle. The Steam-TCR plant has efficiency more than 3 percentage points higher than that of the steam-injected plant. Like the steam-injected plant, the Steam-TCR plant eliminates the steam bottoming cycle and reduces the deionized water consumption rate by 35%. The water rate is much higher than in the combined or simple cycles. The Steam-TCR efficiency is 6.7 %-points less than the conventional combined cycle efficiency.

At the selected thermochemical reformer conditions, carbon formation is expected to be negligible in the reforming reactor. It is also expected that the hot, low-thermal-value fuel gas combustibility will be excellent based on Westinghouse experience with similar fuel gases. Combustion stability is also expected to be improved in comparison with that obtained with the steam-injected cycle.

Utilization of the Steam-TCR cycle has several impacts on the combustion turbine. It requires a number of modifications to the normal combined cycle configuration:

- only slight reduction in compressor air rate,
- combustor modifications for combustion of hot, low-thermal-value fuel gas,
- elimination of the steam bottoming turbine cycle,
- modifications to the HRSG,
- modifications to the control system.

Modifications are similar to those made if the steam-injected turbine cycle were to be used. The impact on the turbine is less than it is when using the steam-injected cycle. This evaluation has considered the steam reforming of nature gas. The steam reforming of other fuels with lower reforming temperatures should perform better than the natural gas case considered (Rostrup-Nielsen et al., 1995).

FLUE GAS-TCR POWER CYCLE

The components in the cycle are the air compressor system, the flue gas recycle system, the combustors, the turbine expander, the HRSG, and the thermochemical reformer. The turbine exhaust gas oxygen content must be maintained at a low level in this cycle, and this is achieved by appropriate combustion conditions and by cooling the turbine airfoils with recycled flue gas rather than air. Key factors are:

- flue gas recycle-to-natural gas mass ratio: 32.3
- combustor outlet excess oxygen content (vol%): 1
- reformed fuel exit temperature °F (°C): 1107 (597)
- fuel reformer conversion (%): 56

The main process parameters of interest to the cycle performance are listed in Table 2 and are compared to the performance of the simple cycle, the combined cycle and the steam injected cycle. Flue Gas-TCR is only slightly more efficient than the conventional combined and simple cycles. It results in much less consumption of deionized water than is needed for Steam-TCR or the steam-injected cycle.

At the selected thermochemical reformer conditions, carbon formation should be negligible in the reactor. It is also expected that the hot, low heating value fuel gas combustibility will be excellent, but the low excess oxygen content of the combustion products may result in high carbon monoxide production.

Utilization of the Flue Gas-TCR cycle has several impacts on the combustion turbine and requires a number of modifications to the normal combined cycle configuration:

- substantial reduction in compressor air rate,
- addition of flue gas compression system,
- potential need for flue gas cleaning system for turbine cooling,
- combustor modifications to combustion of hot, low-heating value fuel gas,
- conversion of turbine to flue gas airfoil cooling,
- reduction in capacity of the steam bottoming turbine cycle,
- modifications to the HRSG,
- modifications to the control system.

A major design effort would be needed to apply Flue Gas-TCR, and it is complex and highly integrated in its nature.

CONCLUSIONS

Steam-TCR with heavy duty combustion turbines fueled by natural gas has the potential for cycle efficiencies significantly higher than the steam-injected cycle, but lower than the conventional combined cycle. The relatively simple equipment modifications required and the potentially improved NOx emissions that result make Steam-TCR a valid candidate for continued development. Its application to alternative turbine fuels having lower reforming temperatures than natural gas may be very attractive.

Flue Gas-TCR with heavy duty combustion turbines fueled by natural gas shows a small efficiency advantage over conventional cycles. The complexity of the cycle, the significant equipment modifications and development effort required to utilize the technique, and the possible technical uncertainties of Flue Gas-TCR make it questionable for continued consideration.

ACKNOWLEDGMENTS

Westinghouse was supported in this evaluation by the US Department of Energy, Morgantown Energy Technology Center under contract DE-FG21-94MC32071. Richard Johnson is the METC Program Manager. The Institute of Gas Technology provided technical assistance and a review of fuel reforming technology. The authors acknowledge the technical support of IGT's Joseph Rabovitser and Mark Khinkis.

REFERENCES

Bannister, R. L. et al., 1995, "Development Requirements for an Advanced Gas Turbine System," ASME *Journal of Engineering for Gas Turbines and Power*," Vol. 117, pp. 724-733.

Briesch, M. S. et al., 1995, "A Combined Cycle Designed to Achieve Greater than 60 Percent Efficiency," ASME *Journal of Engineering for Gas Turbines and Power*, Vol. 117, No. 4, pp. 734-741.

Homer, M. W., and W. R. Hines, 1992, Chemically Recuperated Gas Turbine, US Patent 5,133,180, July.

Janes, J. et al., 1990, Chemically Recuperated Gas Turbine, California Energy Commission, January.

Kesser, K. F. et al., 1994, Analysis of a Basic Chemically Recuperated Gas Turbine Power Plant, J. Engineering for Gas Turbines and Power, Vol. 116, p. 277, April.

Ottarsson, Kari, 1991, Comparison of a Combined Cycle with a Chemically Recuperated Cycle, LUTMDN-TMVK--5204-1-49-91, June.

Rabovister, J. K. et al., 1996, "Evaluation of Thermochemical Recuperation and Partial Oxidation Cocnepts for Natural Gas-Fired Advanced Turbine Systems," ASME Paper 96-GT-290.

Rao, A. et al., 1993, Evaluation of Advanced Gas Turbine Cycles, Final Report to Gas Research Institute, GRI-93/0250, August.

Rostrup-Nielsen, J. R. et al., 1995, "Chemical Recuperation and Gas Turbines, Presented at the EPRI Conf. on New Power Generation Technologies," San Francisco, CA, October.

Scalzo, A. J. et al., 1989, "A New 150 MW High Efficiency, Heavy-Duty Combustion Turbine," ASME *Journal of Engineering for Gas Turbines and Power*, Vol. 111, pp. 211-217.

Scalzo, A. J. et al., 1996, "Evaluation of Westinghouse Heavy-Duty Power Generation and Industrial Combustion Turbines," ASME *Journal of Engineering for Gas Turbines and Power*, Vol. 118, pp. 316-330.

Vakil, H. B., 1983, Thermodynamic Analysis of Gas Turbine Cycles with Chemical Reactions, American Chemical Society, 0097-6156/83/0235.

Walters, A. B. W. H. Weber, 1995, "Power Generation Applications of Reformed Methane with Carbon Dioxide," Presented at the EPRI Conf. on New Power Generation.

Table 1 - Steam-TCR performance comparisons

	Steam-TCR	Conventional Simple Cycle	Conventional Combined Cycle	Steam Injected Cycle
steam-to-natural gas ratio (mass):	6.6	NA	NA	8.2
air-to-natural gas ratio (mass):	43.0	42.7	42.7	35.9
makeup water rate (kg/kWh):	1.0	0	0.02	1.3
stack gas temperature (°C):	126	590	129	89
Net cycle power predicted (MWe):	215	166	264	241
Net cycle efficiency predicted (% LHV):	48.7	35.7	56.8	45.6

Table 2 - Flue gas-TCR performance comparisons

	Flue Gas-TCR Simple Cycle	Flue Gas-TCR Combined	Conventional Simple Cycle	Conventional Combined Cycle
recycle flue gas -to-air ratio (mass)	2.0	2.0	0	0
air-to-natural gas ratio (mass):	18.1	18.1	42.7	42.7
makeup water rate (kg/kWh):	0	0.01	0	0.02
stack gas temperature (°C):	433	93	590	129
Net cycle power predicted (MWe):	181	228	166	264
Net cycle efficiency predicted (% LHV):	38.7	57.1	35.7	56.8

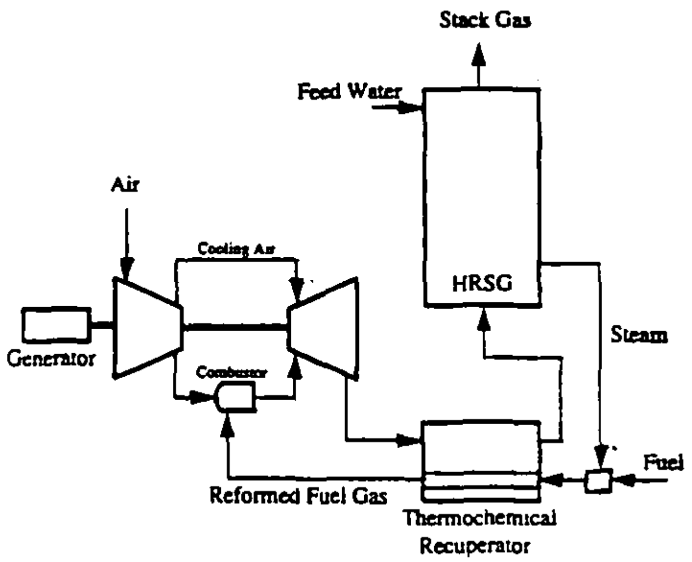

Figure 1 - Steam-TCR Cycle Diagram

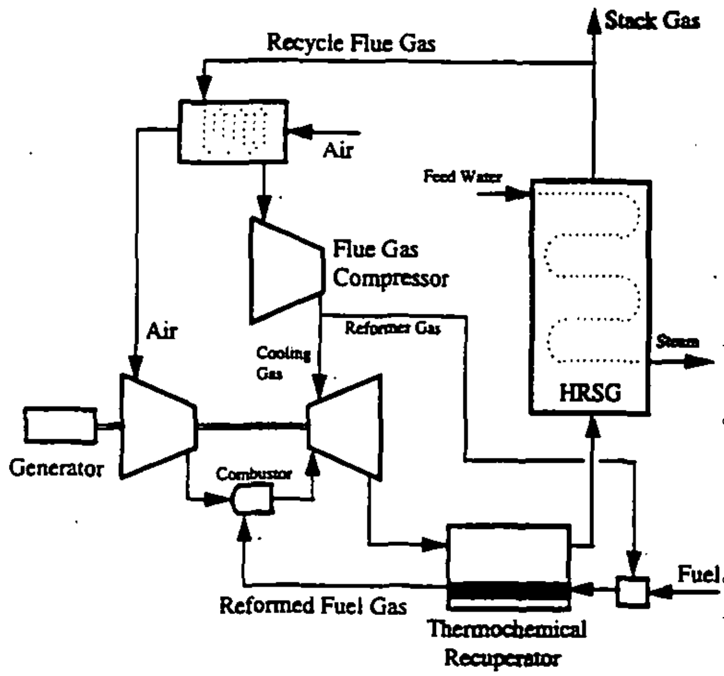

Figure 3 - Flue Gas-TCR Cycle Diagram

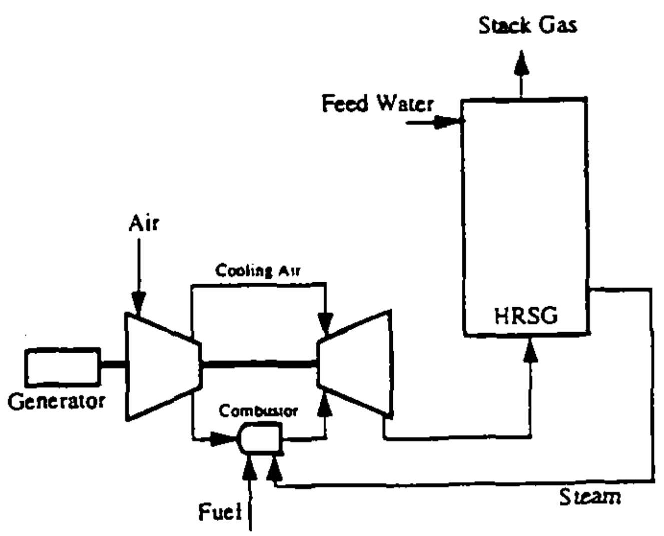

Figure 2 - Steam Injected Turbine Cycle Diagram