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AN EVALUATION OF A PARTIAL OXIDATION CONCEPT FOR COMBUSTION TURBINE POWER SYSTEMS

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ABSTRACT

In the partial oxidation concept, a high pressure, low-heating-value fuel gas is generated by partially combusting fuel with air. This fuel gas is expanded in a high-pressure turbine prior to being burned in a second-stage, conventional combustion turbine. This process reduces the specific air requirements of the power system and increases the power output. The performance, practicality, and cost of a heavy duty combustion turbine power system incorporating partial oxidation (PO) of natural gas has been estimated to assess the potential merits of this technology. Compared to conventional combustion turbine power cycles, the PO power cycle shows the potential for significant plant heat rate and cost-of-electricity improvements. However, significant development remains to verify and commercialize PO for combustion turbine power systems

INTRODUCTION

Numerous approaches for improving the thermal performance of combustion turbine power generation systems have been proposed since the early 1950s when combustion turbines were first applied to stationary power generation. Alternative approaches range from advanced topping and bottoming cycles, to advanced turbine firing conditions (Scalzo et al., 1996). Some of these approaches have been put into practice to reach the current level of performance that combustion turbine power generation has evolved to. The prevalent factor enhancing performance has been increases in firing conditions (temperatures and pressures) through advances in airfoil design, materials and cooling methods (Bannister et al., 1995). Cycle variations, such as evaporative cooling cycles, recuperative cycles, intercooled cycles, humid air cycles, reheat cycles, advanced bottoming cycles, and elevated steam bottoming conditions (Briesch et al., 1995), are also being developed to improve system performance (in contrast to hardware improvements).

Many proposed approaches for advanced combustion turbine power cycles have been rejected as being unworkable or uneconomical, and some have not yet been developed sufficiently to be verified, demonstrated and commercialized. Partial oxidation (PO) is an advanced technique proposed as a means to increase the performance of combustion turbine power systems based on theoretical, undemonstrated benefits. PO is a commercial process used in the process industries for generating syngases from hydrocarbons, but under conditions differing from those in power generation applications. A few evaluations of PO have appeared in the literature (Harvey, et al., 1995; Walters and Weber, 1995), but assessment of its application to actual heavy duty industrial combustion turbines have not been reported.

In this evaluation, the potential incentives for developing this advanced cycle for use with heavy duty combustion turbines are assessed. The thermal performance potential of the power

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plant cycles is only one aspect of the evaluation. Technical feasibility and economic estimates are also required to make a judgment of the merits of the technology. The evaluation estimates budgetary costs for the equipment.

CYCLE DESCRIPTION

The partial oxidation (PO) of hydrocarbons is a technique used extensively in the chemical process industries to generate a wide variety of petrochemicals. It has been previously presented in the literature as a means for improving the performance of combustion turbine power plants (Rabovitser et al., 1996).

In partial oxidation, a substoichiometric quantity of air is mixed with the turbine fuel to result in the generation of a low-heating-value fuel gas by the following basic reactions (illustrated for methane):

- partial oxidation reaction

$CH_4 + 1/2\ O_2 = CO + 2\ H_2$
(ΔH = -44 kJ/mole) (1)

- water-shift reaction

$CO + H_2O <=> CO_2 + H_2$
(ΔH = 41 kJ/mole) (2)

- steam reforming reaction

$CH_4 + H_2O => CO + 3\ H_2$
(ΔH = 226 kJ/mole) (3)

- Boudouard reaction, and direct methane decomposition

$2\ CO <=> C(solid) + CO_2$
(ΔH = -173 kJ/mole) (4)

$CH_4 <=> C(solid) + 2\ H_2$
(ΔH = 75 kJ/mole) (5)

The formation of carbon (soot) must be minimized in the operation of the partial oxidizer to minimize equipment fouling and erosion, and to minimize carbon losses. None of the reactions require catalysis, and the fuel does not require desulfurization.

A schematic flow diagram for the Partial oxidation power cycle is shown in Figure 1. The fuel is partially oxidized in the PO reactor. The resulting fuel gas is expanded through the high-pressure, PO turbine. The air for partial oxidation is compressed in stages with intercooling. The air for the PO turbine may be extracted from the combustion turbine compressor or may be taken from ambient air, or a combination of the two. The high-pressure PO turbine is cooled by steam. Additional steam is also injected into the PO reactor to control the reaction temperature and to minimize soot formation. The fuel gas generated in the PO reactor, after expanding through the PO turbine, is combusted and expanded in a conventional, heavy duty combustion turbine. The energy in the combustion turbine exhaust is recovered to generate steam for use in the PO reactor and PO turbine. There is no steam turbine in this cycle, so it is a simple cycle form of the PO

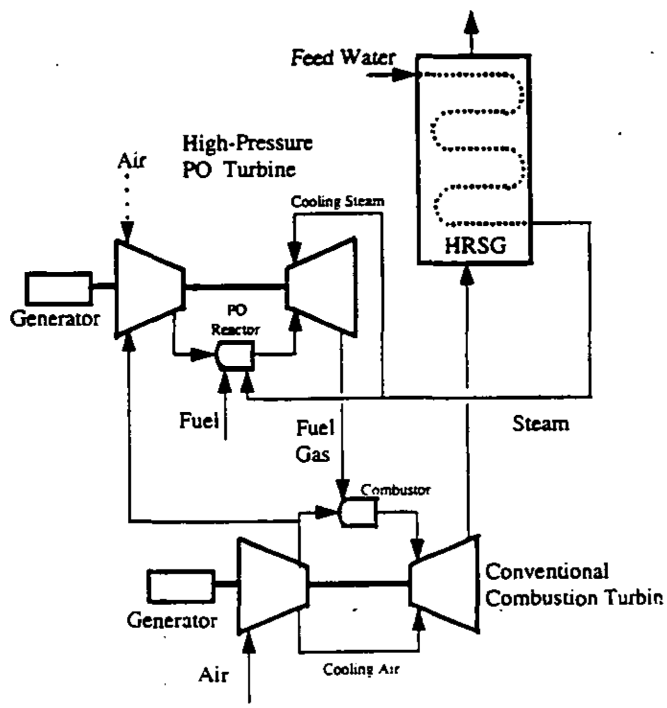

Figure 1 - Partial Oxidation Cycle Diagram

power cycle. A combined cycle form might be utilized if the steam consumption needed for PO turbine cooling and for moderation of the PO reactor can be reduced substantially below the very conservative assumptions made here.

Partial oxidation benefits the power cycle by providing several potential advantages over conventional cycles or reheat cycles: lower specific air consumption and reduced air compressor work; increased power plant thermal efficiency; and potentially lower NO_x emissions with improved combustion stability.

EVALUATION BASIS

The partial oxidation cycle has been evaluated for a specific, heavy duty industrial combustion turbine in combination with a hypothetical, high-pressure PO turbine:

- The PO turbine is a hypothetical engine, specifically designed for the PO application
- The combustion turbine is a Westinghouse 501F
- Turbine mass flow is maintained at the 501F design mass flow
- Rotor inlet temperature is maintained at the 501F design rotor inlet temperature
- Fuel: natural gas
- Conditions: ISO, base load
- Partial oxidation conversion performance estimated at equilibrium conversion
- Heat recovery steam generator pinch point temperature: 10°C
- The PO air compressor air source is ambient, rather than extracted from the combustion turbine compressor. This was done to make convergence of the cycle calculations simpler and does not reflect the best configuration or the true capabilities of the cycle. This would not be done in actual practice.
- The PO air compressor is intercooled by indirect water heat exchange, and the cooling energy is not recovered in the cycle calculations.

The process flow diagram has been evaluated using the ASPEN Plus™ process simulator which is well adapted to handling power cycles with non-standard chemical conversions. A detailed stage-by-stage model of the 501F was incorporated into the process simulator. An approximate stage-by-stage model of the PO turbine was also utilized. The turbine stages were modeled, as with other turbine simulators, by joining a series of heat exchangers, flow mixers and splitters, and expanders that best depict the turbine flow path, cooling, and leakage arrangement. A detailed design was not conducted on the PO reactor, estimating only its thermodynamic potential and rough sizing.

The PO process and cycle conditions were not optimized in the evaluation, but acceptable conditions for the PO reactor were selected and applied, and only limited cycle variations were considered. Standard assumptions used in Westinghouse commercial cycle estimates for power island component heat losses, pressure drops, mechanical losses, efficiency factors and auxiliary losses were applied.

The 501F engine is a 3600-rpm heavy duty industrial combustion turbine designed to serve the 60-Hz power generation needs. The 701F is a 240 MWe-class heavy duty gas turbine for 50-Hz markets. Some major 501F/701F characteristics based on natural gas fuel are:

	501F	701F
Air flow, kg/s:	436	652
No. of compressor stages:	16	16
Compression ratio:	14.6	15.6
No. of combustor cans:	16	16
Turbine exhaust gas flow, kg/s:	445	661
Rotor inlet temperature, °C:	1316	1260
Exhaust temperature, °C:	607	551
No. of turbine stages:	4	4
No. of cooled turbine rows:	6	6

To date, 60 of the 501F/701F machines have been sold, and the 23 units currently operating have accumulated a combined, approximate 215,000 operating hours. The longest operating 501Fs are located at the FPL, Lauderdale plant. The 4 units at this site have compiled more than 120,000 hours of operation with an average availability of over 94%.

The economic premises applied were:

- Cost year: 2000
- General inflation rate: 4%
- Construction period: 12 months
- Construction period interest rate: 8 %
- Plant boundary: tumkey plant
- Fuel cost: $3.00/MMBtu
- Capacity factor: 85%
- Capacity degradation: 2 %/yr
- Heat rate degradation: 2 %/yr
- other commercial cost premises applied by Westinghouse

Equipment costs for non-standard components, such as the PO reactor, were order-of-magnitude estimates based on general cost correlations and cost data for similar equipment. The costs of standard equipment in the plant were taken from recent commercial cost quotes scaled to the simulated plant conditions as needed.

CYCLE PERFORMANCE

A major parameter in the cycle evaluation was the PO turbine inlet pressure. The evaluation was simplified in that the PO air compressor efficiency, the PO turbine efficiency, and the PO turbine coolant-to-expansion gas mass ratio were all held constant over the range of pressures considered. Table 1 lists the performance results for the PO power plant, showing the breakdown of power generated in the PO power plant for three different PO turbine inlet pressures: 45 bar, 60 bar and 100 bar. The projected cycle net efficiency ranges from 48.4% lower heating value (LHV) for a PO turbine operating pressure of 45 bar to 49.6% (LHV) for an operating pressure of 100 bar. There is no steam turbine in this cycle. Additional optimization of the cycle to improve the efficiency is possible, for example, by integrating the PO turbine compressor and the combustion turbine compressor.

Operating at pressures of 45 bar and 60 bar, the cycle attains maximum steam generation (or energy recovery) when a pinch point of 10°C is reached at the economizer. However, when operating at a pressure of 100 bar, the cycle controlling mechanism becomes combustion in the 501F. Attempts to increase steam generation in the boiler result in incomplete combustion (or oxygen deficiency) in the 501F combustor giving lower than intended temperature at the combustor outlet. This is evident from the continuing decreases of oxygen concentration at the 501F combustor outlet when the operating pressure increases from 45 bar to 100 bar. That is why the efficiency improvement is marginal, from 49.3% to 49.6%, when operating pressure is increased from 60 bar to 100 bar. Substantial increase beyond an operating pressure of 60 bar is not recommended.

The PO gas turbine is a hypothetical turbine unique to each set of conditions evaluated in this analysis, i.e., operating inlet pressures at 45 bar, 60 bar, and 100 bar. It is relatively small, producing about 20 to 50 MW. While the PO turbine has a high inlet pressure, it also has a small expansion ratio. In this evaluation, the energy from the intercooling of the PO turbine compressor was not recovered.

The conditions of a few key streams are summarized in Table 2 for operating pressures of 60 bar, the near-optimum inlet pressure for the PO cycle. The composition of the low-heating-value fuel gas issued from the PO turbine is shown in Table 2. This fuel gas has a total heating value (LHV) of about 2.3 MJ/nm^3 (63 Btu/scf). The warm fuel gas (773°C) should combust efficiently. The fuel gas molecular weight is about 20.7. The fuel thermal value can be increased by reducing the consumption of steam for soot control. This reduction needs to be established though subscale testing.

The oxygen concentration in the stack for the PO cycle is generally less than 7% compared to a value of 12.7% for the conventional simple cycle. The higher the PO turbine operating pressure, the lower the oxygen content becomes. Indeed, the total air requirement is smaller than that of a conventional simple cycle, reducing air compressor power significantly.

The rate of demineralized water consumption is relatively large in this simple cycle configuration. The mass ratio of water to fuel (methane) is about 6.6, about 5 times the water usage typical in a conventional combined cycle plant. Total water consumption is about the same as in a combined cycle plant with a water evaporative cooling tower. While estimates of equilibrium soot formation are very small at the PO reactor operating conditions (Table 2, last row), the reaction kinetics and mixing phenomena will dictate the actual soot formation performance. It is expected that through optimization of the cycle and equipment designs, the simple cycle configuration evaluated might be converted to a combined cycle configuration having higher thermal performance.

TECHNICAL FEASIBILITY AND ECONOMICS

The major equipment components in the PO power plant are the

- PO air compressor (intercooled)
- PO reactor
- PO turbine
- Combustion turbine
- HRSG

As individual components, all of these components are technically feasible. The components of greatest uncertainty are the PO reactor and the PO turbine. The PO reactor is a relatively simple device and its design can follow the extensive commercial experience with partial oxidation of hydrocarbons in the chemical process industries. One issue for the partial oxidation of natural gas is the potential formation of soot. It is estimated that under the selected conditions of operation soot formation should be minimal, but demonstration of soot-free performance over the range of power plant operating conditions would be required.

The PO turbine is a hypothetical component with unproven technical feasibility at the selected design conditions. The expansion of hot, clean flue gases in similar expander equipment has been considered in the past as being commercially viable for application in coal gasification plants, although the inlet pressure, expansion ratio, and inlet temperature (80 bar, 3, 300°C, respectively) were similar, but not as challenging as the PO turbine conditions (60 bar, 3.7, 760°C, respectively) (Feerrar et al., 1978). Engineering methods are well developed that permit the airfoil cooling design using either open-loop or closed-loop steam.

The conventional combustion turbine can be easily adapted to function in the PO power plant. Modifications to the combustion turbine air compressor, combustors and expander section to utilize the hot, low-heating-value fuel gas are technically feasible using existing engineering techniques and materials. The efficient combustion of the hot, low-heating-value fuel gas with the low excess air levels required in the PO power plant is a technical issue requiring further evaluation and testing.

The PO power plant is not unusually complex compared to commercial power plants. Integration of the PO power plant components into a reliable, controllable power plant is an area for additional evaluation, but is not a technical feasibility issue. It is expected that such integration is technically feasible based on experience with other relatively complex

The development requirements for the PO power plant to reach a state of commercial readiness are:

- sub-scale experimental verification of the partial oxidation reactor performance,
- detailed cycle optimization evaluations in parallel with PO reactor design optimization,

- sub-scale combustor performance verification testing with the very low-heating-value fuel gas and low excess oxygen,
- detailed cycle optimization and plant integration evaluations,
- demonstration plant operation.

The PO power plant will compete with conventional combined cycle and simple cycle plants. Economic comparison is made in Table 3. The PO power plant capital investment is intermediate to that of the conventional simple cycle and combined cycle power plants. Its cost-of-electricity is very close to that of the conventional combined cycle. Several areas of potential cost reduction for the PO power plant have been identified. The technical performance required to make such cost improvements and thus relax the conservative assumptions applied need to be experimentally substantiated.

CONCLUSIONS

Simple cycle PO has the potential for efficiency more than 13 percentage points (net, LHV) higher than that of conventional simple cycle power plants, but about 7 percentage points less than that of conventional combined cycles. The simple cycle PO power plant has cost-of-electricity considerably less than that of the conventional simple cycle and comparable to that of the conventional combined cycle. The simple cycle PO power plant also has the potential to produce considerably more power than the conventional simple cycle and combined cycle power plants, but with several technical issues.

The PO power plant does not require significant modifications to combustion turbine equipment. Design modifications that are required can be performed with a strong background from similar turbine modifications and similar combustor modifications for other applications. A commercial background in the area of partial oxidation of fuels exists that can be drawn upon to design the PO reactor. The development of a new, high-pressure PO turbine is required to use the cycle, and new turbine development is normally an expensive undertaking requiring several years of development time. Existing high-pressure turbines that can be modified for this application need to be identified and evaluated. Thus, the PO cycle development requirements could be extensive in cost and schedule, although the technology can be considered highly feasible and practical. In general, PO merits further evaluation, and the cycle configuration and major equipment designs and operating conditions should be optimized. Some alternative fuel types might be utilized in this cycle more efficiently than can natural gas. Also, combustion turbines more advanced than the reference 501F used in this evaluation will probably have greater efficiency and cost benefits from these advanced cycles. Both of these variations should be considered.

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Table 1 - Performance of the Partial oxidation Power Plant

PO Turbine Pressure, Bar	45	60	100
PO Turbine Results			
Shaft Power (MW)	16.9	33.9	51.4
Generator Losses (kW)	338	679	1027
Net GT Power (MW)	16.6	33.2	50.3
501F Turbine Results			
Shaft Power (MW)	303.3	305.6	303.8
Generator Losses (kW)	3545.7	3545.7	3545.7
Net GT Power (MW)	299.8	302.0	300.3
Overall Cycle Results			
BOP Losses (kW)	4131	4131	4131
Water Pump (kW)	463.5	635.0	986.6
Net Cycle Power (MW)	315.6	334.7	350.1
Net Efficiency, %-LHV	48.4	49.3	49.7

Table 2: Conditions of Selected Gas Streams - 60 Bar PO Turbine Pressure

Stream	PO Reactor Outlet	PO Turbine Outlet	Combustion Turbine Outlet	Steam	Stack Gas
Temperature,°C	1316	773	608	575	98
Pressure, bar	59.3	15.9	1.05	65.5	1.01
Mass Flow (kg/hr)	0.56×10^6	0.81×10^6	1.77×10^6	0.33×10^6	1.77×10^6
Composition (mole fraction)					
O_2	0	0	0.0571		0.0574
N_2	0.4646	0.3002	0.5421		0.5426
CO	0.0780	0.0504	0		0
CO_2	0.0430	0.0278	0.0444		0.0443
H_2O	0.2529	0.5173	0.3498	1.0	0.3491
CH_4	0	0	0		0
H_2	0.1558	0.1006	0		0
Ar	0.0055	0.0036	0.0065		0.0065
C (solid)	1.96E-20	1.27E-20	0		0

Table 3 - Comparison of PO Power Plant with Conventional Combustion Turbine Power Plants (60 bar case)

	Capacity (MWe)	Efficiency (%, LHV)	Capital Cost ($/kW)	COE (cents/kWh)
PO Power Plant	335	49.3	291	3.6
Conventional 501F Simple Cycle Plant	166	35.7	276	4.6
Conventional 501F Combined Cycle Plant	264	56.8	410	3.5