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EFFICIENT GAS STREAM COOLING IN SECOND-GENERATION PFBC PLANTS

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Abstract

The coal-fueled Advanced or Second-Generation Pressurized Fluidized Bed Combustor concept (APFBC) is an efficient combined cycle in which coal is carbonized (partially gasified) to fuel a gas turbine, gas turbine exhaust heats feedwater for the steam cycle, and carbonizer char is used to generate steam for a steam turbine while heating combustion air for the gas turbine. The system can be described as an energy cascade in which chemical energy in solid coal is converted to gaseous form and flows to the gas turbine followed by the steam turbine, where it is converted to electrical power. Likewise, chemical energy in the char flows to both turbines generating electrical power in parallel.

The fuel gas and vitiated air (PFBC exhaust) streams must be cleaned of entrained particulates by high-temperature equipment representing significant extensions of current technology. The energy recovery in the APFBC cycle allows these streams to be cooled to lower temperatures without significantly reducing the efficiency of the plant. Cooling these streams would allow the use of lower-temperature gas cleanup equipment that more closely approaches commercially available equipment, reducing cost and technological risk, and providing an earlier path to commercialization.

This paper describes the performance effects of cooling the two hottest APFBC process gas streams: carbonizer fuel gas and vitiated air. Each cooling variation is described in terms of energy utilization, cycle efficiency, and cost implications.

Thermal Characteristics of APFBC Plants

By combining fluidized bed technology with coal gasification technology, an APFBC plant generates clean power from coal at 45-percent efficiency (HHV) and reduced cost of electricity (Robertson and others, 1992).

Figure 1 is a simplified block diagram of the APFBC power plant. Coal is converted to a low-Btu gas and char in the carbonizer, a bubbling-bed reactor operating at approximately 14 atmospheres. Sorbent is fed to minimize the amount of gaseous sulfur emissions. The low-Btu fuel gas is burned and expanded in the gas turbine producing electrical power. The PFBC operates around 14 atmospheres and utilizes char combustion to directly heat the gas turbine combustion air.

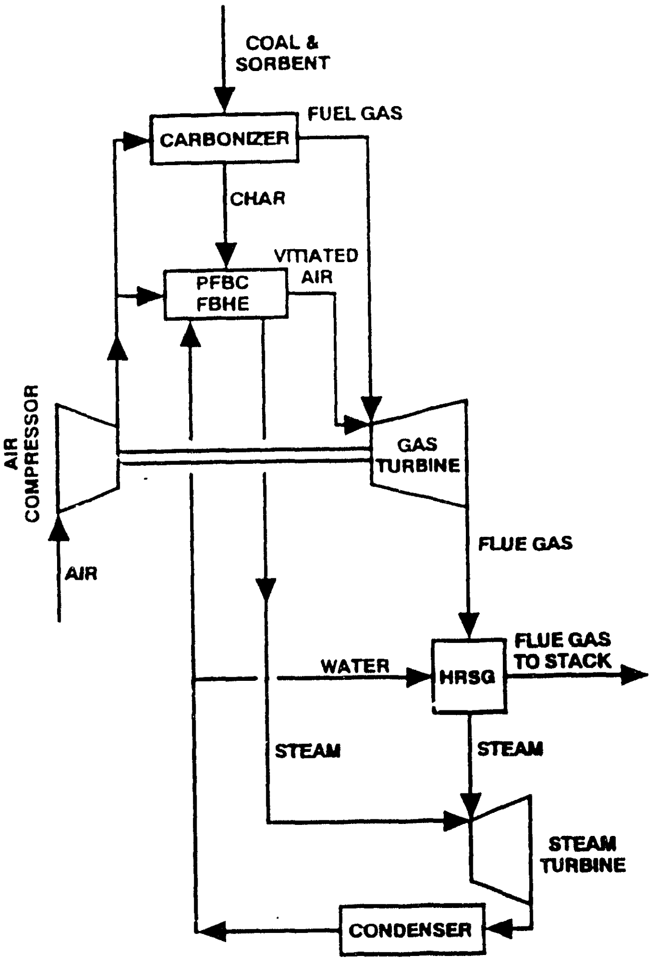

Figure 1: APFBC Schematic

Waste heat from the PFBC and heat recovery steam generator (HRSG) is recovered and used to generate high-pressure steam, which is utilized in a condensing steam turbine bottoming cycle. The maximum working temperatures in the gas and steam turbine are approximately 1330 °C (2425 °F) and 540 °C (1000 °F), respectively.

This paper compares the performance of competing cycle configurations to a base case. The base case APFBC Power Plant utilizes a carbonizer and PFBC each of which has an operating temperature of 870 °C (1600 °F). The gas turbine has a combustor exit temperature of 1330 °C (2425 °F), a rotor inlet temperature of 1217 °C (2233 °F), and has cooling flows inferred from published operating parameters of the Westinghouse 501F gas turbine. The steam bottoming cycle has 16.6 MPa, 540 °C (2400 psig, 1000 °F) throttle steam, 540 °C (1000 °F) reheat steam, and an 8.5-kPa (2.5-in(Hg)) condenser. This base case power plant has an estimated thermal efficiency of 46.41 percent (HHV) and produces 537 MWe of power.

Study Approach

Variations of the advanced PFBC cycle have been investigated with the goal of easing the design requirements for selected items of equipment. One conceptual study (Robertson and Horazak, 1993) used an atmospheric bed combustor to reduce the volumetric flow through the gas stream cleanup system. Another study (Robertson and others, 1994) showed that cooling the char stream in the topping cycle could reduce the operating temperature of the char-handling equipment with minimal impact on plant performance if the cooling flows were cascaded to the bottoming cycle.

The objective of this study is to determine the effect on cycle performance caused by cooling the fuel and/or vitiated air process streams in a APFBC plant. To determine the effect, conceptual designs of commercial scale APFBC power plants with and without process gas cooling were modeled and performance simulated with the steady-state modeling code ASPEN. Model results were used to generate performance data, which were compared to determine the effect of hot gas cooling on plant performance.

Table 1
Summary of Modeled Performance Results
(All cases with 870 °F (1600 °F) carbonizer and 1330 °F (2425 °F) Turbine Inlet Temperature)

Case	Base	C1	C2	C3	C4
Fuel Gas Cooling, °C	0	167	0	83	0
(°F)	(0)	(300)	(0)	(150)	(0)
Vitiated Air Cooling, °C	0	167	167	0	83
(°F)	(0)	(300)	(300)	(0)	(150)
Fuel Gas Temperature, °C	870	705	870	790	870
(°F)	(1600)	(1300)	(1600)	(1450)	(1600)
Vitiated Air Temperature, °C	870	705	705	870	790
(°F)	(1600)	(1300)	(1300)	(1600)	(1450)
Plant Thermal Input, MWt	1157.9	1617.2	1530.7	1189.9	1347.3
Gas Turbine Net Power, MWe	279.5	287.0	284.9	276.6	280.4
Steam Turbine Net Power, MWe	280.0	456.6	424.4	291.6	353.5
Fuel Gas Cooling, MWt	0	29.62	0	10.8	0
Vitiated Air Cooling, MWt	0	124.7	125.2	0	63.5
Total Gas Cooling, MWt	0	154.3	125.2	10.8	63.5
Plant Excess Air, %	124.9	60.6	69.77	118.8	93.12
PFBC Excess Air, %	216.8	118.1	132.1	207.4	167.9
Net Plant Efficiency, % HHV	46.41	44.00	44.37	45.84	45.10

Identical carbonizer and PFBC performance were assumed for each case, although vessel sizes were scaled to accommodate variable coal feed rates. The gas turbine was treated as a constant volumetric flow rate machine. At a specified temperature and pressure, specified volumetric flows must pass through the compressor and expander. The steam bottoming cycles had identical throttle, reheat, and condenser conditions but were scaled to accommodate variable waste heat recovery duties.

The two gas stream cooling approaches discussed in this paper are fuel gas cooling with waste heat transferred to the steam cycle, and, vitiated air cooling with waste heat transferred to the steam cycle. Five cycles were evaluated for this study. A summary of performance results can be seen in Table 1.

Fuel Gas Cooling

In this process variation, heat is removed from the fuel gas stream downstream from the cyclone and prior to entering the particulate capturing barrier filter. The waste heat is recovered by generating hot water for the bottoming cycle. Figure 2 is a schematic representation of the heat removal.

Removing heat from the fuel gas stream decreases the sensible heat input to the gas turbine combustor. To achieve a consistent gas turbine rotor inlet temperature, more fuel is required to counter the decrease in sensible energy input. Greater gas turbine fuel requirements result in increased coal and air flow to the carbonizer.

Assuming constant volumetric flow through the gas turbine results in relatively constant power production. An increase in carbonizer coal feed does not increase power production by the gas turbine, but results in a larger steam turbine power cycle. Increased thermal energy is transferred to the steam cycle in two ways. First, sensible heat from the cooled fuel gas is directly transferred to the steam cycle. Second, decreased excess air fraction caused by increased coal input results in larger steam requirements for solids cooling in the fluidized-bed heat exchanger (FBHE). Thermal energy generated during char combustion in the PFBC is removed either as sensible heat of the air or as steam generated in the FBHE. When lower amounts of excess air are available in the PFBC, greater steam generation in the FBHE is required to maintain a constant PFBC operating temperature.

The Base cycle has no gas cooling. Table 1 shows that cooling the fuel gas by 83 °C (150 °F) (compare Base and C3) results in a decrease in plant thermal efficiency of 0.57 percent. Also, plant and PFBC excess air values decrease and the power produced by the steam turbine is greatly increased. Producing relatively greater amounts of power in the steam turbine rather than the gas turbine decreases the overall plant efficiency because the steam turbine is relatively less efficient than the gas turbine. The higher operating temperature of the gas turbine enhances the gas turbine efficiency in comparison to that of the steam turbine.

Cooling the fuel gas prior to the barrier filter decreases the overall thermal efficiency of the power cycle. At the same time, operating the barrier filter at lower temperatures results in cost savings due to less stringent material requirements. The most desirable operating temperature could be determined by weighing cost against plant thermal efficiency.

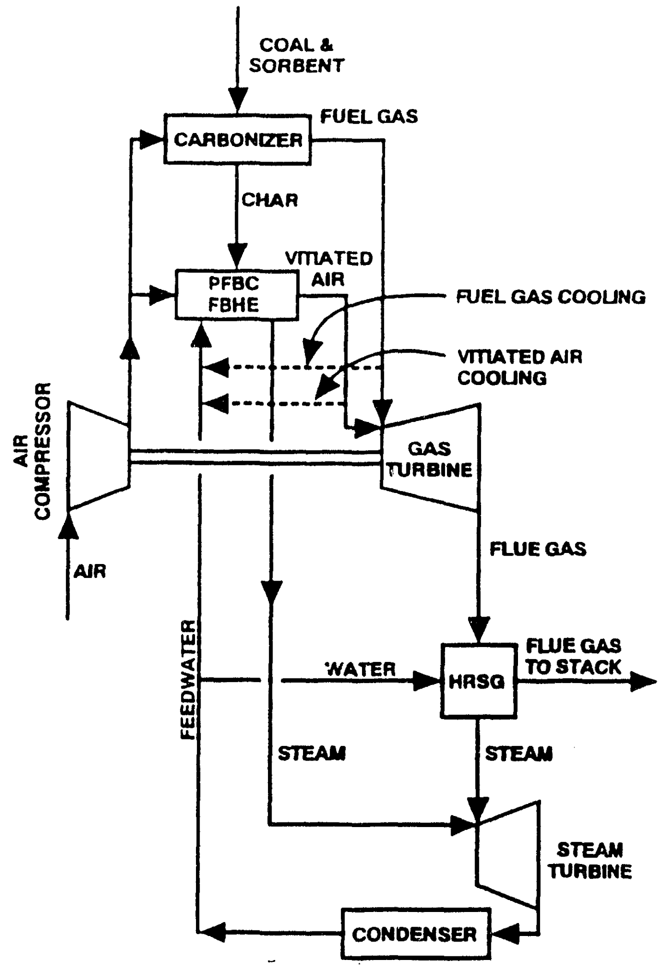

Figure 2: APFBC with Gas Cooling

Vitiated Air Cooling

In this process variation, heat is removed from the vitiated air stream following exhaust from the PFBC cyclone and prior to entering the particulate capturing barrier filter. The waste heat is recovered by generating hot water which is utilized by the bottoming cycle. Figure 2 contains a schematic representation of the heat removal scheme.

In a manner identical to that described for fuel gas cooling, removing heat from the vitiated air stream will produce an increase in the amount of fuel required by the gas turbine to achieve the appropriate rotor inlet temperature. Sensible heat removed from the vitiated air stream is compensated for by increased chemical energy input. Coal feed requirements increase, requiring relatively greater amounts of air in the carbonizer. As described above, this results in larger steam cycle size and lower plant excess air values.

Cooling the vitiated air causes a decrease in the overall plant thermal efficiency for the same reasons described for the case of fuel gas cooling. Comparison of the Base case and C4 in Table 1 shows that a 83 °C (150 °F) decrease in the vitiated air temperature results in a decreased thermal efficiency of 1.31 percent. This value shows that the APFBC plant is 2.3 times as sensitive to vitiated air cooling as to fuel gas cooling, mainly because the vitiated air flow rate is about 10 times the fuel gas flow rate. The decrease in the thermal efficiency is accompanied by decreased plant excess air values and increased steam turbine cycle size.

Cooling the fuel gas prior to the barrier filter decreases the overall thermal efficiency of the power cycle. At the same time, operating the barrier filter at decreased thermal conditions results in cost savings due to less stringent material requirements.

Conclusions

At a given carbonizer temperature, APFBC plant thermal efficiency decreases with increases in process gas cooling. Process gas cooling promotes a larger steam turbine power cycle, and the addition of this relatively less efficiently produced power to the total power output causes the net cycle efficiency to decrease. Due to the smaller mass flow of the gas turbine fuel gas stream compared to the vitiated air stream, the thermal efficiency of the cycle is correspondingly less sensitive to the fuel gas temperature than it is to the PFBC exhaust temperature. This can be seen by examining Figure 3, which shows thermal efficiency as a function of process gas cooling. The slope for vitiated air cooling is much steeper than for fuel gas cooling indicating a more marked decrease in plant efficiency for the same temperature change.

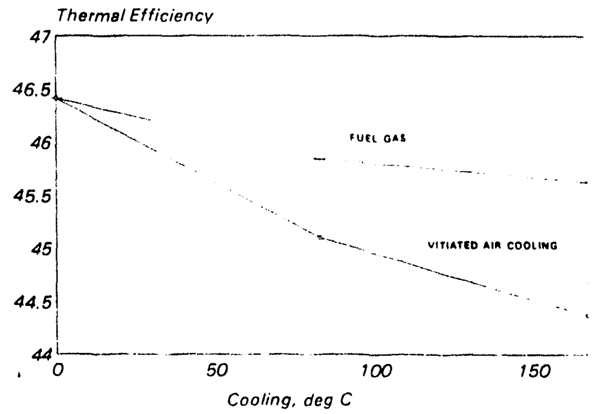

Figure 3: Efficiency and Gas Cooling (1°C Cooling equals 1.8°F Cooling)

Generally speaking, any process modification that increases the percentage of excess air in the APFBC plant will increase the thermal efficiency of the cycle. Plants with higher excess air have higher thermal efficiencies because more thermal energy is carried into the gas turbine combustor, rather than into the steam turbine. The increased thermal energy infusion decreases the fuel flow requirement and decreases the amount of thermal energy cascaded to the less efficient bottoming cycle. Utilizing the thermal energy directly in the gas turbine expander at high temperature is more efficient than transferring the thermal energy to steam evaporation, then to relatively lower temperature utilization in the steam turbine.

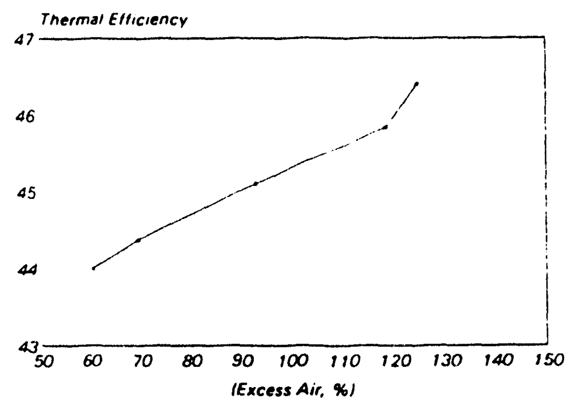

Figure 4: Efficiency and Plant Excess Air

Figure 4 shows a plot of the thermal efficiency as a function of plant excess air. A significant change in slope at the tail of the almost linear line is easily noticeable in Figure 4.

Plotting the effects of both vitiated air and fuel gas cooling on a single chart emphasizes the difference in magnitude of each effect. This difference is represented in Figure 3 which shows that vitiated air cooling has a more severe effect on thermal plant efficiency. Although excess air is a dependent variable in this study, it can be used as a relative indicator of thermal plant efficiency.

The results of our analysis show that the efficiency of the 870 °C (1600 °F) carbonizer-based APFBC power plant seems to correlate with three key variables: excess air, vitiated air cooling, and, to a lesser degree, fuel gas cooling. In the cases presented in this paper, the excess air value was a variable of the gas cooling, and therefore, uncontrolled. In other possible cooling schemes, plant air may be controlled to accommodate temperature constraints in downstream equipment which could be met by direct air cooling.

In summary, the higher the gas turbine fuel and vitiated air feed temperatures, the higher the APFBC cycle thermal efficiency. Also, the higher the excess air value, the higher the APFBC cycle thermal efficiency. Cost benefits due to cooler operating conditions may warrant a decrease in the operating temperatures of the process gas streams. This analysis may serve as a guide in determining the cost savings for such cooling schemes.

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