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High-Pressure Ceramic Air Heater for Indirectly Fired Gas Turbine Applications

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DISCLAIMER

"High–Pressure Ceramic Air Heater for Indirectly Fired Gas Turbine Applications"

CONTRACT INFORMATION

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Period of Performance	February 7, 1990 to February 7, 1994

FY 92–93 EFCC PROGRAM SCHEDULE

		N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F
1)	CERHX	—	—	—	—	—	—										
2)	CONSTRUCT TEST FACILITY	—	—	—	—												
3)	H. P. AIR SYSTEM	—	—	—	—	—	—	—									
4)	COMBUSTOR	—	—	—	—	—	—	—									
5)	SHAKEDOWN							—	—	—							
6)	FULL SCALE TESTING										—	—	—	—	—		
7)	DISMANTLE FACILITY															—	

OBJECTIVES

The Externally–Fired Combined Cycle (EFCC) offers a method for operating high–efficiency gas and steam turbine combined cycles on coal. In the EFCC, an air heater replaces the gas turbine combustor so that the turbine can be indirectly fired. Ceramic materials are required for the heat exchange surfaces to accommodate the operating temperatures of modern gas turbines.

The ceramic air heater or heat exchanger is the focus of this program, and the two primary objectives are 1) to demonstrate that a ceramic air heater can be reliably pressurized to a level of 225 psia (1.5 MPa), and 2) to show that the air heater can withstand exposure to the products of coal combustion at elevated temperatures. By replacing the gas turbine combustor with a ceramic air heater, the cycle can use coal or other ash–bearing fuels.

Numerous programs have attempted to fuel high efficiency gas turbines directly with coal, often resulting in significant ash deposition upon turbine components and corrosion or erosion of turbine blades. This report will show that a ceramic air heater is significantly less susceptible to ash deposition or corrosion than a gas turbine when protected by rudimentary methods of gas–stream clean–up.

A 25 × 10^6 Btu/hr (7 MW) test facility is under construction in Kennebunk, Maine. It is anticipated that this proof of concept program will lead to commercialization of the EFCC by electric utility and industrial organizations. Applications are being pursued for power plants ranging from 10 to 100 megawatts.

BACKGROUND INFORMATION

In the past, the conversion of the chemical energy in coal to electric power was restricted to conventional steam cycles due to the ash content of this fuel. External firing would permit the use of coal in a combined gas and steam turbine cycle. In some cases, pre–existing steam plants could be upgraded to become an EFCC through addition of the gas turbine topping cycle, resulting in a reduction in heat rate of approximately 25 percent, narrowing the heat rate advantage enjoyed by natural gas and distillate oils. Higher efficiency relates to reduced fuel consumption for a given electric power output, resulting in inherently lower emissions.

Major components of the EFCC, shown diagrammatically as Figure 1, are: the ceramic air heater, the solid fuels combustor, the gas turbine and compressor, the heat recovery steam generator, and the steam turbine. Clean filtered air enters the compressor where it is pressurized to approximately 150 psia (1.0 MPa), with a temperature of 700°F (375°C). This flow becomes the tube–side flow through the ceramic air heater, where temperature is raised to about 2000°F (1100°C); this high temperature, pressurized air enters the gas turbine where it expands to generate power. Clean air exits the turbine at a temperature of 1000°F (540°C) and slightly above atmospheric pressure to become the combustion air supplied to the solid–fuels combustor. Energy supplied by the fuel raises the gas temperature to above 2500°F (1370°C); the products of combustion flow through the shell–side of the air heater. Shell–side exit temperatures are above 1000°F (540°C), sufficiently high to fire the bottoming Rankine Cycle. Steam injection can raise the gas turbine power by increasing the heat capacity of the pressurized air stream and the mass flow through the gas turbine.

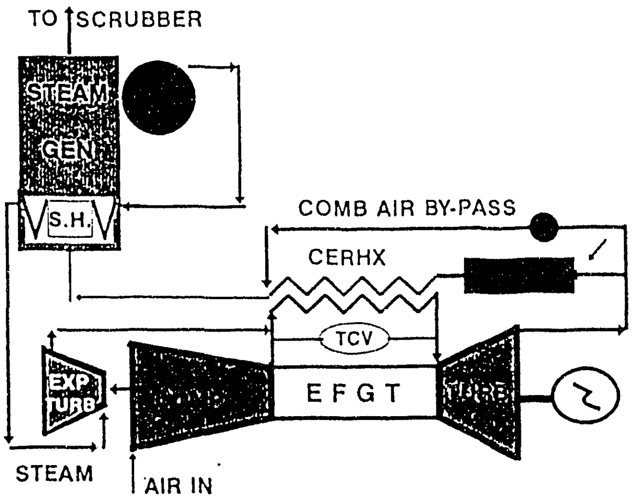

Figure 1. Steam Injected EFCC

Power plants employing indirect fired gas turbines have been studied since the 1930's. One of the first technical papers in this area was offered by Keller [1], published in 1945. Pioneering small–scale studies with coal and peat–fired air heaters followed in 1950 and 1951 at the John Brown works, Clydebank, Scotland under license of Escher Wyss, reported by Keller and Gaehler [2]. The first gas turbine (500 kW) with a peat–fired air heater was built at this location, leading to installation of the first industrial pulverized coal–fired plant in Ravensburg, West Germany. This was a cogeneration facility for electric power production (2300 kW) and industrial steam production. Operating experience showed that the austenitic stainless steel air heater performed reliably. Simultaneously, experimental studies showed promising results for an open–cycle indirect–fired gas turbine, as discussed by Mordell [3]. Metallic heat exchangers did not allow sufficiently high turbine inlet temperatures for economic power production. Use of a ceramic air heater alleviates this obstacle; ceramics can endure temperatures above 2500°F (1370°C) in the chemically harsh environments produced by the combustion of coal.

Subsequently, a development program was initiated in the early 1960's in the General Electric Company Research and Development Center in Schenectady, New York, to determine the feasibility of a closed cycle coal–fired gas turbine air heater. This early work was pursued by Dr. Paul Kydd through the mid–60's. During this period of low–cost energy there was, unfortunately, no appetite for developing more complex thermal conversion cycles solely for the purpose of improving efficiency. This work consisted primarily of paper studies and cycle evaluations, summarized by LaHaye [4].

In 1971 Hague International (HI) began a series of experiments on ceramic heat exchanger components that culminated in the construction of the first ceramic heat exchanger for a high temperature process furnace in 1973. Most of the work during this period was on low pressure heat recovery equipment (recuperators) for the secondary metal industry. A shell and tube heat exchanger design was selected at the outset, primarily because the constraints imposed by ceramics are more easily addressed by using tubes for the heat transfer surface, and because heat exchangers of the tubular type offer a wide range of flexibility in mechanical arrangements. By the early 1980's Hague had about fifty low pressure units in operation in the metals industry in the U.S. In 1983 NGK Insulators Ltd. of Nagoya, Japan, was licensed to manufacture and sell the low pressure units for the Japanese and the Pacific basin markets. NGK had formed a product division for the purpose of making and selling the product. These applications of ceramic heat exchangers in extremely corrosive and high temperature environments have produced over two million hours of operating experience.

HI has based the design of the current high pressure unit on these low pressure designs. In 1987, a consortium of government agencies, electric utilities and industrial organizations was formed and work was initiated on Phase I of the EFCC program. Results were reported by LaHaye et al. [5] and LaHaye and Zabolotny [6]. A low pressure recuperator was exposed to the products of combustion of a coal/water slurry over a time interval of up to 40 hours. Build–up of ash occurred on the heat exchanger tubes, indicating the need for an upstream ash collection system. However, the ceramic tubes exhibited good durability under all test conditions. Phase II involves the design, construction, and operation of the Kennebunk Test Facility (KTF), discussed by Vandervort et al. [7] and updated in this report.

PROJECT DESCRIPTION AND RESULTS

The ceramic air heater for the KTF is a multi–pass shell and tube heat exchanger. High pressure air exits the gas turbine compressor and enters the inlet header and the ceramic tubes. Energy is transported from the products of coal combustion that flow on the shell–side to the high pressure air in the tubes, raising the temperature to approximately 2000°F (1100°C). These tubes are supported vertically in compression, with the compressive forces developed by a spring pack and bellows assembly. The complete tube–string is shown as Figure 2. This illustration shows a two–pass heat exchanger with a center "hex–sleeve" that separates the two passes. It is important to note that the spring–pack and bellows assembly are located on the cold end of the tube–string; these components are never exposed to temperatures above 400°F (200°C). The heat exchanger tubes are internally enhanced, resulting in a tube–side convection resistance that is approximately equal to the shell–side convection resistance. The overall heat transfer coefficient for the air heater is approximately 30 W/m^2–°C.

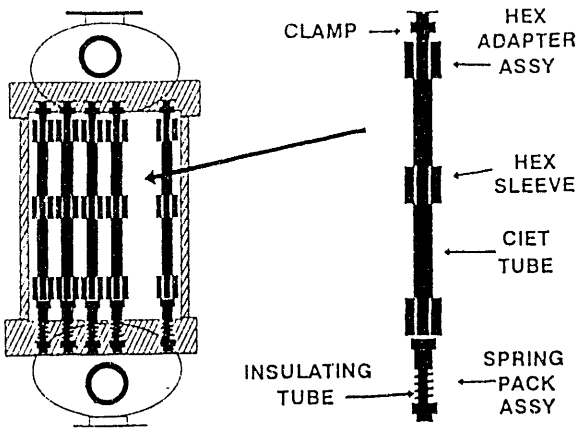

Figure 2. Ceramic Air Heater

TUBE–STRING PRESSURIZATION

Single tube–string tests are being performed in the apparatus shown as Figure 3, and referred to as the Component Pressure Integrity Test Facility. The tube–string can be pressurized to 225 psia (1.5 MPa) and heated to above 2000°F (1100°C). Heating is provided by electric "clamshell" heaters, that are individually controlled for each simulated shell–side pass and spring pack assembly. Air leakage from the interfaces between these components is measured, comprising the first series of CPI testing. Results of these CPI tests have exceeded expectations. The initial goal for minimum leakage was attained, less than 1.5 percent of the total tube–side flow for a power plant utilizing the GE MS7001 gas turbine. At 3 percent leakage,the approximate penalty in the net cycle thermal efficiency is 1 percent. Figure 4 represents the measured leakage rates for the first five CPI tests.

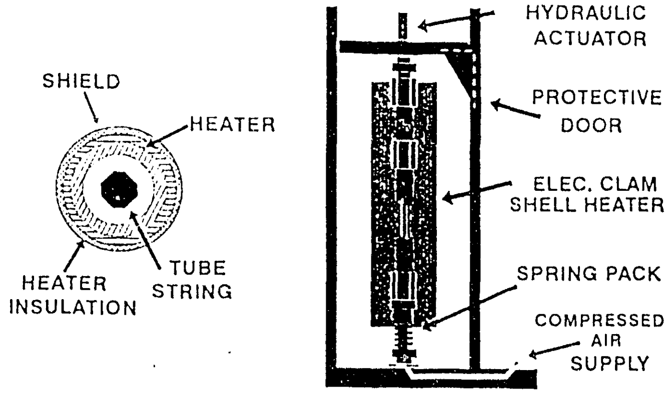

Figure 3. CPI Test Rig

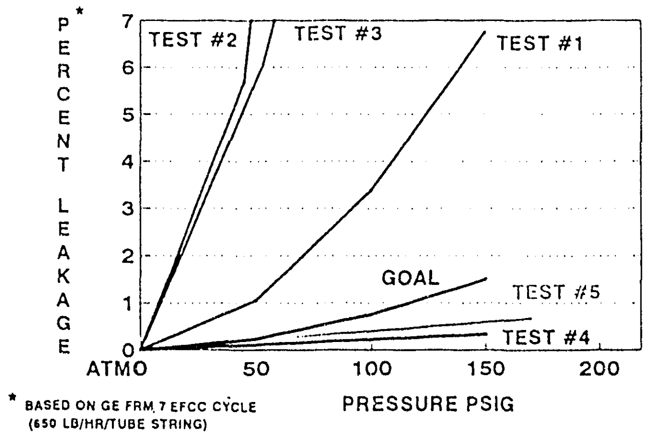

Figure 4. Tube–String Leakage Results

Recent tests have focused on tube–string integrity over extended time intervals at temperature and the influence of thermal cycling. Total accumulated test time on this apparatus now exceeds 1500 hours, with continued testing in progress. Thermal cycling tests are intended to simulate operating transients for an EFCC plant, including startup and shutdown. A typical test sequence is shown by Figure 5. The heat exchanger temperature is raised to about 1200°F (650°C), corresponding to the approximate temperature required for self–sustaining operation of the gas turbine. Pressure is raised to operating levels, simulating compressor start. The tube–side temperature is raised to approximately 2000°F (1100°C) simulating power increase to full–load conditions. Temperature and pressure are held constant for several hours. Then the temperature is returned to self–sustaining levels where pressure is reduced to atmospheric. Following a soak period, the process is repeated. Over two–hundred of these cycles have been completed, with satisfactory results.

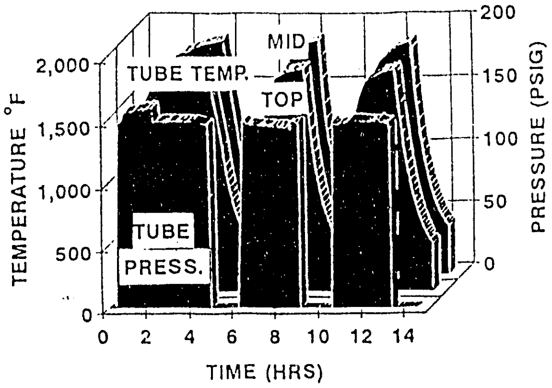

Figure 5. CPI Cycle Sequence

ASH DEPOSITION STUDIES

In addition to the leakage concern, combustion of coal results in the presence of ash particles, suspended in the products of combustion. As the ceramic air heater replaces the gas turbine combustor, the EFCC shows promise because it is easier to prevent ash buildup on tubes of a shell and tube heat exchanger than on the blades of a gas turbine. Ceramic air heater components can also be chosen which exhibit excellent resistance to chemical attack when exposed to the products of coal combustion.

Ash deposition for the EFCC is controlled through the use of a slag screen, discussed in detail by Vandervort [8]. This device is a staggered array of refractory tubes, acting as an impact separator. Particle inertia tends to counteract the fluid drag forces which act to "sweep" the particles past the separator tubes. Impact separators are quite effective for removing particles above a certain diameter, ranging from 5 to 50 microns. If these particles are not removed by the slag screen, these same inertial forces can cause impaction upon the ceramic air heater tubes. Resulting ash buildup can hinder heat transfer and, eventually, bridge the gaps between tubes and clog the device.

A slag screen/ceramic air heater system can be designed where all particles of sufficient inertia to impact the heat exchanger tubes are removed upstream by the slag screen. Slag screen tubes also represent a flow obstruction and, accordingly, a source of pressure loss. For optimal efficiency of the EFCC, pressure loss between the combustor and the heat exchanger must be maintained as low as possible. Optimal cycle efficiency requires that pressure drop across the slag screen is maintained at less than 10 in. w.g (0.0025 MPa). A clear tradeoff exists between separator performance and pressure drop.

Ash size distribution is important, as impact separator efficiency is a strong function of particle diameter, particle density, gas stream velocity and impact target size. Particle density is similarly affected by the chemical composition of the fuel. As stated, chemical composition influences the fusion temperature, which impacts the "stickiness" of the coal ash particles. Thus, ash fusion temperature and combustor exit temperature combine to affect collection efficiency and subsequent reentrainment rates. Success of the slag screen/heat exchanger system for ash deposition control strongly depends upon the performance of the combustor. It is necessary to minimize the average ash particle size exiting the combustor. Ash particle size is also a strong function of the coal chemical composition and size distribution; maximum ash particles sizes may exceed 15 microns for certain coal types. An average particle size of 10 microns can be assumed. At this size, the majority of ash particles will pass directly through the slag screen and the air heater to be collected in a baghouse.

Preliminary design of the slag screen is shown as Figure 6. The slag screen rods are supported by a hexagonal lattice of refractory blocks. Products of combustion exit the combustor with a relatively high velocity; smaller particles will be carried by the hot gas stream into the slag screen where all particles larger than about 12 microns impact upon the slag screen tubes. At the exit of the slag screen, the gas stream is directed into an ash collection area. Following this bend, the gas flow is decelerated into the air heater. Within the air heater, the lower gas velocity and larger tube diameters significantly lower the particle collection efficiency; particles over 30 microns will impact the heat exchanger tubes.

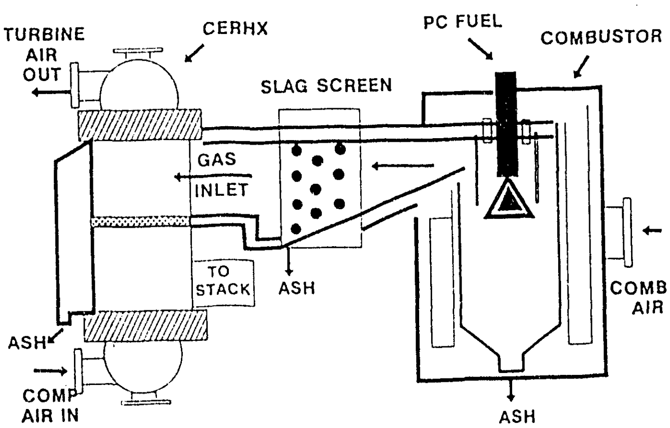

Figure 6. Slag Screen Design

Performance of this system is summarized in Figure 7. Particles less than 12 microns can be collected in a baghouse; the region between 12 microns and 30 microns can be considered the "safety factor". These are particles which impact the slag screen but are swept around the heat exchanger tubes.

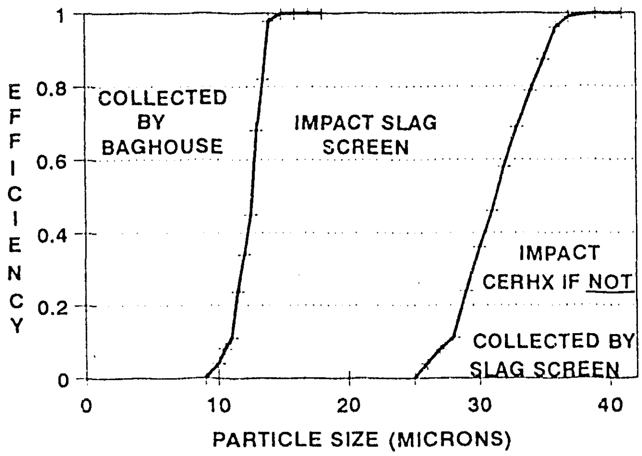

Figure 7. Slag Screen Performance

COAL COMBUSTION SYSTEM

Originally, the program called for purchase of a coal combustor. A specification was prepared and released to several prospective suppliers. Unfortunately, because of the specialized requirements, no satisfactory bids were received. As a result, the system has been designed by HI with support from Foster Wheeler Corporation, EPRI, and other members of the EFCC Consortium. The resulting system is an adiabatic, high excess air, vertical, air–staged prototype that consumes approximately 2000 lb/hr (0.25 kg/s) of pulverized coal. Because the unit is adiabatic (i. e., uses no water cooling of the refractory walls), it is necessary to control the combustion gas temperature by dilution with the high levels of excess air available in the cycle. This amount (approximately 180 percent) is supplied by the simulated exhaust from the indirectly–fired air turbine. Primary air must also be supplied to the coal handling system for transport of pulverized coal to the coal burner.

The combustion chamber or furnace is cylindrical with a height of about 39 feet (12 m) and outer diameter of 13 feet (4 m). The burner is located at the top and fires vertically down into the chamber. The furnace will operate at temperatures above the ash fusion point so that molten ash can be collected at the base through a slag trap. Air–staging can be used for NO_x reduction by operating fuel–rich in the upper section and then applying an air quench for lean operation in the lower section. Staging is expected to reduce NO_x levels to well below the New Source Performance Standards, based on previous experimental results for coal–burning.

FUTURE WORK

Proving the commercial viability of the ceramic air heater is the primary goal of this program The test facility is being built at a pre–existing industrial site in southern Maine. The environmental permitting process was completed in July of 1992, allowing construction to begin. Permission was required from the Town of Kennebunk, State of Maine, and the Federal Government through the

Department of Energy in accordance with the National Environmental Policy Act. This facility will house the test ceramic air heater, slag screen, combustion system, air compressor, and auxiliary components. A sketch of the facility is shown by Figure 8, with the air heater to the left and the combustor to the right.

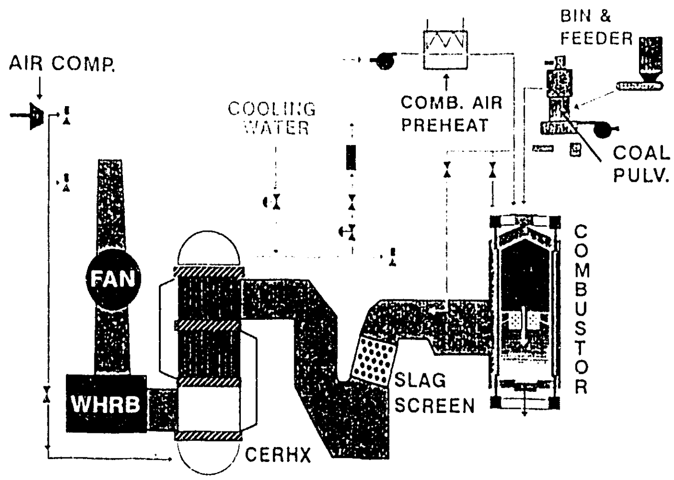

Figure 8. Kennebunk Test Facility

Three stages of testing are planned leading to a total of 300 to 600 hours of operation on coal, and beginning in spring of 1993. In the first stage, the heat exchanger is constructed with a full assembly of tubes. In order to minimize the cost and initial risk, the first array of tubes is metallic. Approximately forty hours of operation on natural gas are anticipated, with the goal of verifying the facility controls and instrumentation systems. These initial tests will be run at temperatures below 1560°F (850°C) to avoid over–heating the metal tubes.

A brief second stage of testing will follow with the metal tubes using coal as fuel. Again, these tests will be performed at reduced temperatures. Their purpose will be to verify operation of the coal–handling system and slag screen. A maximum of forty hours of testing is anticipated. Ceramic tubes will replace the metal tubes in the first and second shell passes for the third phase of testing. These tests will verify operation of the full indirect–fired cycle, including slag screen performance, thermal characteristics, pressure integrity, material durability, and control methodology. The goal of these tests is to complete an uninterrupted 100–hour run.

This amount of operating time is not sufficient to prove the concept as commercially viable, so that additional operation of the facility is anticipated during 1994 and 1995. In parallel with this program, conceptual designs have been initiated for Phase III, a retrofit application of an existing coal–fired steam plant. A ceramic air heater, slag screen, combustor and gas turbine of approximately 20 MW would be retrofitted to an existing power plant. Steam produced by a new heat recovery steam generator would be used for steam injection and power production using the existing steam turbines. This system is expected to produce electricity by the late 1990's at a cost competitive with other emerging technologies.

Experience gained through design and operation at the retrofit facility will be applied to Phase IV, the construction of large, utility–scale EFCC plants. For production of 100 MW of electrical energy with conventional gas and steam turbine technology, heat rates are predicted to range from 7000 to 8000 Btu/kW–hr. There are no other means of achieving performance at this level with coal in an economically viable fashion.

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