20-Mw Prototype MHD Coal-Fired Combustor

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20-MW PROTOTYPE MHD COAL-FIRED COMBUSTOR*

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Abstract

This paper describes a prototype 20-MW MHD coal-fired combustor that was designed, fabricated, and tested under contract to the Department of Energy. The design incorporates features to (1) maximize the plasma electrical conductivity, (2) minimize the thermal heat loss, (3) maximize the slag removal efficiency, and (4) minimize constraints on scaleup. A two-stage combustor was selected with a slag separator located between the two combustors. The intermediate temperature and associated first-stage stoichiometry ratio were selected to provide adequate slagging temperatures, temperatures within state-of-the-art material limitations, and minimum slag vaporization. The slag separator selected was a high-efficiency cyclone with refractory lining to minimize heat loss. Each of the two first-stage combustors has a combined water-cooled and refractory-lined combustion chamber. These combustors fire tangentially into the slag separator. The second-stage combustor is a single unit and is completely water cooled. A performance evaluation module is located downstream from the second-stage combustor to measure the plasma electrical conductivity. Unfortunately, funding and schedule constraints prevented completion of the test program. Limited results to date, however, indicate promising combustor performance.

I. Design Objectives

The design objectives used for the 20-MW coal-fired combustor are to:

1. Maximize combustor performance (plasma electrical conductivity) consistent with the program requirements.
2. Provide a design with minimum constraints in system scaleup for 50-MW and larger sizes.
3. Provide a modular design so that each component can be optimized and rapidly changed or modified to accommodate development program variations.

These design objectives resulted in the following combustor key features:

1. A two-stage combustor with an intermediate slag separator to remove slag at a low temperature, thus minimizing enthalpy losses associated with heating and vaporizing the slag.
2. A first-stage pentad (four air streams impinging on one coal stream) injector design with demonstrated efficient mixing to promote high carbon burnout.
3. A two-section, first-stage combustion chamber with the first stage using a thin, water-cooled, slag-protected refractory layer and the second section using a thick refractory layer, both to minimize heat losses.
4. A refractory lining in the slag separator to minimize heat losses.
5. A second-stage combustor providing both de-swirl of the combustion products exiting from the slag separator and simple mixing of the vitiated secondary air and seed.
6. A dense-phase coal feed system to minimize cold carrier gas entering the first-stage combustors.
7. A dry seed injection system using pulverized K_2CO_3 with a 1% amorphous, fumed silicon dioxide additive to enhance flowability, resulting in rapid vaporization and ionization and ensuring maximum performance.
8. A performance evaluation module (PEM) of rugged design based on an existing, successfully tested unit.

These design features result in the highest theoretical electrical conductivity achievable consistent with state-of-the-art material limitations and system design requirements.

II. Combustor Configuration

The combustor system is illustrated in Figure 1. The combustor consists of three major subassemblies: the two first-stage (or primary) combustors, the slag separator, and a single second-stage secondary combustor. All of the coal is injected into the two primary combustors, where it is mixed and combusted with ~37% of the air oxidizer. The air is preheated to 800°F and then vitiated, utilizing oil and gaseous oxygen to

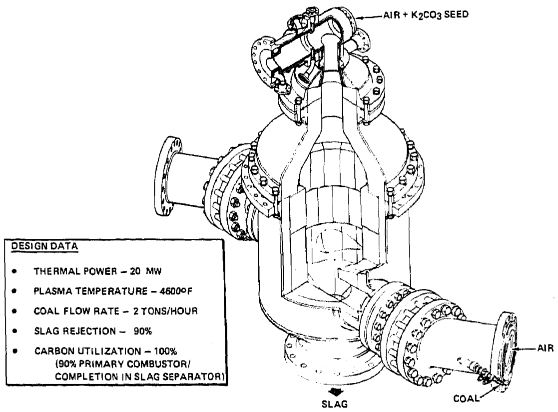


Figure 1. 20-MW MHD Coal Combustor Design

*This work was performed under Contract DE-AC22-78ET-11054, Department of Energy obtain a temperature of 2900^{o}F. The coal and preheated air are injected into the combustion chamber through a primary injector assembly in which four air streams impinge on a single coal stream and produce a uniform dispersion of reactants across the chamber. The entire upstream side of the injectors, including the vitiated air entrance, is refractory lined to minimize heat loss.

The primary combustors are designed to operate at a stoichiometric ratio of 0.33. This stoichiometry was selected to ensure slagging operation of the primary combustion chambers, temperatures within state-of-the-art material limitations, and minimum slag vaporization. This tradeoff between stoichiometry and temperature is illustrated in Figure 2. In the primary combustors, two processes occur — combustion and gasification. The combustion process is exothermic, the gasification process endothermic. As a result, the gas temperature in the exothermic reaction may reach ~3700^{o}F. For this reason, the initial length of the primary combustion chamber is water cooled. The remaining primary combustion chamber length, which attaches to the slag separator, is refractory lined. A design goal was to achieve at least 90% carbon burnout in the primary combustors. The design of the first-stage injector is shown in Figure 3. The injector receives heated air through four nozzles on the injector face. Coal is injected at the center of the face through a water-cooled tube. The impingement of the air and coal provides highly efficient mixing and combustion. Heat loss has been minimized by lining the injector housing with refractory material.

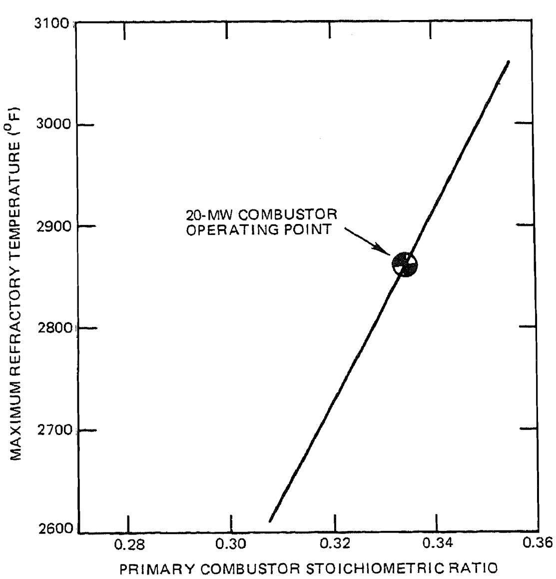


Figure 2. First-Stage Combustor Operating Point Selection

The exit gases of the primary combustors containing entrained slag droplets are injected tangentially into the slag separator. Because of the additional residence time in the slag separator, most of the remaining carbon will be reacted. The slag removal occurs as a result of the cyclonic action of the gases imposed by the tangential entrance. The slag is thrown to the wall, moves to the bottom of the slag separator

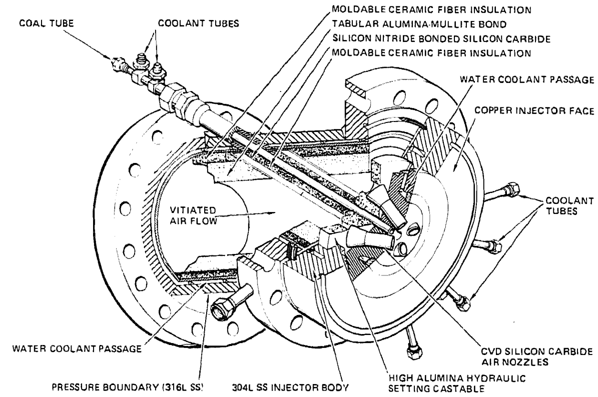


Figure 3. MHD Primary Combustor Injector

by gravity action, and exits through a tap at the bottom center of the unit.

The slag separator consists of a natural-convection-cooled, carbon steel pressure vessel which is refractory lined. The lining consists of fused-cast Cr_2O_3/Al_2O_3 blocks backed up with high alumina hydraulic setting castable. An identical refractory lining is used in the primary combustion chambers. The fused-cast refractory used has been tested by ANL. Specimens have been exposed to agitated Rosebud coal slag for 500 h with no perceptible corrosion. Temperatures of these specimens ranged from 2700 to 2800^{o}F and reached greater than 3000^{o}F for ~20 h.

The "cleaned" hot gases then pass from the slag separator to the second stage or secondary combustor, where the remainder of the vitiated oxidizer air is added. This completes the combustion process at an overall stoichiometry of 0.95, achieving the required exit temperature. Potassium carbonate (K_2CO_2) seed is also added to the secondary air and dispersed uniformly across the secondary combustor. The product gases heat and vaporize the K_2CO_3 seed to produce an electrically conductive plasma. The resulting plasma then flows through the combustor to an exit nozzle, where the gas is accelerated to Mach 0.3. The secondary combustor is water-cooled to accommodate the high combustor temperature in this stage.

The hot plasma from the secondary combustor enters a performance evaluation module. The PEM is utilized to establish the conductivity of combustor plasma; it was designed and fabricated by J. B. Dicks and Associates, Inc., under subcontract to Rockwell International. The PEM test section consisted of 30 electrodes insulated from each other in such a way that, by imposing a constant voltage between selected electrodes, the resulting current flow through the plasma allowed determining the bulk electrical conductivity.

III. Combustor Performance

The original performance parameters selected to establish baseline operating conditions were based on using a 21% oxygen enrichment for the vitiated air and an overall stoichiometric ratio of 0.9. Also, a conservative carbon burnout of 90% was selected because of the unknown effect of the slag separator in the complete reaction of the coal. The resultant baseline operating conditions are presented in the first column of Table 1. Before running the demonstration tests, technical requirements were received from DOE altering the baseline operating conditions. The resultant operating conditions and performance predictions for these requirements are presented in the second column of Table 1. Since checkout testing had demonstrated the ability of the combustor to achieve 100% carbon burnout, this value was used in predicting performance for the demonstration test conditions. It can be noted from Table 1 that the predicted electrical conductivity for the demonstration test operating conditions is 90% greater than for the baseline operating conditions.

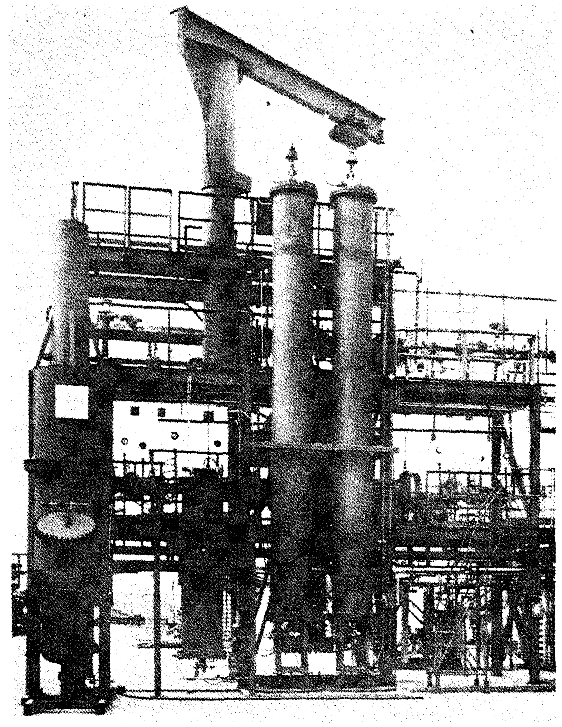
Table 1. 20-MW Combustor Performance Parameters

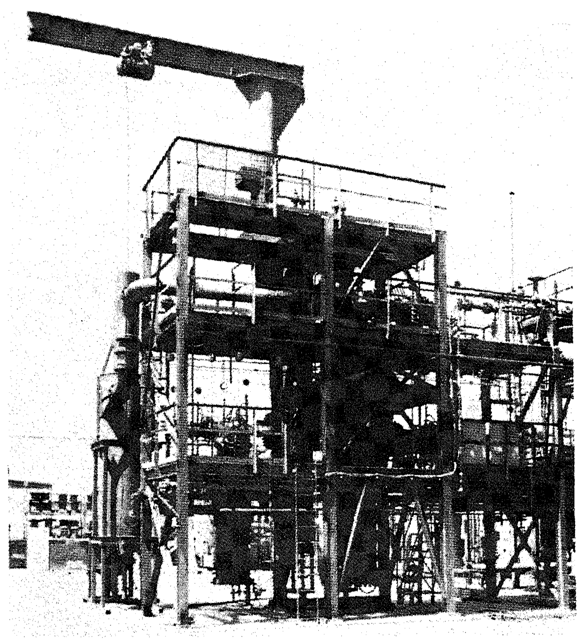
	Baseline Design Operating Conditions	Demonstration Test Operating Conditions
First-stage stoichiometric ratio	0.33	0.34
Overall stoichiometric ratio	0.90	0.95
Design carbon burnout (%)	90	100
GOX enrichment (%)	21	30
Inlet air temperature (^{o}F)	800	600
Adiabatic exit temperature (^{o}F)	4584	4864
Adiabatic electrical conductivity (S/m)	7.66	15.09
Thermal input (MW)	20.0	20.65
Predicted heat loss (%)	7.0	7.0
Predicted exit temperature (^{o}F)	4427	4649
Predicted electrical conductivity (S/m)	5.35	10.18

IV. 20-MW Testing

The 20-MW combustor was tested at the Thermodynamics Laboratory of Rockwell International. Photographs of the test setup are shown in Figures 4 and 5.

A total of four tests were conducted on the 20-MW combustor. Table 2 summarizes the combustor test history. The checkout test (Test 001) accumulated 37 min at coal-flow operation, and all systems operated successfully. The first two performance tests (Tests 002 and 003) were terminated because of minor, easily corrected hardware problems. The third performance test (Test 004) accumulated 65 min of coal-flow and 56 min of seed-flow operation. During Test 004, control difficulties occurred with the coal feed system, causing testing to be run over a wide range of stoichiometric conditions rather than continuously at the design point. This feed system problem resulted from the compaction of coal in the run tanks, which caused unstable coal flow. Schedule and money did not permit repeating the performance test at the reference operating conditions.





Because of the range of stoichiometric conditions encountered during the test, data were analyzed at discrete times when steady-state conditions occurred. PEM data were analyzed at these times; the results are presented in Figure 6. At the design point, the indicated electrical conductivity was 9.7 S/m, compared to a predicted value of 10.2 S/m. Heat loss measurements were made on all components during the test. For the design condition (stoichiometry

Table 2. 20-MW MHD Coal Combustor Test History

Test	Date	Test Objective	Results
001	07/17/80-07/20/80	Check out; characterize facility systems	Test of 37-min duration. All systems characterized except seed feed. Hardware ok.
002	08/27/80-08/29/80	Performance demonstration with PEM	Two PEM electrodes overheated during warmup. Cooling passages restricted. Electrodes replaced.
003	09/03/80-09/06/80	Performance demonstration with PEM	Secondary combustor coolant over temperature at initiation of coal combustion.
004	09/10/80-09/14/80	Performance demonstration with PEM	Test of 65-min duration.

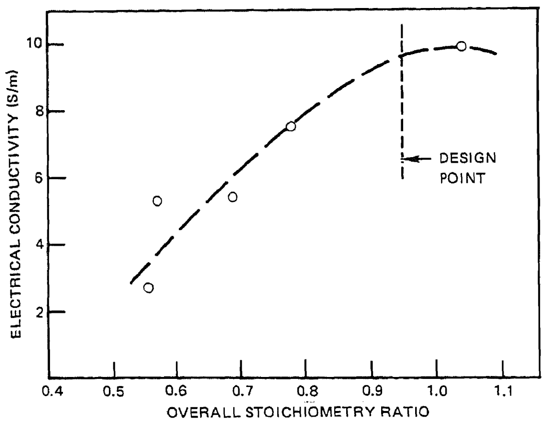


Figure 6. Electrical Conductivity Versus Stoichiometry Ratio — Test 004

ratio = 0.95), the combustor heat loss was 8.0%, compared with the predicted value of 7.0%.

Although much more testing is needed to establish combustor performance firmly, the limited results to date are indicative of the performance potential that can be realized by using a refractory approach to limit heat losses. Major questions regarding refractory life, slag separator efficiency, and combustor operating limits remain. We hope that additional testing can be conducted at a future date to address these issues.

V. Acknowledgements

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The performance evaluation module was designed and fabricated by J. B. Dicks and Associates, Inc., under subcontract to Rockwell International. The contributions of Dr. William Holt, of the J. B. Dick staff, in PEM design and data reduction are also acknowledged with appreciation.