Mixing and Kinetic Processes in Pulverized Coal Combustors

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ABSTRACT

An atmospheric coal combustion furnace was designed and constructed to study the effects of turbulent mixing and the kinetic processes occurring in pulverized coal furnaces. The coal furnace feeds up to 57 kg of coal per hour. The reactor was constructed in sections with one section containing several sampling probes. The probes allow for simultaneous gas-particulate sampling and are positioned in the reactor to sample both radially and axially. The use of gas and particulate tracers in conjunction with the sampling and analysis permits the determination of: 1) the local extent of mixing of primary and secondary gases, 2) the local extent of particle dispersion, 3) the local extent of particle reaction and 4) the local extent of pollutant formation. The atmospheric coal furnace has been constructed, checked out, and the test data have been collected. Two additional tasks have supported the combustion testing, a pulverized coal furnace modeling development and a series of cold-flow jet mixing experiments. Two computer models have been identified. The first, a one-dimensional model which is fully developed, empirically inputs jet and recirculation mixing rates and accounts for coal pyrolysis, radiation, char oxidation, gas phase reaction, and particle-gas heat transfer effects. The one-dimensional model has been successfully applied to predict the characteristics of laboratory and industrial pulverized coal and furnaces and gasifiers. The second model is a generalized multidimensional model whose development was initiated under this contract but whose development is continuing under DOE contract (No. EF-77-S-01-2666). The cold-flow tests have investigated the mixing characteristics of particle laden, confined jets under conditions that simulate the operations of industrial pulverized coal furnaces and gasifiers but without chemical reaction. The effects of geometry and flow conditions have been investigated in 120 cold tests.

EPRI PERSPECTIVE

PROJECT DESCRIPTION

This project is a concurrent experimental and analytical effort to obtain a better scientific understanding of the influence of turbulent mixing on the combustion of pulverized coal and the resulting chemical reactions and product yields.

Understanding these kinetic processes is essential if changes in coals and/or equipment, for satisfying increasing reliability and environmental requirements, are to be conceived, developed and/or implemented based on proven scientific rationale.

This project is an integral and supportive part of the fossil fuel programs addressing the coal-related reliability, performance, and environmental problems of utility boilers.

Mixing and Kinetic Processes in Pulverized Coal Combustors is a final report and describes the objectives, approach, and results of this forty-one (41) month effort.

PROJECT OBJECTIVES

By combining an experimental laboratory combustor test program with a concurrent pulverized coal combustor model development program, the following objectives were established:

a) Based on operating variables for pulverized coal combustors, to determine the turbulent mixing rates and the rates of reaction of coal-char with variations in coal-char type, coal size, coal loading level, percent excess air, inlet velocity, and injection angle.

b) To develop computer codes which can be used for correlating experimental measurements and as an effective design tool for predicting local combustion behavior in pulverized coal furnaces. The correlation of theoretical models with the experimental data determined in (a) will provide an increased understanding of the combustion behavior.

CONCLUSIONS AND RECOMMENDATIONS

The significance of the experimental and technical accomplishments presented in this report to the utility industry depends greatly on the technical transfer to and its use by the major boiler manufacturers. It has been demonstrated on a laboratory-scale pulverized coal combustor that the total local combustion process can be analyzed using water-quenched sampling probes and a total gas, liquid, solid sample collection system. It has also been demonstrated that some of the key process variables can be predicted using a developed one (1) dimensional computer model validated by test results. These experimental and analytical tools will provide the boiler manufacturers with a stronger scientific basis for developing improved combustor and furnace designs and/or operating concepts for satisfying the utility industry's needs for increasing reliability and satisfying environmental requirements.

J. P. Dimmer, Project Manager
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ACKNOWLEDGMENTS

This report summarizes technical progress accomplished during a forty-one month study conducted by EPRI under Contract RP-364-1. The work period was 1 November 1974 to 31 March 1978. Work was accomplished under the direction of Dr. L. Douglas Smoot, principal investigator, and Dr. Paul O. Hedman, senior investigator. Mr. John Dimmer, Mr. Robert C. Carr and Dr. L. King Isaacson have served as EPRI project officers.

Graduate and undergraduate students who contributed to the technical work accomplished at Brigham Young University on this contract study and to the report were Rand Thurgood, Dee Rees, Philip Smith, Max Lewis, Jerald Sharp, Donald Leavitt, Stanley Harding, Scott Woodfield, Brent Montague, Charles Ngai, Craig Crompton, Christopher Tice, Deborah Owens, Gerald Williams, Vincent Memmott, James Barnett, and David Moser. Mr. James Hoen, Supervisor of the Research Machine Shop, has provided significant help in the reactor design and construction. Michael King, Scott Folster, Jean Vanderhood, Mary Jo Schaub, Karen Weis, and Elaine Alger, who typed this final report, provided technician, typing and drafting services.

Work was also continued on a program toward development of a mathematical model of pulverized coal burning processes. Initial funding for this program was provided by EPRI under this contract while present funding is provided by the Department of Energy under a separate contract. Contributors to this modeling work have included Dr. L. Douglas Smoot and Mr. Philip Smith at Brigham Young University, Dr. David T. Pratt, Dr. John Wormeck and Miss Angela Varma of the University of Utah, and Dr. Clayton T. Crowe and Mr. M. Sharma of Washington State University.

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(For Entire Final Report)

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Section 1
INTRODUCTION AND SUMMARY

BACKGROUND

The recent emphasis on the energy requirements for our country has demonstrated the need to develop alternate energy sources. However, the majority of available domestic energy resources cannot presently be used directly without degrading the environment beyond that specified by current environmental laws. It is possible that nuclear, geothermal, or solar energy sources may eventually meet part of this increasing energy need. However, with our present level of technology, we may not be able to supply all of the increasing demands economically from these sources during the present century. As a consequence, we are required to convert energy from fossil fuels into a more desirable form as an intermediate solution to the energy problem (1-1,1-2).

Interest in entrained coal gasifiers and combustors to convert fossil fuels into energy is rapidly expanding. Pulverized coal-fired furnaces are increasing in use as a result of growing demands for new electrical energy. Requirements for control of nitrogen oxides and removal of sulfur dioxide are a major concern for these furnaces (1-3,1-4). Particle agglomeration and slagging, with associated reduction in heat transfer to the boiler walls, is also of concern in design and operation of coal combustion plants (1-4).

Associated with such entrained particle processes are technological problems involving the mixing and combustion of the pulverized coal. One such problem is the influence of the turbulent mixing characteristics of a particle-laden gas stream on chemical reactions which take place in the furnace, and on the subsequent yield of products. Such mixing problems have been identified (1-5) as among the most critical and key problems which need to be solved in order to conduct optimal design of pulverized coal furnaces and entrained gasifiers.

PROGRAM OBJECTIVES

This research program was an experimental and theoretical study of turbulent mixing and kinetic processes in laboratory-scale pulverized coal combustors. Objectives of this study were to:

- Identify the basic rate-controlling processes in combustion of pulverized coal and the influence of key experimental variables on these rate processes. Results should suggest potential techniques for reducing furnace size, increasing efficiency, controlling pollutant formation, or reducing operating costs.
- Provide basic local experimental measurements of concentration and temperature inside the pulverized coal combustor with which to evaluate potential furnace design techniques.

Specific research tasks which were designed to accomplish the above objectives are as follows:

Task 1 (Laboratory Combustor Tests). The objective of this task was to conduct a test program based on operating variables for pulverized coal furnaces to determine the rates of mixing and reaction of pulverized coal and char in a laboratory-scale combustor at atmospheric pressure. In this task, 50 to 100 tests were planned with variation in coal/char type, coal size, coal loading level, excess air percentage, inlet velocity and injection angle.

Task 2 (Pulverized Coal Combustor Model Development). In this task, two separate models were identified for development. The first was a one-dimensional computer model for describing the mixing and combustion of pulverized coal and char and for interpreting test results. This code was to empirically input jet mixing and recirculation rates, and was to account for coal pyrolysis, radiation, char oxidation, gas phase reaction, and particle-gas heat transfer effects. Second, initial work toward development of a generalized, multidimensional computer model for predicting local conditions inside a pulverized coal combustor was specified. Predictive results were to be compared directly with local measurements from inside the combustor in subsequent programs and the code was to eventually provide the basis for a furnace design method.

Task 3 (Cold-Flow Mixing Tests). In this task, the rates of turbulent mixing of particle-gas streams with and without recirculation effects were to be measured in a cold-flow test facility. Approximately 50 tests were outlined with variation in velocity, density, particle size, solids loading level, secondary stream angle, and duct diameter.

Task 4 (Reports and Technical Contacts). The results of the research project were to be reported in a series of quarterly technical reports and in a comprehensive final report, together with publication of theses and dissertations and appropriate technical papers. A technical advisory committee was to be established and contact with other technical workers through visits to their facilities or by having them visit the BYU Combustion Laboratory was to be made.

Accomplishments on each of these tasks are summarized below and discussed in detail in the report sections which follow.

LABORATORY-SCALE COMBUSTOR TESTS

Objectives and Approach

The objectives of the laboratory combustor test program were to: (1) design a test program based on industrial furnace operating conditions, as determined from contact with furnace designers and inspection of operating furnaces; (2) to design and fabricate the laboratory-scale pulverized coal combustor;[1] (3) to use the combustor to resolve the turbulent mixing rates and the rates of reaction of coal-char with variations in coal-char type, coal size, coal loading level, percent excess air, inlet velocity, and injection angle. The results obtained from this task provide data and criteria for more effective design of pulverized coal combustors. Such design improvements could possibly lead to increased combustion efficiency or to reduction or control of pollutants formed during the combustion process. The results also provide detailed local combustion measurements which can be used for evaluating computer codes for furnace design and analysis.

Key to the technical approach is the probe-sampling of the gas/particle mixture at various radial and axial locations within the combustor. An inert gas (argon) is introduced into the primary stream and is used with inert nitrogen already present in the combustion air to deduce the rate of gas mixing. A particle sample, collected from a probe of known size for a measured time interval, allows the local particle mass flux to be determined. The ratio of local particle mass flux to particle mass flux in the primary jet provides a measure of the extent of particle dispersion in the combustor. The local percent of coal ash is used as a particle tracer and permits the extent of coal burnout to be deduced. The particle mass flux and the coal burnout provide a good description of the particle dispersion and reaction within the combustor. Gas chromatographic analyses of the gaseous combustion products allow direct determination of the extent of chemical reaction

[1] The BYU pulverized coal combustor has been named the Rate Resolution Combustor.

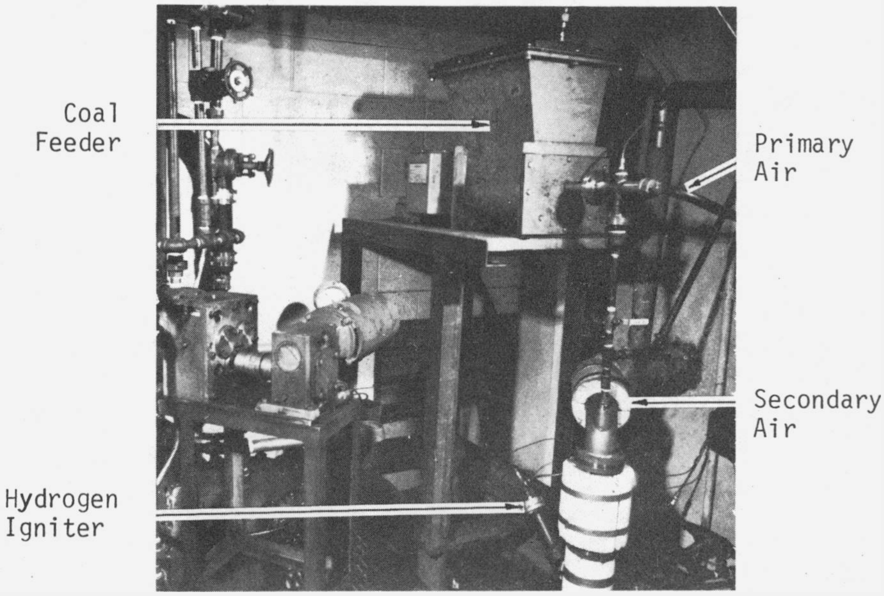
and formation of key pollutant species. In addition, an on-line analyzer was also recently installed to measure directly the extent of formation of NO_x pollutant products locally inside the combustor.

Test Facility

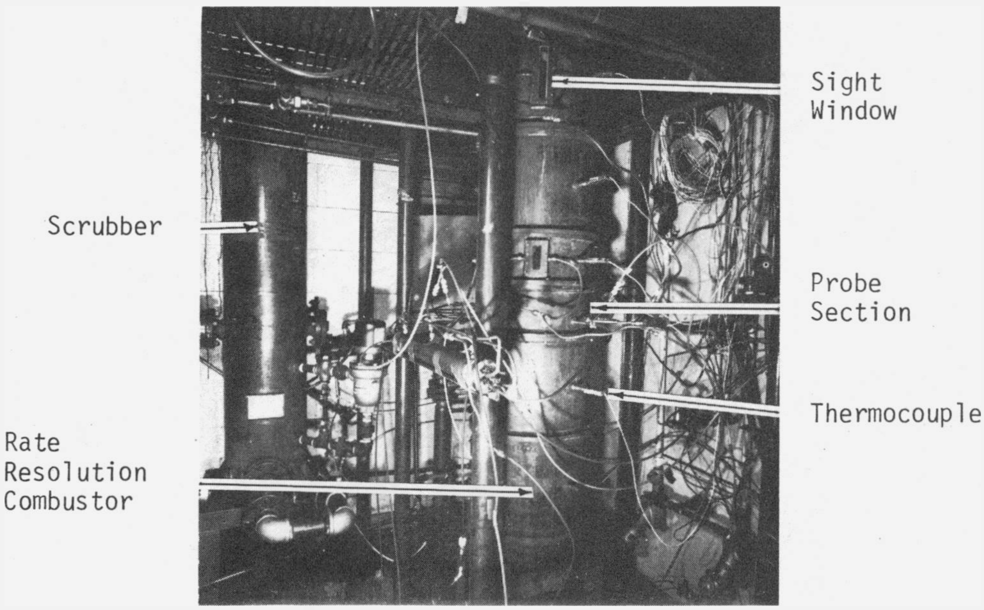
For these tests a unique laboratory-scale coal combustor was designed, constructed, and installed. This reactor, referred to as the "Rate Resolution Combustor," provides for evaluation of the details of combustion processes by means of local sampling probes. The experimental reactor was oriented vertically to facilitate particulate and ash removal and to minimize particle settling and natural convection problems. A preheated, primary air stream carries the coal particles to the reactor where the preheated secondary stream is injected.

The primary and secondary streams flow through individual circulation heaters to generate the desired preheat temperatures. Particles are fed with a multiple screw feeder. A hydrogen-air igniter is used to light a methane-air flame, which is then used to preheat the reactor and to ignite the coal-air flame. The combustor consists of several interchangeable sections, each lined with castable ceramic insulation. One of these sections houses the sampling probes, which are located at various radial positions in the section. The sample probe section can be placed at various axial positions in the furnace, thus enabling both radial and axial sampling of gas and coal. Figure 1-1 is a photograph of the installed laboratory combustor as well as the coal feeder, which is physically located above the reactor.

The sample probes are water-cooled and also the water is injected directly into the sample port to quench the chemical reactions, prevent plugging of the probe by ash, char or slag, to adjust the sample entrainment rate to near iso-kinetic conditions. The sample probes and the associated sample collection system were designed to make a total gas, liquid, and solid sample collection. After a test, a gas sample is taken for analysis in a gas chromatograph and the char collected is filtered and dried before performing an ultimate coal analysis. The liquid can be analyzed for dissolved NH_3 and HCN using selective ion probes. An on-line, ThermoElectron Corporation chemiluminescent NO - NO_x analyzer has been recently added to the instrumentation system. Some preliminary pollutant data have been obtained and selected results are reported in Section 2 of this report.



(A) View from above showing coal feeder



(B) View from below showing combustor and scrubber.

Figure 1-1. Photographs of rate resolution combustor, coal feeder and scrubber.

Test Program

Test Conditions. Information and data on pulverized coal combustion found in the literature and through technical visits made to industrial manufacturers were used to determine a base set of furnace operating conditions and parameters. Experimental variables considered were: 1) coal loading in the primary stream, 2) coal particle size, 3) secondary stream velocity, 4) secondary stream temperature, and 5) injection angle of the secondary stream. A set of four experimental test conditions were identified for the current test program as summarized in Table 1-1. In all cases, the design exit velocity of the primary stream was set at 30.5 m/s (100 fps). The effect of the secondary to primary velocity variation was obtained by changing the secondary velocity only.

Table 1-1

SUMMARY OF COMBUSTOR TEST CONDITIONS

CONDITION	1	2	3	4
Injection Angle, degrees	0	30	30	0
Primary Velocity, m/s	30.5	30.5	30.5	30.5
Secondary Velocity, m/s	34.6	34.6	55.2	34.6
Primary Temperature, K	355	355	355	355
Secondary Temperature, K	589	589	589	589
Solids Loading, %	40	40	40	40
Excess Air, %	15	15	15	15
Mass Mean Coal Particle Diameter, μm	48.0	48.0	48.0	20.1
$\dot{m}_c$, kg/hr	13.6	13.6	13.6	13.6
$\dot{m}_{pg}$, kg/hr	20.2	20.2	20.2	20.2
$\dot{m}_{sg}$, kg/hr	130.4	130.4	130.4	130.4

Experiments Conducted. One hundred and twelve experiments have been performed during the contract period using the laboratory Rate Resolution Combustor. Ninety of these tests were conducted to verify injector configuration, sample probe and collection system operation, and the argon gas tracer system. Twenty-two tests have provided reliable final data, from which several trends have been observed. Six tests were performed for case 1 (parallel (0°) secondary injection), and six were performed for case 2 (nonparallel (30°) secondary injection). Three tests were completed for test condition 3 (higher secondary velocity and 30° secondary injection) and five tests have been made at test condition 4 (smaller (ca. 22 μm) mean coal particle size). Radial and axial sampling allowed the mixing and the combustion profiles for the entire reactor to be determined. The gas samples were analyzed for Ar, H_2, O_2, N_2, CH_4, CO and CO_2. The particle samples were analyzed by both proximate (ASTM) and ultimate techniques. Selected local measurements were also made for NH_3, HCN and NO_x gas concentrations to demonstrate this capability. Figure 1-2 provides an illustration of detailed gas-phase and concentration coal particle burnout data that have been obtained from this experimental program.

Accomplishments

Several significant accomplishments have been completed for the pulverized coal laboratory combustion tests. A number of the more significant accomplishments are noted.

- The design and construction of a unique, highly-instrumented, laboratory-scale pulverized coal reactor, referred to as the Rate Resolution Combustor.
- The development of workable, water-quenched sampling probes and a total gas, liquid, solid sample collection and analysis system.
- The ignition and stabilization of methane-air diffusion flames in the combustor.
- The ignition and stabilization of coal-air diffusion flames in the combustor.
- The demonstration of the operation of the laboratory combustor to obtain reliable data on combustion and mixing rate processes.
- The collection of combustion test data (22 tests) at various operating conditions and geometries.
- The development of a theory and a technique for measuring local gas-particle mixing rates in a reacting system.
- The development of data analyses and methods for presentation and comparison of local combustion measurements.
- The measurement of the effects of several test variables on gas and particle mixing rates.
- The measurement of the effects of several test variables on the chemical reactions in the combustor.
- The measurement of the extent of coal burnout as a function of location within the combustor.
- The evaluation of the effects of gas mixing rates on the coal combustion rate.
- The determination of the relative rate of release of H, C, N, O, and S from the coal as combustion proceeds.
- The demonstration of capability to measure concentrations of NH_3, HCN, and NO_x pollutants locally inside the combustor.

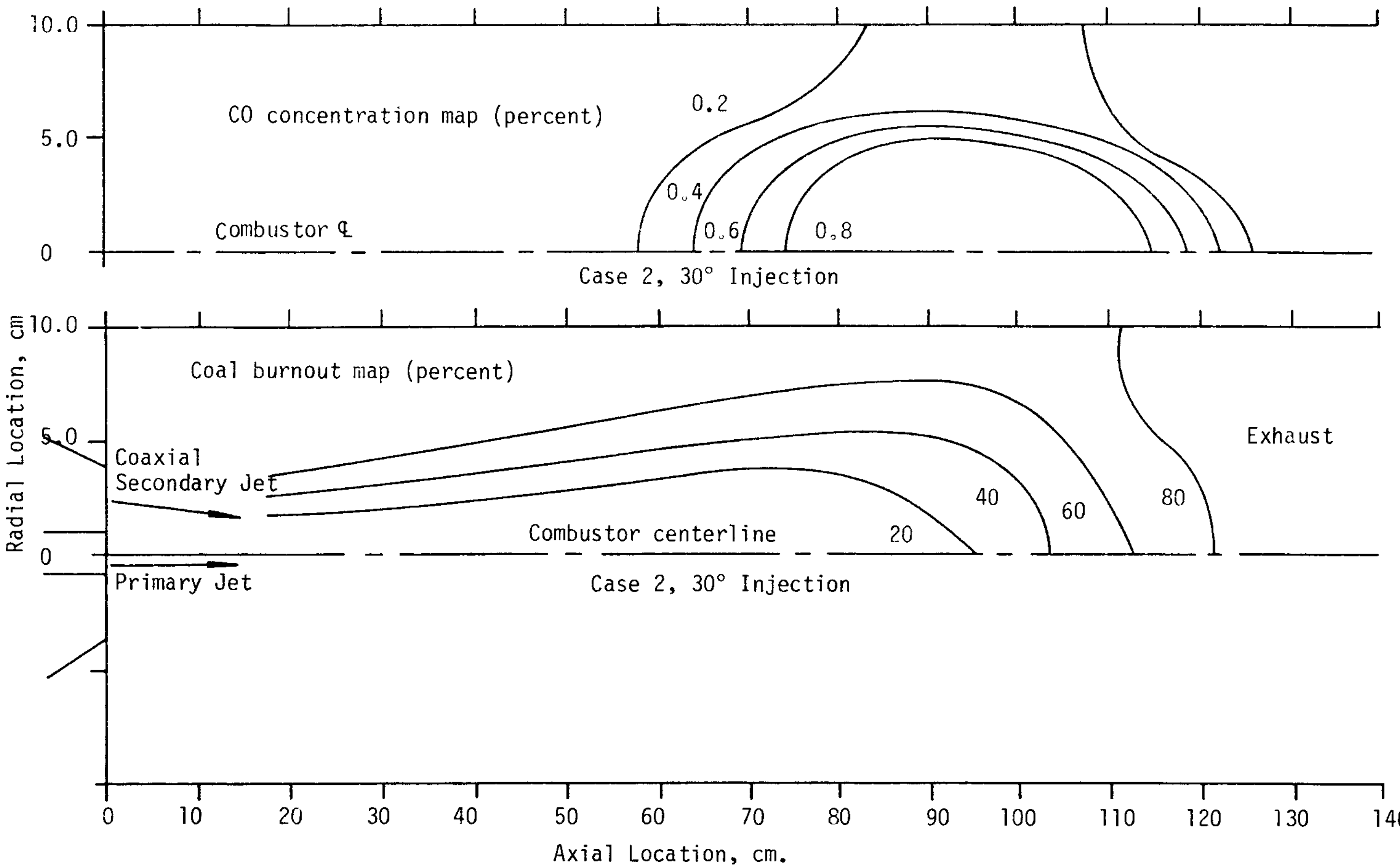


Figure 1-2. Example of laboratory combustor data showing details of combustion profiles.

Conclusions

Specific conclusions and observations from the laboratory combustion test data collected and analyzed during this research study are summarized below and discussed in more detail in Section 2.

- The primary and secondary gas streams are well mixed in both the 0° and 30° injection cases at about 80 cm (30 inches) from the inlet. However, at 18 cm (7 inches) after the inlet, gas mixing is not at all complete.
- Dispersion of the pulverized coal is much slower than gas mixing in both the 0° and 30° cases.
- Changes in particle dispersion rate seem to affect coal burnout, since the 30° case is more completely combusted.
- The extent of coal burnout is often very nonuniform radially across the combustor.
- Combustion in this combustor is not gas-phase limited, since reactions are continuing well after the primary and secondary stream gases are well mixed.
- Evidence of recirculating flow is observed in the upper regions of the combustor.
- Increased secondary velocity at 30° injection increased the gas mixing rate but had little effect on the particle mixing rate.
- Based on centerline decay plots, the parallel injection of secondary air showed slightly more rapid gas mixing than the 30° case, when the secondary velocity was low.
- The major oxygen depletion occurs in the recirculation zone and in the aft-regions of the combustor for both the 0° and 30° cases.
- Hydrogen is released from the coal more rapidly and nitrogen slightly less rapidly than carbon. Sulfur is released at essentially the same rate as carbon with oxygen slightly more rapid.
- Levels of CO observed in the 30° case are higher than in the 0° case.
- Local concentrations of NO, NO_2, NH_3 and HCN can be measured inside this combustor and use of the method may, in the future, provide valuable insight to causes and control of pollutant formation.

PULVERIZED COAL COMBUSTOR MODEL DEVELOPMENT

Objectives and Approach

The objective of the pulverized coal combustor model development program is to develop computer codes which can be used to (1) correlate experimental measurements and (2) provide an effective method of predicting local combustion behavior for pulverized coal furnaces. The correlation of theoretical models and experimental data will provide an increased understanding of the combustion behavior. Such codes have potential use in making predictions at other conditions, in performing engineering design studies, and in diagnosis of operating problems in existing hardware.

Two separate codes have been identified for development in this study. The first, which is fully developed, is a one-dimensional computer model. This code requires empirical input values for jet mixing and recirculation rates, and will account for coal pyrolysis, radiation, char oxidation, gas-phase reaction, and gas-particle-wall heat transfer effects.

The second code, the development of which was initiated under this research contract but which is being continued under support of a related research program (DOE Contract No. EF-77-S-01-2666), is a generalized, multi-dimensional computer model for predicting local conditions inside a pulverized coal furnace. This code is being formed by revising and integrating existing model components. Predictive results can be compared directly with local measurements from inside the combustor, and may eventually provide the basis for a furnace design code.

One-Dimensional Model Development. The general approach used in development of the one-dimensional model was to provide a detailed description of the physical and chemical processes that take place in the reacting regions within pulverized coal combustors and gasifiers. Experimental observations and model parameters obtained from data correlations from independent investigators were used wherever possible. For example, coal reaction parameters from devolatilization studies and char oxidation studies were used as input for model predictions. The following aspects of pulverized coal combustion and gasification were included in the model: (1) mixing of primary and secondary stream (specified as input); (2) recirculation of reacted products (specified as input); (3) pyrolysis and swelling of coal; (4) oxidation of the char by oxygen, steam and carbon dioxide; (5) conductive and convective heat transfer between the coal or char particles, gases and reactor walls; (6) variations in composition of inlet gases and solids; (7) variation in coal-char particle size; (8) oxidation of the coal pyrolysis products; (9) radiative interchange among particles and with the furnace walls. The model allows for treatment of up to five sizes or types of coal particles, each with their own individual properties, composition, and reaction rates.

The one-dimensional computer model was applied to predict the characteristics of laboratory-scale pulverized coal combustors and industrial gasifiers. Figure 1-3

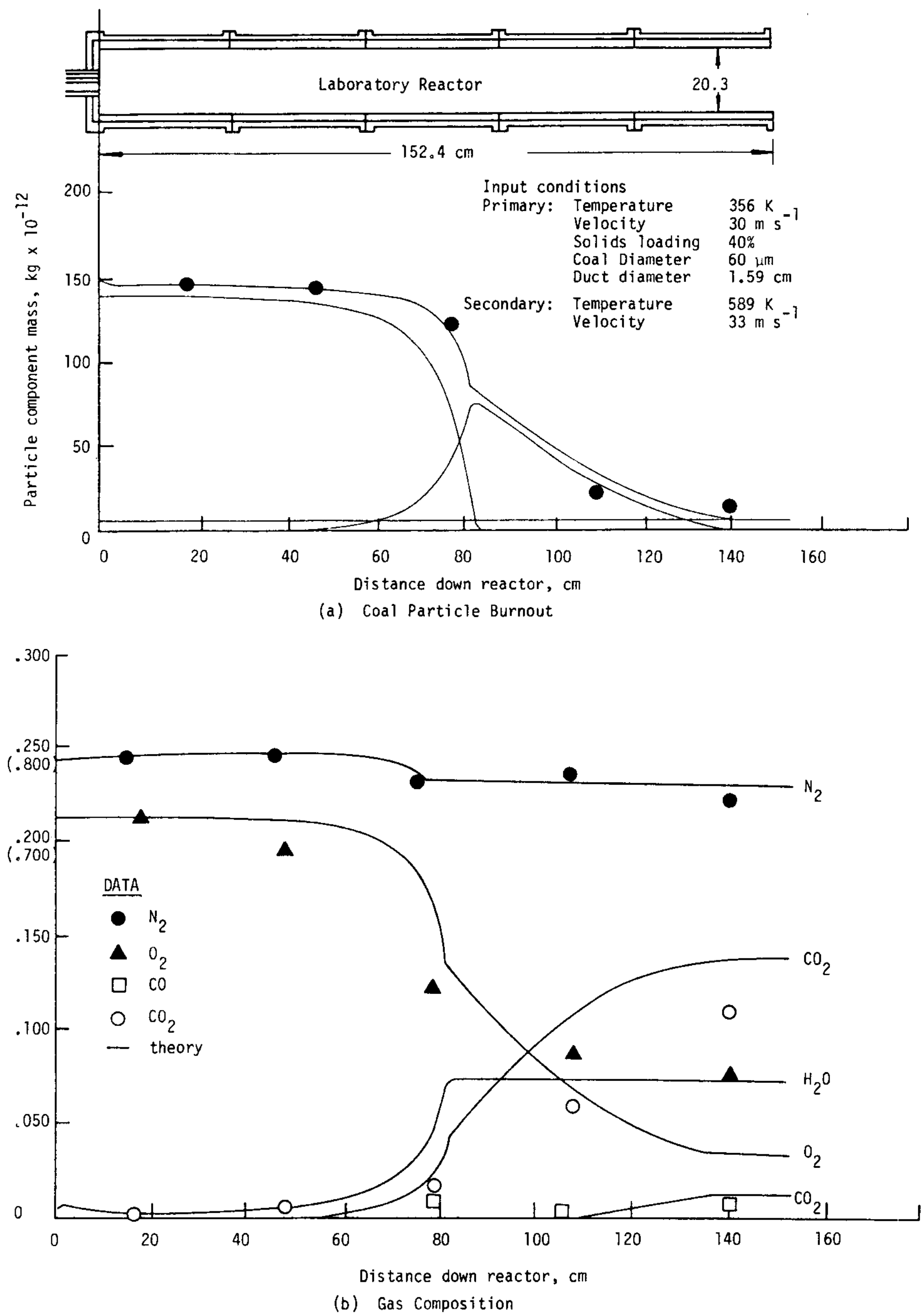


Figure 1-3. Predictions and measurements of coal particle burnout and gas composition for mono-dispersed particles.

presents comparison of predictions with measurements from the laboratory combustor. Figure 1-3(a) shows the predicted particle burnout for ash, coal, char and total particulate and compares the total particulate with the test results. Figure 1-3(b) compares the gas composition predictions with the experimental data. The agreement is very good. This prediction was made with a single initial coal particle size of 60 μm. The results from other predictions are included in Section 3.

Generalized Model Development. As an amendment to the original contract, work on the generalized coal combustion model was begun on September 1, 1976 under EPRI sponsorship. Work has been continued on this model development since June 1, 1977 under sponsorship of a related coal gasification contract (DOE Contract No. EF-77-S-01-2666). As the latter contract is still in force, the present report of activities is not a final report, but rather a progress report of work accomplished to date under both EPRI and DOE sponsorship.

This activity is directed toward modular construction of a comprehensive computer code to analytically investigate the effect of variations in geometry and flow conditions for scaling, and ultimately for engineering design of continuous, pulverized coal furnaces. In addition to the MAIN routine, which controls the linkage of all program modules, the key subcomponents of the code are FLOW, CHEM, PSIC, QRAD, and COAL. In the order cited, these subelements solve the governing differential and algebraic physical model equations related to (1) turbulent gas-phase flow dynamics, (2) turbulent gas-phase chemistry and heat release, (3) interaction of turbulent gas flow with coal particles, (4) thermal radiation transfer between gas, walls and particles, and (5) physical chemical processes occurring within the coal particles. Much of the work on this code development is being completed through a subcontract to the University of Utah under the direction of Dr. David T. Pratt.

Accomplishments

One-Dimensional Model Development. Principal accomplishments for the one-dimensional model are:

- Formulation of a one-dimensional model, which includes recirculation and secondary mixing effects as input parameters, for predicting the behavior of pulverized coal combustors and entrained flow gasifiers; this approach provides for a detailed description of the physical and chemical processes that take place in the reacting regions with such systems.
- Development of an Adams Moulton predictor-corrector solution technique for solving the differential and auxiliary equations of the one-dimensional code.

- The inclusion of up to five separate coal particle sizes and/or types.
- The verification of the code by comparison of predicted and measured properties of a laboratory coal combustor.
- Application of the code to predict the characteristics of the laboratory-scale coal combustor, the laboratory gasifier, and the first stage of the Foster Wheeler Gasifier being designed for DOE. Predictions have included the effect of poly-dispersed particles in these systems as well as the effects of particle diameter change on the heterogenous reaction process.

Generalized Model Development. While development of the generalized model is continuing under independent sponsorship, a number of significant accomplishments have been completed. These are summarized below:

- Detailed documentation of the general technical basis for modeling pulverized coal combustion processes, in the form of a book to be published by Plenum Publishing Company (this accomplishment relates directly to this generalized model and was completed without direct financial support from EPRI).
- Formulation of differential and auxiliary equations for a generalized two-dimensional steady-state treatment of pulverized coal furnaces and gasifiers.
- Development of a logistic scheme for numerically solving the model equations by integrating several components of the generalized code. These components include FLOW, CHEM, PSIC, QRAD, and COAL.
- Completion of FLOW, the routine which initializes all of the hydrodynamic variables.
- Near completion of PSIC, the routine which integrates particle trajectories from specified furnace inlet distributions in a given velocity and density field.
- Demonstration of the linkage of PSIC and FLOW.
- Near completion of subroutine COAL, which calculates the response of the coal particle to its thermal, chemical and radiative environment.
- Development of a special output plotter package.
- Computation of some simplified combustor examples to test various model components.

Conclusions

One-Dimensional Model Development. The one-dimensional code is fully developed, and has been applied to both laboratory-scale pulverized coal combustors and gasifiers. The results obtained by applying the code to these combustors and gasifiers suggest several conclusions:

- First predictions of gas composition and char burnout for the laboratory combustor agree well with measurements.
- The multiple particle option showed that small particles have a significant influence in the combustor, including earlier ignition and faster temperature rise.
- Devolatilization rates are nearly the same for all particle sizes, and are very high.
- The extent of char burnout is very different for each particle size. Small particles burn out rapidly while larger particles burn much more slowly.
- Pyrolysis and subsequent oxidation of the pyrolyzate is very rapid in entrained gasifier; oxygen is depleted in this devolatilization step and the oxidation of the char by steam and carbon dioxide proceeds slowly.
- Gasification and combustion rates are affected by the mixing and recirculation processes.
- Large particles (ca. 1000 μm) heat slowly in an entrained reactor, retarding the entire reaction system, and never achieve significant burnout.
- The model has potential practical application to large-scale equipment analysis and design by predicting reaction rates and the chemical products formed.

Generalized Model Development. Development of the generalized two-dimensional code is about 80% complete overall. It is expected that the first application of the integrated model will be accomplished by late in 1978. The model will first be used to predict the combustion results obtained in the laboratory-scale pulverized coal combustor.

COLD-FLOW MIXING TESTS

Objectives and Approach

The purpose of the cold-flow tests in the current study was to experimentally investigate the mixing characteristics of particle-laden, confined jets under conditions that would simulate the operations of industrial pulverized coal furnaces and entrained gasifiers but without chemical reaction. The data obtained from these tests can be used to verify analytical mixing models and can be used to develop empirical gas and particle mixing correlations. Both the analytical mixing model and the empirical correlations can also be applied in analyzing existing combustor and gasifier performance or can be used by the design engineer as new furnace or gasifier designs are created.

Radial profiles for gas composition, particle mass flux and gas velocity were measured in the mixing zone at various axial locations downstream of the inlet.

Effects of velocity, density, mass flow rate, injection angle, particle loading level and particle size on the rates of particle and gas mixing have been examined. This program provides support to the coal combustor test program described above.

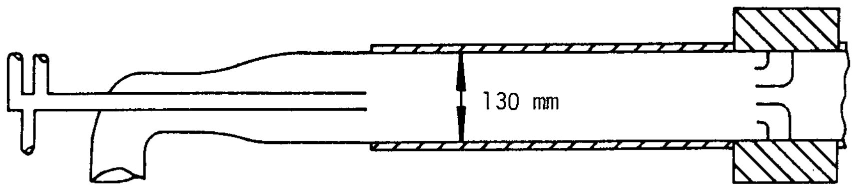
Test Facility

The cold-flow test facility for this portion of the research study uses a storage tank to supply air to both a primary stream (25 mm diameter) and a concentric secondary stream (130 mm diameter). Argon, a gas tracer, and silicon particles, to simulate pulverized coal, are added to the primary air stream. The secondary stream can be injected parallel (0°) to the primary stream or can be injected inward at a 30° impingement angle to the primary stream (nonparallel injection). The facility can also be adapted for discharge into small (206 mm diameter), medium (260 mm diameter), or large (343 mm diameter) mixing chambers, as illustrated in Figure 1-4. The expanded mixing chambers more closely duplicate the characteristics of commercial pulverized coal furnaces and cause significant flow recirculation to occur. A series of up to eleven instrument probes were used to make pressure measurements, from which gas velocity was determined, and to collect gas and particle samples, from which local (radial and axial) gas composition and particle mass flux were determined.

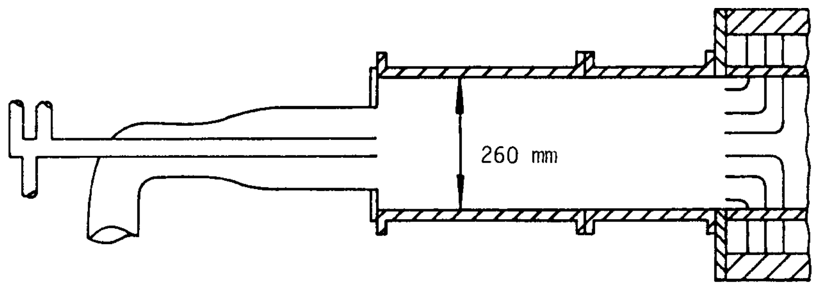
Test Program

Two series of tests were completed. The first series (1-6) emphasized effects of 30° secondary stream injection angle on the mixing process. The second series (1-7) emphasized the effects of increasing mixing duct diameter on the mixing process. Two mixing ducts were tested, a small duct (206 mm) and a large duct (343 mm). The first test series evaluated the effects of solid loading, high secondary velocity, low secondary density, and both a smaller and a larger silicon powder on the gas and particle mixing rates with both parallel and nonparallel secondary injection. The second series of tests emphasized the effects of high secondary velocity, large silicon powder, large silicon powder at high solids loading on mixing rate into the expanded mixing chambers. One hundred and sixteen cold-flow mixing tests were completed in these two test series. A third series of tests has been initiated under the related DOE program (DOE Contract EF-77-S-01-2666) which will emphasize the combined effects of angular injection with enlarged mixing ducts. Eight tests have been completed thus far in this third test series.

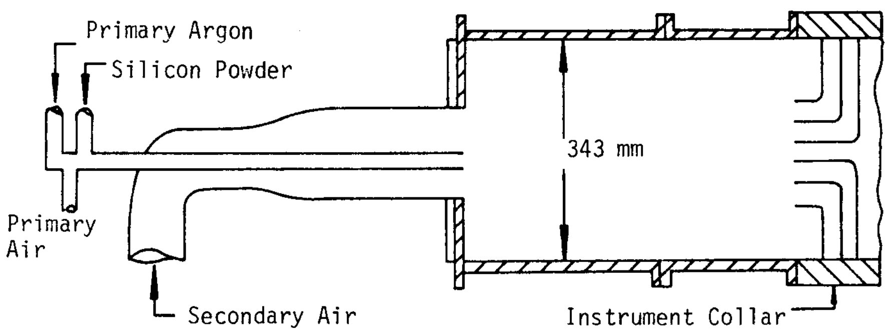
The cold-flow tests have been used to determine both gas and particle mixing rates at various geometries and flow conditions; these results are discussed in detail



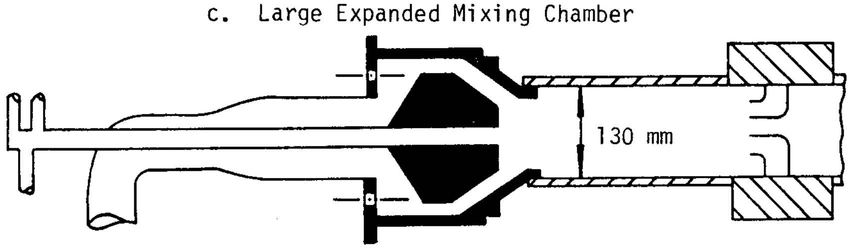
a. Mixing Chamber without Recirculation



b. Small Expanded Mixing Chamber



c. Large Expanded Mixing Chamber



d. Mixing Chamber with 30° Secondary Injection

Figure 1-4. Schematics of flow systems with recirculation, with 30° secondary injection and without recirculation.

in Section 4. Correlations of particle and gas mixing rates are shown in Figure 1-5, where the reciprocal of the particle core length is plotted versus the reciprocal of the gas core length for the parallel, expanded mixing chamber, and for the nonparallel systems respectively. Since the rate of mixing is inversely proportional to the core length, the plots of Figure 1-5 are essentially of particle mixing rate versus gas mixing rate.

For the parallel and expanded mixing chamber systems, changing the test variables appeared to have had a significant effect on gas mixing rates, but almost no effect on particle mixing rate. A much stronger interaction of particle and gas mixing rates was observed for the nonparallel system. Both particle mixing rates and gas mixing rates appear to be affected significantly by changing the test variables. This correlation of cold-flow data suggests that it may be possible to control the mixing rates of coal and gases independently in order to control the rates of chemical reaction and possibly pollutant formation rates in pulverized coal furnaces. This special control is achieved by controlling the injection angle.

Accomplishments

Several accomplishments have been completed during the cold-flow test program. Some of the more significant are summarized below:

- Modified an existing test facility to permit cold-flow testing with conditions simulating pulverized coal furnaces.
- Successfully used an argon gas tracer to characterize the gas mixing rates.
- Developed methods for simultaneous measurement of particle and gas mixing rates.
- Completed one hundred and twenty-four tests wherein effects of geometry and flow condition on gas and particle mixing rate were measured in an environment that simulated pulverized coal furnaces.
- Successfully obtained radial profiles of gas composition and particle mass flux at various axial positions from which mixing rates were deduced.
- Applied cold-flow mixing test results to interpretation of laboratory combustor measurements.
- Developed a new potential concept which suggests that independent control of gas and particle mixing rates can be achieved through control of injection angle.

Conclusions

Experimental measurements were made of radial profiles for velocity, argon concentration and particle mass flux in confined jet systems. These profiles provided

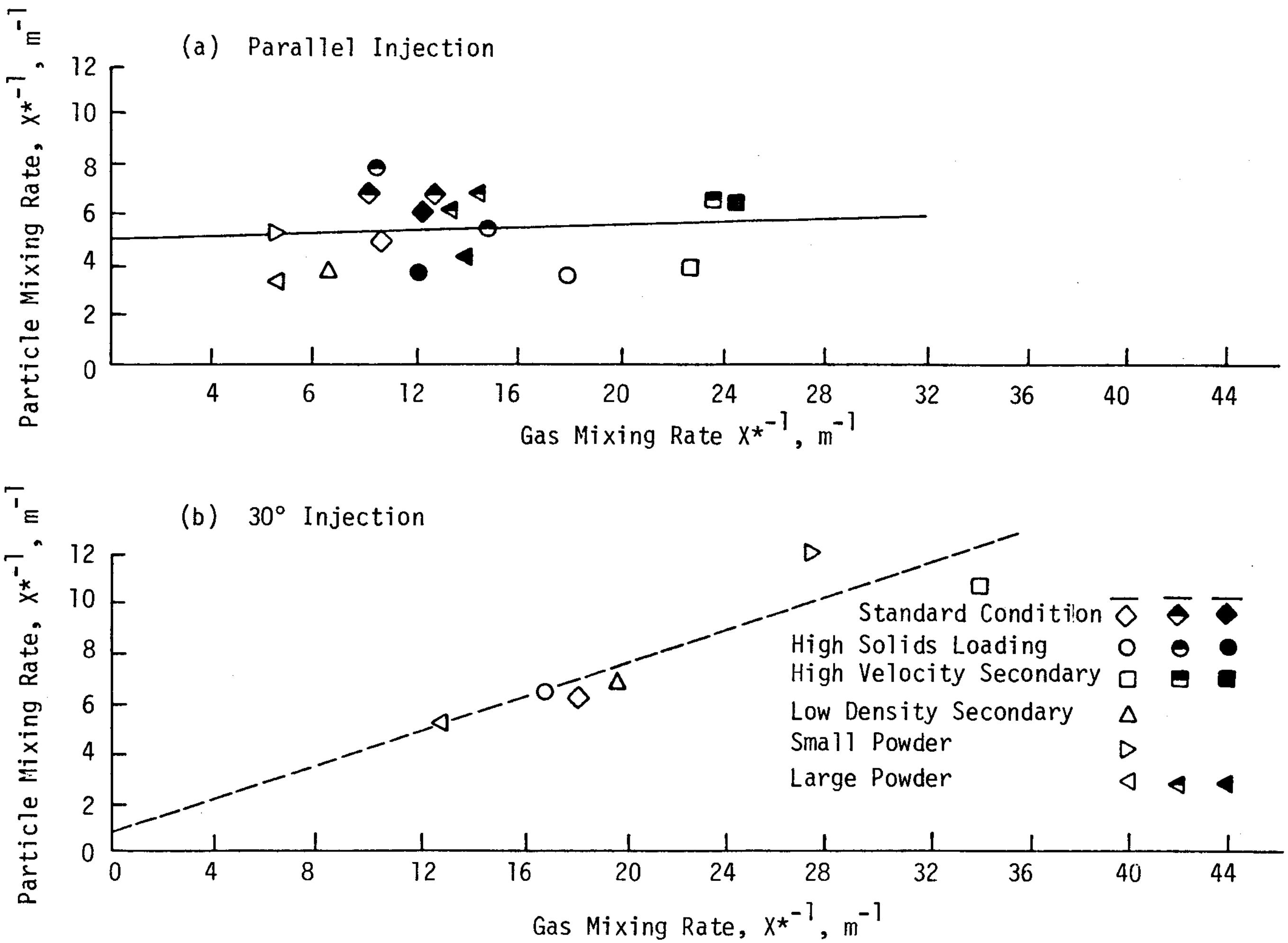


Figure 1-5. Comparison of Gas and Particle Mixing Rates.

a method for the evaluation of the mixing characteristics of particles and gases in coaxial jets with gross recirculation. The test variables of parallel and nonparallel injection, mixing chamber diameter, secondary velocity, particle size, solids loading level and primary screen were used to investigate gas and particle mixing rates. Logarithmic centerline axial decay plots were made from these data, allowing several conclusions concerning the rates of mixing to be made.

- Primary and secondary gases mixed faster than the particles in the parallel and nonparallel cases, with the ratio of gas to particle mixing rates ranging from 1.4 to 6.
- Gases mixed from 1.3 to 3.6 times faster than particles for all conditions with expanded mixing chambers.
- Mixing was generally from 2 to 3 times faster in the nonparallel injector system than in the parallel injector system for both particles and gases.
- Enlarging the mixing chamber diameter from 130 mm to 206 mm to permit recirculation increased gas and particle mixing rates by about 1.7 times, depending upon other test conditions. Particle mixing rates increased by factors ranging from 1.4 to 1.9 and gas mixing rates increased by factors from 1.2 to 2.4 in all cases but one. A further increase in the mixing chamber diameter from 206 mm to 343 mm did not affect gas or particle mixing rates appreciably, except to cause a decrease in mixing rates of large particles.
- Smaller particles mixed faster than larger particles. The effect of particle size on particle mixing rate was greater in the non-parallel system than in the parallel system where small particles mixed about twice as fast as the large particles. Increasing particle size in the expanded chamber tests caused small decreases in particle mixing rates, except in the largest mixing chamber where large particles mixed much more slowly.
- The effect of particle size on gas mixing rates was very small.
- An increase in the secondary velocity caused an increase in the gas mixing rates in both the parallel and nonparallel systems. Gas mixing rates using higher secondary velocities were about twice those observed for the lower secondary velocity.
- In the expanded duct tests, a high secondary jet velocity substantially increased the gas mixing rate (factor of 1.9) but had little effect on particle mixing rate.
- Little correlation was observed between gas and particle mixing rates in the parallel and expanded duct systems. Changing flow condition significantly affected the gas mixing rate, while much less effect was generally observed in the particle mixing rate. A significant correlation between particle and gas mixing rates was observed for the nonparallel injector system, with changes in gas mixing rate accompanied by similar changes in particle mixing rate.
- The effect of nonparallel injection was diminished for cases where rapid mixing was observed in the parallel system.

- Addition of a wire screen near the primary stream exit in the expanded duct tests improved particle distribution in the primary jet, particularly for the large particles, but had little effect on the gas mixing rate.
- Reducing density of the secondary stream caused very little change in mixing rates in the nonparallel system, while the mixing rates decreased by a factor of approximately 1.2-1.3 in the parallel system.
- The test results have indicated that a certain amount of independent control of the gas and particle mixing is possible. Thus, control of the mixing processes may provide a basis for controlling combustion and pollutant formation in pulverized coal combustors and entrained gasifiers.

REPORTS AND TECHNICAL CONTACTS

Industrial Interaction

The establishment of a close working relationship among the workers of this research study and potential users of these research results was a particularly important aspect of this study. The following tasks have been completed relating to these industrial contacts:

- At the onset of this study, several industrial organizations in the U.S. and Europe were visited, where this research program was reviewed. U.S. visits were made to Utah Power and Light Co., Foster-Wheeler Corp., Combustion Engineering Corp., Babcock and Wilcox, Koppers Corp., the U.S. Bureau of Mines, and Stearns and Rogers. Also, seventeen separate organizations and laboratories were visited in Europe. These are summarized in Section 5 of this report.
- Over forty technical visitors from industry, government and universities have visited the laboratory during the contract period. These visits are also summarized in Section 5 of this report.
- An industrial advisory committee was organized with members as follows: Charles E. Blakeslee, KVB, Inc., Tustin, California; Val A. Finlayson, Director of Research and Development, Utah Power and Light Co., Salt Lake City, Utah; Reginald Wintrell, Director of Iron and Steel Development, Arthur G. McKee & Co., Cleveland, Ohio; and R.J. Zoschak, Technical Director, Applied Thermo-Research, Foster-Wheeler Energy Co., Livingston, New Jersey. A technical meeting of these advisors was held at this laboratory in March of 1977, at which time this project was reviewed in detail.
- All quarterly progress reports from the EPRI study have been forwarded regularly to the major U.S. furnace design companies, including Babcock-Wilcox, Foster-Wheeler and Combustion Engineering.
- The one-dimensional coal combustor computer code has been used to make predictions for Foster-Wheeler Corp. Predictions for three other corporations were planned.

Publications

A list of all publications and presentations made on this EPRI contract study is included in Section 5 of this report. In addition to the twelve quarterly reports submitted, 6 technical presentations, 8 technical publications, and 6 theses or dissertations have been or will have been completed as part of this study. In addition, preparation of the book "Pulverized Coal Combustion and Gasification" edited by L.D. Smoot and D.T. Pratt was completed during the study period. Authors, in addition to the editors, included several of the graduate students who have worked on this research project. The book, to be published by Plenum Publishing Co. in September 1978, documents in some detail the technical basis for furnace models which have been developed for the EPRI contract.

POTENTIAL APPLICATION OF RESULTS

Possibly the most significant achievement of this study has been the design, installation, and verification of a unique laboratory-scale Rate Resolution Combustor. Use of this combustor to determine rates of mixing, combustion, and pollutant formation has been demonstrated. The unique feature of this device is the capability to provide detailed local data from inside the combustor from which combustion and pollution formation processes can be deduced. This reactor can now be applied to a wide range of industrial problems. These include addition of methane to achieve efficient combustion of char, formation of NO_x pollutants in a fuel-rich environment, combustion of solvent-refined coal, formation processes of ash and slag, and related problems. While the laboratory combustor development has been the most important task, this study has included three separate but related tasks, the pulverized coal combustion tests, the pulverized coal combustor model development, and the cold-flow jet mixing experiments. These three tasks are complementary and are considered jointly as a set of basic data and techniques related to pulverized coal furnaces. The use of these tools could possibly lead to increased combustion efficiency of the coal or a reduction of pollutants/emissions.

The cold-flow tests provide an inexpensive research tool which has been used to collect basic gas/particle mixing data as a function of system geometry and operating conditions. These data can be used to provide mixing rate information for analytical models (e.g., the one-dimensional combustion model), and can be used to validate the predictions of jet mixing computer codes; when properly correlated, results might also be used directly to estimate mixing rates as well as gas and particle composition profiles.

The pulverized coal combustion tests provide verification of the cold-flow gas and particle mixing rates, and also provide directly the details of the coal combustion process. The data from the coal combustor, coupled with the cold-flow test results, provide basic information regarding the effects of combustion on gas and particle mixing rates. In addition, the rates of chemical reaction can be deduced. The products of combustion and the extent of coal combustion at various locations in the combustor are also provided.

The influence of the various operating parameters and injection geometry have been determined. This information is of potential value to the furnace designer as both an indication of which operating variables influence combustion and mixing and by how much the combustion process is influenced.

The results of the coal combustion tests provided basic experimental data which was used to validate the one-dimensional coal combustion model and which will be used to validate the general multi-dimensional model. The development of proven computer codes will provide analytical tools which can be used to diagnose the operation of existing pulverized coal furnaces or to make predictions for new furnaces.

REFERENCES FOR EXECUTIVE SUMMARY

Section 1

1-1 Searl, M.R. and Schurr, S.H., "An Overview of Supply/Demand for the Decade," Chem. Engr. Progr., 69, 27 (June 1973).

1-2 Hottel, H.D., "Challenges in Production of Fossil Fuels," Chem. Engr. Progr., 69, 35 (1973).

1-3 Sarofim, A.F. and Flagan, R.C., "Nitrogen Oxide Control Techniques," Air Quality and Stationary Source Emission Control, A Report by The Commission on National Resources, National Academy of Sciences. National Academy of Engineering, National Research Council, Serial No. 94-4 U.S. Government Printing Office, March 1975, pp. 808-909.

1-4 Squires, A.M., "Pulverized Fuel Combustion in Trouble," Symposium Combustion in Present and Future Power Cycles, American Chemical Society Reprint, Division of Fuel Chemistry, Vol. 14, No. 2, 24-29 (May 1970).

1-5 Farnsworth, F.J. and Glenn, R.A., "Status and Design Characteristics of the BCR/OCR Bi-Gas Pilot Plant," 162nd National Meeting, ACS, Vol. 14, No. 3, 12, Washington, D.C. (September 1971).

1-6 Memmott, V.J., "Rates of Mixing of Particles and Gases in Confined Jets," M.S. Thesis, Brigham Young University, Provo, Utah (April 1977).

1-7 Tice, C.H., "Particle and Gas Mixing Rates in Confined, Coaxial Jets with Recirculation," M.S. Thesis, Brigham Young University, Provo, Utah (1977).