PARTICULATE PROCESSES IN PULVERIZED COAL FLAMES

QUARTERLY TECHNICAL PROGRESS REPORT

FOR THE PERIOD

OCTOBER through DECEMBER 1980

MASTER

JANUARY 1981

SDL No. 81-2177-05Q

Prepared for:

THE UNITED STATES DEPARTMENT OF ENERGY
PITTSBURGH ENERGY TECHNOLOGY CENTER

Under Contract No.

DE-AC22-80PC30300

SPECTRON
DEVELOPMENT
LABORATORIES
INC.

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TABLE OF CONTENTS

	<u>Page</u>
SECTION 1 : OBJECTIVE AND SCOPE OF WORK.	1
SECTION 2 : SUMMARY OF PROGRESS TO DATE.	8
SECTION 3 : DETAILED DESCRIPTION OF TECHNICAL PROGRESS	9
3.1 Design, Fabrication, Assembly, and Checkout of the Experimental Apparatus (Task 1.0).	9
3.1.1 Design of Dilute Particle Reactor Head (Task 1.1)	9
3.1.2 Design of the Tube Reactor (Task 1.3) . . .	10
3.1.3 Design of Instrumentation Interface (Task 1.4).	20
3.1.4 Fabrication of Dilute Particle Reactor (Task 1.5).	20
3.1.5 Fabrication of Tube Reactor (Task 1.7). . .	20
3.1.6 Fabrication of Instrumentation Interface (Task 1.8).	20
SECTION 4 : REFERENCES	24

APPENDIX A - FURNACE DESIGN ANALYSIS

Section I

OBJECTIVE AND SCOPE OF WORK

The primary objective of the present investigation is to obtain fundamental physical data on particulate reaction processes in pulverized coal flames. Specific particulate processes to be considered are:

- (a) feed coal devolatilization and ignition,
- (b) soot formation and burnout,
- (c) char burnout,
- (d) large flyash melt and agglomeration, and
- (e) fine flyash vaporization and condensation.

Specific objectives of the investigation are summarized in Table 1. The program principally involves the qualitative and quantitative physical characterization of the above process; however, sufficient chemical characterization is intended to optimize the interpretation of the results.

The relevance of the above study has both fundamental and application oriented impacts. Fundamental information is yet critically needed to understand coal combustion processes. Data, of the form to be derived, is needed to allow the development of more qualitatively realistic and quantitatively precise models of the particulate processes indicated. More detailed knowledge of these particulate processes will provide information relevant to heat transfer, corrosion, fouling, slagging, and flyash and soot pollutant formation. Insight to the influence of operating variables such as fuel quality and combustion modifications will also be developed.

The progressive stages of coal particle combustion are depicted in Figure 1. The current investigation intends to qualitatively and quantitatively characterize these processes. Demonstrated nonintrusive optical diagnostic measurement techniques (specifically: flash laser holography and continuous particle sizing by light scattering measurement techniques) will be used to develop both mechanistic and statistical information on particulate processes. The nonintrusive measurements will be complemented by data obtained from probe sampling and subsequent

TABLE 1. PROGRAM OBJECTIVES: PARTICULATE PROCESSES IN PULVERIZED COAL FLAMES

GENERAL OBJECTIVE:

Obtain fundamental physical data on particulate behavior in pulverized coal flames.

SPECIFIC OBJECTIVES:

- (1) Establish rates and mechanisms controlling the disposition of feed particles, soot, char, and ash particulate in the combustion of pulverized coal.
- (2) Determine the effect of coal type (proximate and ultimate analysis) and size on the above particulate phenomena.
- (3) Determine the influence of coal composition (oxygen, metals, alkali content, etc.) on particulate. Assess possible catalytic effects.
- (4) Determine the effect of stoichiometry and heating rate on particulate behavior. Assess particle interaction effects.
- (5) Assess the effect of particle structural changes, such as fragmentation, on coal combustion processes.
- (6) Identify problems associated with sampling and analysis of particulates in pulverized coal flames and the contribution of in situ measurement techniques to the solution of these problems.

FIGURE 1. PROGRESSIVE STAGES OF COAL PARTICLE COMBUSTION

analysis which will provide information needed for mass flux (particle and species) tracking during the combustion process.

During the past two years, significant progress has been made in the application of nonintrusive optical diagnostic methods to particulate processes in combustion. Perhaps the most dramatic application to date is the capture of devolatilization and ignition events of feed coal particles using nano-second pulsed laser holography (Spectron Development Laboratories, 1978, Reference 1) and shadowgraphy (Sandia Laboratories, 1980, Reference 2). Equally important are the capabilities to (1) measure simultaneously the size and velocity of individual particles in the range of 3 to 300 μm and (2) to measure the size of individual sub-micron particles (Spectron Development Laboratories, 1979, Reference 3). The latter techniques have been demonstrated in combustion flowfields (References 4 and 5) and offer the opportunity to obtain particle size statistics, an important missing link in the existing mostly qualitative data base for particulate processes in coal flames.

A key consideration of the present program will be the development of a laboratory combustor capable of conducting a comprehensive experiment. This implies that temperatures and residence times will be adequate to achieve char and soot burnout and ash vaporization. It is also important that temperatures are not so high as to produce non-realistic reaction rates.

The need exists to develop information relevant to both dilute and dense particle laden reacting flows. Dilute reacting particle streams are useful in looking at individual particle events. This approach is important from the viewpoint of making detailed observations. However, real flames contain dense particle fields. Therefore, it is important that data also be developed for such cases. Furthermore, it is important that the dense particle field case be developed by a coal sustained flame front so that the gradients and synergistic events of combustion are realistically represented.

The present investigation will investigate both dilute particle and dense particle behavior. To accomplish this, two reactor heads are planned: (1) a premixed gas flat flame reactor in which a dilute stream

of coal particles are injected into the center of the burner, and (2) a pulverized coal flat flame reactor in which the entire flame is sustained by coal combustion. These heads will be fitted to a tubular reactor body (Figure 2). The reactor body will have a total length of 60 inches. The initial 48 inches will be heavily insulated. The last 12 inches will be water cooled to provide for rapid heat loss and the subsequent condensation of vaporized flyash.

The program work structure has been divided into three primary tasks as follows:

Task 1 - Design, Fabrication, Assembly, and Checkout of the
Experimental Apparatus

Task 2 - Experimental Program

Task 3 - Data Reduction and Analysis

These tasks have been further divided into key subtasks as indicated in the program schedule, Figure 3.

FIGURE 2. FLOW REACTOR CONFIGURATION

FIGURE 3. PROGRAM SCHEDULE

1. Contract Identification Particulate Processes in Pulverized Coal Flames														2. Reporting Period 15 Sep 80 through 15 Nov 82										3. Contract Number DE-AC22-80PC30300									
4. Contractor (name, address) SPECTRON DEVELOPMENT LABORATORIES, INC. 3303 Harbor Boulevard, Suite G-3 Costa Mesa, California 92626														5. Contract Start Date 15 Sep 80										6. Contract Completion Date 15 Nov 82									
7. Identification Number		8. Reporting Category (e.g., contract line item or work breakdown structure element)		9. Fiscal Years and Months														FY82														10. Percent Complete	
Task				O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	Q4	Q1	a) Planned	b) Actual					
1.1		Design dilute particle reactor head		<div><div></div><div></div><div></div><div></div><div></div><div></div><div></div><div></div><div></div><div></div><div></div><div></div><div></div><div></div><div></div><div></div></div>																													
1.2		Design pulverized coal reactor head		<div><div></div><div></div><div></div><div></div><div></div><div></div><div></div><div></div><div></div><div></div><div></div><div></div><div></div><div></div><div></div><div></div></div>																													
1.3		Design tube reactor		<div><div></div><div></div><div></div><div></div><div></div><div></div><div></div><div></div><div></div><div></div><div></div><div></div><div></div><div></div><div></div><div></div></div>																													
1.4		Design instrumentation interface		<div><div></div><div></div><div></div><div></div><div></div><div></div><div></div><div></div><div></div><div></div><div></div><div></div><div></div><div></div><div></div><div></div></div>																													
1.5		Fabricate dilute particle reactor head		<div><div></div><div></div><div></div><div></div><div></div><div></div><div></div><div></div><div></div><div></div><div></div><div></div><div></div><div></div><div></div><div></div></div>																													
1.6		Fabricate pulverized coal reactor head		<div><div></div><div></div><div></div><div></div><div></div><div></div><div></div><div></div><div></div><div></div><div></div><div></div><div></div><div></div><div></div><div></div></div>																													
1.7		Fabricate tube reactor		<div><div></div><div></div><div></div><div></div><div></div><div></div><div></div><div></div><div></div><div></div><div></div><div></div><div></div><div></div><div></div><div></div></div>																													
1.8		Fabricate instrumentation interface		<div><div></div><div></div><div></div><div></div><div></div><div></div><div></div><div></div><div></div><div></div><div></div><div></div><div></div><div></div><div></div><div></div></div>																													
2.1		Dilute particle devolatilization experiment		<div><div></div><div></div><div></div><div></div><div></div><div></div><div></div><div></div><div></div><div></div><div></div><div></div><div></div><div></div><div></div><div></div></div>																													
2.2		Dilute particle burnout and flyash experiment		<div><div></div><div></div><div></div><div></div><div></div><div></div><div></div><div></div><div></div><div></div><div></div><div></div><div></div><div></div><div></div><div></div></div>																													
2.3		Pulverized coal flame particle devolatilization exp.		<div><div></div><div></div><div></div><div></div><div></div><div></div><div></div><div></div><div></div><div></div><div></div><div></div><div></div><div></div><div></div><div></div></div>																													
2.4		Pulverized coal flame burnout and flyash experiment		<div><div></div><div></div><div></div><div></div><div></div><div></div><div></div><div></div><div></div><div></div><div></div><div></div><div></div><div></div><div></div><div></div></div>																													
3.0		Data analysis and model correlation		<div><div></div><div></div><div></div><div></div><div></div><div></div><div></div><div></div><div></div><div></div><div></div><div></div><div></div><div></div><div></div><div></div></div>																													
4.0		Technical reports		<div><div></div><div></div><div></div><div></div><div></div><div></div><div></div><div></div><div></div><div></div><div></div><div></div><div></div><div></div><div></div><div></div></div>																													

Section 2

SUMMARY OF PROGRESS TO DATE

During this initial reporting period, major attention has been focused on the design and construction of the experiment. The design of two dilute coal stream reactor heads was completed as was the fabrication of one of the reactor heads. A parametric furnace design analysis was conducted to allow operating conditions and insulation configurations to be selected to provide an axial temperature drop of less than 200°K/m with a 1-second residence time in the reactor. Final design of the reactor body is in progress.

Design of the instrumentation interface with the experiment was initiated. Emphasis during the present report period has been placed on reactants metering and interface requirements for frontlight and backlight holography. Fabrication of the gas phase reactants metering system is in progress as are exploratory studies of particulate phase metering systems.

Section 3

DETAILED DESCRIPTION OF TECHNICAL PROGRESS

3.1 DESIGN, FABRICATION, ASSEMBLY, AND CHECKOUT OF THE EXPERIMENTAL APPARATUS (TASK 1.0)

Task 1.0 involves the design, fabrication and development of the apparatus to be used in the experimental program. The principal end product of this task is a characterized flow tube reactor with the capability to burn a dilute coal particle stream or a totally coal-fired flame. The reactor configuration was illustrated in Figure 2. The two-particle combustion modes are achieved by the utilization of two different particle reactor heads.

This task has been divided into eight elements as indicated on the program schedule, Figure 3. Work has been accomplished on all six of the subtasks scheduled during this report period. A report of the progress on each of these subtasks follows.

3.1.1 Design of Dilute Particle Reactor Head (Task 1.1)

Two dilute particle reactors have been designed. One is an inert gas-shrouded particle reactor while the other is a reactor to be used on the furnace. The advantage of the inert gas-shrouded particle reactor is that it will provide unrestricted optical access to the reacting particles during the initial devolatilization process. This reactor will serve several purposes:

- it will provide an early opportunity to validate the basic design of the furnace reactor head,
 - it will provide information critical for optical access (window) location in the furnace body,
 - it will provide a nonintrusive view of particles during initial reaction which will optimize the conditions for viewing reacting particles with frontlight holography.
- This technique will allow visualization of particle surface

morphology as opposed to shadow images which have been principally employed in related investigations.

The basic designs of the two dilute particle reactor heads are very similar. The coal particle injection system and the cross-sections of the sintered burner are identical as are the planned reactant parameters.

The assembly drawing of the inert gas-shrouded dilute particle reactor head is shown in Figure 4. Indicated are the key components. Critical dimensions of the system are indicated in Table 2. The permeability and thickness of the sintered disk is such to provide a uniform flat flame with minimum pressure head in the reservoir. A wide range of flow rates can be achieved. A detailed characterization of the basic burner design is provided in reference 6. Observed operating characteristics of such burners are listed in Table 3.

The assembly drawing of the dilute particle furnace reactor head is shown in Figure 5. The similarity between the burner elements of the two reactors is evident. The furnace reactor head has a somewhat larger diameter sintered burner and is mounted in a water cooled copper (OFHC) flange to provide a thermally protected interface between the reactor head and the furnace.

Task 1.1 was completed on 30 November 1980. Fabrication of the dilute particle reactors is discussed in Section 3.1.4.

3.1.2 Design of the Tube Reactor (Task 1.3)

A key requirement of the present program is to develop a tube furnace which possesses a minimum axial temperature drop. This feature is important in simplifying interpretation of the experimental data, i.e., effects of reaction rates on temperature changes are minimized. A goal of limiting the axial temperature drop to 200°K per meter of furnace length has been set. The planned furnace length is 1.2 meters (48 inches).

Two furnace configurations have been considered, one with passive insulated walls and one with electrically heated walls to actively minimize

TABLE 2. DILUTE PARTICLE REACTOR DIMENSIONS

<u>REACTOR ELEMENT</u>	<u>INERT GAS-SHROUDED SYSTEM (mm)</u>	<u>FURNACE HEAD SYSTEM (mm)</u>
<u>Sintered Burner</u>		
• outside diameter	60	98
• thickness	16.5	16.5
<u>Inert Gas Shroud</u>		
• outside diameter	74	-
• inside diameter	63	-
<u>Coal Injection Tube</u>		
• outside diameter	1.6	1.6
• inside diameter	1.2	1.2

COMPONENT DESCRIPTION

- A. BURNER HOUSING
- B. SINTERED BURNER
- C. SINTERED HIGH PRESSURE SHROUD RING
- D. PARTICLE INJECTION TUBE
- E. SHROUD HOUSING
- F. SHROUD MOUNTING PLATE
- G. COOLING WATER COIL

FIGURE 4

Spectron Development Labs.

COSTA MESA, CA. 92626

SCALE:

APPROVED BY

DRAWN BY TUYEN

DATE: 2.4.1981

REVISED

INERT GAS SHROUDED DILUTE PARTICLE REACTOR

DRAWING NUMBER

1060-001-000

COMPONENT DESCRIPTION

- A. BURNER HOUSING
- B. FURNACE ADAPTOR FLANGE
- C. SINTERED BURNER
- D. PARTICLE INJECTION TUBE
- E. BURNER COOLING WATER COIL
- F. FLANGE COOLING WATER INLET

FIGURE 5

<h2 style="text-align: center;">Spectron Development Labs.</h2> <p style="text-align: center;">COSTA MESA, CA. 92626</p>		
SCALE: <u>Full</u>	APPROVED BY: <i>J.E. Guerra</i>	DRAWN BY <u>H. Crum</u>
DATE: <u>2-2-81</u>		REVISED
DILUTE PARTICLE FURNACE REACTOR HEAD		
		DRAWING NUMBER <u>1060-002-000</u>

TABLE 3. PEAK GAS TEMPERATURE OBSERVED IN PREMIXED FLAMES

<u>REACTANTS</u>	<u>ϕ</u>	<u>REACTOR CARRIER GAS TEMPERATURE RANGE °(K)</u>	<u>REACTANT VELOCITY (m/sec)</u>	<u>REFERENCE</u>
CH ₄ , H ₂ , Air	≤ 1.0	1100 - 1800	0.15	7
CH ₄ , Air	.077	1750	0.30	8

thermal gradients. The use of passively insulated walls would greatly simplify the overall furnace design as well as the installation of optical access ports. Therefore, this design has been examined in some detail.

A furnace performance analysis was conducted to examine the heat loss characteristics for a passively insulated furnace. The primary design parameters considered were as follows:

Insulation Configuration	Figure 6
Furnace Radius	0.2 - 0.3 m
Reactant Inlet Velocity	.05 - 0.4 m/sec
Residence Time	0.5 - 5 sec
Peak Products Temperature	1800 - 2000°K

Key features of the analysis included: internal forced convection heat transfer, temperature dependent gas phase and thermal insulation properties, and gas phase radiation. A description of the analysis approach and results are provided in Appendix A.

A survey of commercial high temperature insulations was made and two insulation materials were selected, KAOLITE (3300) and INDOFORM (3000). These two insulation materials provided the lowest thermal conductivity for the two considered maximum working temperatures, 1800°K and 2000°K, respectively.

Three insulation configurations were considered as shown in Figure 6. Configuration A (1800) is optimized for furnace inlet conditions of 1800°K. Configuration B (2000) is a simple annular configuration sized for furnace inlet conditions of 2000°K. Configuration C (2000) is a complex cross-section annular insulation sized for furnace inlet conditions of 2000°K. Configuration C (2000) is optimized for inlet conditions of 2000°K and the length ℓ (0.2 m) is that length where the inside furnace wall temperature reaches 1920°K, the maximum working temperature of the higher efficiency INDOFORM (3000).

A summary of the furnace design analysis results is provided in Table 4. Detailed results are provided in Appendix A. Results are shown for the ranges of design parameters indicated above. The key

FIGURE 6. FURNACE INSULATION CONFIGURATIONS

TABLE 4. SUMMARY OF FURNACE THERMAL PERFORMANCE ANALYSIS

CASE	SYMBOL	INLET VELOCITY	FURNACE SIZE		INSULATION CONFIG.	τ (sec)	TEMPERATURE		$\Delta T/\Delta L$ (°K/m)
		U_o (m/sec)	R_i (cm)	R_s (cm)			T_o (°K)	$T_{1,2}$ (°K)	
1	⊖	.051	4.9	20	A(1800)	5.5	1800	1100	583
2	—	.051	4.9	30	A(1800)	5.3	1800	1170	525
3	▽	.203	4.9	20	A(1800)	1.1	1800	1530	225
4	△	.203	4.9	30	A(1800)	1.1	1800	1600	167
5	⊙	.203	4.9	30	B(2000)	1.1	1800	1545	213
6	◆	.203	4.9	20	B(2000)	1.0	2000	1590	341
7	⊗	.203	4.9	30	B(2000)	1.0	2000	1680	266
8	⊠	.203	4.9	30	C(2000)	1.0	1800	1581	182
9	⊞	.203	4.9	30	C(2000)	1.0	2000	1720	233
10	⊔	.406	4.9	20	A(1800)	0.5	1800	1660	117

results are residence time, $T_{1.2}$ (the gas temperature at the furnace exit) and the effective axial temperature gradient ($\Delta T/\Delta L$).

Key results of the analysis are shown in Figure 7. The open and closed symbols represent results for peak gas temperatures of 1800 and 2000°K, respectively. The ordinate in each of the plots is the parameter $\Delta T/\Delta L$ (°K/m). Since the furnace is 1.2 meters long, this parameter approximately represents the temperature drop in the furnace. Figures 7(a) and 7(b) show the influence of insulation configuration changes. Figure 7(a) shows the penalty of introducing a high refractory insulation next to the alumina furnace tube [Configuration B (2000)]. Approximately a 55°K/m penalty is observed by adding 2.54 cm (1 inch) of the higher temperature capability insulation. Figure 7(b) shows the influence of increasing the overall furnace radius from 20 to 30 cm. Benefits of decreasing the axial temperature gradient 70 and 90°K/m are observed for the A (1800) and B (2000) insulation configurations, respectively.

The strong influence of reactant inlet velocity (and conversely residence time) on $\Delta T/\Delta L$ is shown in Figure 7(c). A reactant inlet velocity of about 2.2 m/sec provides a sufficient energy input rate to hold $\Delta T/\Delta L = 200^\circ\text{K}$. This provides a furnace residence time of slightly less than 1 sec. The design goal is to have a residence time of 1 second or greater.

Figure 7(d) shows the advantage of insulation configuration optimization. A roughly 32°K/m decrease in temperature drop was achieved using insulation configuration C (2000) instead of B (2000), Figure 6.

The design analysis indicates that for the case of an inlet gas temperature of 1800°K, the axial temperature drop of the gases in the furnace can be held to less than 200°K/m, cases 4 and 8, Table 4. For the case of an inlet gas temperature of 2000°K, the analysis indicates that the temperature drop will be slightly greater, 233°K, case 9. This increase, however, is not considered excessive. In light of this result, it is concluded that the passive insulation system will adequately limit furnace heat losses. This design will be pursued for the current experiment.

FIGURE 7. FURNACE DESIGN SENSITIVITY STUDY

(a) HIGH REFRACTORY THICKNESS

(b) FURNACE RADIUS

(c) REACTANT INLET VELOCITY

(d) PEAK GAS TEMPERATURE

OPEN SYMBOLS INDICATE A PEAK PRODUCTS TEMPERATURE OF 1800°K

CLOSED SYMBOLS INDICATE A PEAK PRODUCTS TEMPERATURE OF 2000°K

3.1.3 Design of Instrumentation Interface (Task 1.4)

This task encompasses the specification of and interface of the following categories of instrumentation for the various experimental configurations:

- Reactants Metering:
 - Gases
 - Particles
- Gas Phase Measurements (intrusive)
- Particle Phase Measurements (intrusive)
- Optical Measurements (nonintrusive)

Emphasis during the present report period has been placed on reactants metering and interface requirements for frontlight and backlight holography. This work is in progress and details will be reported during the next report period. A summary of the planned physical and chemical measurements and optical measurement methods are shown in Tables 5 and 6, respectively.

3.1.4 Fabrication of Dilute Particle Reactor (Task 1.5)

The fabrication of the inert gas-shrouded dilute particle reactor head (Figure 4) was completed during the present report period. The design of the dilute particle furnace reactor head was also completed, and long lead time materials are currently being procured. Actual fabrication of furnace reactor head (Figure 5) will be delayed pending initial experiments using the inert gas-shrouded reactor.

3.1.5 Fabrication of Tube Reactor (Task 1.7)

Actual fabrication of the tube reactor will not commence until final design constraints including the instrumentation are established. However, long lead time items (e.g., castable insulation KAOLITE 3300) have been identified and ordered.

3.1.6 Fabrication of Instrumentation Interface (Task 1.8)

Fabrication of the gas phase reactants metering system is in progress as is the traverse system for the inert gas-shrouded dilute

TABLE 5. PHYSICAL AND CHEMICAL MEASUREMENTS

MEASUREMENT	METHOD
<p>Gas Phase Measurements</p> <p>Temperature</p> <p>O₂ Concentration</p> <p>CO, CO₂, H₂O</p>	<p>Radiation Shielded Thermocouple</p> <p>Paramagnetic Detection</p> <p>Gas Chromatograph</p>
<p>Particle Phase Measurements</p> <p>Volatiles, Moisture, Ash</p> <p>H, C, N, S, O, Ash</p> <p>Ash Components</p> <p>Particle Density</p> <p>Particle Structure</p>	<p>Proximate Analysis Procedure</p> <p>Ultimate Analysis Procedure</p> <p>X-ray Fluorescence</p> <p>Separation and Mass Determination</p> <p>Scanning Electron Microscope</p>

TABLE 6. APPLICATION OF OPTICAL MEASUREMENT METHODS

PARTICULATE PROCESS	PARTICLE SIZE (μm)	COMBUSTOR STATION(in)	MEASUREMENT METHOD(S)
1. Feed Coal Devolatilization and Ignition	10-50	1-12	<ul style="list-style-type: none"> • Pulsed Laser Holography • Particle Sizing Interferometry
2. Soot Formation and Burnout	.02-(1)	1-12, 24	<ul style="list-style-type: none"> • Pulsed Laser Holography • Fine Particle Sizing (depends on agglomeration)
3. Char Burnout	1-50	1-12, 24,42	<ul style="list-style-type: none"> • Pulsed Laser Holography • Particle Sizing Interferometry
4. Large Flyash Melt and Agglomeration	1-20	42, 48-60	<ul style="list-style-type: none"> • Pulsed Laser Holography • Particle Sizing Interferometry
5. Fine Flyash Vaporization and Condensation	.02-1.0	48-60	<ul style="list-style-type: none"> • Fine Particle Sizing
6. Particle Temperature	All	All	<ul style="list-style-type: none"> • 2-Color Optical Pyrometry

(1) Upper bound depends upon soot particle agglomeration.

particle reactor. During the next report period, emphasis will be placed on design and fabrication of reactant particle metering system and optical access for the tube reactor.

Section 4

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APPENDIX A

FURNACE DESIGN ANALYSIS

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FURNACE DESIGN ANALYSIS

Guidelines for constructing the furnace are established by determining the furnace exit temperature and wall temperature distribution for various insulating schemes and heat loads. The basic energy balance for steady one-dimensional plug flow of mean axial velocity V_x down a cylinder of radius r_o is as follows (Reference 9):

$$\pi r_o^2 \rho c_p V_x \frac{\partial T}{\partial x} = -q \quad (1)$$

Inserting the heat loss contributions from gas radiation and convection to the interior furnace wall, conduction through the composite insulated wall, and radiation and convection to the surroundings from the furnace exterior into Equation (1) yields the governing differential equation

$$\frac{dT}{dx} = \frac{-2(T - T_a)/r_o^2 \rho c_p V_x}{\frac{1}{r_o h_o} + \frac{\ln(r_1/r_o)}{k_1} + \frac{\ln(r_2/r_1)}{k_2} + \frac{\ln(r_3/r_2)}{k_3} + \frac{\ln(r_4/r_3)}{k_4} + \frac{1}{r_4 h_4}} \quad (2)$$

h_o and h_4 represent combined radiation/convection heat transfer coefficients, i.e., $h = h_{rad} + h_{conv}$, evaluated at the inner (o) and outer (4) furnace walls. By assuming a surrounding wall emissivity of one and using average gas and wall temperatures, the overall radiation heat transfer coefficients are given by

$$\bar{h}_{o,rad} = \epsilon_g \sigma (\bar{T}_g^4 - \bar{T}_w^4) / (\bar{T}_g - \bar{T}_w) \quad (3)$$

and

$$\bar{h}_{4_{\text{rad}}} = \epsilon_4 \sigma (\bar{T}_4^4 - \bar{T}_a^4) / (T_4 - T_a) \quad (4)$$

For all preliminary calculations, the emissivity of the gas (ϵ_g) and the furnace exterior (ϵ_4) were set equal to 0.1 and 0.2 respectively.

The internal forced convection heat transfer coefficient, $h_{o_{\text{conv}}}$, is evaluated for local conditions in a developing laminar flow in a tube following the methods of Reference 10. The overall external natural convection heat transfer coefficient, $\bar{h}_{4_{\text{conv}}}$, is obtained from the following correlation for vertical cylinders (Reference 11):

$$\overline{\text{Nu}}_L = 0.678 \text{ Ra}_L^{1/4} \left(\frac{\text{Pr}}{0.952 + \text{Pr}} \right)^{1/4} \quad (5)$$

Thermal conductivities ($k_1 - k_4$) used in the various furnace wall shells are listed in Table A-1. K_3 is evaluated at the mean wall temperature.

Equation (2) is numerically integrated on an IBM 370 computer using a variable-step Runge-Kutta method to give the axial temperature distribution $T(x)$. Ancillary results, such as wall temperature distribution, residence time, etc., are calculated at each axial station. The results of preliminary calculations [$T(x)$; $T(r)$] for various heat loads (U_{in} ; T_{in}) and insulation dimensions are shown in Figures A-2 through A-11.

Figure A-1. FURNACE CONSTRUCTION

MATLS 1. ALUMINA LINER TUBE

2. KAOLITE 3300,

3. INDOFORM 3000

4. STEEL SHELL

3-0235 - 50 SHEETS - 5 SQUARES
3-0236 - 100 SHEETS - 5 SQUARES
3-0237 - 200 SHEETS - 5 SQUARES

GOLD KEY

Table A-1. FURNACE CONSTRUCTION

THERMAL PROPERTIES

MATERIAL	TEMPERATURE LIMIT (K)	THERMAL CONDUCTIVITY (W/mK)
1. ALUMINA	2223	7.8
2. KAOLITE 5300	2090	0.65
3. INDOFORM 3000	1920	see below
4. carbon steel	—	40.

Figure A-2. FURNACE ANALYSIS, CASE 1

Figure A-3. FURNACE ANALYSIS, CASE 2

Figure A-4. FURNACE ANALYSIS, CASE 3

Figure A-5. FURNACE ANALYSIS, CASE 4

Figure A-6. FURNACE ANALYSIS, CASE 5

Figure A-7. FURNACE ANALYSIS, CASE 6

Figure A-8. FURNACE ANALYSIS, CASE 7

Figure A-11. FURNACE ANALYSIS, CASE 10