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FINAL TECHNICAL REPORT
on

DOE/ET/10639--T1

DE82 011170

PARTICULATE REMOVAL AT HIGH
TEMPERATURE AND PRESSURE BY
SELF-AGGLOMERATION IN
A CYCLONE

MASTER

Covering the Period from
September 1, 1977 to December 31, 1979

Submitted to:

University Programs
Materials & Exploratory Research
Department of Energy
Program Officer: Dr. Paul E. Scott
Grant No. ~~EE-77-G-01-2753~~

FG 01-77 ET 10639

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ABSTRACT

An analytical and experimental study on a high temperature agglomerating cyclone was carried out to determine the cyclone collection efficiency as a function of dust loading and its operating parameters. Experimental data are presented and indicate that the high temperature cyclone collection efficiency based on the ash mass collected in the hopper varies from 89 to 94%. Microscopic examination of collected particles on the filter paper at cyclone out exhibits that the collected particles are mostly of 2m diameter size. Mathematical modeling indicates that the collection efficiencies of submicron particulates are increased from 19.81% to 36.6% and from 75 to 89.2% for 2m and 5m size particles respectively. Experimental data agree qualitatively with the computed value. Agglomeration mechanism modeling indicates that the particle kinetic energy before collision, the thickness of molten surface layer, the viscosity and surface tension of pseudo-molten ash are the principal factors affecting the agglomeration process.

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LIST OF SYMBOLS AND ABBREVIATIONS

A.R.	average "Size-Weighted" agglomeration rate
b	inlet duct width
B_c	gas inlet width of high efficiency cyclone
$C(d_l, d_s, t)$	total number of inelastic collisions at time t
Cr	circumference of contact area between two molten layers
$\bar{d}(t)$	particle mean diameter at time t
d_l	diameter of larger particle
$d_m(t)$	log-normal mean diameter at time t
d_s	diameter of smaller particle
D	diameter
D_c	major cylinder diameter of high efficiency cyclone
E_{f_n}	energy dissipated due to form drag
E_{f_t}	energy dissipated due to friction drag
E_s	work done in changing the area of surface film after collision
F_n	form drag
F_t	friction drag
g	gravitational constant
H_c	gas inlet height of high efficiency cyclone
J_c	dust outlet
L_c	major cylinder length of high efficiency cyclone
m_l	mass of larger particle
m_s	mass of smaller particle
$n(d, t)$	number concentration of particles of diameter d, at time t.
$N(t)$	total number of particles at time t
P.S.	particle size composition
Q	volumetric flow rate

r	cyclone cylinder radius
r_1	inner radius
r_2	outer radius
Re	Reynolds number
R_l	radius of larger particle
R_s	radius of smaller particle
S	separation factor
T	temperature in degrees celsius
$u(\bar{d})$	increase of collection efficiency due to collision and agglomeration
v	relative velocity between larger and smaller particles
v_c	velocity of combined system
v_r	radial velocity
V	inlet velocity
W	inlet duct height
X	linear distance of common liquid layer along with line of impaction
Z_c	cone length of high efficiency cyclone

Greek

δ_l	molten layer thickness of larger particle
δ_s	molten layer thickness of smaller particle
μ	viscosity
μ'	overall collection efficiency
$\mu(\bar{d}, t)$	cyclone collection efficiency
θ_b	angle of contact
H	angle of liquid layer overlapping each other between larger and smaller particles
μ	viscosity of molten layer
ρ	mass density of molten layer
ρ_p	mass density of solid particle

μ_a	viscosity of air at operating temperature and pressure
$\Sigma_{s,l}$	collision cross-sectional area
σ	surface tension
$\sigma(t)$	standard deviation at time t
$\sigma_m(t)$	standard deviation of log-normal distribution at time t

ACKNOWLEDGEMENT

The authors wish to express their appreciation to the Division of University Programs, Materials and Exploratory Research, the Department of Energy Research and Development Administration for the financial support under Starter Grants in September 1977. Constant encouragement and direction were offered by Dr. P.E. Scott for which we are grateful. Partial financial support from the Department of Natural Resources, the State of Wisconsin is also acknowledged.

CONCLUSIONS

This study achieved the primary objective of evaluating the agglomeration process of coal-ash particles in a high temperature cyclone. The following conclusions regarding the high temperature cyclone are based on the results of our evaluations.

1. Microscope and scanning electron-microscope examination indicate that agglomeration of coal ash particles do take place in a high temperature cyclone.
2. Experimental data exhibit that the high temperature cyclone collection efficiency based on the mass collected in the hopper varies from 89% to 94% as compared with 75% at room temperature.
3. The cyclone collection efficiency based on dust loading at the cyclone outlet as measured by isokinetic gas sampling technique varies from 95% to 98%.
4. Microscopic examination of collected particles on the filter paper at discharge section is estimated that 85% of those collected are 2μ size or smaller.
5. Mathematical modeling predicts the increase of submicron collection-efficiency from 19.81% to 36.6% for 2μ particles and from 75% to 89.21% for 5μ particles.
6. Agglomeration mechanism modeling indicates that the particle kinetic energy before collision, the thickness of molten surface layer, and the viscosity and surface tension of pseudo-molten ash are the principle factors affecting the agglomeration process.
7. The cyclone radius and gas inlet velocity can be optimized to achieve the highest collection efficiency.
8. High temperature/pressure agglomerating cyclone appears to be an effective means to alleviate the high temperature dust cleaning problem in addition to its simplicity, reliability, maintenance and cost effectiveness.

I. INTRODUCTION

The effective use of fluidized bed combustion products and coal gasifier outputs at high temperature and pressure in a combined steam and gas turbine cycle plant depends on the particulate removal efficiency to insure safe operation of gas turbines (1).

Presently, there are numerous research and development projects involving cyclones (2), granular bed filters (3), molten salt scrubbers (4) and other hybrid processes such as sonic agglomerations (5) and charged filters in modified electrostatic precipitators (6). However, some specific problems such as the effect of sticking of adherent particles and decreasing of collection efficiency at high temperature in clean-up apparatus result in making hot gas clean-up a major technical challenge. It was proposed that a new approach utilizing the self-agglomeration phenomena of carbon-ash particles near its fusion temperature to a modified multi-inlet, multi-pass cyclone be investigated.

I.1. Single Cyclone Separators

A cyclone, which is an inertial separator without moving parts, separates particulate matter from a carrier gas by transforming the tangential velocity of an inlet stream into a double vortex confined within the cyclone. In the double vortex, the entering gas spirals downward at the outside and spirals upward at the inside then to the cyclone outlet. The particulates, because of their inertia, tend to move toward the outside wall, from which they are led to a receiver.

Cyclones can be designed to handle a wider range of chemical and physical conditions of operation than most other types of collection equipment can handle. Any conditions for which structural materials are available can be met by a cyclone, if the degree of collection falls within the operation range of the cyclone, and physical characteristics of the particulates are such that no fouling of the cyclone or excessive wall buildup occurs.

Because of its versatility and low cost, the single-cyclone separator is probably the most widely used of the dry centrifugal separators. These cyclones are made in a wide variety of configurations. Although many design factors must be considered, the degree of collection efficiency is most dependent upon the horsepower expended. Hence, cyclones with high inlet velocities, small diameters, and long cylinders are generally found the most efficient. They are commonly called pencil cyclones or high efficiency cyclones (7). Figure 1 shows a single high-efficiency cyclone (8) with typical dimension ratios as follows:

Major cylinder diameter	D_c
Major cylinder length	$L_c = 2D_c$
Gas outlet diameter	$D_e = D_c/2$
Gas outlet length	$H_c + S_c = 5/8 D_c$
Gas inlet height	$H_c = D_c/2$
Gas inlet width	$B_c = D_c/4$
Dust outlet	$J_c = D_c/4$

In figure 1, this cyclone consists of a cylinder with a tangential gas inlet, an axial gas outlet, and a conical lower section with an axial dust outlet. The gas inlet is a rectangular opening, with the height of the opening equal to twice the width. The gas outlet is a tube approximately one half the diameter of the major cylinder, concentric with and extending inside the major cylinder to slightly below the lower edge of the gas inlet. The tangential, high-velocity gas entry imparts circular motion to the gas stream; the particulates, because of their greater inertia, tend to concentrate on the walls of the cyclone. The inlet gas follows a double vortex path, spiraling downward at the outside and spiraling upward at the inside to the gas outlet.

Figure 2 illustrates the double-vortex path of the gas stream. The downward spiral, assisted by gravity, carries the particulates downward to the dust outlet where they drop into a dust-tight bin, or are removed by a rotary valve or screw conveyor.

FIGURE 1

**HIGH EFFICIENCY CYCLONE WITH
TYPICAL DIMENSIONAL RATIOS**

FIGURE 2

**DOUBLE-VORTEX PATH OF THE
GAS STREAM IN A CYCLONE**

The centrifugal force applied to particulates varies as the square of the inlet velocity and inversely as the radius of the cyclone. These factors have been combined into a dimensionless quantity called the separation factor (7):

$$S = v^2 / rg$$

where:

S = separation factor

V. = inlet velocity, ft/sec

r = cyclone cylinder radius, ft

g = gravitational constant, 32.2 ft/sec².

It has not been possible to establish a definite correlation between separation factor and collection efficiency; yet, for cyclones of similar design and use, collection generally varies directly as a function of the separation factor.

Stern et al. (9) (1956) discusses the variation of collection efficiency with inlet velocity. Several theoretical formulas are presented in which critical particle size is shown to vary as $1/v^{1/2}$. Critical particle size is defined as the largest sized particle not separated from the gas stream, all larger particles being separated and particles smaller than the critical-size will be lost into the outlet duct. The critical size varies inversely as the velocity, and the greater the critical size, the less efficient is the cyclone collection. The collection efficiency, therefore, varies as the inlet velocity. There are, however, limits to the inlet velocity; if it is too great, turbulence develops to such a degree at the inlet that overall cyclone efficiency is reduced. The velocity at which excessive turbulence occurs is dependent upon configuration of the inlet, design of the cyclone, and the characteristics of the carrier gas.

I.3. Separation efficiency

For high efficiency, the separating forces should be large and the dust removal effective so that separated dust is not reentrained. In general, cyclone efficiency increases with an increase in the following (9):

1. Density of the particulate matter.
2. Inlet velocity into the cyclone.
3. Cyclone body length.
4. Number of gas revolutions (experiments indicate that the number of revolutions made by the gas stream in a typical simple cyclone ranges from 0.5 to 3 and averages 1.5 for cyclones of normal configuration.
5. Ratio of cyclone body diameter to cyclone outlet diameter.
6. Particle diameter.
7. Amount of dust entrained in carrier gas.
8. Smoothness of inner cyclone wall.

An increase in the following will decrease the overall efficiency:

1. Carrier gas viscosity.
2. Cyclone diameter.
3. Gas outlet diameter.
4. Gas inlet duct width.
5. Inlet area.
6. Gas density.

Collection efficiency is noticeably reduced by the installation of inlet vanes, probably because of interference with the normal flow pattern. In general, all sorts of guide vanes, straightening vanes, baffles, and so forth placed inside an otherwise well-designed cyclone have been found of little value or actually detrimental. In some instances, for poorly designed cyclones, these devices have improved performance. Baffles designed to reduce leakage of air into the dust outlet are sometimes helpful. These consist of a horizontal, circular device installed on the cyclone axis near the dust outlet.

In practice, extensive agglomeration may be expected for dust concentrations greater than 100 grains per cubic foot and may be present at much smaller concentrations, depending upon the physical properties of the particulates being collected. Fibrous or tacky particles are especially apt to agglomerate. Agglomeration produces a larger effective particle size and thereby increases the efficiency of separation. Nevertheless, extremely sticky, hygroscopic, or similar material that could possibly plug the dust outlet or accumulate on the cyclone walls adversely affects cyclone operation. In addition, the agglomeration effect is reduced sharply when very high inlet velocities are used. In some cases where agglomeration was significant, an increase in cyclone inlet velocity actually reduced the collection efficiency. Conversely, the efficiency was improved by reducing the inlet velocity.

Combustion products and coal-ash particle laden gas as produced from either fluidized bed combustion plants or from a coal gasification process must be cleaned to an acceptable degree for safe operation in a combined gas-steam-turbine cycle plant. The present research reports the continued progress on the proposed innovative hot gas cleaning technique. The hot gas is cleaned through a single inlet, single pass cyclone operated near coal-ash fusion temperature. Partially molten solid particulates of self-agglomeration characteristics will grow to larger sizes upon impaction, adhesion, collision and agglomeration. Under the centrifugal action, while submicron particles continue to agglomerate, the larger particles of an equivalent diameter greater than $5\ \mu$ will be separated out from the main gas stream, thus increasing the sub-micron particle removal efficiency. This research shows that this high temperature cyclone offers not only this very high collection efficiency but also provides maintenance-free operation. Hence, it is the most cost-effective.

This report summarizes the progress made, analytical and experimental, during almost two years research. The conceptual model of agglomeration mechanism and experimental data in a high temperature cyclone are presented. The proposed hot gas cleaning technique as evidenced by this research results in the high temperature agglomeration cyclone being a viable and effective approach for hot gas cleaning.

II. MATHEMATICAL MODELING AND CALCULATIONS

The analytical study consists of:

- 1) the building of a mathematical model to simulate the particle collision phenomenon in a single gas stream for which the particles are of various sizes and concentrations at different radial velocities;
- 2) to estimate the degree of improvement of cyclone collection efficiency with and without particle collision and agglomeration phenomenon; and,
- 3) the simplified mechanism of self-agglomeration as a function of momentum of particles, the thickness of pseudo-molten boundary layer enclosing the solid particles, surface tension, and the viscosity of molten state of coal ash.

II.1. Single Jet Particle Collision

It is generally agreed that in a physical process and as a prerequisite of this study, the particle size and number distributions tend to be log-normal (8). The number concentration of particles of diameter d , at time t , is

$$n(d,t) = \frac{N(t)}{\sqrt{2\pi} d \ln \sigma_m(t)} \exp \left[-\frac{1}{2} \left[\frac{\ln \frac{d(t)}{d_m(t)}}{\ln \sigma_m(t)} \right]^2 \right] \quad (1)$$

where $N(t)$ = total number of particles at time t

$\sigma_m(t)$ = standard deviation of log-normal distribution at time t , and

$$\sigma_m(t) = \exp \left[\ln \left(1 + \frac{\sigma^2(t)}{\bar{d}^2(t)} \right) \right]^{\frac{1}{2}} \quad (2)$$

$\sigma(t)$ = standard deviation at time t ;

$\bar{d}(t)$ = particle mean diameter at time t ;

$d_m(t)$ = log-normal mean diameter at time t .

The formulation of the mathematical model is based fundamentally upon the collision of elastic spheres as in the kinetic theory (9). The number of elastic collisions between a group of large particles of diameter d_l , concentration $n(d_l, t)$ and a group of small particles of diameter d_s , concentration $n(d_s, t)$ at time t is (9);

$$n(d_l, t) n(d_s, t) v \sum_{s, l} \quad (3)$$

where v = relative velocity between the two groups of particles, and

$$\sum_{s, l} = \frac{\pi}{4} (d_l^2 + d_s^2)$$

is the collision cross-sectional area.

For the tractability of the problem (10), assuming that the total number of inelastic collisions at time t is,

$$C(d_l, d_s, t) = [n(d_l, t) n(d_s, t)]^{\frac{1}{2}} v \sum_{s, l} \quad (4)$$

and all particles have the same inlet tangential velocity, then the relative velocity v , Figure 3, in the cyclone becomes the difference of radial velocity of the large and small particles. That is,

$$\begin{aligned} V &= V_r(d_l, t) - V_r(d_s, t) \\ &= \frac{\rho_p Q^2}{72 \mu_a w^2 (\sqrt{r_2} - \sqrt{r_1})^2} \frac{1}{r^2} (d_l^2 - d_s^2) \end{aligned} \quad (5)$$

where r_1 = inner radius;

r_2 = outer radius;

w = inlet duct height;

b = inlet duct width;

Q = volumetric flow rate;

μ_a = viscosity of air at operating temperature and pressure;

ρ_p = mass density of solid particles.

FIGURE 3

COLLISION DUE TO DIFFERENT RADIAL
VELOCITIES OF PAPTICLE

Combining equations (1), (2), (3), (4), and (5), we obtain

$$C(d_l, d_s, t) = \text{CONST} \cdot N(t) \cdot \frac{1}{r^2} \cdot \text{DIA} \quad (6)$$

where

$$\text{CONST} = \frac{\sqrt{\pi}}{228 \sqrt{2} \ln \sigma_m(t) (\sqrt{r_2} - \sqrt{r_1})^2} \cdot \frac{\rho_p}{\mu_a} \left(\frac{Q}{W} \right)^2 \quad (7)$$

$$\text{DIA} = \frac{d_l^4 - d_s^4}{(d_l d_s)^{1/2}} \exp \left[-\frac{1}{4} \left[\left(\frac{\ln \frac{d_s}{d_m(t)}}{\ln \sigma_m(t)} \right)^2 + \left(\frac{\ln \frac{d_l}{d_m(t)}}{\ln \sigma_m(t)} \right)^2 \right] \right] \quad (8)$$

Equations (7) and (8) are functions of cyclone geometry and particle size, respectively.

In order to obtain the total number of collisions $c(t)$ occurring at time t (take $t = 0$ at cyclone entrance), we need to integrate equation (8) for all small and large particles and $1/r^2$ term in equation (6) over the particle trajectory traveled from r_1 to r_2 in the radial direction. Hence,

$$C(t) = N(t) \cdot \text{CONST} \cdot \int_{r_1}^{r_2} \frac{dr}{r^2} \int_{d_l > d_s}^{\infty} d(d_l) \int_0^{\infty} d(d_s) (\text{DIA}) \quad (9)$$

$$\begin{aligned} \text{or } \frac{C(t)}{N(t)} &= \text{CONST} \cdot \left(\frac{1}{r_1} - \frac{1}{r_2} \right) \int_{d_l > d_s}^{\infty} d(d_l) \int_0^{\infty} d(d_s) (\text{DIA}) \\ &= \text{CONST} \cdot \left(\frac{1}{r_1} - \frac{1}{r_2} \right) \cdot \text{INT} \end{aligned} \quad (10)$$

which represents, at time t , the ratio of the number of collisions occurring to the number density of existing particles (10).

For the cyclone under testing, Figure 4, the geometrical parameters are $r_1 = 1.15$ inches, $r_2 = 1.905$ inches, $w = 1.70$ inches and $b = 0.75$ inches. The operating parameters are pressure at 1.069 atmospheres, temperatures between 1650 to 2200°F, and volumetric flow rate between 13 to 20 cfm.

FIGURE 4 DIMENSION PARAMETERS OF CYCLONE

To carry out the numerical computation, we further assumed that the shape of the particle size distribution curve remains similar even though the number and size of the particles in the gas stream is changing. This is to say that mathematically

$$\frac{\bar{G}(t)}{\bar{d}(t)} = \frac{\bar{G}(0)}{\bar{d}(0)}$$

and therefore $\bar{G}_m$ is calculated to be 1.604 for $\bar{d}(t) = 10 \mu$, $\bar{G}(t) = 5 \mu$, and $d_m(t) = 8.994 \mu$. Incorporating all the $\bar{G}$'s and d 's, we obtain the value of CONST to be 3.279×10^8 ft/sec.

Evaluation of DIA term is based on a fundamental premise that the removal efficiency of a conventional cyclone is 75% at 5μ size particles. Smaller size particles must be agglomerated to form a new particle of diameter greater than 5μ to be separated out. That is, in the computational process, when two particles adhere together, they shall have an equivalent diameter of $(d_l^3 + d_s^3)^{1/3} \geq 5 \mu$ before separated out.

The total number of collisions, at position r and time t , which would generate a new particle of size greater than or equal to 5μ among all the particles is to integrate the INT term with respect to all proper values of d_l and d_s . For simplicity and savings of computing time, we divided d_s into five size ranges: $0.1-0.5-1.0-2.1-3.0-3.968 \mu$ and the corresponding size limits of d_l are $5.0-4.97-4.90-4.87-4.61-3.969 \mu$. Particles of 100μ size are considered to be the upper limit. Hence,

$$\begin{aligned} \text{INT} &= \int_{0.1}^{0.5} d(d_s) \int_5^{100} d(d_l) (DIA) + \int_{0.5}^{1.0} d(d_s) \int_{4.97}^{100} d(d_l) (DIA) \\ &+ \int_{1.0}^{2.1} d(d_s) \int_{4.90}^{100} d(d_l) (DIA) + \int_{2.1}^{3.968} d(d_s) \int_{3.0}^{100} d(d_l) (DIA) \\ &+ \int_{3.968}^{3.969} d(d_s) \int_{3.969}^{100} d(d_l) (DIA) \\ &= 5.1804 \times 10^{-10} \text{ ft}^3 \end{aligned} \quad (11)$$

Consequently $c(t)/N(t) = 69.44\%$. This fraction represents the formation of new particles through collision with a diameter greater than 5μ . This value represents also the improvement of collection efficiency over cyclone without collision agglomeration. Similarly, the computation process can be carried out for particles of mean diameter $\bar{d}(t)$ at 1μ , 2μ , etc.

II.3. Comparison of Cyclone Collection Efficiency With and Without Agglomeration

The cyclone collection efficiency $\eta(\bar{d}, t)$ is computed by equation (7)

$$\eta(\bar{d}, t) = 1 - \exp\left[- \frac{P_p Q \bar{d}^2 v}{36 \mu_a w (r_2 - \sqrt{r_1 r_2}) (r_2 - r_1) 2 \pi t}\right] \quad (12)$$

or,
$$\frac{N(\bar{d}, t)}{N(\bar{d}, 0)} = 1 - \eta(\bar{d}, t) \quad (13)$$

is the ratio of the number of particles remaining in the gas stream to the initial total number of particles at the cyclone entrance. Multiplication of $\frac{N(\bar{d}, t)}{N(\bar{d}, 0)}$ by $\frac{C(\bar{d}, t)}{N(\bar{d}, t)}$ and by 0.75 for 5μ particles, the increase of collection efficiency due to collision and agglomeration $U(\bar{d})$ is

$$U(\bar{d}) = \frac{C(\bar{d}, t)}{N(\bar{d}, t)} \cdot \frac{N(\bar{d}, t)}{N(\bar{d}, 0)} \cdot 75\% \quad (14)$$

The 0.75 factor is arbitrarily incorporated into equation (14) since the collection efficiency of a conventional cyclone is 75% efficient for 5μ cut size particle. Adding $u(\bar{d})$ to the original $\eta(\bar{d})$ gives the overall collection efficiency $\eta'(\bar{d})$ of a high temperature cyclone. The results are presented in Table 1 and graphically in Figure 5. The computed cyclone efficiency is based on the particles undergoing single collision. It is highly probable that multiple collision process, fluid turbulence and pressure effect would increase further the collection efficiency in high temperature/pressure operations.

FIGURE 5 COMPUTED EFFICIENCY VS.
PARTICLE MEAN DIAMETER

As we mentioned that particulate removal efficiency will be increased far beyond the performance of a conventional cyclone which is effective only for particles larger than two microns. It was reported that the ability of an experimental high temperature cyclone to collect submicron particles (particles on the order of 2μ) were increased substantially (11). However, the coal-ash agglomeration mechanism as it is occurring in a high temperature cyclone is not fully understood.

Table 1 lists the computed results of the cyclone collection efficiency with and without agglomeration. Computations were carried out at four mean particle sizes of 1, 2, 5, and 10μ . Particle removal efficiency, $\eta(\bar{d})$, Equation (13) represents a conventional high efficiency cyclone performance. The high temperature agglomeration cyclone would show the same removal efficiency if it were operated at the same tangential velocity but at room temperature. The efficiency is 19.81% and 75% for mean particle size of 2μ and 5μ respectively.

Since the chance of collision increases from 1.42% to 75.63% when particle mean diameter is increased from 1 to 5μ (2,10). The improvement of collection efficiency due to collision and agglomeration is boosted by additional 16.88% and 14.21% at 2 and 5μ size particles which offers a relative percentage increase of 85% and 18.9%. These increases are of particular interest and are significant. Hence, it is expected that the overall performance of a high temperature cyclone be on the order of 89-90% or greater. This conclusion is further verified by later section of experimental results.

II.4. Mechanism of Self-Agglomeration

Based upon the observed coal-ash agglomeration phenomena in a laboratory high temperature cyclone, Figure 6, this report presents a conceptual model of agglomeration mechanism before and after collision. Effects of particle size, molten layer thickness enclosing the solid particle, and the kinetic energy of particles before collision in the agglomeration process were examined.

TABLE 1

COMPUTED CYCLONE PERFORMANCE WITH AND WITHOUT AGGLOMERATION

$\bar{d}$ (μ)	1	2	5	10
$(d) = 1 - \frac{N(d,t)}{N(d,0)}$ (%)	5.37	19.81	75	99.5
$\frac{C(d,t)}{N(d,t)}$, (%)	1.42	28.07	75.63	69.44
$U(d,t) =$ $\frac{C(d,t) N(d,t)}{N(d,t) N(d,0)}$, (75%) (%)	0.99	16.88	14.21	0.26
$(d) = (d) + U(d)$, (%)	6.36	36.69	89.21	99.76
, (%)	18.4	85	18.9	0.2

FIGURE 6 PHOTO OF AGGLOMERATED PARTICLES

It was premised that the major mechanism of coal-ash agglomeration as it occurs in a cyclone is due to the particle collision. While the cyclone is operated near coal-ash fusion temperature, the incoming particles are subjected to a region of high temperature zone, thus momentarily approaching a pseudo-molten state. A thin molten liquid layer of thickness, δ , encloses the solid core of each particle. This thin layer of molten ash will embrace and fuse together as a result of collision and impaction, thus forming a greater size of particle.

Figures (7a), (7b), and (7c) show the collision mechanism of two particles with radii R_1 and R_s ; molten layer thicknesses, δ_1 and δ_s ; and approaching velocity v in Equation (5). Under the assumptions that all of the particles are spherical and the solid core is perfectly elastic, Figures 7b and 7c hypothesize the particle interfacial mechanism during and after colliding. An actual sample photo was taken from a scanning electron microscope as shown in Figure 8 to support this assumption.

At the instant of direct contact of the two molten liquid layers, two cases would prevail. Should the larger particle have a greater velocity, the liquid would spill over and then enclose the smaller particle. On the other hand, if the smaller particle is striking upon the larger ones, the smaller particle will indent and sink into the viscous region of the larger particle at the interface. In either case, the kinetic energy of the moving particle is being retarded, absorbed and dissipated, thus favoring agglomeration. Figures 7b and 7c show also the forces acting upon both particles during and after collision. The interacting forces are the viscous shear of the molten boundary layer, the surface tension and the momentum of the striking particles. Agglomeration of particles will occur if the kinetic energy required for separation is smaller than the sum of frictional drag and the interfacial tension. That is,

$$\left(\begin{array}{l} \text{Kinetic energy} \\ \text{for separation} \end{array} \right) \leq \left(\begin{array}{l} \text{Energy dissipation due to} \\ \text{friction and form drag} \end{array} \right) + \left(\begin{array}{l} \text{Work done due to interfacial} \\ \text{force of liquid layer} \end{array} \right)$$

FIGURE 7 SCHEMATIC DIAGRAM OF COLLISION

FIGURE 8 PHOTO OF SPHERICAL COAL ASH PARTICLES

According to conservation of momentum, the velocity of the combined system is

$$V_c = \frac{m_l V_r(d_l) + m_s V_r(d_s)}{m_l + m_s} \quad (15)$$

where m 's are the masses of particles, v_r 's the radial velocity and subscripts l and s refer to larger and smaller particles. Since at the instant of colliding of two particles, the Reynolds number of the molten liquid layer during the collision has been estimated as on the order of 0.01 or smaller, the particle form and friction drags are then approximated as in the creeping flow (12), and is calculated from (12) respectively as:

$$F_n = \int_0^{2\pi} \int_0^H \left(\frac{3}{2} \frac{\mu V_c}{R_s} \cos^2 \theta \right) R_s^2 \sin \theta d\theta d\phi \quad (16)$$

$$F_t = \int_0^{2\pi} \int_0^H \left(\frac{3}{2} \frac{\mu V_c}{R_s} \sin^2 \theta \right) R_s^2 \sin \theta d\theta d\phi \quad (17)$$

where H is the angle of liquid layer overlapping each other and is assumed to be twice the angle of contact, θ_b , of the particle solid core, Figure 7b, where

$$\theta_b = \cos^{-1} \left(\frac{R_s - \delta_s}{R_s} \right) \quad (18)$$

Multiplying equations (16) and (17) by $x (= R_s - R_s \cos \theta)$, the linear distance of common liquid layer along the line of impaction, and integrate

$$E_{fn} = \int_0^{2\pi} \int_0^H \left[\left(\frac{3}{2} \frac{\mu V_c}{R_s} \cos \theta \right) \cos \theta \right] (R_s - R_s \cos \theta) R_s^2 \sin \theta d\theta d\phi \quad (19)$$

$$= 3\pi \mu V_c R_s^2 \left(\frac{7}{12} - \cos^3 H - \cos^4 H \right)$$

$$E_{ft} = \int_0^{2\pi} \int_0^H \left[\frac{3}{2} \frac{\mu V_c}{R_s} \sin \theta \sin \theta \right] (R_s - R_s \sin \theta) R_s^2 \sin \theta d\theta d\phi \quad (20)$$

$$= 3\pi \mu V_c R_s^2 \left(\frac{2}{3} \cos H - \cos^4 H + \frac{\sin^4 H}{4} \right)$$

$$E_f = E_{fn} + E_{ft} \quad (21)$$

where E_{fn} and E_{ft} are the energy dissipated due to form drag and friction drag, respectively. Equation (21) is the total energy dissipated due to viscous effect.

However, right after the elastic collision between the solid cores, the particles tend to move away from each other causing the stretching of molten interface as shown in Figure 7c.

Assuming the circumference, C_r , of the contact area decreases linearly with respect to the distance between the particle centers, the colliding particles will detach completely if the center distance reaches $(R_1 + \delta_1 + R_s + \delta_s)$. The energy needed to separate the two particles after collision is the work done in changing the area of the surface film, which is

$$E_s = C_r \sigma \cdot \frac{2(\delta_1 + \delta_s)}{2} \quad (22)$$

where σ is the surface tension of the molten coal-ash layer, and

$$C_r = 2\pi (R_1^2 - (R_1 - \delta_1)^2)^{\frac{1}{2}} \quad (23)$$

For simplicity, take the origin of coordinate of approaching system at the center of the smaller particle, the kinetic energy E , as carried by the larger particle is $1/2 M_1 v^2$. Prediction of agglomeration or fragmentation after the particle collision is to examine the relative kinetic energy E , whether it is large enough to overcome the resistance as caused by the effect of fluid drag and surface tension.

With the availability of coal-ash physical and chemical properties (13) such as the composition of synthetic coal slags, the viscosity of slag and the surface tension of slag, we are able to understand the mechanism of agglomeration much more in detail. Viscosity of a range of slag compositions representing U.S. coals has been measured from 1350° to 1600°C at the National Bureau of Standards. The viscosity-temperature relationship for some of the synthetic slags is given in Figure 9.

FIGURE 9 VISCOSITY-TEMPERATURE RELATIONSHIPS FOR
SOME MODEL COAL SLAGS - IGT REPORT NO.
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Watt and Fereday (14) proposed the following viscosity-temperature relationship for completely melted coal ash, based on the experimental measurements on ashes of more than 100 British coals:

$$\text{Log}_{10} \eta = 10^7 M / (T-150)^2 + C \quad (24)$$

where

η = viscosity in poises

$$M = 0.00835 (\text{SiO}_2 + 0.00601 (\text{Al}_2\text{O}_3) - 0.109$$

$$= 0.0415 (\text{SiO}_2) + 0.0192 (\text{Al}_2\text{O}_3)$$

$$+ 0.0276 (\text{equivalent Fe}_2)_3) + 0.0160 (\text{CaO}) - 3.92$$

T = temperature in degrees Celsius

The oxides in parentheses are concentrations of these oxides in the melt expressed in weight percent of sum of SiO_2 , Al_2O_3 , Fe_2O_3 , CaO , MgO .

To improve the accuracy of viscosity predictions, the measured values of 23 synthetic melts were used to determine a least-squares solution to the Watt-Fereday equation; to account for the MgO content, an extra term was included. New constants were derived entirely from synthetic melts, modifying the equation to

$$\text{Log}_{10} \eta = 10^7 M' / (T-150)^2 + C' \quad (25)$$

where

$$M' = 0.0104291 (\text{SiO}_2) + 0.0100297 (\text{Al}_2\text{O}_3) - 0.296285$$

$$C' = 0.01541481 (\text{SiO}_2) - 0.03880471 (\text{Al}_2\text{O}_3)$$

$$- 0.0167264 (\text{Fe}_3\text{O}_4) - 0.0089096 (\text{CaO})$$

$$- 0.012932 (\text{MgO}) + 1.04678$$

Figure 10 compares the viscosity-temperature relationships of several typical model slags using the original Watt-Faraday equation. The slag compositions are shown in Table III.

FIGURE 10 COMPARISON OF MEASURED VALUES, WATT-FEREDAY VALUES, AND MODIFIED WATT-FEREDAY VALUES, 1GT REPORT NO. HCP/T2286-01, IIT CENTER, CHICAGO, ILLINOIS.

Table II

COMPOSITION OF SYNTHETIC COAL SLAGS (13)

	SiO_2	Al_2O_3	Fe_3O_4	CaO	MgO
Melt	wt%				
K257	43	19	30	0	8
K325	47.90	18.76	28.40	0	4.94
K385	40	15	20	17	8
K390	30	15	15	30	10
K392	60	20	17	2	1

We have chosen the sample K 257 for our sample calculation. At temperature 1800°F, the viscosity was found to be 558 poise.

The surface tension of the molten layer has been estimated to be equal to 150 dyne/sec which is in the range of surface tension for the metals.

At the conditions described with these properties we found for computation, the effect of molten layer thickness enclosing the smaller particles, δ_s , upon agglomeration is shown in Figures 11a, 11b, and 11c. The collision of 2μ and 22μ particles at a radial position of 2.96 cm away from cyclone center does show that the particles will stay together after collision, if $\delta_s \leq 0.1R_s$ and vice versa. For particles smaller than 10μ , Figure 11a, and greater than 30μ , Figure 11c, agglomeration and fragmentation will take place, respectively. This is due to the fact that the energy required for separation is greater or smaller than the energy of approaching particles before collision.

Figure 12b indicates that for a given pair of particles, there exists an optimum location for which particles will stick together after collision. This optimum location shifts toward larger cyclone radius as the size of the particle pair becomes closer, Figure 12a shows such a case where entire cyclone space can be utilized for the intended agglomeration process. Figure 12c indicates that the opposite is true.

Since the capacity of cleaning equipment is predominately determined by the volumetric flow rate of hot gases, once again, for a chosen set of operating parameters, Figure 13 shows that there exists a critical flow rate for which fragmentation may occur after collision.

In summary, the high temperature cyclone collection efficiency is governed by those intermingling factors such as the particle size, the geometry, the molten layer thickness enclosing each particle, volumetric flow rate and the dust properties. For particles smaller than 10μ , the high temperature cyclone is an effective device favoring agglomeration.

FIGURE 11a ENERGY VERSUS MOLTEN LAYER THICKNESS

FIGURE 11 b ENERGY VERSUS MOLTEN LAYER THICKNESS

FIGURE 11c ENERGY VERSUS MOLTEN LAYER THICKNESS

FIGURE 12 a ENERGY VERSUS RADIAL POSITION r

FIGURE 12 b ENERGY VERSUS RADIAL POSITION r

 FIGURE 12 c ENERGY VERSUS RADIAL POSITION r

$r = 2.96 \text{ CM}$

$\delta = .22 R_S$

$\eta = 558 \text{ POISE}$

$\sigma = 150 \text{ DYNE/CM}$

----- ENERGY REQUIRED FOR SEPARATION

———— ENERGY OF APPROCHING BEFORE COLLISION

FIGURE 13 ENERGY VERSUS VOLUMETRIC FLOW RATE Q

III. Experimental Results and Findings

III.1 Introduction

As a design and operating criteria for the cyclone, the agglomeration rate must be known in conjunction with the probability of particle collisions (2). The value of the agglomeration rate at the variable operating conditions allows an efficient operation of the cyclone by maximizing the probability of collisions and the subsequent agglomeration thus increasing the removal efficiency.

Goldberger (15) working with a fluidized bed coal combustor concerning with the measurement of agglomerated coal-ash particles and collection efficiency found that collection of ash and agglomeration and growth of the bed particles occurred at temperatures as low as 1400°F, the sticking tendency of the bed was too great for stable fluidization.

Particle growth was found to take place by a combination of two mechanisms. Below 1950°F, the particles of ash fused. The coating was rather dense and contained only minor amounts of unburned carbon. At temperatures above 1975°F, the ash coatings were sufficiently tacky to cause bed particles adhering to each other and forming coarse agglomerates.

The agglomeration of ash or the tendency of ash to sinter above about 1050°C is called the Godel Phenomenon (16). The article describing the Godel Phenomenon details the Phenomena as follows:

In a bed of anthracite or bituminous coke fluidized by air at 10 to 15 meters per second at 1200°C to 1400°C, molten ash forms beads on the surface of a coke particle, some exuding from its interior. The beads merge and detach themselves to grow further as loose fluidized ash agglomerates of low carbon content.

This agglomerating process proceeds in four stages as described by the Godel Phenomenon in the same article.

Stage 1.) In the first stage, small glassy beads appear on the surface of particles undergoing gasification. Some of the beads appear to have oozed from microcracks having migrated at least a short distance from the particle's interior.

Stage 2.) In the second stage, the ash beads grow by several mechanisms. As coke is consumed by its gasification, molten ash continues to accumulate on the coke particle's surface, and nearby beads merge. The particle can also capture ash beads from another particle when the two touch each other in the fluidized bed.

Stage 3.) Molten ash has a high surface tension and does not readily wet coke. As the molten beads grow, they eventually separate from the coke surface, and this begins the third stage of the Godel phenomenon. In the turbulent currents of fluidized bed, a loose bead may be accreted by ash agglomerated or another bead present in the bed, or it may be captured by ash still attached to a coke surface by molten matter that is rooted into capillary pores of coke particle. Carryover material from the ignifluid bed, which is predominately particles of coke, also contains a few ash beads that were swept up by the rising gas.

Stage 4.) The final stage involves coalescence and growth of the ash agglomerates may also grow by plucking ash beads still attached to coke surface. Some agglomerates are round, while others (usually the larger ones) exhibit composite structure that resulted from coalescence and fusion of smaller agglomerates. The degree of fusion varies over the full range from weak adherence to complete assimilation.

III.2. COAL-ASH PARTICLE AGGLOMERATION IN A STATIC FURNACE

This phase of experimental study was concerned with coal-ash particle agglomeration in a controlled static furnace environment done by Bradley (17). The static furnace approach was utilized to investigate the agglomeration phenomena without air movement produced interactions. The adherence of adjacent particles is facilitated and should reveal significant data to justify and conclusions concerning the agglomeration rate determination.

The objective of the static furnace experiment was to determine the operating conditions of a multi-inlet, multi-pass high temperature cyclone to facilitate sub-micron particulate agglomeration. The operating conditions will aid the construction of a cyclone at its highest collection efficiency. Based on Godel phenomenon, the

agglomeration rate of coal-ash particles is observed as a function of the temperature, the time of exposure, the initial particle size, and the coal to ash composition ratio.

To measure quantitatively the change of size distribution before and after the experiment, an average "size weighted" Agglomeration Rate, $\overline{A.R.}$ was defined:

$$\overline{A.R.} = 1 -$$

$$\frac{\begin{array}{c} \text{(Percent of} \\ \text{screened sample} \\ \text{after exposure)} \end{array} \begin{array}{c} \text{(Weight of} \\ \text{fraction)} \\ \text{(Average size for} \\ \text{agglomerates range)} \end{array}}{\begin{array}{c} \text{(Percent ash} \\ \text{before exposure)} \end{array} \begin{array}{c} \text{(Weight of} \\ \text{ash)} \\ \text{(Average size} \\ \text{of ash for} \\ \text{range)} \end{array} \begin{array}{c} \text{(Percent coal} \\ \text{before exposure)} \end{array} \begin{array}{c} \text{(Weight of} \\ \text{coal)} \\ \text{(Average size} \\ \text{of coal for} \\ \text{range)} \end{array}} \quad (26)$$

which is a function of temperature, exposure time, and initial particle size composition and was formulated out from 54 experimental runs. A statistical regression equation of average agglomeration rate was developed.

$$\overline{A.R.} = -4.695 + 0.00247(T) + 0.00394(t) + 0.00445(X) \quad (27)$$

where T is the temperature in °F, t is the exposure time in seconds, and X is the initial particle size composition in gram-microns. The initial particle size composition was calculated from the following equation:

$$P.S. = \left[\begin{array}{c} \text{Percent ash} \\ \text{before} \\ \text{exposure} \end{array} \right] \left[\begin{array}{c} \text{Weight of} \\ \text{ash (in grams)} \end{array} \right] \left[\begin{array}{c} \text{Average size of} \\ \text{ash for range} \\ \text{(in microns)} \end{array} \right] + \left[\begin{array}{c} \text{Percent coal} \\ \text{before exposure} \end{array} \right] \left[\begin{array}{c} \text{Weight of} \\ \text{coal (in grams)} \end{array} \right] \left[\begin{array}{c} \text{Average size of} \\ \text{coal for range} \\ \text{in microns} \end{array} \right] \quad (28)$$

Figures 14 and 15 show that the average agglomeration rate versus computed sample initial particle size composition for exposure time 30 seconds and 60 seconds respectively.

III.3. HIGH TEMPERATURE CYCLONE EXPERIMENTAL SET-UP

Equipment was selected to simulate the particulate laden gases generated by a coal gasified coal-fired boiler or a fluidized combustion system. A cyclone was designed and fabricated to remove the particulates from the gas stream. Along with other supportive equipment, this testing station was designed with one primary objective--

FIGURE 14 AVERAGE AGGLOMERATION RATE VERSUS COMPUTED SAMPLE INITIAL PARTICLE SIZE COMPOSITION FOR 30 SECONDS EXPOSURE TIME.

FIGURE 15 AVERAGE AGGLOMERATION RATE VERSUS COMPUTED SAMPLE INITIAL PARTICLE SIZE COMPOSITION FOR 60 SECONDS EXPOSURE TIME.

the determination of whether or not coal ash particulates in a gas stream could be induced to agglomerate, thus indirectly but effectively increasing the efficiency of a cyclone.

There are two ways to alter the efficiency of a cyclone; by varying its operating conditions or by changing its design. The experimental objective in this study is, firstly, to improve the efficiency by changing the operating parameters to induce agglomeration of the inlet sub-micron particulates.

By operating the cyclone at high temperatures, the outer surfaces of the coal ash particles become pseudo-molten. Upon collision with other semi-molten particles, agglomeration occurs resulting in the growth of particles having greater masses and diameters. These larger, heavier particles are now in a size range which can be collected with high efficiency, thus allowing the cyclone to collect particulates previously beyond its capacity.

Figures 16 and 17 show the schematic diagram and photograph of the set-up.

III.3.1. Cyclone Materials

The cyclone had to be capable of sustainable operation at temperatures as high as 2100°F. Temperatures in this range had been previously determined and demonstrated capable of inducing agglomeration of coal-ash particles. To meet these operating temperatures, Type 304 stainless steel was used for fabricating all high temperature elements. Type 304 stainless steel has a high melting point (2800°F), a good resistance to oxidation and good machineability. Type 314 stainless steel would provide better service, but was not adopted due to limitations imposed by machine shop facilities.

III.3.2. Cyclone Dimension

The cyclone must be of high efficiency design having a target efficiency of 100% when controlling particulates in the 10-20 μ range. To meet this requirement, a standard high efficiency design was adopted (18). These dimensions are given in the drawings (Figure a to g of Appendix).

FIGURE 16 SCHEMATICS OF SET UP

FIGURE 17 PHOTO OF TESTING SET-UP

The design also incorporates a Feifel Hopper with a downward discharge (19). The Feifel Hopper is comprised of cylindrical hopper with a separator plate placed above it. The separator plate has annular slits and a central hole as shown in Figure (e) of the appendix. Since this design requires no cone for its operation, fabrication expenses are minimized. The operation of the Feifel Hopper is illustrated in Figure 18. Particulates, concentrated in the downward spiraling outer-vortex, pass through the annular slits of the separator plate and are then deposited into the hopper. The cleaned gas then passes through the central hole on its upward spiraling path, forming the inner-vortex and rejoining the main gas stream.

The cyclone was designed with the aspect of versatility. A bolt-together construction allows complete interchangeability of its components. This versatility allows straight flow, reverse flow, and multi-inlet designs to be investigated with a minimum of added parts. The effect of dimensional modification of the cyclone components can be determined with a minimum of effort and re-design. For example, by fabricating two body cylinder extensions and one additional separator plate, eight additional cyclone configurations are possible. This allows a 'fine-tuning' of the best configuration for obtaining maximum collection efficiency.

Flanges between the sections were specified 3/8" thickness to assure dimensional stability of the mated surfaces after rigorous thermal cycling. The inlet and body sections were specified 3/8" thick to prevent warpage and assure structural stability of these parts at their elevated operating temperature. Asbestos gaskets (1/16" thick) were placed between the sections of the cyclone to insure completely leakproof operation.

All Stainless cyclone parts were Tungsten-Inert-Gas welded using Type 308 weld rod where welds were specified. Type 308 has high alloy content allowing it to compensate for alloy loss by oxidation during welding.

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III.3.3. Heat Source

A heat source was needed to supply a minimum of 80,000 BTU/HR. This rate would hold the steady-state inlet temperature at 2100°F, thus supporting agglomeration of the coal ash particulates. This rate reflects convective and radiative heat losses of the cyclone surfaces along with the heat utilized in raising the temperature of the inlet gases.

To meet this requirement an Eclipse Model 53 TA Burner of the Eclipse Combustion Division, Rockford, Illinois was selected. Its output is variable between 20,000 and 100,000 BTU/HR which allows a wide range of inlet temperatures. The "TA" burners have separate air and gas inlets so that no mixing will take place until the gas and air reach the throat of combustion block. This feature prevents flashback and allows a 0 to 300% excess air for an adiabatic flame temperature range of 1400 to 3200°F.

III.3.4. Coal Ash Sample Feeder Mechanism

A feeder mechanism was needed to supply the inlet gas stream with coal ash particulates. Inlet dust loadings between 1 and 30 grains per cubic foot were desired to provide the cyclone with a wide range of input conditions.

To meet this requirement a positive displacement rotary feeder was developed. Other feeder designs were investigated including a rotary screw feeder and an induced suction feeder (the suction was generated at a tap located just beyond an orifice plate placed in a high velocity gas stream) but the rotary slot feeder provided the most stable and uniform operation. The selected feeder can be seen in Figure 19.

As the feeder shaft rotates, small milled out slots or cups pick up coal ash from the supply hopper. The particulates are then deposited into the connecting tube and are dispensed into the inlet manifold. The inlet manifold is located in the converging section where the burner block connects the cyclone inlet. This location insures complete mixing and dispersing uniformly of ash sample in the high temperature gas stream. A Variac supplies power to a variable speed motor which drives the feeder shaft, thus allowing a predetermined dust loading input condition to be simulated.

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The relative position of the feeder can be seen in Figure 21.

The dust samples tested were taken from a central power station boiler bottom ash, electrostatic precipitator dust, and Exxon fluidized bed cyclone throughput.

III.3.5. Gas Sampling Apparatus

Gas sampling apparatus was needed to confirm the operating efficiencies, output dust loading, and the particle size distribution of the cleaned gas. These criteria were satisfied with the construction of the sampling apparatus illustrated in Figure 20.

A small sample is bled off the outlet gases and then passed through a Whatman GF/A, 7 cm diameter glass fiber filter paper. The sampling probe is made of 304 stainless steel and contoured as specified by EPA manual for isokinetic sampling. The gas then continues through a condenser which removes any water vapor from the bleed gas to insure stable operation of the gas displacement meter (wet test meter) and the vacuum pump. The gas is routed through the gas displacement meter, valve, vacuum pump, and finally a flow meter and then vented to the atmosphere. The gas displacement meter precisely measures the volume of the gas sample in the operating time interval while the flow meter indicates the instantaneous flowrate; the flowrate can be varied with the valve such that the sampling speed matches that of the outlet gas velocity from cyclone.

The filter papers are dessicated for 24 hours before all the weighings.

The output dust loading is the ratio of the weight of the particulates collected (final filter weight minus initial filter weight) to the volume of the gas sampled (as measured by the gas displacement meter). Presently, the particle size distribution is obtained by microscopic examination of the particulates collected; however, this method will be replaced with the use of a cascade impactor. Recently, a model 226, six stage inStack cascade impactor as manufactured by Sierra Instruments plus built-in back-up filter stage was available for particulate sizing.

FIGURE 20 SAMPLING APPARATUS

III.3.6. Operation Procedure

A schematic of the cyclone and support equipment is shown in Figure 21. The operation of the station can be followed in this schematic. The burner supplies hot gases to the inlet manifold; the hot gases are needed to support agglomeration of ash particulates. Ash particulates are deposited into the inlet manifold from the feeder mechanism. The particulates are brought up to fusion temperature as they mix with the hot gases in the inlet manifold and inlet section of the cyclone. As the particulates begin their downward spiraling path to the hopper, inelastic collision of particles with other particles result in a growth or agglomeration of these particles into larger particles. The particulates cool as they move farther from the heat source and are then collected in the hopper.

To begin and maintain the previously described operation of the station a procedure was adopted as follows:

- 1) Preliminary Setup: Wall valves for the air and gas supplies are opened, the air regulator is adjusted to 20 psi, the feeder is loaded with the preweighed and sample particulates, and a filter paper is installed into the sampling apparatus and tested for leaks.
- 2) Burner Ignition: The spark ignition system is energized, the pilot air supply is opened, the pilot gas supply is opened, the pilot is lit, air supply to the burner is opened to 1/2, the gas supply to the burner is opened to 1/2, ignition is visually confirmed through the peep sight, the air is opened to full, the gas is opened to full, a 15 minute or longer warm-up brings components to steady-state operating condition, the air and gas supply are adjusted to read desired flowrates and produce desired inlet temperature as read with thermocouple.
- 3) Feeder Mechanism Start-up: Power is connected to the feeder shaft motor, the stirrer, and vacuum pump of the sampling system, and the timer, cooling water is opened to the condenser, and the test run is begun.
- 4) Feeder Mechanism Shut Off: Power is disconnected from the feeder shaft motor, the stirrer, the vacuum pump, cooling water flow to the condenser is stopped, and the test run is stopped.
- 5) Burner Shutdown: The gas supply to the burner is closed, the gas supply to the pilot is closed, the air supply is closed, and the spark ignition is turned off.
- 6) Station Closing: Wall valves for the air and gas supplies are closed, the gas displacement meter reading is recorded and zeroed, the timer reading is recorded and zeroed, the filter paper is removed for examination, the feeder is emptied to determine ash fed, the cyclone hopper is removed--the collected ash emptied, the cyclone parts are cleaned with compressed air, the hopper is replaced, the condenser of the sampling apparatus is emptied, and the station closing is completed.

FIGURE 21 STATION SCHEMATIC

III.4. Experimental Results

Experiments were carried out at various loading and in a temperature range of 1650 to 2250°F. The cyclone is operated slightly above the atmospheric pressure. Because of the accuracy we are dealing with, the experimental procedure has to be followed as below:

1). Let the coal-ash particles and filter papers bake inside an electric oven for 24 hours at 120°F to release the moisture so that it will prevent the coal-ash particles from sticking in the feeder and the chance of misweighing the sample.

2.) Before all the runs, the coal-ash feed samples were sieved with 400 mesh screen that all particles are 38 μ or less.

3.) Light up the burner and warm it up at least for 30 minutes, this is the time needed to stabilize the temperature inside the burner and the cyclone.

4.) Filter paper and coal-ash samples are weighed on a microbalance, then added into the feeder. The 7 cm diameter glass fibre filter paper is inserted into the gas sampler.

5.) Set the feeder and sampler to their desired position shown on Figure 16, start the motor on the feeder and the vacuum pump connected with the gas sampler simultaneously. A timer and a flow meter have been started to register the operation time and the gas flow rate.

6.) After a preassigned running time, shut off the gas and air, stop the operation. Let the cyclone body cool down to a manageable temperature.

7.) Weigh the particles collected in the hopper and the filter paper with a precision electronic microbalance.

8.) Then, the hopper collection efficiency, sampler collection efficiency and other parameters can be calculated as follows:

$$\text{Hopper collection efficiency} = \frac{\text{weight of ash collected in the hopper}}{\text{weight of ash fed in}}$$

$$\text{Sampler collection efficiency} = \frac{(\text{weight of ash collected on the filter paper}) \times \left(\frac{\text{volume of gas drawn in cyclone}}{\text{volume of air drawn by sampler}} \right)}{\text{weight of ash fed in}}$$

$$\text{Input dust loading} = \frac{\text{weight of ash fed in}}{\text{volume of gas throughput in cyclone}}$$

$$\text{Output dust loading} = \frac{\text{weight of ash exhausted}}{\text{volume of gas throughput in cyclone}}$$

Actual pictures were taken for the particles collected in the hopper and on the filter paper as shown in Figure 22. It shows that the agglomerated particles in the hopper and the very small size particles of the order of 2μ on the filter paper.

Figure 23 shows the semi-log plot of the output dust loading versus input dust concentration. An enlarged insert is also shown for the cyclone performance at low particulate loading of incoming dust-laden gas. The output dust loading can be lowered to 0.025 grains per cubic foot of gas flow after clean-up.

Figure 24 shows the experimental hopper collection efficiency which is defined as before for 23 test runs. A collection efficiency of 92% is achieved in most of the test runs. The hopper collection efficiency is increased further and approaching the collection efficiency based on output dust loading measurements, if the weight of ashes lost in handling were excluded from the ash mass fed at the inlet. Table IV lists the test runs from #44 to #69 and their corresponding collection efficiency and operating conditions for the high temperature cyclone. This table includes the effect of various nature of dust on collection efficiency.

III.5. Work in Progress

Most recent work is progressing towards the following phases:

- 1) Particle size differentiation at both the inlet and outlet section with a seven stage cascade impactor.
- 2) Further examination of agglomerated particles with a scanning electron microscope.
- 3) Multi-inlet cyclone testing.
- 4) Modification of cyclone geometry to enhance collection efficiency.
- 5) Optimize the operating parameters.

(FILTER PAPER)

(HOPPER)

FIGURE 22 PHOTO OF PARTICLS COLLECTED IN THE HOPPER AND ON THE FILTER PAPER

(FILTER PAPER)

(HOPPER)

FIGURE 22 PHOTO OF PARTICLS COLLECTED IN THE HOPPER AND ON THE FILTER PAPER

FIGURE 23 CYCLONE PERFORMANCE BASED ON OUTPUT DUST LOADING

FIGURE 24 CYCLONE PERFORMANCE BASED ON ASH HOPPER COLLECTION

TABLE III

HIGH TEMPERATURE CYCLONE EFFICIENCY AND OPERATION CONDITION SUMMARY

<u>Run #</u>	<u>Hopper Collect. Efficiency, %</u>	<u>Sampler Collect. Efficiency, %</u>	<u>Temp., °F</u>	<u>Run Time, Sec.</u>
15	90.7	93.8	2100	300
16	86.7	93.0	2250	300
18	86.9	92.6	2250	300
21	88.2	93.3	2250	300
22	90.7	94.5	2200	300
24	84.2	93.1	1900	300
25	82.2	94.9	2050	300
27	84.7	96.9	1900	300
28	84.0	95.9	1950	300
30	81.9	98.4	1720	300
31	79.5	99.5	2000	300
32	93.2	99.6	2000	600
33	86.0	97.6	2000	600
36	83.2	98.7	2000	600
37	84.4	98.5	2000	600
38	85.9	98.8	2000	600
39	93.2	98.9	2000	600
40	88.6	98.9	2000	600
41	90.9	98.9	2000	1800
42	91.1	98.6	2000	1800
43	92.0	99.0	2000	1800
<hr/>				
Average of	87.1 $\pm$ 3.9	96.8 $\pm$ 2.5		

TABLE IV

HIGH TEMPERATURE CYCLONE EFFICIENCY AND OPERATION SUMMARY

RUN #	HOPPER COLLECTION EFFICIENCY, %	SAMPLER COLLECTION EFFICIENCY, %	INPUT DUST LOADING, GR/FT ³ ,	TEMPERATURE °F	RUN TIME, SEC	DUST
58	90.4	97.8	7.16	2000	1500	Plant Bottom Ash-seived
59	88.9	96.8	6.12	2000	1900	electro-static precipitator
60	84.4	94.3	6.75	1600	1200	
61	82.5	92.3	7.07	1600	1390	
62	Dust from the third cyclone as supplied by Exxon, feeder-stalled					
63	84.5	98.7	4.8	1800	900	Exxon 2nd cyclone -unseived
64	91.7	97.3	6.2	1800	1500	
65	92.6	97.7	6.6	1600	1200	
66	91.9	96.7	6.6	1800	1260	
67	system leak					
68	90.4	98.1	6.93	1800	1150	Exxon 2nd cyclone -seived
69	92.1	98.8	5.65	1800	1500	

TABLE IV(cont.)

RUN #	HOPPER COLLECTION EFFICIENCY, %	SAMPLER COLLECTION EFFICIENCY, %	INPUT DUST LOADING, GR/FT ³	TEMPERATURE °F	RUN TIME, SEC	DUST
44	90.2	99.5	3.03	2000	1800	Bottom ash sieved
45	91.1	98.4	3.95	2000	1800	
46	87.2	94.5	7.86	2000	1500	
47A	90.8	99.2	7.45	2000	1160	Bottom ash
47B	90.1	98.3	9.37	2000	1160	Bottom ash
48	90.7	98.9	11.46	2000	900	
49	91.0	98.7	16.21	2000	1500	
50	91.2	98.7	14.6	2000	900	
50A	86.2	98.7	10.36	2000	1160	ESP
51	81.9	99.2	6.94	2000	1800	ESP
52	85.4	98.9	5.92	2000	1500	ESP
53	86.6	96.8	6.97	2000	1800	Exxon 2nd cyclone
54	84.5	91.8	7.91	1800	1500	ESP
55	90.1	98.9	5.22	2000	1500	Bottom ash
56	84.7	98.6	2.83	1800	1520	ESP
57	90.6	99.5	6.72	1800	900	Exxon 2nd

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FIGURE B CYCLONE BODY

FIGURE C

CYCLONE OUTLET

FIGURE D CYCLONE INLET

FIGURE E CYCLONE

FIGURE F

SEPARATOR PLATE

FIGURE G HOPPER

THE UNIVERSITY OF WISCONSIN—MILWAUKEE/P. O. Box 784, Milwaukee, Wisconsin 53201

COLLEGE OF ENGINEERING AND APPLIED SCIENCE
MECHANICAL ENGINEERING DEPARTMENT

(414) 963-5191

March 5, 1989

Dr. Paul C. Scott
Program Officer
Division of Planning and Systems
Department of Energy-Fossil Energy
Washington, D.C.

RE: Final Tech. Report, Grant #EF-77-G-01-2753

Dear Dr. Scott:

In accordance with the grant award provisions, I am submitting two copies of the final technical report for the grant period (9/1/77-12/31/79) on "Particulate Removal at High Temperature and Pressure by Self-Agglomeration in a Cyclone" for your review and comment.

The study of a high temperature agglomeration cyclone for particulate removal reveals that the approach is reliable, cost effective and good submicron particle removal efficiency. The method is analytically sound and verified in the laboratory. We strongly recommend that the project be pursued further for scale-up test as an alternate and practical method in hot gas clean up systems.

We appreciate the financial support from ERDA during the grant period and are looking for other opportunities to serve the needs in fossil energy research.

Thank you very much.

Sincerely,

Keh C. Tsao
Professor of Mechanical Engineering

Encl.

cc: DOE Grant Officer: Ms. Amy L. Simpson
DON-ONR-Chicago Office: Mr. J. Michalski
UWM Grants and Contracts

FIGURE 1 **HIGH EFFICIENCY CYCLONE WITH**
TYPICAL DIMENSIONAL RATIOS

FIGURE 2 **DOUBLE-VORTEX PATH OF THE
GAS STREAM IN A CYCLONE**

FIGURE 3

COLLISION DUE TO DIFFERENT RADIAL
VELOCITIES OF PARTICLE

FIGURE 4 DIMENSION PARAMETERS OF CYCLONE

FIGURE 5 COMPUTED EFFICIENCY VS.
PARTICLE MEAN DIAMETER

(a) BEFORE

(b) DURING

(c) AFTER

FIGURE 7 SCHEMATIC DIAGRAM OF COLLISION

FIGURE 9 VISCOSITY-TEMPERATURE RELATIONSHIPS FOR
SOME MODEL COAL SLAGS - IGT REPORT NO.
HCP/T2286-01, IIT CENTER, CHICAGO, ILLINOIS

FIGURE 10 COMPARISON OF MEASURED VALUES, WATT-FEREDAY VALUES, AND MODIFIED WATT-FEREDAY VALUES, IGT REPORT NO. HCP/T2286-01, IIT CENTER, CHICAGO, ILLINOIS.

$r = 2.96$ CM
 $Q = .388$ M³/MIN
 $\mu = 558$ POISE
 $\delta = 150$ DYNE/CM

FIGURE 11a ENERGY VERSUS MOLTEN LAYER THICKNESS

$r = 2.96 \text{ CM}$
 $Q = .388 \text{ M}^3/\text{MIN}$
 $U = 558 \text{ POISE}$
 $\sigma = 150 \text{ DYNE/CM}$

FIGURE 11 b ENERGY VERSUS MOLTEN LAYER
 THICKNESS

$r = 2.96$ CM
 $Q = .388$ M³/MIN
 $U = 558$ POISE
 $\delta = 150$ DYNE/CM

FIGURE II C ENERGY VERSUS MOLTEN LAYER
 THICKNESS

FIGURE 12 a ENERGY VERSUS RADIAL POSITION r

FIGURE 12 b ENERGY VERSUS RADIAL POSITION r

FIGURE 12 c ENERGY VERSUS RADIAL POSITION r

$r = 2.96 \text{ CM}$

$\delta = .22 R_S$

$\mu = 558 \text{ POISE}$

$\sigma = 150 \text{ DYNE/CM}$

----- ENERGY REQUIRED FOR SEPARATION

———— ENERGY OF APPROCHING BEFORE COLLISION

FIGURE 13 ENERGY VERSUS VOLUMETRIC FLOW
RATE Q

FIGURE 14 AVERAGE AGGLOMERATION RATE VERSUS COMPUTED SAMPLE INITIAL PARTICLE SIZE COMPOSITION FOR 30 SECONDS EXPOSURE TIME.

FIGURE 15

AVERAGE AGGLOMERATION RATE VERSUS COMPUTED SAMPLE INITIAL PARTICLE SIZE COMPOSITION FOR 60 SECONDS EXPOSURE TIME.

FIGURE 16 SCHEMATICS OF SET UP

FIGURE 18 CONSTRUCTION OF FEIFEL HOPPER
WITH SEPERATOR PLATE

FIGURE 19 FEEDER MECHANISM

FIGURE 20 SAMPLING APPARATUS

FIGURE 21 STATION SCHEMATIC

FIGURE 23 CYCLONE PERFORMANCE BASED ON OUTPUT DUST LOADING

FIGURE 24

CYCLONE PERFORMANCE BASED ON ASH HOPPER COLLECTION

FIGURE B CYCLONE BODY

FIGURE C CYCLONE OUTLET

FIGURE D CYCLONE INLET

FIGURE E CYCLONE

FIGURE F SEPARATOR PLATE

FIGURE G HOPPER