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COAL-ASH AGGLOMERATION MECHANISM AND ITS APPLICATION IN HIGH TEMPERATURE CYCLONES

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ABSTRACT

The increase of particulate removal efficiency in a high-temperature cyclone is being examined analytically. A simple and effective approach is presented to view the coal-ash agglomeration phenomenon near its softening/fusion temperature. The probability of adhesion of the neighboring particles when coupled with the number of collisions of particles in a high-temperature cyclone appears to demonstrate that the high-temperature/pressure cyclone dust collector is capable of meeting the challenge of hot-gas cleanup problems. The effect of momentum of particles, surface tension, and viscosity of molten boundary layer enclosing a core particle is investigated for the enhancement of particle adhesion. Analytical computations and laboratory experience of a high-temperature cyclone are presented.

INTRODUCTION

The effective use of fluidized bed combustion products at high temperature and pressure in a combined steam and gas turbine cycle plant depends on the particulate removal efficiency in a hot gas clean-up system to insure safe operation of gas turbines (1,2). Presently, there are numerous research and development projects involving cyclones (3,4), granular bed filters (5), molten salt scrubbers (6) and other hybrid processes such as sonic agglomerators(7) and charged filters in modified electrostatic precipitators (8). However, some specific problems such as the effect of sticking of adherent particles, recycling of cleaning media and decreasing of collection efficiency at high temperature in clean-up apparatus result in making hot gas particle removal a major technical challenge.

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An efficient and cost-effective approach utilizing the self-agglomeration phenomena of carbon-ash particles near its fusion temperature to a modified multi-pass cyclone was proposed for feasibility study (3). The combustion products, or the coal-ash particle-ladden gas when passing a high temperature zone in the cyclone, would enter momentarily a pseudo-molten state. The particles will coagulate, agglomerate and adhere together to grow to larger sizes. The larger size particle will subsequently be separated out under the centrifugal action. Particulate removal efficiency will be increased far beyond the performance of a conventional cyclone which is effective only for particles larger than ten microns. It was reported that the ability of an experimental high temperature cyclone to collect submicron particles (particles on the order of 2 μ) were increased substantially (9). However, the coal-ash agglomeration mechanism as it is occuring in a high temperature cyclone is not fully understood.

Based upon the observed coal-ash agglomeration phenomena in a laboratory high temperature cyclone, Figure 1, this study presents a conceptual model of agglomeration mechanism before and after collision. Effects of particle size, molten layer size, molten layer thickness enclosing the solid particle, and the kinetic energy of particles before collision are examined.

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ANALYTICAL FORMULATION

The general design of a dry involute cyclone with rectangular inlet section assumes that the particles in the dirty gas stream have the same tangential velocity (10). After entering the cyclone proper, the magnitude of radial velocity component varies according to its size. Under the centrifugal action, it is expected that collision will take place among the particles along its spiral path. At any time t after the particles passed the inlet section, and at any radius r, the relative velocity in the radial direction between a larger and a smaller particle was given by (10,11),

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

where r_1 is the inner radius of the cyclone; r_2 is the radius of the cyclone body ($r_2 = r_1 + b$); b is the inlet section width; w is the inlet duct height; Q, the gas volumetric flow rate; μ_a, the viscosity of air at operating temperature and pressure, ρ_p, the mass density of the solid particle; and d_l and d_s are the diameters of larger and smaller particles.

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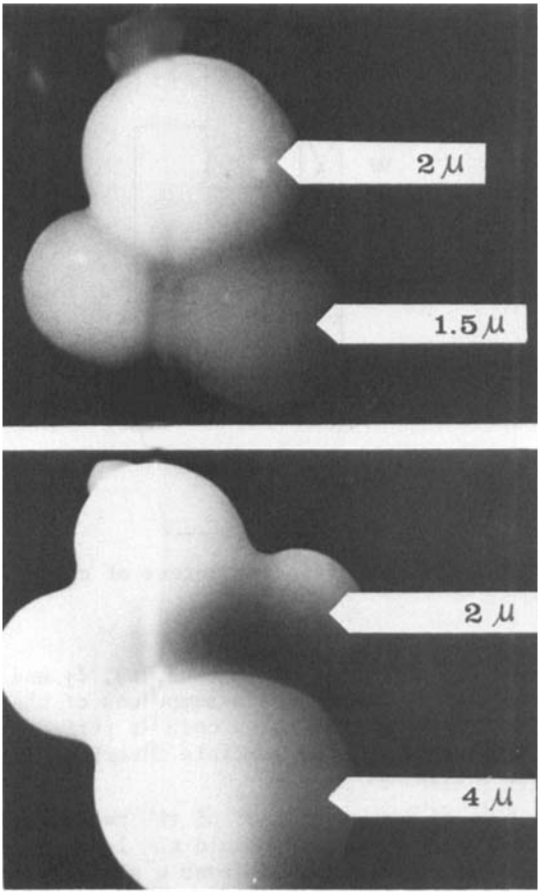

FIGURE 1. Photograph of agglomerated particles.

It was premised that a 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 embraces and fuses together as a result of collision and impaction, thus forming a greater size of particle.

Figure 2 shows the geometry of the cyclone under study. Figures 3a, 3b, 3c show the collision mechanism of two particles

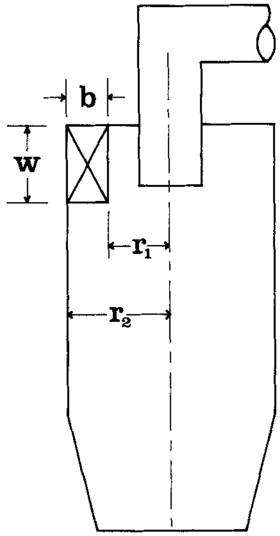

FIGURE 2. Dimension parameters of cyclone.

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with radii R_l and R_s; molten layer thicknesses, δ_l and δ_s; and approaching velocity v. Under the assumptions of that all the particles are spherical and the solid core is perfectly elastic, Figure 3b and 3c hypothesize the particle interfacial mechanism during and after colliding.

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 layer 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 interface. In either case, the kinetic energy of the moving particle is being retarded, absorbed and dissipated, thus favoring agglomeration. Figures 3b and 3c show also the forces acting upon both particles during and after collision. 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,

$$\text{Kinetic energy for separation} \leq \text{Energy dissipation due to friction and form drag} + \text{Work done due to interfacial force of liquid layer} \quad (2)$$

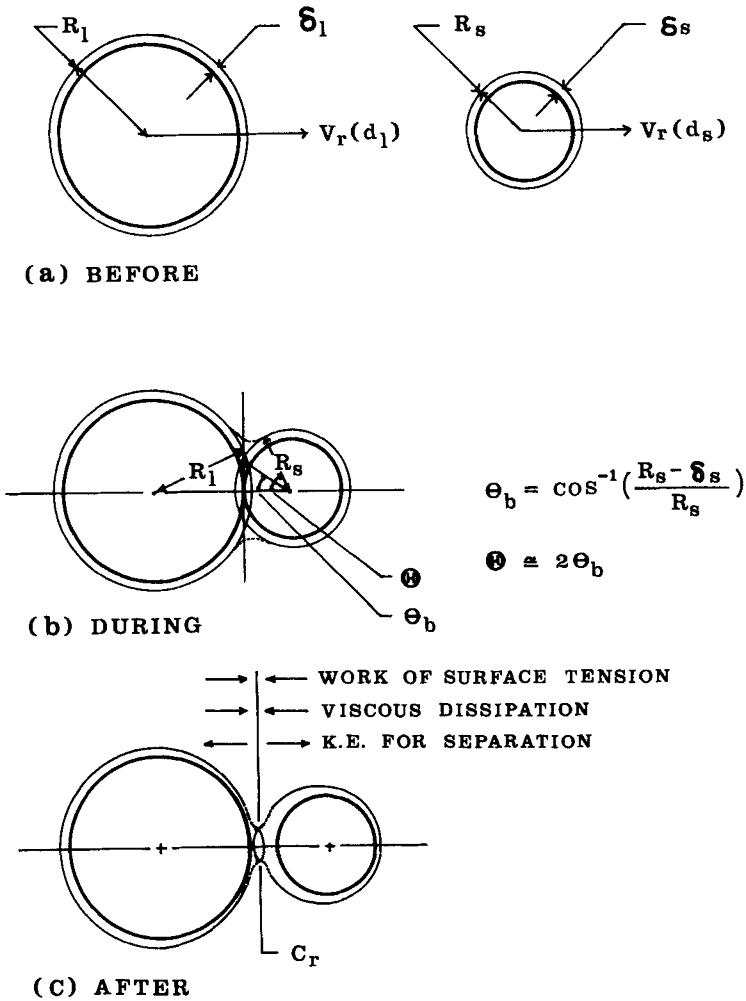

FIGURE 3. Schematic diagram of collision.

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

$$V_c = \frac{m_l V_r(d_l) + m_s V_r(d_s)}{m_l + m_s} \tag{3}$$

where m's are the masses of particles, v_r's the radial velocity;

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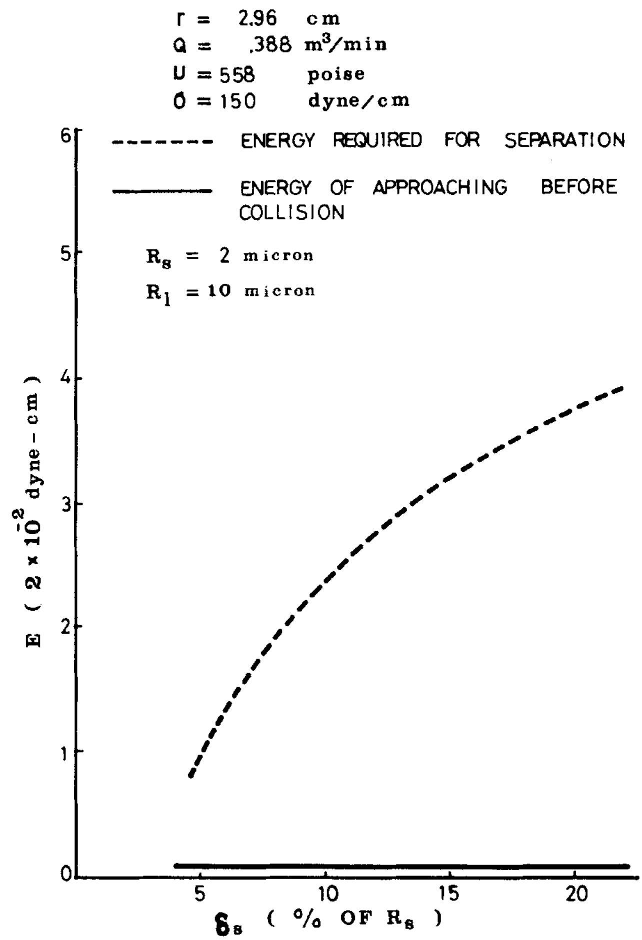

FIGURE 4a,b,c. Energy versus molten layer thickness δ_s.

and subscripts l and s refer to larger and smaller particles. Since at the instant of colliding of two particles, the estimated Reynolds number of the molten liquid layer is found to be on the order of 0.01 or smaller, the particle drags are then approximated as in the creeping flow (12) and is calculated from

$$F_n = \int_0^{2\pi}\int_0^{\Theta} \left(\frac{3}{2} \frac{\mu V_c}{R_s} \cos^2\theta \right) R_s^2 \sin\theta \, d\theta \, d\phi \qquad (4)$$

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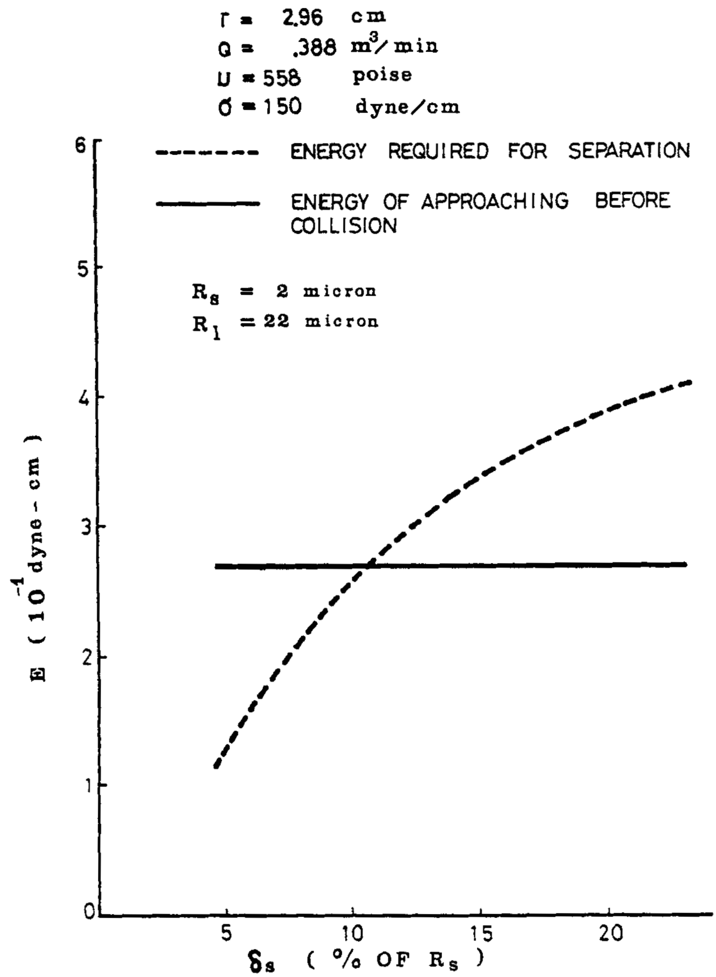

FIGURE 4B

$$F_t = \int_0^{2\pi}\int_0^{\Theta} \left(\frac{3}{2}\frac{\mu V_c}{R_s}\sin^2\theta\right) R_s^2 \sin\theta \, d\theta \, d\phi \qquad (5)$$

where Θ 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 3b,

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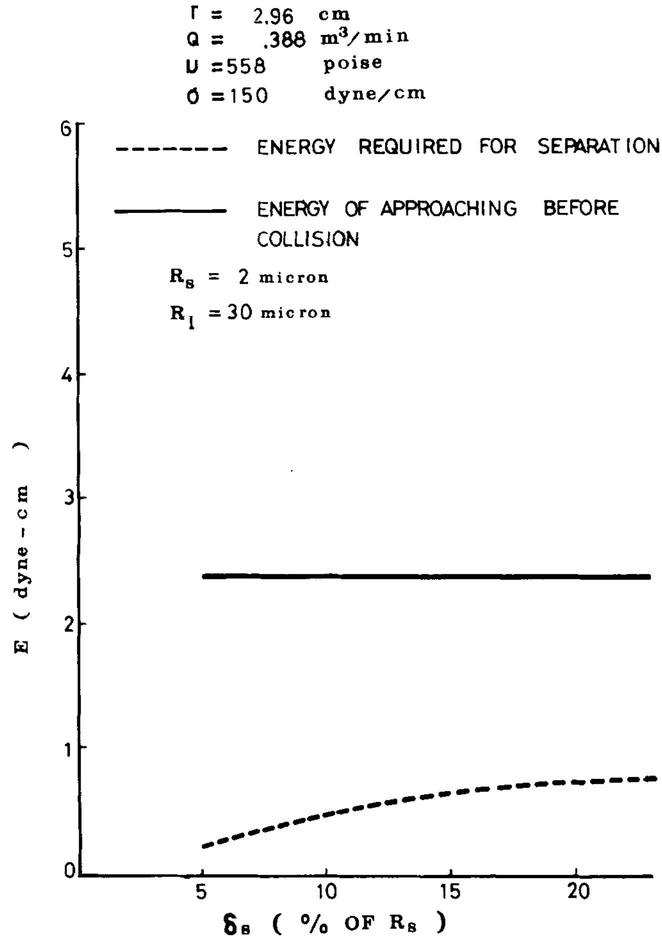

FIGURE 4C

$$\theta_b = \cos^{-1}\left(\frac{R_s - \delta_s}{R_s}\right) \tag{6}$$

multiplication equations (4) and (6) by x (= R_s - $R_s \cos\theta$), the linear distance of common liquid layer along the line of impaction, represents the energy, E_f, dissipated through viscous effect,

$$E_f = 3\pi\mu V_c R_s^2\left(\frac{5}{4} - \cos\theta - \cos^4\theta + \frac{\sin^4\theta}{4}\right) \tag{7}$$

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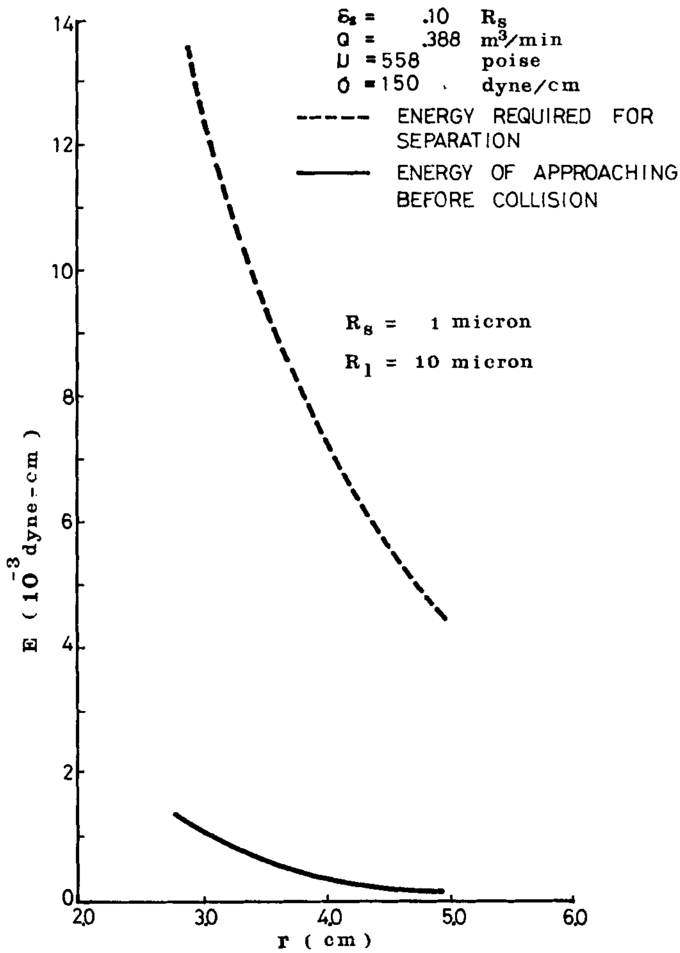

FIGURE 5a,b,c. Energy versus radial position r.

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 3c.

Assuming the circumference, Cr, of the contact area decreases linearly with respect to the distance between the particle center, two particles will be detached completely if the center distance reaches (R_1 + δ_1 + R_s + δ_s). The energy needed to separate the two particles after collision is the work done in changing the area of a surface film, which is

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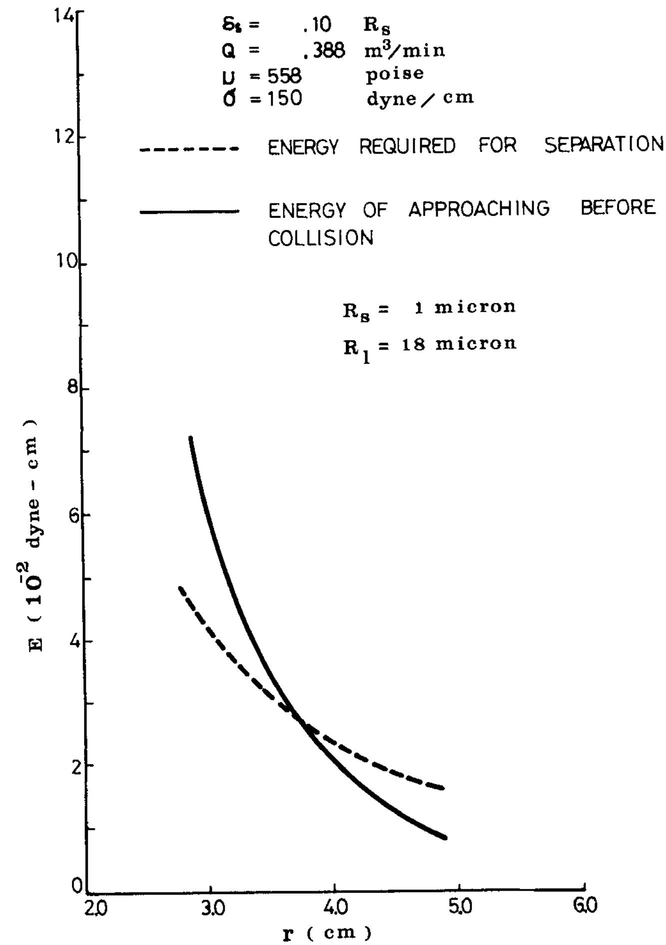

FIGURE 5B

$$E_s = (C_r \sigma) \cdot \frac{2(\delta_l + \delta_s)}{2} \qquad (8)$$

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

$$C_r = 2\pi\sqrt{R_l^2 - (R_l - \delta_l)^2}$$

For simplicity, take the origin of coordinate of approaching system at the center of the smaller particle, the kinetic energy

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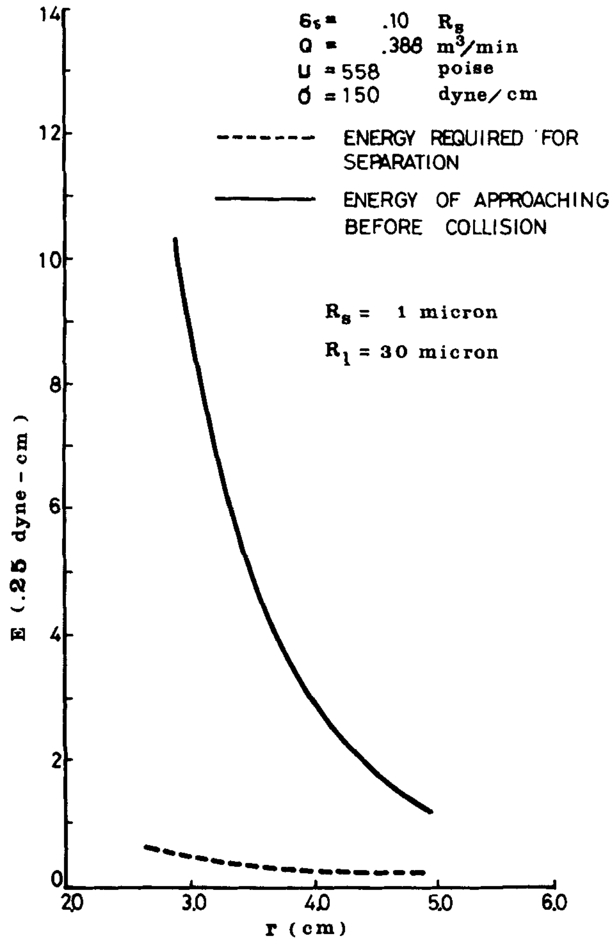

FIGURE 5C

E, as carried by the larger particle is 1/2 $M_l v^2$. 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.

RESULTS AND DISCUSSION

With the availability of coal-ash physical and chemical properties (13), the effect of molten layer thickness enclosing the smaller particle, δ_s, upon agglomeration is shown in Figures 4a,

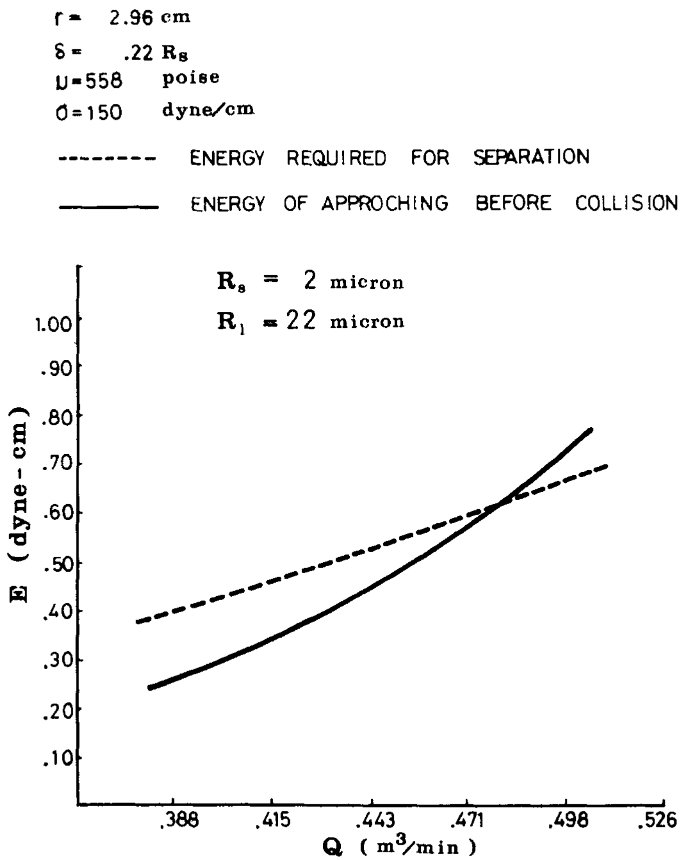

FIGURE 6. Energy versus volumetric flow rate Q.

4b, and 4c. At the conditions described for computation, the collision of 2 μ and 22 μ particles at a radial position of 2.96 cm away from the cyclone center, does show that the particles will stay together after collision, if $\delta_s \leq 0.1\ R_s$ and vice versa. For particles smaller than 10 μ , Figure 4a, and greater than 30μ, Figure 4c, agglomeration and fragmentation will taken 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 5b 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 particle pair becomes closer, Figure 5a shows

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such a case where entire cyclone space can be utilized for the intended agglomeration process. Figure 5c 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 chose set of operating parameters Figure 6 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 10 μ , the high temperature cyclone is an effective device favoring agglomeration.

It is of interest to note that the combined effect of volumetric flow rate and the cyclone radii display opposite trends toward agglomeration. It is highly probable that an optimum design incorporating all parameters for high temperature cyclone can be synthesized. Even though the proposed mathematical model did not take into consideration of other physical factors such as the intermolecular and gravitational force effects, the real kinematic and dynamic flow behavior at the interface, yet the model shall serve as an analytical guide in constructing the high temperature cyclone for pilot testing and for further improvement in practical engineering design. In conclusion, the increased collection efficiency of an experimental high temperature cyclone (9) thus can be explained by the proposed simple yet effective conceptual approach.

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