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ABSTRACT

Fluidized bed combustion studies have resulted in the development of a burner with 99.98% carbon utilization efficiency. This was made possible partly by use of a fines burning modeling technique that predicts burning efficiencies as a function of process parameters. A shrinking sphere reaction model was used in conjunction with empirical combustion kinetics data, actual particle size distribution, and gas environment variables such as temperature, pressure, and composition to determine required recycle rates for complete combustion.

The fines burning model was verified on a 0.40-m (16-in.) diameter atmospheric burner operated at 1.1-m/s (3.6-ft/s) superficial velocity at 900°C (1650°F). During a 50-h test, burn rates of over 60 kg/h (130 lb/h) were attained. Carbon fines generation amounted to over 30% of the feed [which was sized to -5 mm (-3/16 in.) ring size], but the final carbon inventory was less than 0.5 kg (1 lb) upon completion of the test. Fines recycle rates during the test averaged 7 kg/min (15 lb/min); the fines combustion model had predicted a required recycle rate of 8 kg/min (17 lb/min). This close correlation lends a good measure of credibility to the techniques used in analyzing fine carbon combustion characteristics.

This technique was also used to analyze coal fines combustion by recycle to the fluid bed. Reasonable recycle rates are predicted for lower bed fines injection.

INTRODUCTION

General Atomic has been testing fluidized bed combustion concepts since 1969. This work, funded by the Department of Energy (DOE), has been directed toward processing crushed graphite fuel elements discharged from nuclear reactors.

Basic design research for scale-up was carried out on a 0.20-m (8-in.) diameter burner. A 0.40-m (16-in.) diameter burner, constructed in 1976, has successfully operated in processing campaigns since then.

Several fines recycle techniques have been tested on these burners, including both gravity and pneumatic transport to the upper and lower portions of the fluid bed. For graphite combustion, gravity recycle to the upper bed region was found to be optimal. This mode minimized recycle equipment requirements and led to high combustion efficiencies.

It is important to realize that combustion of fuels such as coal may be optimized using other fines recycle techniques, such as pneumatic injection to the lower bed area. The fines combustion modeling technique presented in this paper can be used to help make decisions on fines recycle design.

PROCESS FLOW DESCRIPTION

Typical process flow conditions for the 0.40-m (16-in.) burner during steady-state operations are shown in the process flow diagram (Figure 1). A photograph of the burner is shown in Figure 2. Fluidizing gas is brought into the lower section of the burner to maintain 1.2-m/s (3.6-ft/s) fluidizing velocity at 900°C (1650°F). This inlet gas consists of a mixture of CO_2 and O_2 sufficient to reach a carbon burn rate of 900 g/min

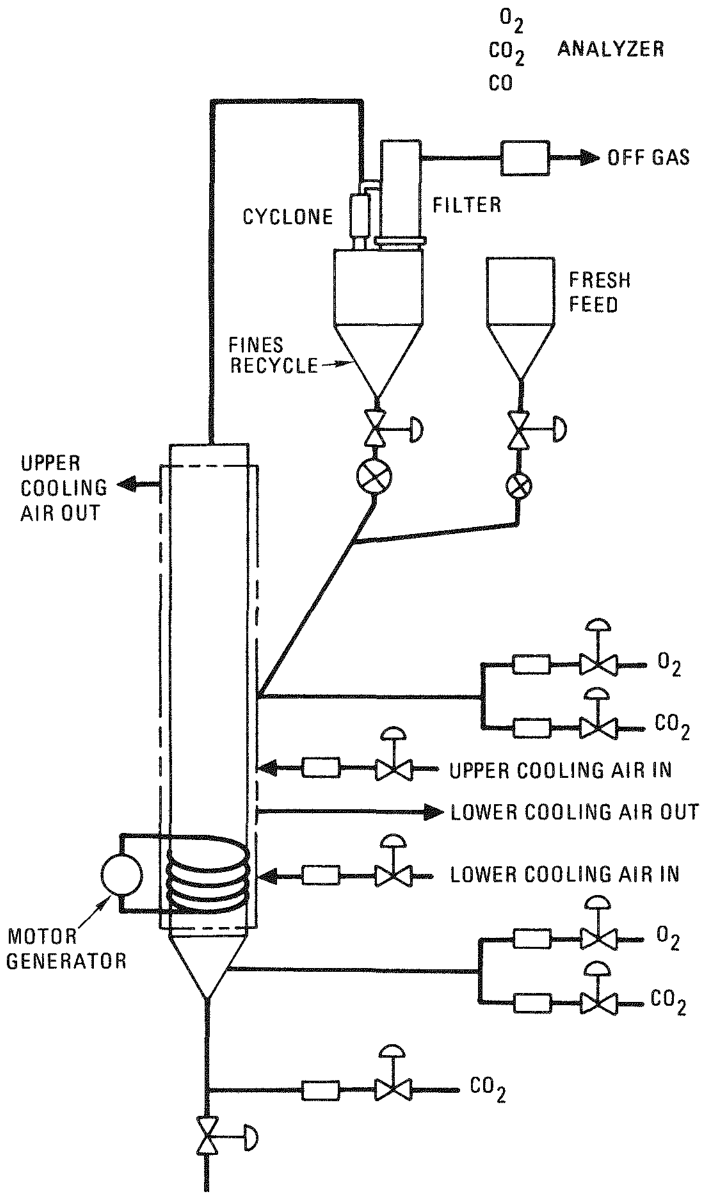


Fig. 1. Process flow diagram for fluidized bed burner.

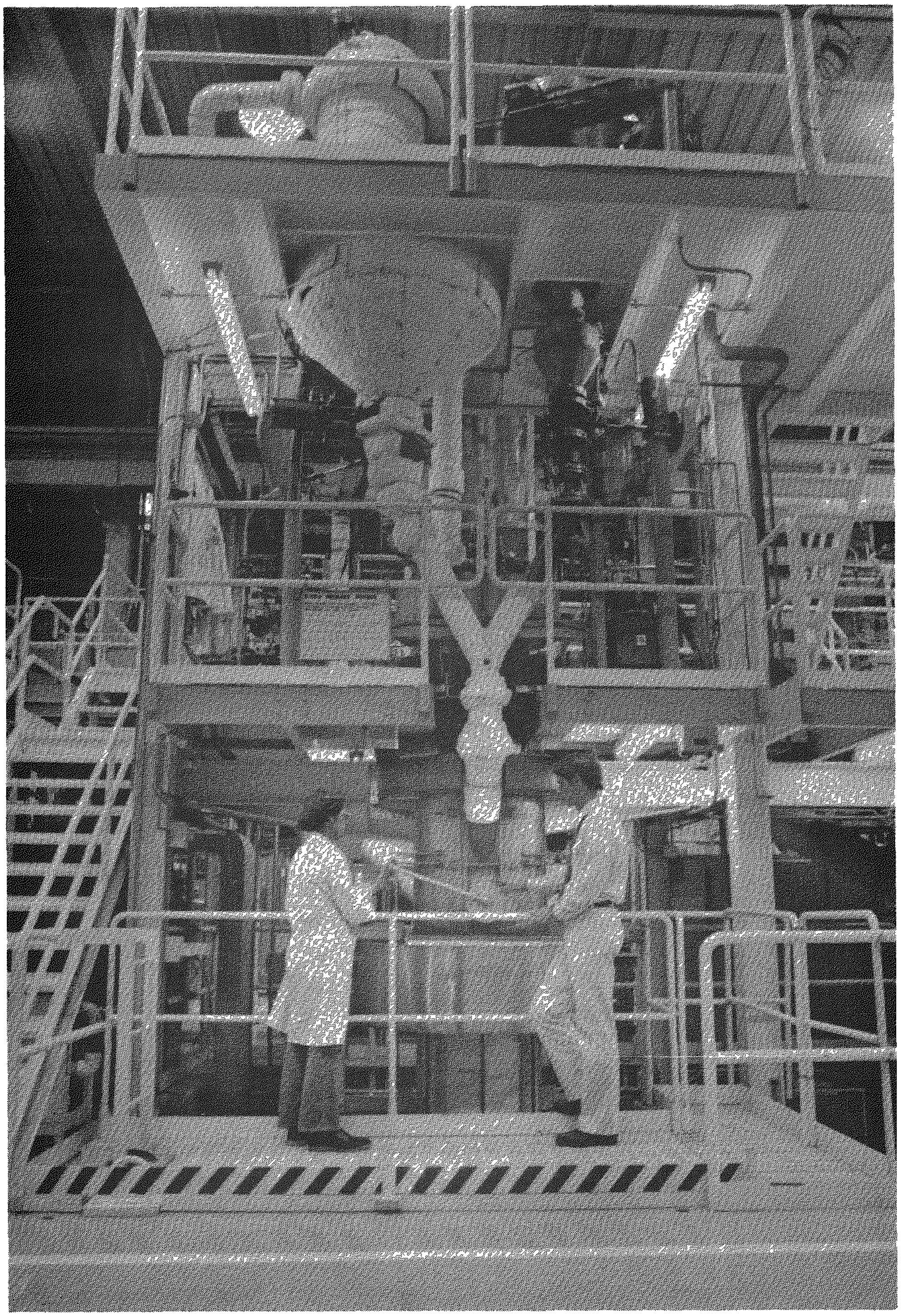


Fig. 2. 0.40-m (16-in.) primary burner

(2 lb/min). This corresponds to a heat generation rate of 420,000 kcal/min (1,700,000 Btu/hr) or 0.5 MW. As the gas leaves the fluid bed, it elutriates fine carbon through the freeboard area, up through a jacketed cooling pipe, to a cyclone and sintered metal filter chamber. The filtered gas (no particles >1 micron) is then routed to subsequent cleaning stages.

The fine carbon drops from the cyclone and filter chamber to an aerated surge bunker. It is metered back into the midburner area by a high-temperature rotary valve operating at 700°C (1300°F). This recycle is gravity-induced with no pressurization required.

A mixture of CO_2 and O_2 enters the burner in the same area as the recycled fines. There is sufficient oxygen to maintain the rates of carbon fines combustion and generation approximately equal. Carbon fines constitute one-third of the burner feed rate.

Feed material is added through a rotary valve to give continuous feed capabilities. The feed is graphite, crushed to less than 5 mm (0.1875 in.). This graphite contains small fuel particles that are impervious to the combustion conditions and remain as intact spheres 500 microns (0.020 in.) in diameter. These particles are dense (5 to 10 Mg/m^3) and comprise 10% of the fuel volume. After each 24 h of combustion, the accumulation of these particles makes it necessary to remove a portion of them, normally 250 kg (550 lb) per day. They are removed through a port at the lower end of the burner.

It should be noted that the graphite fuel is pure carbon, without any volatile combustibles. This means that combustion is much more difficult to sustain than with any type of coal. The recycling fine carbon must be oxidized at temperatures where kinetics are marginal, at best.

Burner heat removal is via cooling air routed through annular cooling jackets (around the lower burner tube, upper burner tube, burner-to-cyclone transfer pipe, and the cyclone itself).

MODEL FOR PREDICTING FINES COMBUSTION REQUIREMENTS

Fluidized bed graphite burners at General Atomic achieve a very high carbon utilization efficiency. A fines burning model that predicts burning efficiencies as a function of process parameters contributed to the development. Figure 3 is a pictorial summary of of the model.

A shrinking sphere reaction model is used in conjunction with empirical combustion kinetics data, actual particle size distribution, and gas environment variables such as temperature, pressure, and composition to determine how long it takes to burn a particle to extinction. Integrating over the range of particle sizes and the variation of gas composition leads to a prediction of carbon combustion rates. Residence times in the combustor are used to determine the fraction of fine carbon burned per recycle pass. Recycle rates and handling requirements can then be calculated and fitted to the overall burner gas flow and heat balance needs.

This model may be readily extended to other fines recycle situations, provided that kinetic data are available and some representation of system flows and concentrations can be assumed.

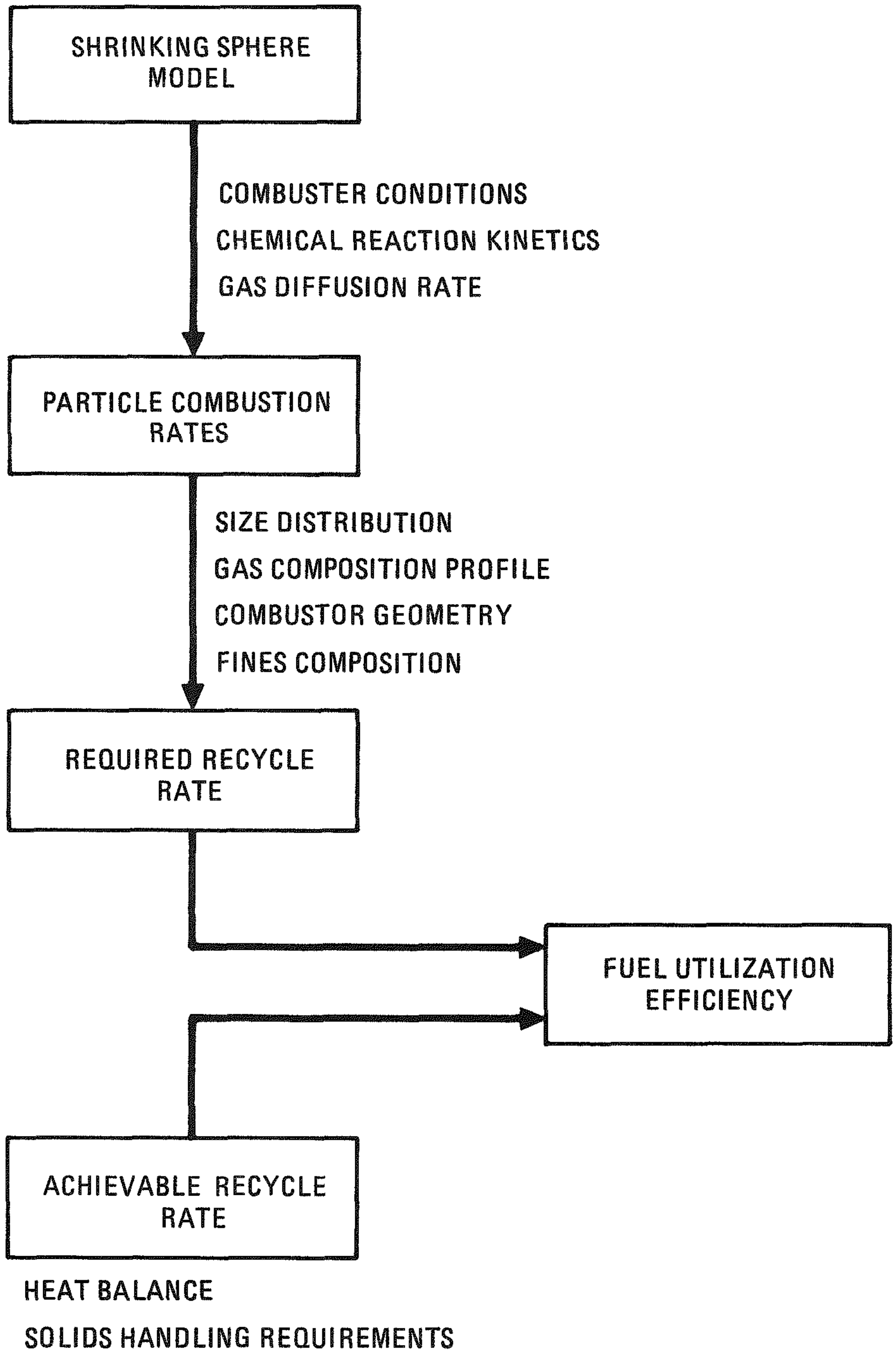
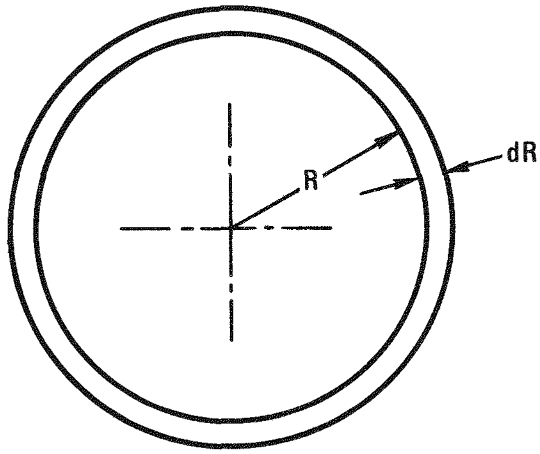


Fig. 3. Model for predicting fuel utilization efficiency for fines recycle.

The shrinking sphere model derivation is as follows:



A_S = particle surface area, cm^2

ρ_B = material molar density, moles/cm^3

ρ_B(graphite) = 0.167 moles/cm^3

C_A = gas O_2 concentration, moles/cm^3

$\bar{k}$ = reaction rate constant, cm/s

($\bar{k}$ based on unit surface is taken directly from Figure 4)

R = particle radius = 1/2 particle diameter = 1/2 d

d_{po} = particle size (cm) = $\frac{dp\ (\text{microns})}{10{,}000}$

Rate of particle shrinkage = rate of reaction

Basic rate equation:

$$-\rho_B \frac{dR}{dt} A_s = k\ A_s\ C_A$$

However, C_A is a function of the time:

$C_A = C_{Ai}$ at $t = 0$

$C_A = C_{Ao}$ at $t = T$ (T = total residence time in burner)

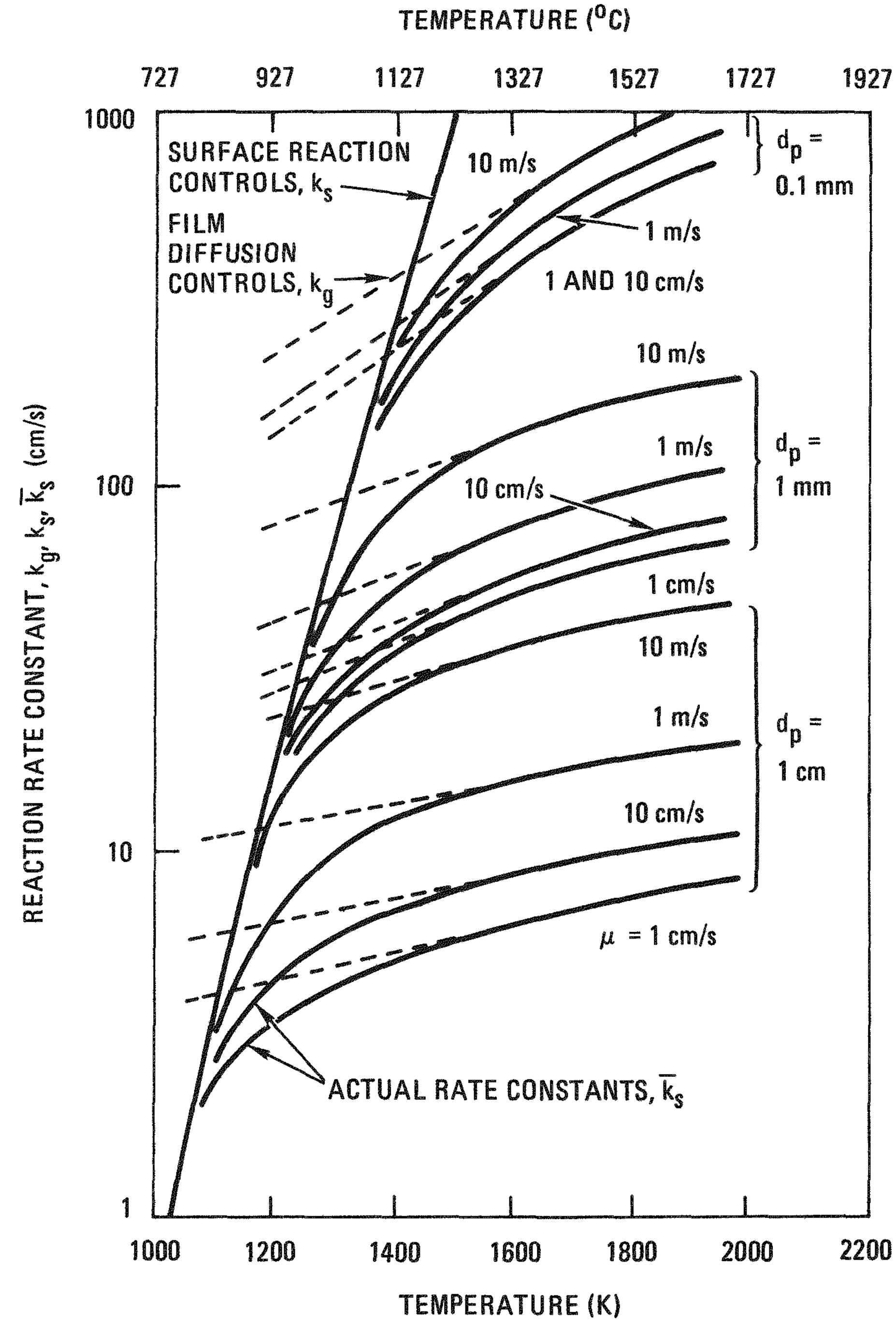


Fig. 4. Rate of combustion of pure carbon particles (from Ref. 3).

Integrating and rearranging,

$$T = \frac{d_{po}\ \rho_B}{K(C_{Ai} + C_{Ao})}$$

The result, T, is the time required to burn the particle to extinction.

As an example, this resulting equation was solved for the burner conditions encountered during a 50-h test. Since the recycling fines have a distribution of sizes, T was solved for five representative particle sizes: 50, 100, 200, 300, and 400 microns. The oxygen concentration where the fines are reintroduced to the burner was 28 vol % or 3.5×10^{-6} moles/cm^3; the off-gas O_2 concentration was 2 vol % or 0.3×10^{-6} moles/cm^3. The burning zone temperature was 900°C (482°F) and the gas velocity was 1.1 m/s (3.6 ft/s). The following results were obtained:

Particle Size, microns	Time To Burn Particle To Extinction, s
50	18
100	35
200	70
300	105
400	140

The size distribution of the fines was as follows:

Size Range, microns	Weight Fraction
0-50	0.30
50-100	0.30
100-200	0.29
200-300	0.08
300-400	0.03

Given that the fines residence time in the burner is 2.1 s, the number of recycle loops to completely combust each size range of particle can be calculated. The weighted average number of recycle loops was then determined to be 23. This means that fines must be recycled at 23 times the required fines burn rate to maintain sufficient reaction surface area in the fines burning zone.

The average fines burn rate during the 50-h test was 340 g/min (0.7 lb/min). This model predicted a required recycle rate of 8 kg/min (17 lb/min). It was found that 7 kg/min (15 lb/min) were required to maintain combustion levels. This close correlation lends a good measure of credibility to the techniques used in analyzing fine carbon combustion characteristics.

Total fines generation during the test was over 500 kg (1100 lb), but the inventory in the burner system at the end of the test was less than 0.5 kg (1 lb). This conclusively demonstrates the concept of fines combustion using a recycle technique.

FINES RECYCLE IN A PRESSURIZED FLUIDIZED BED COAL COMBUSTOR

The fines burning model has been applied to a pressurized coal combustor to determine the feasibility of combustion of recycled fines. Two major cases were examined: recycle to the upper fluid bed region and recycle to the lower fluid bed region. The two cases were compared for the following conditions:

6.96 kW-h/kg (10,800 Btu/lb)

20% excess air

1.01 MPa (10 atm)

Fines burning zone temperature = 843°C (1550°F)

Fluid bed velocity = 1.2 m/s (4 ft/s)

Elutriation: 15% of feed

Two cyclones: ~98% efficient

Fine char has same combustion kinetics
as graphite (conservative assumption)

Freeboard length = 2.03 m (6 ft 8 in.)

Expanded fluid bed depth = 2.69 m (8 ft 10 in.)

Average fines residence time in bed = 30 s

Inlet O_2 concentration = 21%

Given the above, the ratio of recycle rate to feed rate as a function of overall desired fuel utilization efficiency was calculated for lower bed and upper bed recycle. The results are given in Table 1.

Lower bed recycle requires modest recycle rates and was selected as the more favorable of the two cases. As shown in Table 1, a recycle rate of 0.4 times the coal feed rate is required to attain 98% fuel utilization.

TABLE 1
COMPARISON OF LOWER AND UPPER BED RECYCLE (AT 10 ATM)

Overall Fuel Utilization Efficiency	Recycle Rate/Feed Rate	
	Lower Bed Recycle	Upper Bed Recycle
0.85	0	0
0.90	0.03	1.4
0.95	0.12	3.9
0.98	0.4	9.0
0.99	0.8	17.7

Upper bed recycle would require higher rates of solids reinjection in order to attain reasonable efficiencies of fine carbon combustion.

As shown in Figure 5, lower bed recycle would use a portion of the incoming, preheated combustion air for solids transport into the combustion unit. Coal could be combined with the recycled fines in the injection hopper for mixed entry to the fluid bed. Thus, there is no air flow cost specific to recycling the fines.

Internal cooling capabilities would be provided in the bed and in the deentrainment space to keep the entire combustor isothermal at 843°C (1550°F). Hot gas cleanup would be an integral part of the fines recycle system to prepare the hot gas stream for turbine expansion and subsequent release.

Fines inventory would be constantly controlled using a weir overflow arrangement in the fines sytem. Bed depth would be also controlled by continuous ash and sorbent removal from the lower bed area.

An atmospheric pressure unit would require higher recycle rates due to the lower oxygen partial pressure. A factor of approximately 8 times the recycle rate required for pressurized combustion should be used. For atmospheric lower bed recycle at 98% fuel utilization, the required fines recycle rate is predicted to be 3.2 times the coal feed rate.

The assumptions used in this model must be verified using the coal and limestone intended for the large combustor. The size of the test unit should be no less than 30.5-cm (12-in.) diameter to minimize wall effects and allow meaningful scale-up.

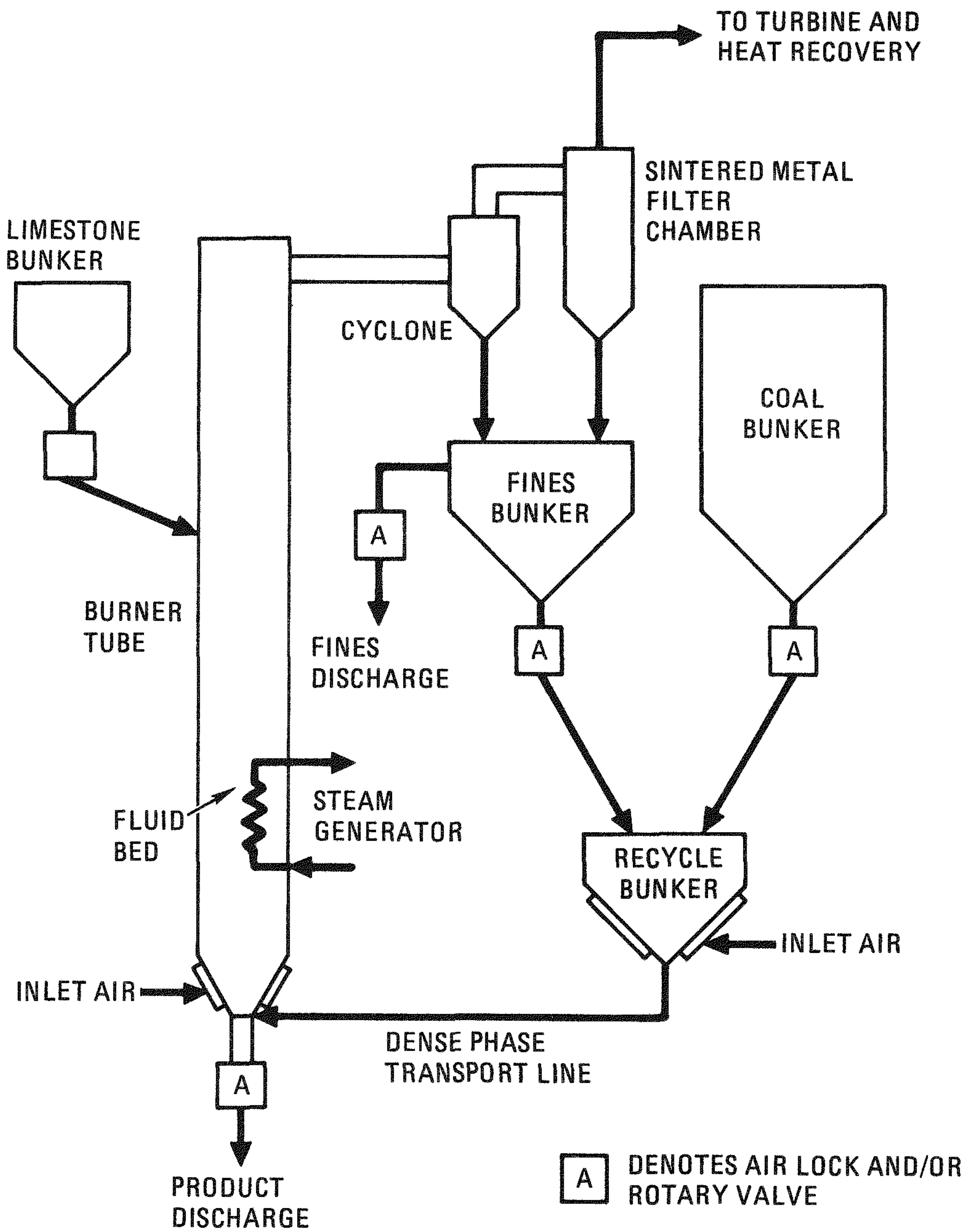


Fig. 5. Pressurized bed coal combustor.

CONCLUSIONS AND RECOMMENDATIONS

Combustion of carbon fines has been demonstrated in a fluidized bed burner system. A recycle technique was required to achieve complete combustion. Modeling of this recycle method resulted in close agreement with experimental data.

The modeling procedure has been applied to coal fines combustion. Predicted fines recycle rates indicate that lower bed recycle will be required to maintain a high fuel utilization efficiency. These predictions should be experimentally verified on a fluidized bed coal combustor.

ACKNOWLEDGMENT

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