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Abstract

Testing and analysis of a number of different fines recycle methods for fluid bed combustors has led to a generalized modeling technique. This model accounts for the effect of pertinent variables in determining overall combustion efficiencies. Computer application of this model has allowed trade-off studies to be performed that show the overall process effects of changes in individual operating parameters.

Verification of the model has been accomplished in processing campaigns while combusting fuels such as graphite and bituminous coal. A 0.4 MW test unit was used for the graphite experimental work. Solid fuel was typically crushed to 5 mm maximum screen size. Bed temperatures were normally controlled at 900°C; the combustor was an atmospheric unit with maximum in-bed pressures of 0.2 atm. Expanded bed depths ranged from 1.5 to 3 meters. Additional data was taken from recycle tests sponsored by EPRI on the B&W 6 ft x 6 ft fluid bed combustor. These tests used high sulfur coal in a 1.2 meter deep, 850°C atmospheric fluidized bed of limestone, with low recycle rates and temperatures. Close agreement between the model and test data has been noted, with combustion efficiency predictions matching experimental results within 1%.

Selecting Fines Recycle Methods to Optimize Fluid Bed Combustor Performance

General Atomic Company (GA) has been developing fluidized bed combustion results 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 been successfully operated in process campaigns since then.

Several fines recycle techniques have been tested on these burners, including both gravity and pneumatic transport to either the upper or 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 while attaining high combustion efficiencies.

Fluid-Bed Graphite Combustor Results

Figure 1 shows a process flow diagram for the 0.40-m (16-in.) graphite burner steady-state operations[1]. A photograph of the graphite burner is shown in Fig. 2. Table 1 lists important parameters during typical steady-state graphite combustion[2].

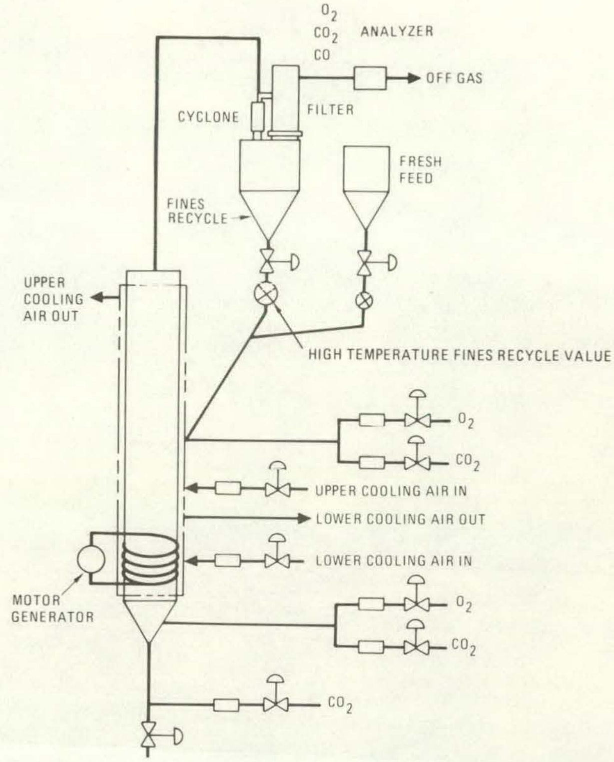

Fig. 1 Process flow diagram for fluidized bed burner.

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

Table I. Important Parameters for 0.4-cm (16-in.) Fluid-Bed Graphite Combustor

Heat generation	0.4 MW(t)
Overall combustor efficiency	>99.98% over 50-h test
Fines recycle rate/graphite feed rate	10
Combustor diameter	0.4 m (16 in.)
Combustor length	4.4 m (14 ft)
Fluidizing velocity	1.2 m/s (3.8 ft/s)
Fluid bed temperature	900°C (1650°F)
Fluid bed temperature control	±10°C (18°F)
Gas solid separation	Cyclone and sintered metal filter at 650°C (1200°F)
Fines recycle mode	Gravity through rotary valve at 600°C (1150°F) to upper bed zone
Feed mode	Gravity through high temperature rotary valve to upper bed zone
O_2 concentration in offgas	<3% at steady state
Expanded fluid bed depth	2 m (6 ft)
Freeboard pressure	10 kPa (1 psig)
Inlet gas composition	50% O_2, balance CO_2
Above bed O_2 injection	1/3 of total O_2 injection
Fluid bed carbon content	83% at start of campaign
Feed composition	83% graphite, 17% SiC-coated microspheres
Feed size distribution	4.4 mm x 0 (3/16 in. x 0), $\hat{d}_{sv}$ = 1 mm (0.04 in.)
Fines elutriation	1/3 of graphite is elutriated
Recycling fines size distribution	91% <200 μm, $\hat{d}_{sv}$ = 58 μm
Product removal	Pneumatic transport once per day
Heat removal mode	Air cooling
Combustor heatup mode	Induction heater

These results are important in that they include both high fines recycle rates and high overall combustion efficiencies.

A unique high temperature rotary valve was used to achieve these high recycle rates (see Fig. 3). It transfers abrasive solids across a pressure boundary to return them to the bed.

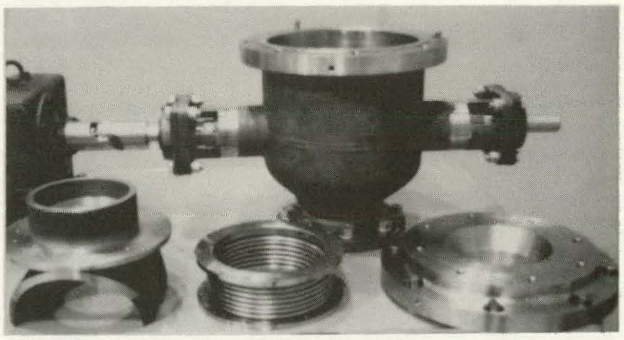

Fig. 3 High temperature rotary solids feeder rated for 700°C (1300°F) operation.

Since the graphite fuel is pure carbon, without any volatile combustibles, combustion is more difficult to sustain than with coal. The recycling fine carbon is oxidized at temperatures where reaction kinetics are slow.

Model for Predicting Fines Combustion Requirements

A fines burning model that predicts burning efficiencies as a function of process parameters contributed to this development program. Figure 4 is a pictorial summary of the model.

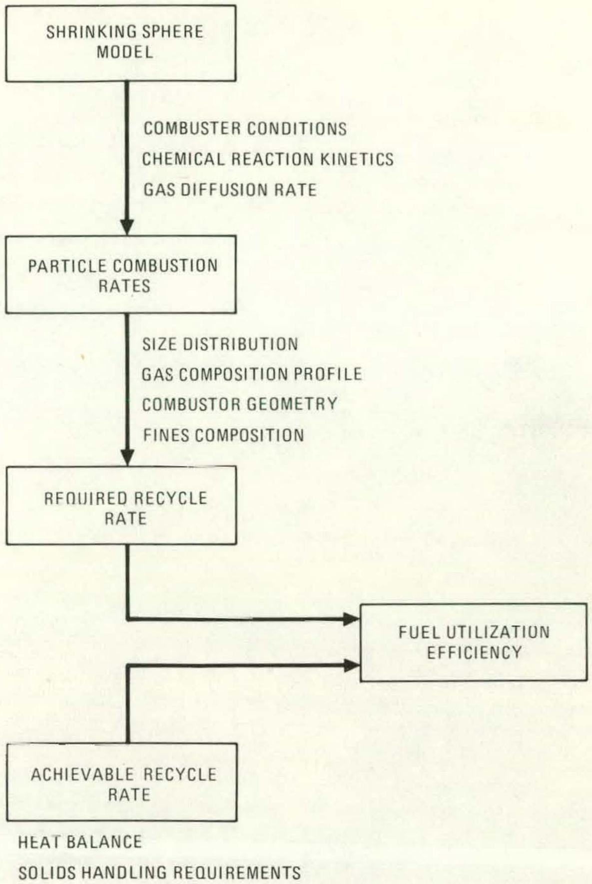

Fig. 4 Model for predicting fuel utilization efficiency for fines recycle.

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 the combustion rate of solid fuel. Integrating the range of particle sizes and the variation of gas composition leads to a prediction of overall combustion rates. Residence times in the combustor are used to determine the fraction of fine carbon burned per recycle pass. Required recycle rates and solids handling needs can then be calculated and fitted to the overall burner gas flow and heat balance needs.

The shrinking sphere model is a standard, textbook treatment of gas-solid reaction rates[3]. It assumes that the burn rate of solid fuel is proportional only to solids surface area and oxygen concentration. The proportionality constant K is a lumped combination of diffusional and kinetic resistances that depend on temperature, relative velocity of gas and solid phases, and solids size. Figure 5 is a plot of these relationships for pure carbon[4].

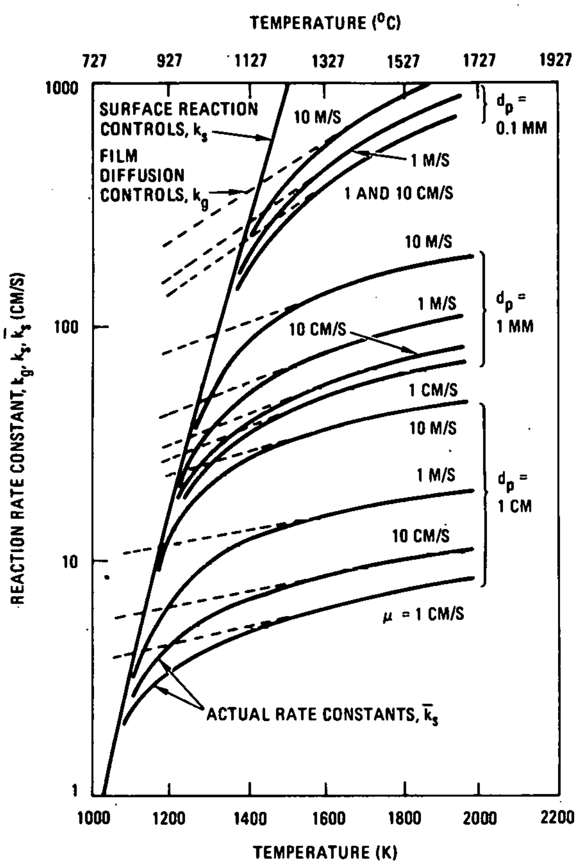

Fig. 5 Rate of combustion of pure carbon particles (from Ref. 4).

For the test data in Table 1, this model predicted a required fines recycle rate only 15% higher than what was actually found to be needed. 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 8kg/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 more than 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 demonstrated the concept of fines combustion using a recycle technique.

Fines Recycle Modeling for a Fluid Bed Coal Combustor

On the basis of these successes, the Electric Power Research Institute (EPRI) contracted with GA to analyze fines recycle test results from the EPRI/Babcock & Wilcox Company (B&W) 6 x 6 ft atmospheric fluid-bed combustor (AFBC). EPRI needed this modeling work done to help guide their test program at B&W, which they are using to verify operating conditions for the upcoming 20-MW(e) AFBC that the Tennessee Valley Authority (TVA), EPRI, and a number of contractors are ambitiously pushing forward, with a target startup date in early 1982.

The graphite fines combustion model was adjusted to account for the differences in kinetics and boundary layer diffusion found in coal char fines. Test data from the 6 x 6 ft AFBC Series 8 fines recycle was entered into a computerized version of the coal fines combustion model[5]. This data included the oxygen concentration profile through the burner, fines size distribution, fines recycle rate, superficial velocity, carbon combustion efficiency, expanded bed height, and freeboard length. Values of the average fines reaction rate constant, which includes both in-bed and freeboard fines burning, were then determined for the specific coal being burned (Ohio No. 6). The calculated fines reaction rate constant was used to extend the model to predict overall combustion efficiencies at conditions other than those tested in the B&W 6 x 6 coal combustor. It is expected that the surface reaction rate constant will vary from coal to coal, but results of these tests are thought to be representative of eastern, high-sulfur bituminous coals.

For each calculation, a set of conditions is assumed. Input variables are the superficial velocity, the fines recycle rate, bed height, freeboard length, and fines reentry temperature. An overall combustion efficiency is initially assumed. Burner heat generation and coal feed rate are calculated as a function of superficial velocity and the net heating value of the coal. Heat consumed by the fines recycle loop is calculated from the fines recycle rate and reentry temperature. The time required to heat the fines to ignition temperature is calculated by an expression developed from radiation, conduction, and convection heat transfer equations. It is dependent on the fines reentry temperature.

From the assumed combustion efficiency, the carbon content in the fines is calculated. Calculation of the fines surface area in the freeboard is based on B&W test data, the assumed fines recycle rate, superficial velocity, and freeboard length. By iteration, the bed/freeboard interface O_2 concentration is calculated based on the freeboard fines burn rate (kinetic equation) and the back-calculated O_2 concentration (material balance). Then, the in-bed fine carbon surface area and burn rate are calculated. The in-bed fines residence time is an estimate, since there is no direct means of measuring this variable in the B&W combustor. The calculational procedure is insensitive to the accuracy of the estimate so long as the same residence time is used for the earlier calculation of k value.

Combustion efficiency is calculated from the in-bed and freeboard fines burn rate, coal feed rate, and zero-recycle efficiency (Fig. 6). The zero-recycle combustion efficiencies are obtained from B&W test data for given superficial velocities and bed heights. The result is obtained when the back-calculated efficiency is equal to the assumed combustion efficiency.

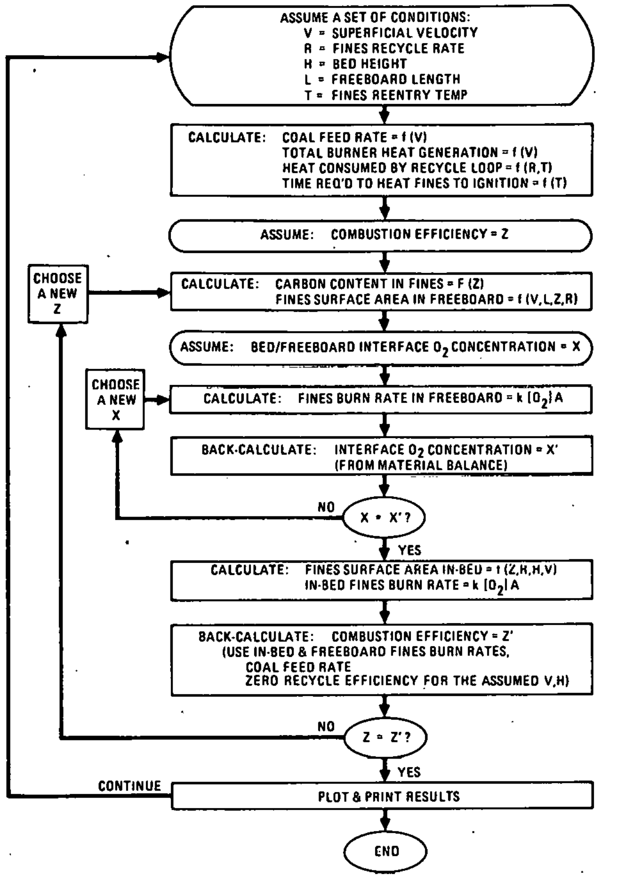

Fig. 6 Computer algorithm for predicting the effects of process variables on combustion efficiency for the B&W 6 x 6 ft fluid-bed coal combustor.

Parameters that can be varied in the model are the bed height, superficial velocity, fines recycle rate, freeboard length, and fines reentry temperature. Figures 7-11 show plots of the combustion efficiency vs. each one of these parameters. The bed temperature is constant (1600°F) for all calculations.

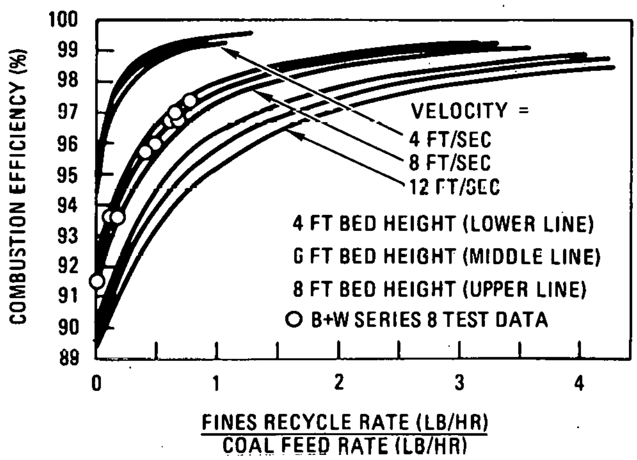

Fig. 7 Combustion efficiency versus some important process variables.

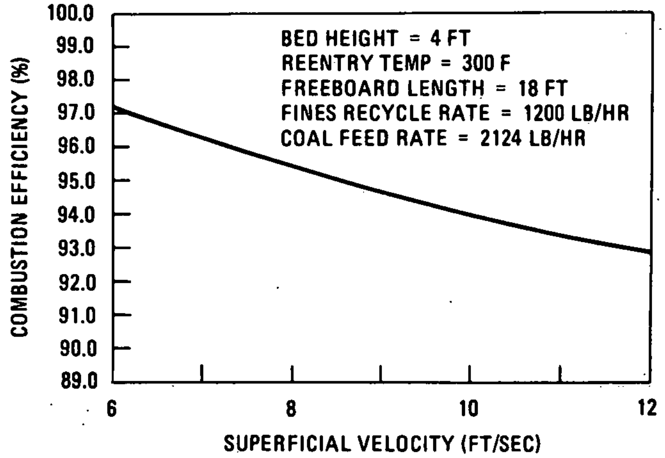

Fig. 8 Carbon combustion efficiency versus superficial velocity.

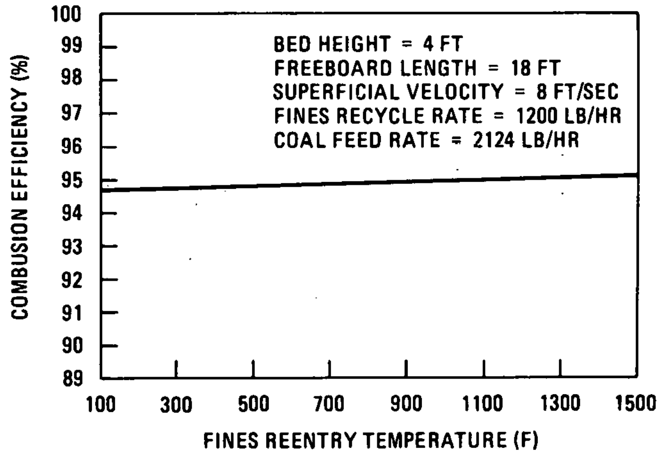

Fig. 9 Combustion efficiency versus fines reentry temperature.

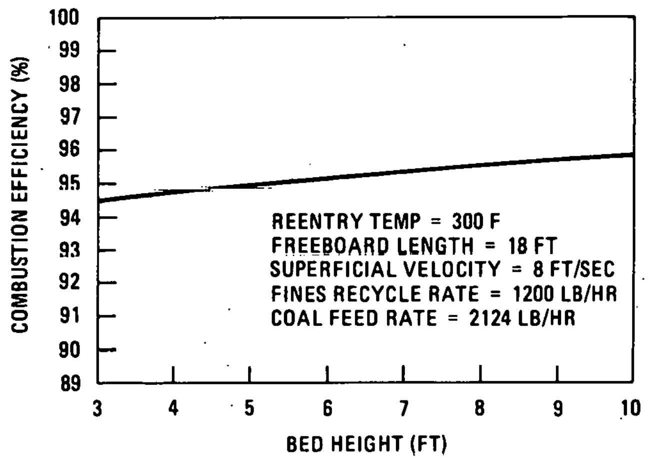

Fig. 10 Combustion efficiency versus bed depth.

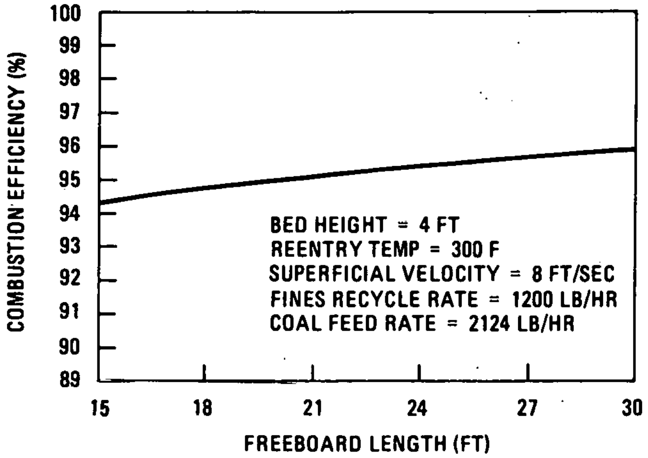

Fig. 11 Combustion efficiency versus freeboard length.

Figure 7 shows that reducing the superficial velocity is particularly effective in increasing overall combustor efficiency[6]. Increased bed depth and freeboard length (Figs. 10, 11) are also helpful, but the magnitude of response is not so dramatic. Figure 9 shows that increased fines reentry temperature has virtually no effect on the combustion efficiency. Since bed velocity is inversely proportional to required combustor cross section, some interesting tradeoff studies may now be made to determine the optimum combination of a low velocity (to avoid wasting fuel) versus a high velocity (to keep combustor size down).

If a 99% overall combustor efficiency is desired, the model predicts that the current operating parameters of 1.2-m (4 ft) bed height and 2.4 m/s (8 ft/s) superficial velocity will require a fines recycle rate more than 2.5 times the coal feed rate. This recycle rate is four times higher than the rate attained in Series 8 at the 6 x 6 ft unit, in which overall combustion efficiencies of ~97% were noted.

Conclusions and Recommendations

A straightforward, yet thorough, fines modeling technique has been used to guide a successful development program for a fluid bed graphite combustor. This model was then computerized to analyze fluid-bed coal combustor data to determine operating conditions that maximize overall combustor efficiency. For a specific combustor, the EPRI/B&W 6 x 6 ft AFBC, operation at 2.4-m/s (8 ft/s) with a 1.2-m (4 ft) deep bed and a fines recycle rate three times the coal feed rate should give 99% overall combustion efficiency.

Plans are underway to modify the 6 x 6 ft AFBC to allow recycle rates up to five times the coal feed rate. This will allow verification of this modeling technique at higher recycle conditions. In a parallel effort, GA is modifying the 0.4-MW(t) graphite burner to permit coal combustion testing. This is funded by TVA, with tests beginning in mid-1980 over a wide range of combustor conditions, including fines recycle rates of up to seven times the coal feed rate and bed heights up to 8 ft.

This will form a fines recycle design data base for the guidance of TVA design and operation efforts. Combining this with the latest cost figures will allow optimization of AFBC plants by minimizing equipment capital costs, while maximizing overall combustion efficiency.

Acknowledgment

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