Progress of combustion in the furnace of a circulating fluidised bed boiler

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PROGRESS OF COMBUSTION IN THE FURNACE OF A CIRCULATING FLUIDIZED BED BOILER

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Gas concentrations were measured in the combustion chamber of a circulating fluidized bed boiler (FBB). Sieved fractions of solid material sampled at different heights were analyzed for combustible matter. Together with the bulk density profile obtained from pressure drop measurements, these data were used to obtain the distribution of combustible matter in the combustion chamber.

High concentrations of combustible gases and low concentrations of oxygen were found in the bottom part, indicating that the bed material to a large extent is subject to reducing conditions. From the gas concentration profile, the degree of combustion/fuel conversion versus boiler height was deduced. This procedure, however, involves a major error since measured concentrations give a misrepresentation of the concentrations of the gas flow. This is explained by a through flow of gas through bubbles or voids in the bottom bed with high velocity and high concentration of oxygen.

A correction for the bypass flow was attempted, which increases the O_2 concentration in the lowest position from 2.5 to 11%. This correction compared favorably with the fuel conversion versus height, derived from the distribution of solid combustibles (char) in the combustion chamber.

The results show that the concentrations measured in the bottom part of the combustion chamber do not represent the flow and cannot, accordingly, be directly used in mass balances. This misrepresentation has consequences for the interpretation of gas measurements in the bottom part of FBBs.

Introduction

The purpose of this work is to improve understanding of combustion in circulating fluidized bed boilers (FBBs), by measuring local concentrations of gas and solid combustibles inside the combustion chamber. It is also intended to provide data that can serve for comparison with fluidized bed combustion modeling.

Most measurements of gas concentrations in fluidized bed combustors are from small units, although some data are available from larger units [1,2]. The fluidization conditions and the solids distribution in small units differ from those observed in larger units. This is reflected in measured gas concentration profiles [3], which are quite different from those obtained in the larger unit of the present study.

This work is part of a broader program involving local measurements under different operating conditions, and the present investigation treats the combustion of coal at full load and under normal air-staging conditions.

Experimental Description

The 12-MW circulating FBB used [4] is a commercial boiler, but it was built for research purposes and is equipped for various types of measurements. The square cross section of the combustion chamber is about 2.5 m^2 and the height is 13.5 m with the cyclone outlet at about 11 m above the bottom plate. The fuel was a bituminous coal with 40% volatiles and a particle size less than 20 mm ($d_{50} \sim 10$ mm). No limestone was added. The bed temperature was 850 °C, the load 8 MW, the air-to-fuel ratio 1.2, the primary-air fraction about 60%, and the dense bottom bed height about 0.5 m.

Gas concentrations were recorded by two sets of analyzers, one for flue gas sampling and the other for measurements inside the combustion chamber (CO and CO_2: infrared; O_2: paramagnetic; HC: flame ionization). The analyzers were calibrated daily and the sets could be switched to double check the accuracy. H_2 was not measured, but later measurements under similar conditions with an H_2 analyzer, and also previous measurements with a gas chromatograph [5], indicate that H_2 is well correlated to hydrocarbon concentration (HC), which allows the assumption that $H_2 = 0.9$HC (methane equivalents).

The concentrations of individual hydrocarbons were obtained from combining the results of previous measurements of individual hydrocarbons with a coal of similar type and under similar operating conditions [5], with calibration data from the HC analyzer for these hydrocarbons. Knowing the composition of hydrocarbons, the stoichiometric oxygen consumption for hydrocarbons was determined to be

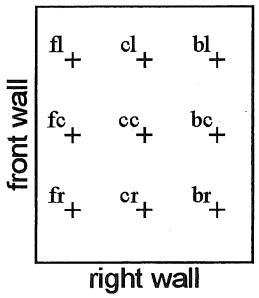

FIG. 1. Measurement positions in the horizontal cross section, 1.7 × 1.4 m.

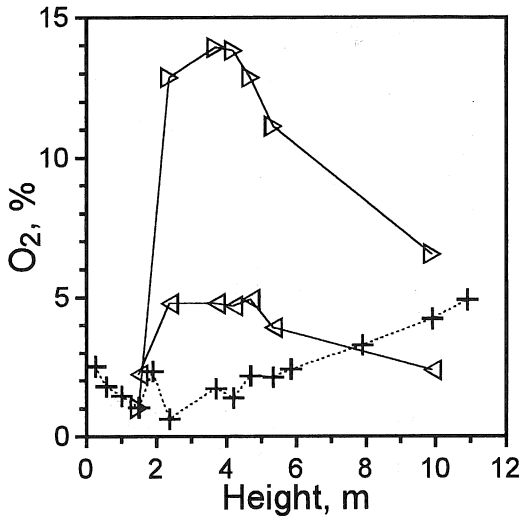

FIG. 2. Oxygen. Concentrations measured in cc (+), fc (▷), and bc (◁).

1.77% O_2 per % HC measured. (Since HC is measured in methane equivalents, that is, approximate number of carbon atoms, the constant is reasonably insensitive to changes in hydrocarbon composition.)

The suction probe for gas sampling has a shielded filter at the end of a water-cooled lance. The probe and the sampling procedure have been described previously [5]. A possible error could be the accumulation and burning of combustible material between the filter and the filter shield. Measurements were, however, made in the most difficult position of the combustion chamber with several probe types, and no significant difference was measured between them. These performance tests included a probe with a horizontal quartz filter close to the tip to prevent accumulation of solid material.

The gas concentrations were measured at various heights along the centerline of the combustion chamber (cc in Fig. 1). Due to large variations over

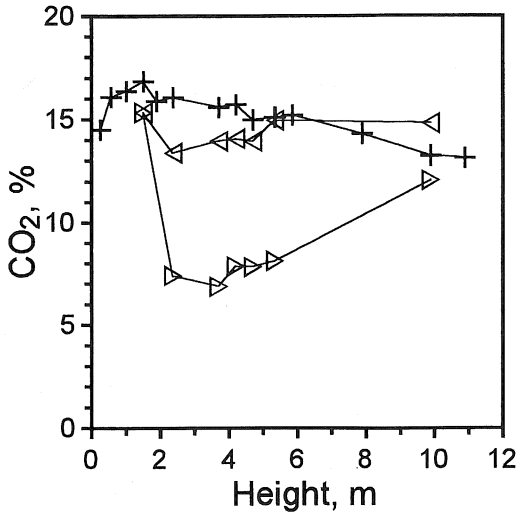

FIG. 3. Carbon dioxide. Concentrations measured in cc (+), fc (▷), and bc (◁).

the cross section, mostly caused by the secondary air, measurements were also made along two lines at the back and the front wall (bc and fc in Fig. 1) and at two heights, 3.7 and 9.9 m, in nine positions in the horizontal cross section. The nine-position measurements verified that the three-position measurements (fc, cc, and bc) gave a reasonable representation of the cross-section average and were used to improve the accuracy of the data. Thus, the cross-sectional averages were obtained from the three-position measurements, after a correction derived from the nine-position measurement data. Below the secondary air inlets, the values measured in the cc position were used as cross-section averages, since there is no significant variation in the time-average concentration over the cross section.

Results

Measured O_2, CO, CO_2, and HC concentrations are shown in Figs. 2–4 versus height above the bottom plate. An example of gas distribution over the cross section is shown in Fig. 5, showing the influence of secondary-air injection. Cross-section averages versus riser height, derived as described above, are presented in Figs. 6–8, including O_2 and CO_2 concentrations corrected for secondary air. The correction below the secondary air inlet at 2.2 m is

$$x_{corr} = x_m f_{prim} + x_{sec}(1 - f_{prim}) \qquad (1)$$

where f_{prim} is fraction of primary air, x_m is measured concentration of the gas species x, and x_{sec} is gas concentration of the secondary air. The corrected gas concentrations are needed to obtain a correct

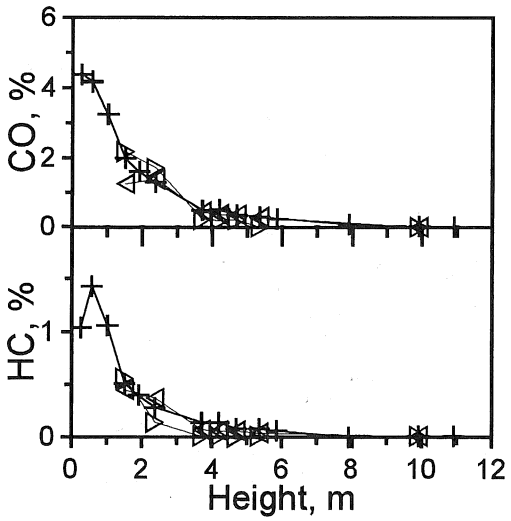

FIG. 4. Carbon monoxide and hydrocarbons. Concentrations measured in cc (+), fc (▷), and bc (◁).

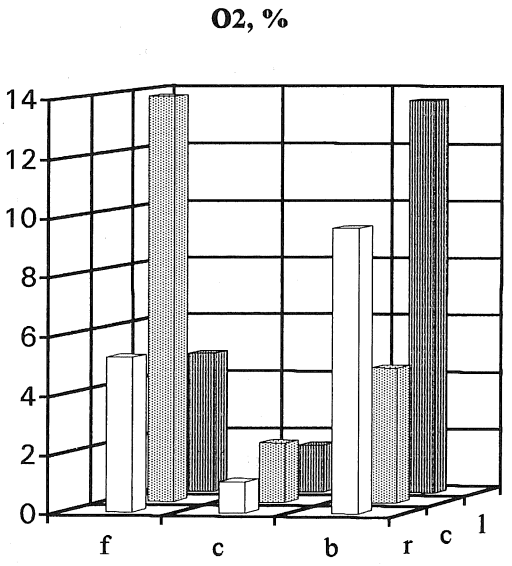

FIG. 5. O_2 concentration in the furnace cross section at 3.7-m height.

mass balance when used to estimate combustion versus boiler height, because concentrations measured below the secondary air inlet are compared to stack concentrations. (At 2.37 m, which is only 0.17 m above the secondary-air inlets, it is assumed that only three-fourths of the secondary air has penetrated far enough to affect the measurements.)

In Fig. 8, the combustible gases CO and HC are shown together with total combustible gas, CG, expressed as oxygen consumption:

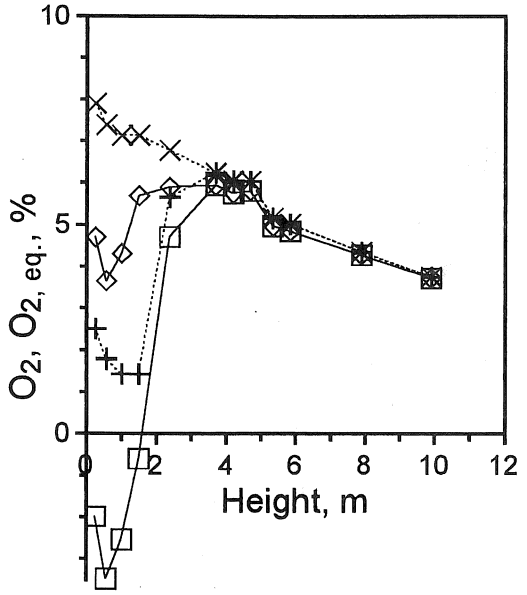

FIG. 6. Cross-section average oxygen concentration. O_2 (+), $O_{2,eq}$ (□), $O_{2,corr}$ (×), and $O_{2,eq,corr}$ (◇). Negative values represent substoichiometric conditions.

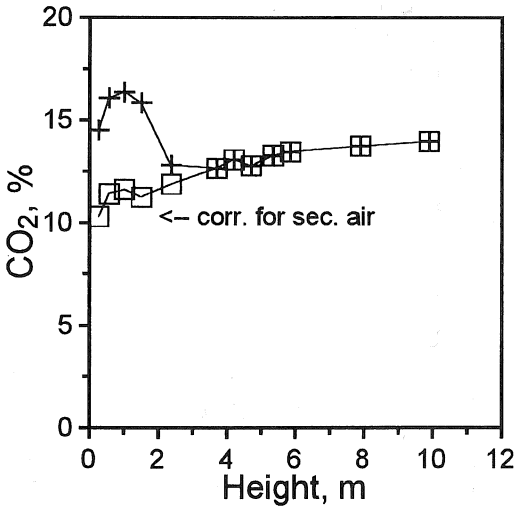

FIG. 7. Cross-section average concentration of CO_2 (×) and $CO_{2,corr}$ (□).

$$CG = 0.5(H_2 + CO) + 1.77HC \quad (2)$$

The total combustible gas, CG, is subtracted from O_2 to give oxygen equivalents, $O_{2,eq}$, shown in Fig. 6:

$$O_{2,eq} = O_2 - CG \quad (3)$$

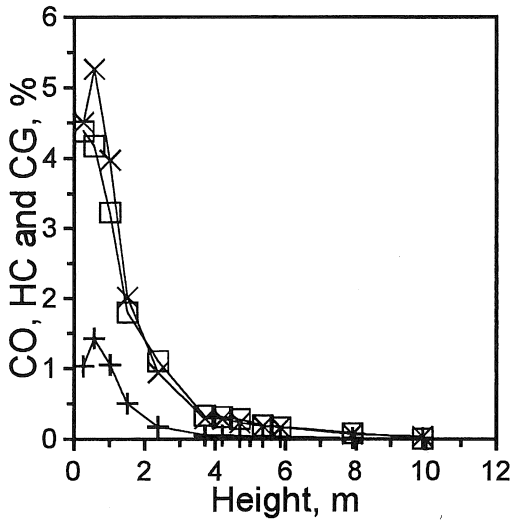

FIG. 8. Cross-section average concentrations of combustible gases: HC (+), CO (□), and CG (×).

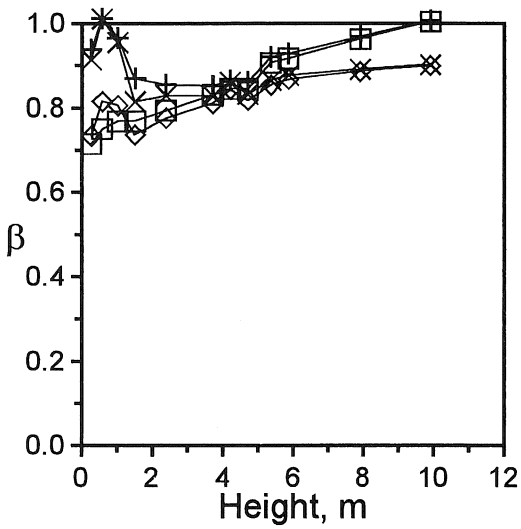

FIG. 9. Cumulative combustion/fuel conversion β versus height: β (□), β_{CO_2} (◇), β_{eq} (+), and β_{eq,CO_2} (×). Note that the values in the bottom part of the combustor are too high, due to bypass of oxygen-rich gas.

$O_{2,eq}$ is negative below the secondary-air injection level, which means that the measured gas as an average can be considered to be reducing. $O_{2,eq}$ can also be corrected for secondary air according to Eq. (1), yielding $O_{2,eq,corr}$. In the splash zone, from 0.5 to 1.5 m, where a significant reduction of $O_{2,eq,corr}$ is expected due to char combustion and volatiles release, $O_{2,eq,corr}$ instead increases (Fig. 6). This behavior, which is discussed below, is explained by a bypass of high-velocity oxygen-rich air.

From the oxygen concentration corrected for secondary air, the progress of combustion, β, versus height is derived from the fraction of oxygen consumption:

$$\beta = \frac{O_{2,in} - O_{2,corr}}{O_{2,in} - O_{2,fluegas}} \tag{4}$$

where $O_{2,in}$ is the concentration of oxygen in the gas supplied, considering that the primary air is diluted with recirculated flue gas. $O_{2,fluegas}$ is the flue gas oxygen concentration as measured in the convection path, and $O_{2,corr}$ is the measured cross-sectional average oxygen concentration, which, below the secondary-air inlet, is corrected according to Eq. (1). Similarly, a measure of the progress of combustion versus height is obtained from the CO_2 and CO measurements:

$$\beta_{CO_2} = \frac{CO_{2,corr} + \frac{1}{2} CO_{corr} - CO_{2,in}}{CO_{2,fluegas} - CO_{2,in}} \tag{5}$$

where $CO_{2,in}$ is the concentration of CO_2 in the gas supplied. Although β_{CO_2} does not include oxygen consumption from H_2O formation, the expected maximum deviation between β and β_{CO_2} is small ($\approx$1%) based on the difference between volatiles and char combustion derived below.

A measure of the progress of fuel conversion, that is, combustion and gasification, can be obtained by including the combustible gases released,

$$\beta_{eq} = \frac{O_{2,in} - O_{2,eq,corr}}{O_{2,in} - O_{2,fluegas}} \tag{6}$$

Similarly, β_{eq,CO_2} is calculated from the carbon-containing combustion gases,

$$\beta_{eq,CO_2} = \frac{CO_{2,corr} + CO_{corr} + HC_{corr} - CO_{2,in}}{CO_{2,fluegas} - CO_{2,in}} \tag{7}$$

The results are shown in Fig. 9. Here, once again, the results are not correct in the bottom part, due to bypass of oxygen-rich gas.

Another measure of the progress of combustion can be deduced from fuel distribution versus height. First, the normalized, cumulative char mass, β_{mass}, versus height, h, is obtained as

$$\beta_{mass}(h) = \frac{\int_0^h \phi_{char} \rho dh}{\int_0^{10} \phi_{char} \rho dh} \tag{8}$$

where ϕ_{char} is the mass fraction of combustibles (mainly char) obtained from analysis of solid samples taken at different heights and the local solids concentration ρ is obtained from the measured pressure

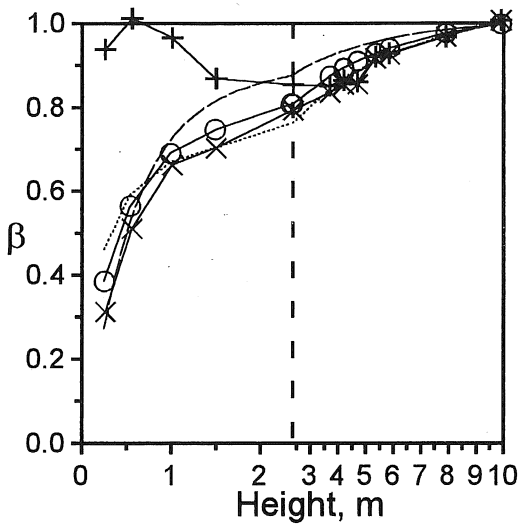

FIG. 10. β_{eq} from Fig. 9 compared to model and char data. β_{eq} (+), $\beta_{eq,mod}$ (×), β_{fuel} (○), β_{mass} (dashed curve), and $\beta_{area \cdot O_2}$ (dotted curve).

gradient. If the local char combustion is assumed to be proportional to the char surface concentration multiplied by the measured O_2 concentration, the cumulative and normalized char combustion, $\beta_{area \cdot O_2}$, is obtained:

$$\beta_{area \cdot O_2}(h) = \frac{\int_0^h \phi_{char} S_g \rho O_2 dh}{\int_0^{10} \phi_{char} S_g \rho O_2 dh} \qquad (9)$$

where S_g is the outer specific area of the char derived from analysis of combustibles of sieved samples taken at different heights. To obtain a measure of where the conversion, that is, combustion and devolatilization, of the fuel takes place, the following assumptions are made:

- The measured mass distribution of the combustibles, β_{mass}, is assumed to give a representation of where the devolatilization occurs. (This is based on the assumption that the mass of the devolatilizing fuel particles has a distribution versus height that is similar to that of the char.)
- $\beta_{area \cdot O_2}$ is assumed to give a reasonable measure of where char combustion takes place.

Thus, the progress of fuel conversion, β_{fuel}, versus height is obtained by weighing

$$\beta_{fuel} = \nu\beta_{mass} + (1 - \nu)\beta_{area \cdot O_2} \qquad (10)$$

where ν is the fractional volatiles content, 0.4. If β_{fuel} is compared to the results from the gas analysis, β_{eq}, a significant discrepancy in the bottom part is noted (Fig. 10). Below, a simple model illustrates how this can be explained by through flow of air at high velocity.

Correction for Bypass Flow

A simple model has been formulated to illustrate the effect of different gas velocities in the bottom part of the combustor. The purpose of the model is not to present "correct" results, but rather to highlight the lack of knowledge regarding the phenomena in this region and the need for further investigation.

It was previously shown [6] that the bottom bed of a circulating FBB operates in the "exploding bubble" regime. This causes high through flow of gas, and a modified two-phase theory can be applied to estimate the flow distribution [7]. Both theory and pressure-drop measurements indicate a dense bottom bed with a bubble volume fraction of about 0.3–0.4. The visible bubble flow is estimated to account for about 29% of the total gas flow. With a minimum fluidization velocity being 1% of the superficial velocity, this leaves a remainder of 70% as through flow or bypass flow. This through flow is assumed to be made up of bubble chains or channels creating short circuits of gas bypassing the bottom bed.

The distinction between dense phase flow, visible bubble flow and through flow is artificial, and these flows are obviously more or less mixed. The simple model assumes that a part of the flow is not mixed at all and the other part is completely mixed:

- The rapid through flow has the same concentrations as the fluidizing gas, that is, $O_{2,b} = 16\%$, and passes through a time-averaged fraction of the cross-section area, ϕ.
- The gas concentration of the visible bubble flow is equal to that of the gas in the dense phase, $O_{2,d}$.

The first assumption probably overestimates O_2 concentrations, which may be counterbalanced by an underestimate of O_2 in the second assumption.

A local measurement of the oxygen concentration spends a fraction of time (ϕ) in the rapid through flow. The measured time-averaged O_2 concentration was $O_{2,m} = 2.5\%$ at 0.26 m in height, and it should relate to the concentrations of the two assumed flows according to

$$O_{2,m} = \phi O_{2,b} + (1 - \phi)O_{2,d} \qquad (11)$$

By assuming values of $O_{2,d}$, we obtain various values of ϕ, according to Eq. (11) (see Table 1). From these values, the mean velocity of the gas in the rapid flow, u_b, can be obtained:

$$u_b = uf_b/\phi \qquad (12)$$

where u is the superficial velocity in the bottom part (3.8 m/s) and f_b is the fraction of through flow (0.7). If the rapidly bypassing gas has not reached the bed

TABLE 1
Results from Eqs. (11)–(13)

$O_{2,d}$, %	0	0.5	1	1.5	2
ϕ	0.16	0.13	0.10	0.07	0.04
u_b, m/s	17	20	26	38	73
$O_{2,flow}$, %	11.2	11.3	11.5	11.6	11.8

temperature, the resulting velocity is lower. At 850 °C, however, the available pressure drop of 5 kPa, is theoretically sufficient to produce a maximum velocity of 180 m/s (cf. velocities in Table 1).

Due to velocity differences, the measured time-averaged oxygen concentration is biased toward slowly moving gas with low oxygen concentration. However, with the above assumptions, the average oxygen concentration of the flow can be obtained as

$$O_{2,flow} = f_b O_{2,b} + (1 - f_b) O_{2,d} \qquad (13)$$

From Table 1, it is clear that $O_{2,flow}$ is significantly higher than the oxygen concentration measured, 2.5%. Based on Table 1, we assume that $O_{2,flow}$ is 11.3% and that the fraction of flow having a high velocity and high oxygen concentration decreases exponentially with height above the dense bed. These assumptions yield $\beta_{eq,mod}$, which is compared to β_{eq} and β_{fuel} in Fig. 10. The values used in the model are assumptions, but it is believed that the general description is justified, and the model agrees reasonably well with β_{fuel}.

Discussion

The gas measurements, if not corrected for the bypass flow, indicate that 71% (β) of the combustion and 94% (β_{eq}) of the fuel conversion take place below 0.26 m. This is unlikely, considering that only 27%/24% of solid combustible mass/surface is found below this level. However, with the above assumption of a considerable bypass of air, reasonable agreement is obtained between data for the progress of fuel conversion based on measurements of solids, β_{fuel}, and gases, $\beta_{eq,mod}$.

The results illustrate the difficulties in interpreting the gas concentration measurements in the bottom zone. The measurements show that the bed material to a large extent is exposed to reducing conditions, which has previously been revealed by zirconia-cell oxygen-probe measurements [4]. However, the measured concentrations give a poor representation of the concentration of the flow due to large velocity differences. This aspect is important, not only for the understanding of the combustion process, but also for the interpretation of other measurements. The problem has previously been noted, for example, in connection with experiments in stationary fluidized beds, where the fraction of dense-phase flow is one order of magnitude greater than that of the present experiments [8]. For instance, bottom-zone measurements of high concentrations of the NO/N_2O precursors, such as NH_3, HCN, and HNCO, may lead to erroneous conclusions if the gas velocity variations are not accomodated.

For modeling, it is important to be aware of the shifts between oxidizing and reducing conditions. The measured concentrations are time averages of concentrations that vary significantly, especially in the bottom bed, where high concentrations of O_2 may occur part of the time, alternating with low concentrations of O_2 and high concentrations of reducing species during the remaining time. Apart from measurements with oxygen probes [4], at present, little is known about these variations.

The 14 secondary-air ports were carefully rinsed during a stop just before the test series. Despite this, significant variations in O_2 over the cross section occurred (see Fig. 5), indicating that an even flow distribution over the secondary-air ports was not attained. Most of the variation, however, has disappeared at the 9.9-m level. It is believed that this type of variation is not uncommon in commercial boilers.

β and β_{CO_2} differ from each other in the upper part of the combustor. Since some combustion takes place in the cyclone, β should be lower than unity. There are several possible sources of minor errors in sampling, and the fraction of combustion taking place in the cyclone cannot confidently be determined from small differences in O_2 or CO_2 concentration as measured in the top of the combustion chamber and in the flue gas channel with the sampling procedures used. (This was not the primary purpose of the investigation anyway.)

Previous measurements with other bituminous coals gave concentrations that were very similar to the present test series. Furthermore, an additional test series was conducted and evaluated, this time with limestone addition, with similar results as in the present test series. Two minor differences were noted: The β and β_{CO_2} values in the upper part did not diverge, and the CO concentration was considerably lower. The latter observation is associated with the catalytic effect of the lime.

Conclusions and Interpretation

The interpretation of gas concentrations measured by a suction probe in the lower part of the combustion chamber of a circulating FBB is difficult because of a considerable bypass flow. Some important conclusions can nevertheless be drawn:

1. High concentrations of combustibles and low concentrations of oxygen are found in the bottom part. The equivalent oxygen concentration, that is,

oxygen concentration reduced by the oxygen demand of the combustible gases, is negative in the bottom part, indicating substoichiometric conditions. This result is consistent with zirconia-cell oxygen-probe measurements [4].

2. Although the results most probably give a good representation of the time-averaged concentration in a given position, the measured gas concentrations in the bottom part cannot be used in mass balances, since they do not represent the concentrations of the gas flow. This is explained by much higher velocities of gas with high oxygen concentrations, compared with gas with low oxygen concentration and high concentration of combustible gases. The reason for this is a through flow of gas, in the form of bubbles or voids in the bottom bed. In relation to the entire gas flow in the bottom part of the combustion chamber, the measurements give too low of an oxygen concentration and too high of a concentration of combustibles. An attempted correction for the bypass flow compared favorably with data based on the distribution of solid combustibles in the combustion chamber.

3. Based on previous knowledge, and consistent with the present data, the following image of coal combustion in a circulating FBB emerges: The major part of the fuel is burned and gasified in the dense bottom bed and in the splash zone above the dense bed. Jets of gas bypassing the bottom bed decelerate above the dense bed, where they mix with a gas having a high content of combustible gas. The mixing of the gases, especially in the bottom part, is incomplete, and the measured concentrations are averages of periods with oxidizing gas, that is, high oxygen concentrations, and periods with reducing gas, that is, high concentrations of combustible gas.

Acknowledgment

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