Fluidized bed combustion of coals and alternative fuels

DOE/METC-85/6021, Vol. 2
(DE85013689)

Proceedings of the Eighth International Conference on Fluidized-Bed Combustion, Volume II

July 1985

Sponsored by
U.S. Department of Energy
Office of Fossil Energy
Morgantown Energy Technology Center
Morgantown, West Virginia

Tennessee Valley Authority
Chattanooga, Tennessee

Electric Power Research Institute
Palo Alto, California

FOSSIL ENERGY

TECHNICAL INFORMATION CENTER
OFFICE OF SCIENTIFIC AND TECHNICAL INFORMATION
UNITED STATES DEPARTMENT OF ENERGY

DOE/METC-85/6021
(CONF-850302--Vol. 2)
(DE85013689)
Distribution Category UC-90c
UC-90e
CU-90h

Proceedings of the Eight International Conference on Fluidized-Bed Combustion, Volume II

By

Special Projects Branch
Coal Projects Management Division

Held at
Westin Galleria Hotel
Houston, Texas
March 18-21, 1985

U.S. Department of Energy
Office of Fossil Energy
Morgantown Energy Technology Center
Morgantown, West Virginia 26505

Tennessee Valley Authority
Chattanooga, Tennessee 37401

Electric Power Research Institute
Palo Alto, California 94303

July 1985

The 8th International Conference on Fluidized Bed Combustion
Houston, March 1985

FLUIDIZED BED COMBUSTION OF COALS AND ALTERNATIVE FUELS

by

Bengt-Åke Andersson [1/]
Bo Leckner [1/]
Lars-Erik Åmand [1/]

Abstract. The 16 MW demonstration plant at Chalmers University of Technology was designed to burn coal but measures were taken also to allow the use of alternative fuels.

Results of comparative tests with bituminous coal and alternative fuels, brown coal, peat, and wood chips, are presented. The combustion characteristics of the various fuels are illustrated with temperature and heat flux profiles in the freeboard.

It is found that the volatile fuels tend to burn to a large extent above the bed and secondary air is necessary to complete the combustion. However, if secondary air is used, a combustion efficiency close to 100% is easily obtained. Bituminous coal, on the other hand, does not readily burn with a high combustion efficiency in the boiler used.

INTRODUCTION

There are two reasons for studying the behavior of various fuels in a fluidized bed combustor: First, a comparison of fuels reveals their combustion characteristics and forms a basis for design. Second, operators of industrial and district heating boilers are interested in being able to change from one fuel to another as a consequence of the fluctuations in price and availability of the fuels.

The present study emphasizes the first aspect and is thus concentrated on the combustion chamber itself. It must be pointed out, however, that an essential problem related to the burning of different fuels is found outside the combustion chamber, namely in the handling of fuels with greatly different volumes per unit of heat power and with different requirements for the design of storage and transportation equipment.

The questions of interest in designing the combustion chamber, and indeed also in operating the boiler, are such as: How much heat is released in the bed and in the freeboard? How much of the fuel is burned in the bed? Which ranges of fuel properties can be tolerated for satisfactory operation of the boiler? The present investigation aims at providing some basis for answering this type of questions by studying the combustion of various fuels such as bituminous coal, brown coal, peat, and wood. To a certain degree, the influence of the size of the fuel particles is also considered. An example to illustrate the impor-

1/ Chalmers University of Technology, Department of Energy Conversion, S-412 96, Göteborg, Sweden.

tance of the last aspect is given in fig. 1, which shows the change in combustion chamber operation at constant boiler operation but with a gradual transition in fuel from brown coal briquettes with a size between 0-20 mm to the same fuel but with a size between 20-40 mm.

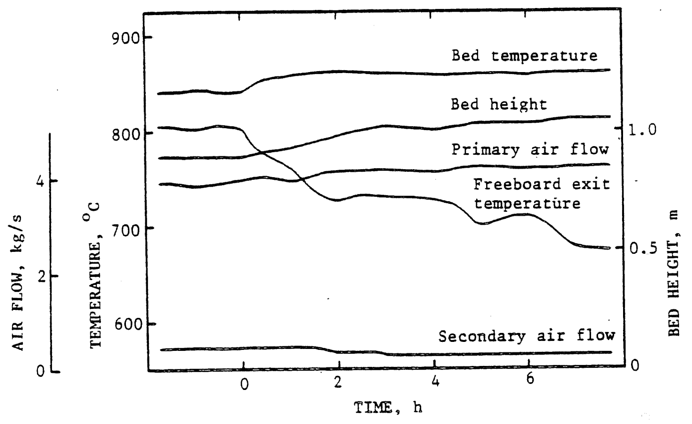

Figure 1. Change in Combustion Chamber Operation with a Gradual Transition in the Fuel Size Distribution. Brown Coal, 0-20 → 20-40 mm.

The figure shows how the control system of the boiler increases the bed height in order to compensate for the increased in-bed combustion resulting from the coarser lumps of fuel. At the same time, the increased in-bed combustion is accompanied by a smaller over-bed combustion which leads to a decrease in the freeboard exit temperature and also to a decrease in the secondary air supply.

For a complete answer to the questions posed there are at least four groups of influencing parameters to consider:

- Fuel composition (volatile matter, fixed carbon, moisture etc.)
- Fuel particle size
- Operating conditions (load, excess-air, secondary air etc.)
- Design variables (boiler size, fuel feed method, fluidization velocity, recirculation ratio etc.)

The present study is focused on the fuel composition and varies primarily the content of volatile matter. As mentioned above, in one case also the size is varied. The operating conditions are kept as constant as possible and the tests are carried out in one particular boiler.

EXPERIMENT

The Boiler

A description of the boiler used for the test runs has previously been published, (Svensson et al. 1982). Only some of the design data and features which are important for the subject treated are given below.

The boiler is built according to the Eckrohr principle and produces superheated steam (425°C, 3.2 MPa) with a capacity of 16 MW. It operates at atmospheric pressure.

The design fuel is bituminous coal but alternative, more voluminous fuels can be employed within the limits imposed by the fuel transportation system, usually at loads less than or equal to 65%. The fuel is fed through the fuel chute (1), fig. 2, onto the 10 m^2 bed surface (2). If desired, the fluidizing air can be preheated in the air-preheater (3) by hot water from the drum before it enters into the air plenum (4) and the bed. Secondary air can be supplied to the freeboard through nozzles (5). The distributor plate, the walls surrounding the bed, the freeboard (6), and the subsequent gas passes (7a) (7b) consist of membrane tubes. A superheater tube bundle is located in the bed region of the combustion chamber. After the flue gas passes there is a cyclone arrangement from which solids can be recirculated to the bed. It is not, at present, possible to control the recirculation ratio. The final cleaning of the flue gas is achieved by a bag-house filter.

Measurements

A data acquisition system is utilized for collecting the data neces-

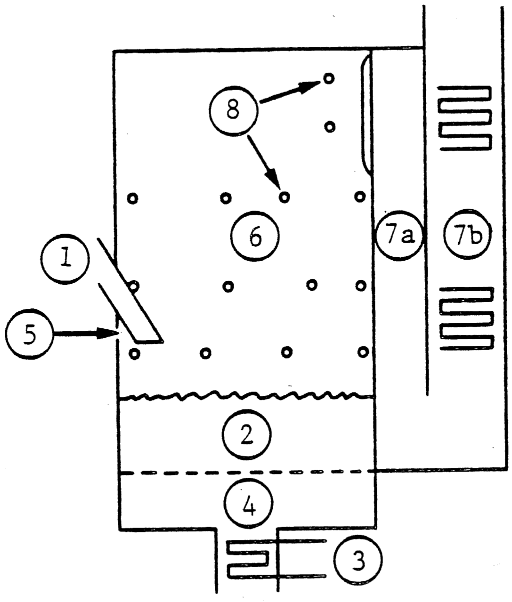

Figure 2. The Boiler

1 Fuel Chute
2 Bed
3 Air-Preheater
4 Air Plenum
5 Secondary Air Nozzles
6 Freeboard
7a Empty Gas Pass
7b Convection Gas Pass
8 Pyrometer and Heat Flux Measurement Positions

sary for mass and heat balances. In addition, the gas temperature field in the freeboard has been measured with a suction pyrometer at various heights above the bed (8), as indicated in fig. 2. The heat flux to the freeboard walls is measured with plug type heat flux meters, also in the positions given in fig. 2. The recorded heat fluxes are averaged on every level of the freeboard in order to obtain a vertical heat flux profile.

THE FUELS AND THE BED MATERIAL

Four types of fuel are used; bituminous coal, brown coal, peat, and wood chips. They are intended to cover a wide range of volatile content. The content of volatile matter varies from 28 to 86% of the combustible matter.

The coal used is a commercially available North American single-screened bituminous coal less than 10 mm in size. The German brown coal is briquetted, crushed and screened before delivery. Two size fractions of the brown coal, <40 mm and <20 mm, were chosen in order to investigate the influence of the fuel particle size on the combustion process. Indigenous peat is available in many different qualities and sizes. The machined peat quality used consists of pieces 70 mm in diameter with a length ranging from 10 to 150 mm. Further, a considerable amount of fines is produced in the transportation system. The wood chips, cut from newly felled birch, are regular in shape and measure 5x20x30 mm.

Some characteristics of the fuels are given in table 1. The size distributions of the two brown coal fractions are presented in fig. 3.

The silica sand used as a bed material is of the same size fraction in all the present test runs. The mass weighted mean particle size is 0.88 mm, but the resulting bed material size was about 0.92 mm.

OPERATING CONDITIONS

The operating conditions for the five selected test runs are given in table 2. The fuel in every test is fed through the chute down onto the bed surface. The load and the overall excess air ratio are the same in all cases except when peat is the fuel. Insufficient capacity of a scraper conveyer in the fuel transportation system limited the load to about 50% in this case.

Secondary air and air-preheat are employed to improve the combustor performance when burning the more volatile and humid fuels.

The recycling ratio is small but significant in the coal tests, whereas it is zero and negligible in the peat and wood tests, respectively.

Table 1. Fuel Characteristics

Fuel	Bituminous coal	Brown coal		Peat	Wood chips
Size, mm	0-10	0-40	0-20	0-150	5x20x30
Proximate analysis:					
Combustibles, %	72.0	73.4	70.8	48.6	55.2
Ash , %	16.7	6.6	8.2	3.2	0.9
Moisture , %	11.3	20.0	21.0	48.2	43.9
Ultimate analysis:					
C , %	83.5	69.4		56.3	51.3
H , %	4.7	4.9		4.6	6.4
N , %	2.0	0.8		2.0	0.3
O , %	8.8	24.0		36.5	42.0
S , %	1.0	0.9		0.6	0.02
Volatile matter, % of combustibles	28	59		72	86
H_{ub}, kJ/kg combustibles	32110	26010		21810	21250

The need for bed cooling surface, i.e. the bed height, depends on the fraction of fuel burned in the bed and thus changes from one fuel to another. The cooling surface configuration of the boiler has resulted in a bed level variation between 0.71 and 0.89 m during the present test series. The bed temperature has been allowed to vary between 806 and 895°C.

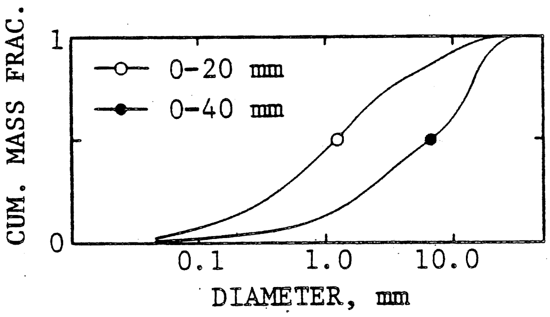

Figure 3. Brown Coal Size Distributions.

Table 2. Operating Conditions

Fuel	Bituminous coal	Brown coal 0-40	Brown coal 0-20	Peat	Wood chips
Load, %	64	64	64	47	64
Total excess air ratio based on O_2	1.32	1.25	1.30	1.34	1.31
Secondary air, % of total air	0	8	10	12	10
Primary air temperature, °C	51	44	48	222	229
Recycling ratio, kg/kg fuel	0.2	0.1	0.1	0	0
Bed height at operation, m	0.89	0.87	0.88	0.73	0.71
Fluidizing velocity, m/s	1.49	1.36	1.26	0.97	1.42
Bed temperature, °C	895	885	830	806	813
Flue gas temperature, °C					
after the freeboard exit	671	737	803	715	840
at the boiler exit	140	166	166	168	156

RESULTS AND DISCUSSION

As a result of the combustion characteristics of the various fuels there are significant differences in the freeboard temperature patterns, the heat fluxes to the walls of the freeboard, and in the heat absorption distribution over the parts of the boiler.

Temperature Profiles

One representative horizontal and one vertical measured temperature profile are selected in order to describe the main features of the freeboard temperature fields, fig. 4.

The temperature profiles are the result of heat release by combustion and cooling by the walls. The vertical profiles express clearly the expected increase of combustion in the freeboard in the case of the more volatile fuels. The bituminous coal gives a smoothly decreasing gas temperature upwards along the freeboard. The brown coal produces a fairly constant gas temperature equal to the bed temperature in most parts of the freeboard. With wood chips as a fuel, on the other hand, the gas temperature exceeds the bed temperature all over the freeboard space. The peak gas temperature resulting from the secondary air injection is some 300^{o} higher than the bed temperature in this case.

Secondary air is necessary to obtain complete combustion of gaseous fuel constituents in all cases except that of the bituminous coal. The secondary air jets penetrate from the boiler front and cause a kind of luminous flame. The shape of this flame is reflected in some of the curves of fig. 4.

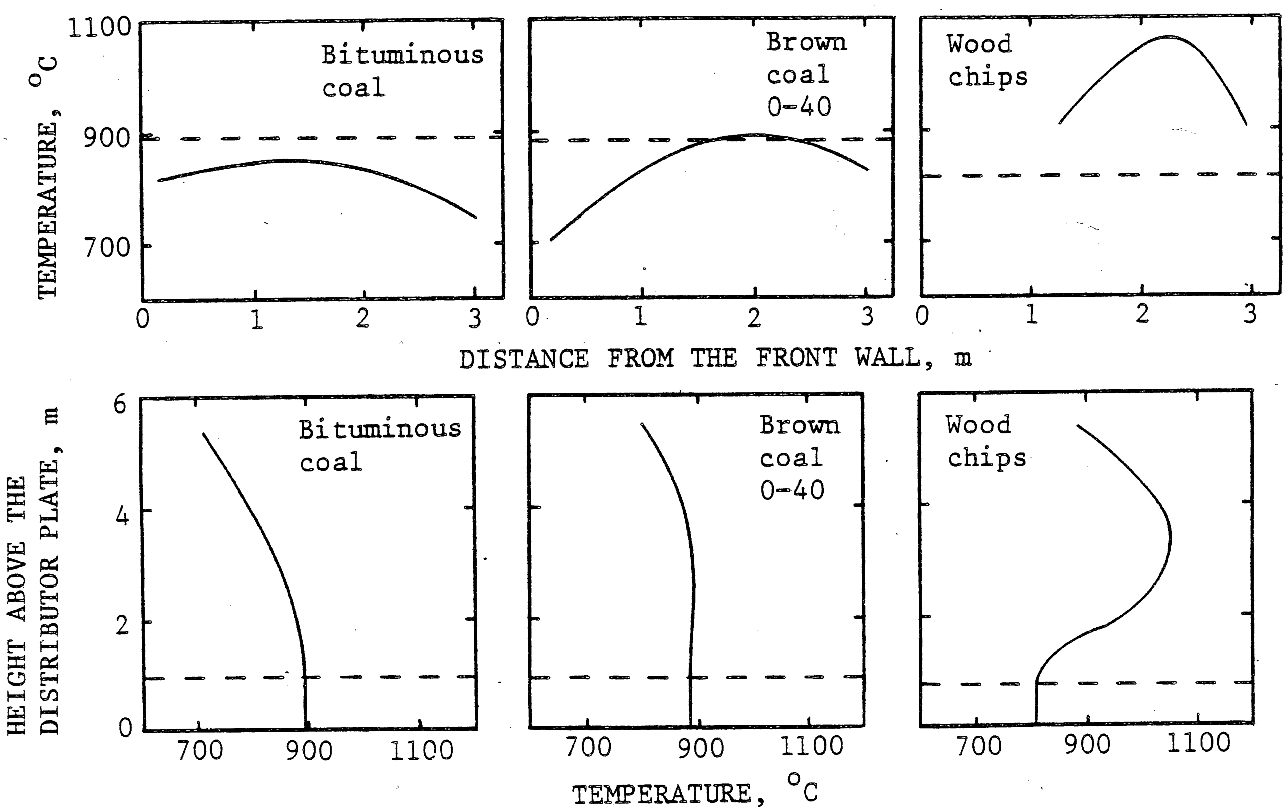

Figure 4. Characteristic Temperature Profiles in the Freeboard.
Upper Row: Horizontal Profiles. Bed Temperature - - -
Lower Row: Vertical Profiles. Bed Height - - -

Heat Flux Profiles

The heat flux to the walls is a result of the convective and the radiative heat exchange between the moving, particle laden gas, the splashing bed surface, and the water-cooled freeboard walls. The magnitude of the heat transfer depends on the gas flow velocity, the gas temperature field, and on the concentration of particles of various kinds in the freeboard.

The optical density of the gas-particle mixture varies in the freeboard. It is particle dominated in the splash zone and gas dominated in the upper freeboard region. The optical density is affected locally by soot (luminous radiation) created by combustion either in the splash zone or in the freeboard.

This fairly complex picture cannot be closely represented by a simple heat transfer model. However, a simple model in combination with heat flux measurements will form a basis for understanding what occurs in the freeboard. The model used here considers the freeboard to be a well-stirred space with an even composition and with a mean temperature evaluated from the measured temperature field. The space is surrounded by the water-cooled walls and the surface of the bed, both of which are characterized by measured temperatures and assumed emissivities. (The emissivity of the walls and that of the bed is put 0.8). The relatively small (<10% of total) gas convective contribution to the heat flux is evaluated according to conventional relationships. With all the temperatures fairly well represented, the well-stirred freeboard is given an emissivity that adjusts the model heat flux to that measured in the central part of the freeboard out of reach of the splashing bed.

The heat fluxes calculated according to the model are plotted as solid curves in fig. 5. The assumption of a homogeneous freeboard results in a constant heat flux contribution. The inclination of the curves is caused by the radiative contribution from the surface of the bed. The model does not consider any influence from particle convection heat transfer.

Measured heat fluxes, averaged over the width of the freeboard wall at various levels above the surface of the bed, are represented by dots in fig. 5. The vertical heat flux pattern is generally smooth with no peaks. The amount of over-bed combustion is reflected in the inclination of the measured profile.

The comparison between calculated and measured heat fluxes will treat two aspects: First, the magnitudes of the resulting emissivities of the freeboard are compared, and then, the deviation at the surface of the bed is considered.

The fitted emissivities are approximately equal to or larger than the emissivity of a freeboard filled with gaseous combustion products (CO_2 and H_2O) from the respective fuels, table 3. This means that the freeboard is filled with a medium that on average contains more radiative active matter than pure gaseous combustion products, e.g. bed material, ash, soot from combustion of hydrocarbons, and char particles. Although a sharp, luminous flame was observed in the case of wood, the fitted effective emissivity in this case is about equal to the corresponding gaseous emissivity. The explanation is most probably that the luminous part of the freeboard is fairly small and an error in the evaluation of the mean temperature reflects itself in the magnitude of the resulting emissivity. Such an error is not unlikely when the temperature field varies significantly.

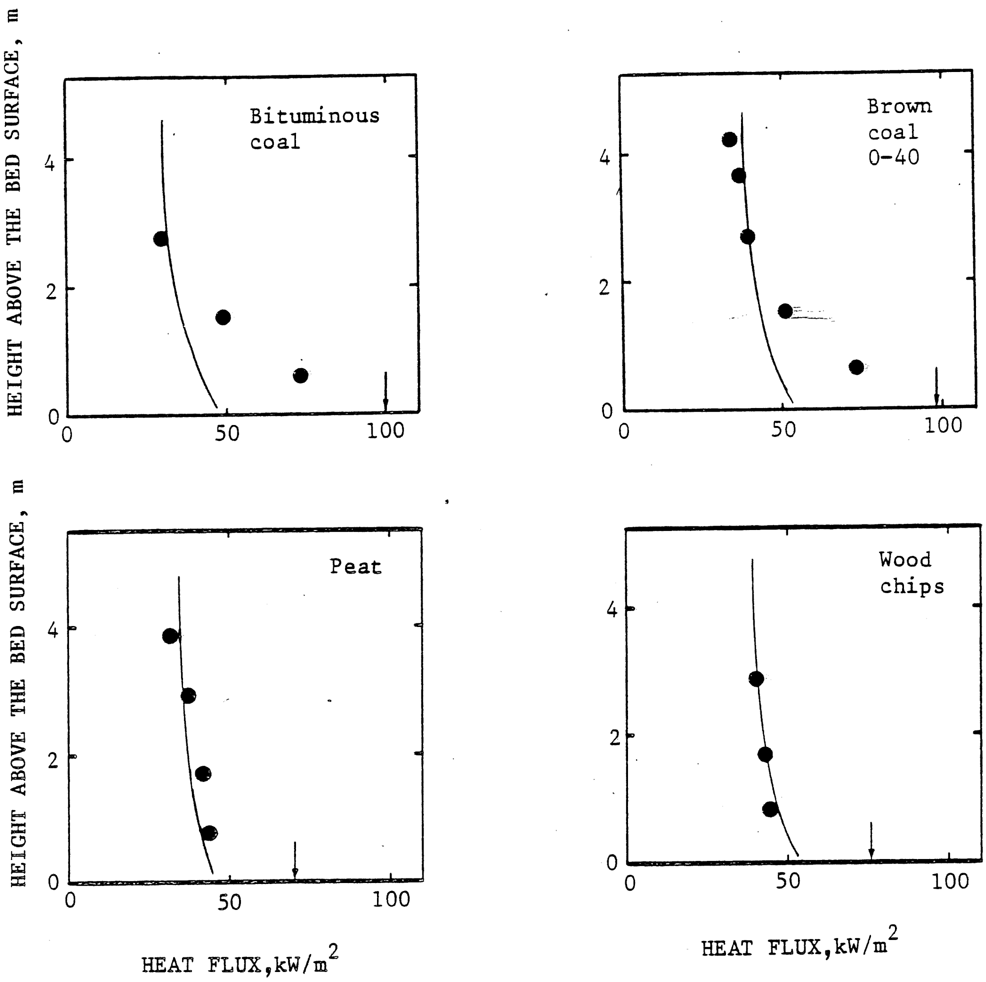

Figure 5. Heat Flux to the Freeboard Side Wall.
● Measured
—— Calculated
↓ Calculated Maximum Heat Flux at the Bed Surface (at Gas Emissivity =1 and Temperature = Bed Temperature).

The deviation between the model and the measured points in the lower region of the freeboard depends to some extent on the difference between the mean and the local gas temperatures, but more important

Table 3. Effective Emissivities and Temperatures of the Freeboard

Fuel	Bituminous coal	Brown coal 0-40	Brown coal 0-20	Peat	Wood chips
Emissivity					
Fitted	0.42	0.45	0.50	0.50	0.35
Gaseous	0.28	0.29	0.29	0.35	0.34
Temperature, °C					
Bed	895	885	830	806	813
Mean	810	855	825	810	926
Exit	671	737	803	715	840

seem to be variations in the optical density. A calculation of the heat flux from a dense gas (ε=1) with the temperature equal to the bed temperature gives a reasonable extreme value at the surface of the bed, as indicated in fig. 5. There is also a contribution to the heat transfer from the splashing bed. This contribution should be the same in all cases and it cannot explain the difference between the coals and the other fuels. A speculative explanation would then be that the less volatile fuels spread somewhat more in the bed while releasing their volatiles which would have more oxygen available for in-bed (in-splash-zone) combustion.

If this combustion forms a luminous flame, this would increase the optical density to a value which is greater than those characteristic of the splashing inert particles themselves. In the case of more volatile fuels, the volatiles are released more readily and they burn to a large extent above the splash zone due to more pronounced local deficiencies of oxygen. This is a tentative explanation of the differences observed, which is supported by oxygen measurements (E. Ljungström 1985).

A comparison between the measured heat flux curves from the two size fractions of the same fuel, the brown coal, gives a picture that is in agreement with the above discussion. The finer fuel (0-20 mm) tends to burn above the bed to a larger extent than the coarser fuel (0-40 mm). This is shown in fig. 6.

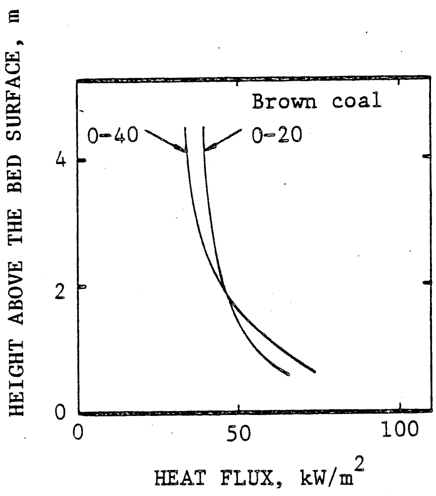

Figure 6. Measured Heat Flux to the Freeboard Side Wall with the Two Brown Coal Size Fractions. To Note the Different Bed Temperatures in the Two Cases, Table 2.

The Heat Absorption Distribution

The heat released by combustion is absorbed by the heat transfer surfaces of the boiler or is emitted with the flue gas in the form of a loss. The combustion chamber heat absorption (P_{CC}) is the difference between the total heat power received by the water-steam (P_{WS}) and the heat power absorbed by the gas passes (P_{GP}):

$$P_{CC} = P_{WS} - P_{GP} \qquad (1)$$

The heat transferred to the freeboard walls (P_F) is evaluated by means of the heat flux profile, as discussed above. Hence, the desired quantity, the heat absorption in the bed (P_B) including the splash-zone, is given by:

$$P_B = P_{CC} - P_F \qquad (2)$$

Fig. 7 gives the fractions of heat transferred to the various parts of the boiler and the losses. In the bituminous coal case, 40% of the heat supplied by the fuel is absorbed in the bed. This portion decreases when the more high-volatile fuels are burned and amounts to only 20% in the case of wood chips. The heat absorption by the freeboard walls is fairly similar in all cases. As a consequence of differences in temperatures and volume flows, the deficiencies in heat absorption in the bed and freeboard are made up in the gas passes so that the losses arising from sensible heat is about the same in all cases. In addition, the coals give a loss due to unburned char, whereas the humid fuels (peat and wood) are burdened with a loss due to water vapor (which happens to be of the same magnitude as that of unburned char in the bituminous coal test, fig. 7).

Once the heat absorption distribution of the boiler is known, it is possible to solve the bed heat balance (Leckner et al. 1984). This gives as a result the amount of fuel that burns in the bed and thus the quantity x, which symbolizes the fraction of the combustibles supplied that do not burn in the bed, i.e. freeboard combustion and losses. Table 4 shows that in this particular boiler, with the actual operating conditions, the quantity x ranges from 0.31 for wood chips to 0.12 for bituminous coal. Considering

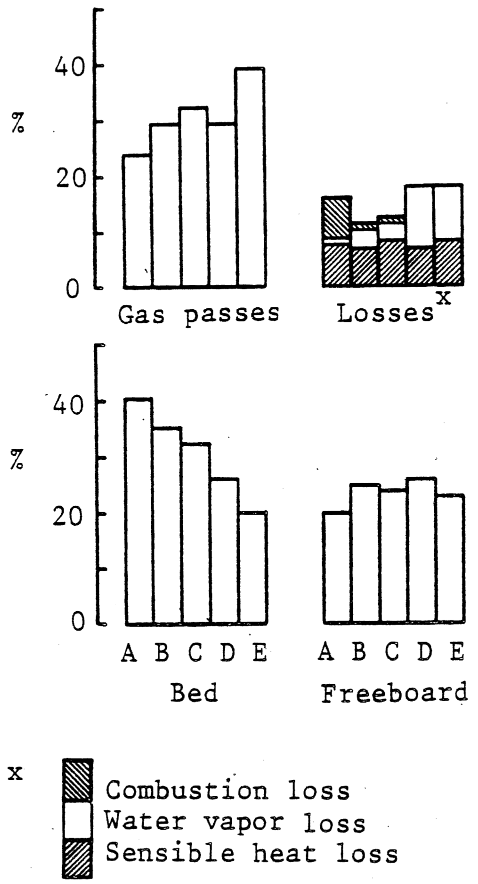

Figure 7. Distribution of Heat Absorption and Losses in Percentage of Fuel Power. A = Bituminous Coal. B = Brown Coal 0-40. C = Brown Coal 0-20. D = Peat. E = Wood Chips. To Note the Lower Load in the Peat Case.

the combustion losses, this means that 31% of the combustibles supplied in the form of wood chips burn above the bed, but only 5% of those of coal. A comparison of the two brown coal tests illustrates, as in fig. 6, the influence of the fuel size. The fraction 0-20 mm gives slightly more than 22% overbed combustion, whereas the coarser 0-40 mm fraction ends up with 17%. The low figure of x in the case of peat can also be interpreted as an effect of the fuel size. The peat used consisted of big and wet pieces and therefore acted as a more slowly burning fuel than would have been expected from its content of volatile matter. Previous tests in the same boiler with small (5x15 mm), dried peat pellets show a combustion pattern that resembles more that of wood chips.

Table 4. Fraction of Combustibles not Burnt in the Bed (x). See note in Fig. 7

Fuel	Bituminous coal	Brown coal 0-40	Brown coal 0-20	Peat	Wood chips
x	0.12	0.18	0.23	0.16	0.31

Combustion Efficiency

The combustion efficiencies obtained are given in table 5. The value for bituminous coal is compatible with results from various types of bituminous coal, e.g. (Davenport et al. 1984). That investigation indicates that there is a trend towards higher combustion efficiencies for coals with higher content of volatiles (or lower content of fixed carbon). The present results extend the range of fuels into the high volatile type of fuels. The tendency to higher combustion efficiency is indeed evident from the values of table 5.

Table 5. Combustion Efficiency

Fuel	Bituminous coal	Brown coal 0-40	Brown coal 0-20	Peat	Wood chips
Combustion efficiency, %	93.5	99.4	99.5	99.4	> 99.9

Whereas a number of design and operational measures influence the combustion efficiency of the low volatile coals, the high volatile fuels burn readily to completion provided that the size of the fuel is not completely unsuitable, the freeboard is sufficiently large, and secondary air is supplied for the freeboard mixing and combustion.

Emissions

The combustion has not been optimized with respect to the emissions in the present test runs. They should therefore not be considered as the minimum emission limits but as the result of ordinary operating conditions.

The carbon monoxide concentrations indicate that combustion is completed, table 6. The comparatively high emission recorded in the bituminous coal run could have been reduced by means of secondary air, as shown previously (Leckner et al. 1982).

The sulfur dioxide emitted is related to the fuel sulfur input to the combustor and to the sulfur capture capacity of the ash. No limestone was added in these tests.

The nitrogen oxide emission is a result of a complicated formation and reduction process. The resulting values shown by the table are not directly correlated with the amount of nitrogen supplied with the fuel. Global and local operating conditions of the bed and the freeboard have influenced the data.

The concentrations of heavy aromatic compounds in the flue gas, after the bag-house filter, were measured during combustion of coal, peat, and wood chips. The detectable emissions are low in all cases at normal operating conditions. Even small disturbances may, however, increase the emissions considerably (Leckner et al. 1985).

CONCLUSIONS

The content of volatile matter in the fuel and the size of the fuel are two important factors that influence the combustion and the heat absorption in a fluidized bed boiler.

For practical reasons the fuel is often supplied to the bed at certain locations (in the present case: one feed point per 10 m^2) and the release of volatiles creates oxygen deficient zones which lead to the existence of unburned gases in the freeboard. This is more pronounced with high volatile fuels, than with coal. Coal has a greater opportunity to spread in the bed and its gaseous constituents are predominantly burned in the bed or in the splash zone.

The combustion of the volatile fuels differs from that of bituminous coal in the following respects:

- The total excess air ratio is the same in all runs, but at the combustion of volatile fuels, part of the air should be supplied in the freeboard, in order to provide mixing and completion of combustion.

Table 6. Emissions

Fuel	Bituminous coal	Brown coal 0-40	Brown coal 0-20	Peat	Wood chips
CO, mg/MJ	404	120	144	209	157
SO_2, mgS/MJ	203	272	290	192	8
NO_x, $mgNO_2$/MJ	172	55	67	125	74
Heavy aromatic compounds, * µg/MJ:					
Naphthalene	0.68	Not measured		0.73	0.89
Phenanthrene	< 0.02			0.036	0.17
Fluoranthrene	"			0.01	< 0.02
Pyrene	"			< 0.005	"

* The concentrations the other polyaromatic hydrocarbons analyzed were below the detection limit of the instruments.

- The greater freeboard combustion in the case of volatile fuels leads to a redistribution of the heat absorption in the boiler. In order to keep a fairly constant (800-900°C) bed temperature, various measures can be taken in order to influence the heat balance of the bed such as cooling surface area adjustment, air preheat, and by-pass of air in the form of secondary air. The heat transfer surfaces of the convection gas pass compensates for the variations in heat absorption of the bed and the loss of sensible heat is about the same in all cases.
- The more volatiles (or the less fixed carbon) the fuel contains, the easier it burns to completion without losses in the form of unburned char. Fuels with a volatile content >50% do burn out without any particular measures taken, such as recirculation of solids, provided that the freeboard is sufficient for burning the gases with secondary air.

The above conclusions are valid for lump fuels of the types used in the present investigation. If ground fuels with fine particles are used, the time for burnout of the particles in suspension becomes important. This case is not treated here. However, a displacement of combustion from the bed to the freeboard due to release of volatiles as the fuel size decreases has been demonstrated.

ACKNOWLEDGEMENT

This work was financed by the Swedish National Energy Administration. The authors are grateful to Sten Johansson for his help in experimental measurements.

REFERENCES

Davenport, A., Struthers, J., Tringham, D.J., and Peirce, T.J., Operating experience with Babcock 'Fluidburn' range of coalfired Fluidised Bed Boilers, 3rd Int. Fluidised Conf., The Institute of Energy, London, Oct. 1984.

Leckner, B., Jansson, B., Lindqvist, O., and Nielsen, B.-M., Emissions from a 16 MW_{th} FBC-boiler, The 7th Int. Conf. on Fluidized Bed Combustion, Philadelphia, Oct. 1982.

Leckner, B., Andersson, B.-Å., and Vijil J., Fluidized bed combustion of coal and biomass, Combustion of Tomorrow's Fuel-II, Engineering Foundation Conference, Davos, Oct. 1984.

Leckner, B., and Åmand, L.-E., Emissions at the combustion of peat in a fluidized bed - summary of tests at Chalmers, Dept. of Energy Conversion. Report A85-141, Jan. 1985. (In Swedish with an English summary).

Ljungström, E., In-Bed Oxygen Measurements in a Commercial Size AFBC, The 8th Int. Conf. on Fluidized Bed Combustion, Houston, March 1985.

Svensson, G., and Leckner, B., The Fluidised Bed Boiler at Chalmers University of Technology, The 7th Int. Conf. on Fluidised Bed Combustion, Philadelphia, Oct. 1982.