VERIFICATION OF METHOD FOR ESTIMATING COMBUSTION EFFICIENCY IN A BUBBLING FB COMBUSTOR

by

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Original scientific paper
UDC: 662.87–912
BIBLID: 0354–9836, *4* (2000), 2, 101–111

The article refers to a mathematical method for estimating the efficiency of the combustion process in bubbling fluidised bed conditions. The calculation procedure used in this work is given elsewhere [1, 2] and, here, it is only briefly described.

The objective of the present investigation is to validate the mentioned method when using brown coal as a fuel in a laboratory fluidised bed combustor. Particular attention is devoted to the subject of elutriation of fuel particles out of the combustor, considering the fact that it is one of the most important factors limiting the combustion efficiency and the furnace design as well. The work presented here contains the conditions and some results of experimental research in heat losses resulting from the phenomenon of elutriation of combustible particles [3]. Experiments were carried out in a combustor with an inner diameter of 200 mm and a height of 1200 mm.

A numerical testing of the method for estimating the combustion efficiency was accomplished within a bed temperature range from 780 °C to 900 °C and a fluidising velocity from 1.20 to 1.32 m/s. The results achieved were compared with the experimentally obtained data. Besides the appearance of some deviations, it may be stated that the results are reasonable and in line with the expectations.

Introduction

Some of the items of interest in designing a fluidised bed (FB) combustor and its operating are such as: fuel quantity that is burned in particular parts of the combustor, amount of heat released in the bed and in the freeboard and allowable ranges of fuel properties for satisfactory operation. This basic information should be also available in making preliminary comparison of design options or comparison between alternative fuels for an existing combustor or FB boiler. In essential relationship with the previous items is the efficiency of the combustion process. One of the difficulties connected with the exploatation of FB combustors and FB boilers is the problem of carryover combustible particles out of the fluidised bed. The subject of elutriation is one of the most important factors limiting the combustor design and the way in which it may be operated.

A simplified engineering calculation method, developed to facilitate the determination of the values of unburned char losses and combustion efficiency, is given elsewhere [1, 2]. The purpose of the investigation presented in this paper was to test and validate the mentioned method for estimating the combustion efficiency in a combustor with bubbling fluidised bed in a case when brown coal is being burned. This work contains some results of experimental research in losses resulting from the phenomenon of elutriation of fuel particles out of the fluidised bed.

Description of the method for estimating the combustion efficiency in a FBC

A number of processes and parameters influence the efficiency of the fuel combustion in the FB combustor: fragmentation and attrition of solid fuel particles, elutriation, devolatilisation, volatile and char combustion, as well as design and technological parameters. Bed material in FB combustors is invariably composed of particles usually with a wide range of sizes and densities. Many solid materials, including coals, undergo attrition when fluidised, or fragmentation due to thermal stresses when put into a hot fluidised bed. Attrition and fragmentation lead to production of fines, that become entrained in the gas leaving the bed.

Figure 1 depicts an idealisation of the combustion sequence of a solid fuel as it is presumed in this work. The overall combustion efficiency is controlled mainly by the unburned carbon loss, which results from elutriation and attrition of fine char particles. It is assumed here that volatiles influence only the combustion split between the in-bed and the freeboard region. Hence, they affect the heat distribution in the bed and freeboard zones, but they do not affect the overall combustion efficiency. Consequently, unburned volatiles loss is taken to be irrelevant. Bed discharge char loss is, also, neglected, although it might play a significant role in some FBC applications.

The fuel volatile matter and char particles during the combustion behave differently. The fuel volatile matter evolves from the coal particles during the initial stage, typically over a period from a few seconds till a few tens of seconds, depending mostly on the coal particle size. The combustion of a char particle, containing mainly carbon and mineral matter, in FB conditions takes, usually, a few minutes, again depending on its size. Char combustion is relatively slow process and it can be assumed that it occurs evenly distributed over the bed.

The method developed for evaluation of the combustion efficiency comprises particular modules that deal with bed and freeboard hydrodynamics, chemical kinetics of devolatilisation and char combustion, solids distribution in the furnace and interphase heat and mass transfer [1, 2, 4].

The following governing assumptions were used in order to simplify the calculation procedure:

– uniform temperature everywhere in the bed, except on the fuel particles surface;

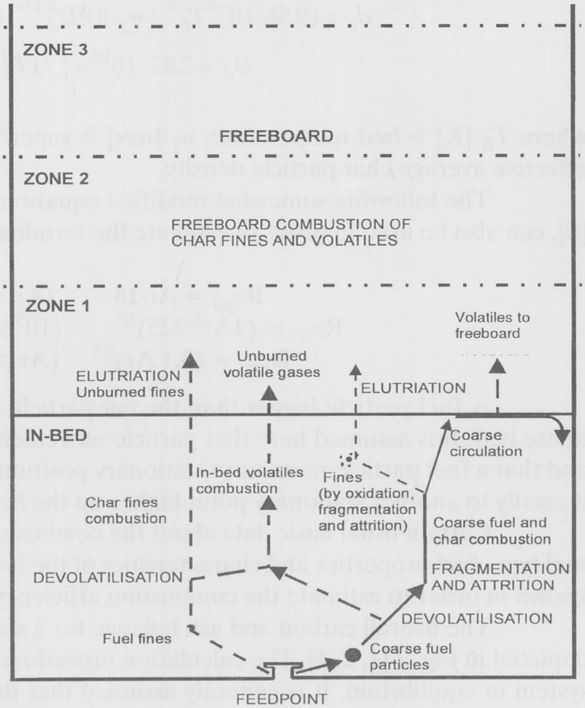


Figure 1. Conceptual scheme of the basic processes during combustion of solid fuel in the stationary FB conditions [2]

- spherical shape of the carbon particles;
- fuel particles well mixed and uniformly distributed in the bed;
- irrelevant temperature gradient inside the char particle;
- devolatilisation rate controlled by the devolatilisation kinetics;
- circulation in the bed of fuel particles bigger than the cut particle size;
- oxidation of the fuel carbon to form CO at the particle surface, what is followed by the gas-phase combustion of CO near the surface;
- plug flow of gases through the bed and the freeboard region.

At this point it should be noted that the experimental data which are used for comparison were gathered from a fluidised bed combustor with over-bed fuel feeding system.

To estimate the fraction of the feed fuel that leaves the dense zone, it is presumed that the elutriable cut particle size is the char particle size that is small enough to be carried by the gas flow in the freeboard zone of the furnace. Thus, the elutriable char particle size can be estimated comparing the average superficial gas velocity and the terminal velocity of the char particle. Particles smaller than the cut size will move upwards until they are consumed or reach the furnace exit. In this case the following equation is used to calculate directly the elutriable char particle diameter (in mm) [5]:

$$\begin{gathered} d_t = (9.58 \cdot 10^{-7} T_B^{1.7} / w_f)(4 D_d^{0.436} + 0.489 D_d^{0.872})^{1.15} \\ D_d = 2.82 \cdot 10^{10} w_f^3 / (T_B^{2.7} \rho_C) \end{gathered} \tag{1}$$

where T_B [K] is bed temperature, w_f [m/s] is superficial gas velocity and ρ_C [kg/m^3] is effective average char particle density.

The following somewhat modified equations, according to Kunii & Levenspiel [6], can also be used in order to estimate the terminal velocity:

$$\begin{aligned} \mathrm{Re}_{p,t} &= \mathrm{Ar}/18 && (\mathrm{Ar} < 10^3) \\ \mathrm{Re}_{p,t} &= (4\mathrm{Ar}^2/225)^{1/3} && (10^3 \le \mathrm{Ar} \le 94260) \\ \mathrm{Re}_{p,t} &= (3.1\,\mathrm{Ar})^{0.5} && (\mathrm{Ar} > 94260) \end{aligned} \tag{2}$$

A fuel particle bigger than the cut particle size undergoes a circulation in the dense bed. It is assumed here that particle movement is caused by the bursting bubbles and that a fuel particle remains in stationary position in the bed until a bubble displaces it axially to another stationary point higher up the bed [7].

Certain usual basic data about the combustor geometry, operating parameters, fuel type, fuel properties and characteristics of the fuel fractional composition should be known in order to estimate the combustion efficiency.

The overall carbon and ash balance for a stationary fluidized bed combustor is depicted in Fig. 2 [1, 2, 4]. The calculation procedure for combustion efficiency refers to system in equilibrium. It is generaly assumed that the char consists only of carbon and ash, the once-through combustion efficiency is independent of the recycle ratio and the

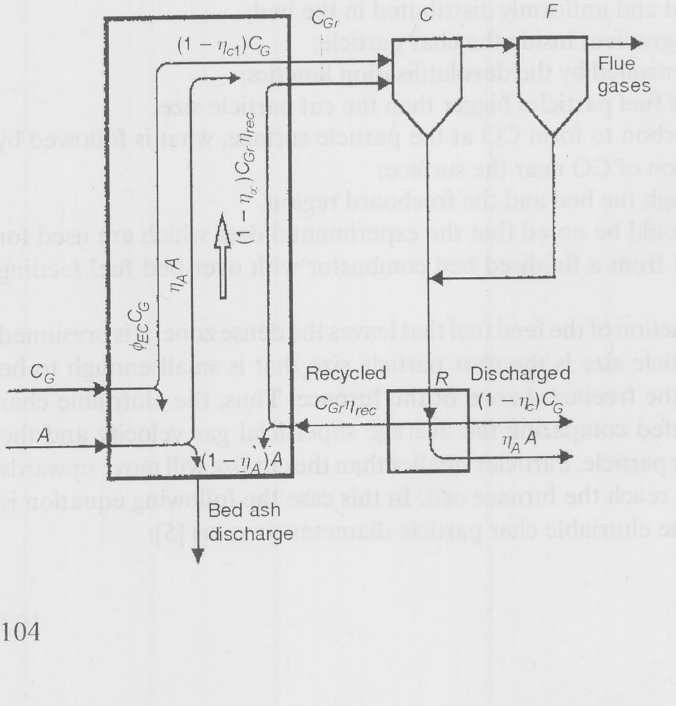


Figure 2. Flow scheme of overall carbon and ash balance for stacionary FB combustor [1, 2, 4] *FBF – fluidised bed furnace; C – cyclon, F – filter;* C_G *– mass flow of feed fuel carbon;* C_{Gr} *– mass flow of carbon carryover from combustor; A – ash content in fuel;* η_c *– overall combustion efficiency;* η_{c1} *– once-through combustion efficiency;* η_A *– coefficient of coal ash elutriation;* η_{rec} *– fraction of char fines recycled;* ϕ_{EC} *– fraction of carbon fines elutriated from dense zone*

unburned char fines leave the furnace as non-volatile. Also, it is considered here that the char combustion process finishes till the particles reach the furnace exit and no combustion occurs outside the furnace.

The total amount of carbon fines, conveyed out of the dense bed zone, can be represented with the expression

$$\phi_{EC} = \phi_{EF} + (1 - \phi_{EF})\phi_{AC} \tag{3}$$

where ϕ_{EF} [–] is weight fraction of feed fuel that is ultimately elutriable and ϕ_{AC} [–] is contribution of attrition to the total amount of elutriating carbon:

$$\phi_{AC} = \frac{3k_a(w_f - w_{mf})t_t}{d_G} \tag{4}$$

In this expression k_a [–] is carbon attrition rate constant, w_{mf} [m/s] is minimum fluidising velocity, d_G [m] is the fuel particle diameter and t_t [s] is particle bed turn-over time. In the present work a linear dependence between the constant k_a and d_G is applied: $k_a = (20.625d_G - 4.750)10^{-8}$ (d_G in mm).

The particle bed turn-over time is calculated by Grubor [8]:

$$t_t = \frac{H_{mf}}{[(w_{mf}/w_d)(w_f - w_{mf})(0.156 - 0.111\log d_G)]} \tag{5}$$

where d_G [m] is fuel particle diameter and the gas velocity in the dense phase is defined with the equation $w_d = w_{mf} + 0.25(w_f - w_{mf})$.

Assuming that carbon content in the bed drain is negligible, the following expression for the carbon utilisation is derived from the overall balance:

$$\eta_{CU} = 1 - (1 - \eta_{rec})\exp\left(-\frac{t_r}{\tau_c}\right)\frac{(\phi_{EC}C_G + \eta_{rec}C_{Gr})}{C_G} \tag{6}$$

where η_{rec} is fraction of the total char fines flow exiting the furnace that is recycled. The degree of char fines combustion above the dense zone is aproximated as an exponential decay [5]: $\exp(-t_r/\tau_c)$. The mean particle residence time in the combustor t_r [s] is determined by dividing the distance between the fuel feedpoint and the furnace outlet to the average upward elutriating velocity w_p. It can be roughly estimated by $w_p = w_f - w_s$, where w_s [m/s] is a slip velocity between gas and particles.

The burning time constant for elutriated char fines, which reflects the fuel reactivity, is estimated using the equation [5, 9]:

$$\tau_c = (\tau_k^2 + \tau_{mt}^2)^{0.5} \tag{7}$$

The chemical kinetics controlled burnout time constant is calculated with the equation:

$$\tau_k = \frac{1.4 d_C \rho_C}{18 k_o \exp(-E / RT_B) p_{O_2}} \tag{8}$$

where d_C [m] is diameter of char particles, ρ_C [kg/m^3] is average density of char particles, k_o [kg/m^{2}sPa] is pre-exponential factor, E [J/mol] is activation energy for the char combustion, $R = 8.314$ J/molK is ideal gas constant and p_{O2} [Pa] is average oxygen partial pressure.

The external mass transfer time constant is calculated as:

$$\tau_{mt} = \frac{2.8 \cdot 10^{11} \rho_C C_{fix}^d d_C^2}{\mathrm{Sh}_e T_B^{0.81} p_{O_2}} \tag{9}$$

where C_{fix}^d [–] is moisture-free fixed carbon in fuel and Sh_e is Sherwood number, which is defined as:

$$\mathrm{Sh}_e = 2 + 20 \cdot 10^3 (d_C w_s / T_B^{1.7})^{0.5} \tag{10}$$

The slip velocity between gas and particles is:

$$w_s = 9.57 \cdot 10^{-10} (T_B^{1.7} / d_C)(9.53 \mathrm{Ar}^{-0.78} + 0.643 \mathrm{Ar}^{-0.39})^{-1.28} \tag{11}$$

where the Archimedes number for fine particles is estimetd by $\mathrm{Ar} = 30 \cdot 10^{15} (\rho_C d_C{}^3 / T_B{}^{2.4})$.

The unburned carbon heat loss, caused by the char fines elutriation, for every char size fraction is expressed with the equation:

$$\Delta q_{4,j} = \frac{337 C_{fix}^d}{H_d} (1 - \eta_{CU,j}) \tag{12}$$

where $\eta_{CU,j}$ [–] is carbon utilisation of the actual fuel fraction, H_d [kJ/kg] is lower calorific value of dry fuel and C_{fix}^d is given in % per mass.

Thus, neglecting the unburned fuel loss caused by chemical reasons, the overall combustion efficiency, as the fraction of the fuel heating value that is actually released, is calculated using the expression:

$$\eta_c = 1 - \Sigma \Delta q_{4,j} \Delta_{xj} \tag{13}$$

where Δ_{xj} is weight fraction of the fuel as it enters the combustor.

Experimental research

Several types of bituminous and brown Polish coal were burned and the research was carried out within a relatively wide range of temperatures of the fluidised bed, value of excess air coefficient λ and fluidising air velocity [3]. In the present work only some results obtained during the investigation of brown coal combustion were used.

The experimental FB combustor used has an inner diameter of 200 mm and a height of 1200 mm, Fig. 3. The air, which is indispensable for fluidisation and combusting of the fuel, was supplied through a distributor of 200 mm in diameter (2) from a blower pipe (3).

The distributor has eight nozzles with a diameter of 32 mm and a height of 76 mm each. Fuel was fed from a bunker (4) over the bed by a variable-speed, calibrated anger (5), placed at height of 800 mm above the air distributor. For the purpose of measuring the particles blown out of the bed, the flue gases were directed to a cyclone (6) of 300 mm in diameter and the height of 920 mm. There was also a cloth filter installed behind the cyclone.

The efficiency of the cyclone was tested during a combustion test by installing an isokinetic sampling probe with a fritted disk filter in the exhaust line following the cyclone. The mass of particles collected by the cyclone was over 97% of all the particles produced by the combustor.

A pipe heat exchanger (7), immersed in the bed, was installed with aim to control the temperature in the fluidised bed. During the experiment the temperature in the bed, as well as in the freeboard was measured with thermocouples (8), whereas an orifice (9) was used to measure the intensity of air flow.

The investigation of brown coal combustion was carried out within the bed temperature range of 780 – 880 °C and bed height between 200 and 220 mm. The excess air coefficient was varied between $\lambda = 1.01 - 1.50$, while the values of the fluidising air velocity were in the interval $w_f = 1.20 - 1.32$ m/s. Natural silica sand with $d_p = 0.6 - 1.0$ mm was used

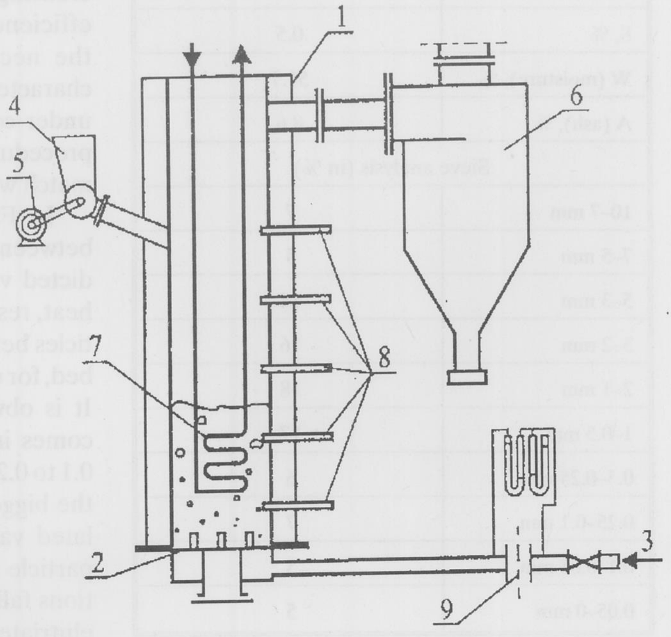


Figure 3. Schematic diagram of the experimental set-up
1. Fluidised bed combustor,
2. Air distributor,
3. Blower pipe
4. Fuel bunker,
5. Calibrated anger,
6. Cyclone,
7. Heat exchanger,
8. Thermocouples,
9. Orifice

as a bed material. The fuel properties such as proximate and ultimate analysis and size distribution are given in Table 1. The lower heating value of moisture free coal is 21683 kJ/kg.

Table 1. Analysis of coal used in the experimental research

Property	As received	Moisture free
Proximate analysis		
Moisture, %	13.93	0.0
Ash, %	7.81	9.08
Volatile matter, %	35.91	41.71
Fixed carbon, %	42.35	49.21
Ultimate analysis		
C, %	26.0	
H, %	1.9	
O, %	10.0	
N, %	1.2	
S, %	0.5	
W (moisture), %	51.7	
A (ash), %	8.6	
Sieve analysis (in %)		
10–7 mm	7	
7–5 mm	5	
5–3 mm	14	
3–2 mm	16	
2–1 mm	18	
1–0.5 mm	17	
0.5–0.25 mm	6	
0.25–0.1 mm	7	
0.1–0.05 mm	5	
0.05–0 mm	5	

Results of the investigation

Some results of the present research are shown in the following charts. Figure 4 compares the experimental loss of heat due to elutriation of combustible particles and the resulting overall combustion efficiency as a function of temperature of the fluidised bed for the brown coal, Table 1, with values predicted by the described calculation method. Despite of certain discrepancies, the dependencies $q_4 = q_4(t)$ and $\eta_c = \eta_c(t)$ clearly point out the fact that the temperature rise causes decreasing of the heat loss due to the unburned char and consequent increasing of the overall combustion efficiency. Previous also emphasizes the necessity to include pertinent characterization properties of the fuel under consideration into calculation procedure in order to obtain better match with the experimental data.

In Fig. 5 a comparison is given between the measurements and predicted values of the relative loss of heat, resulting from combustible particles being elutriated of the fluidised bed, for different temperature ranges. It is obvious that this heat loss becomes intensified by the fraction of 0.1 to 0.25 mm and it sharply drops for the bigger fractions. Since the calculated values for the elutriable char particle size in various regime conditions fall between 0.3 to 0.35 mm, all elutriated char particles, according to

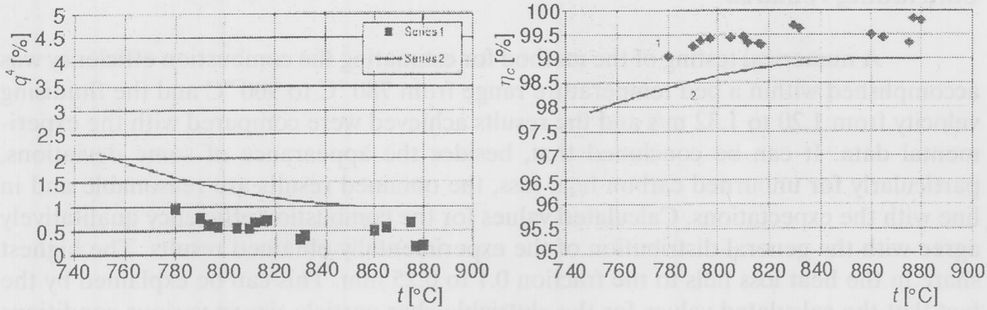
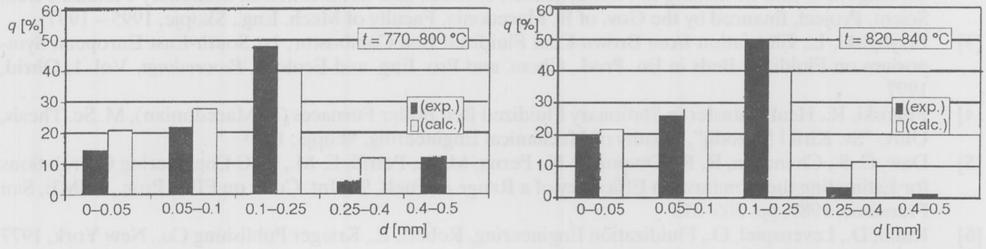


Figure 4. Heat loss and combustion efficiency as functions of the temperature of the fluidised bed

1 – experimental results; 2 – calculations

the calculations, belong to the fractions with diameter smaller than 0.4 mm. A small share in this loss, belonging to the fraction of 0.4 to 0.5 mm, can be explained with so-called "dynamic outbursts". In the calculations this share is not provided.



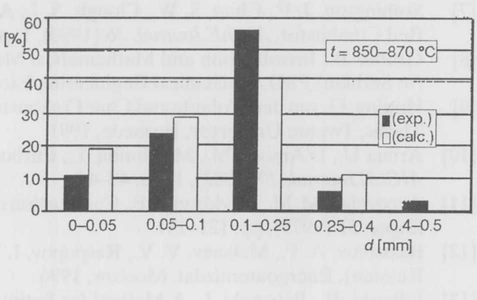


Figure 5. Loss of heat resulting from combustible particles in fly ash as a function of particle fractions in three temperature ranges

Concluding remarks

A numerical testing of the method for estimating the combustion efficiency was accomplished within a bed temperature range from 780 °C to 900 °C and the fluidising velocity from 1.20 to 1.32 m/s and the results achieved were compared with the experimental data. It can be concluded that, besides the appearance of some deviations, particularly for unburned carbon heat loss, the obtained results are reasonable and in line with the expectations. Calculated values for the combustion efficiency qualitatively agree with the general distribution of the experimentally obtained results. The highest share in the heat loss falls to the fraction 0.1 to 0.25 mm. This can be explained by the fact that the calculated values for the elutriable char particle size in various conditions are between 0.3 to 0.35 mm and the residence time in the combustor for such particles is insufficient to complete combustion before they have been elutriated. Generally, the loss of heat resulting from char elutriation, due to the fuel properties and the combustion conditions, in this case is surprisingly insignificant one. The satisfactorily correspondence between the calculated results and the experimental ones for overall combustion efficiency is verification for the right concept of the proposed method. Introduction of certain characterization data for specific fuels under consideration will certainly improve the reliability of the calculation procedure.

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Paper submited: September 1, 2000
Paper revised: November 6, 2000
Paper accepted: February 27, 2001