air to 2.0 with air saturated solution.

Alkaline cyanide solution. Excellent results were achieved with the alkaline cyanide solution; the copper content in the scrap was reduced to less than 0.06%. This is a level which has not been attained by any physical separation method other than strenuous hand picking. Power consumption is low; it ranges from −0.01 W·h/g (no power is needed for the electrolysis) of copper removed at a cell current of 20 mA to 0.49 W·h/g of copper removed at 200 mA. Only one Faraday of electricity is needed to dissolve 1 gram-mole of copper as indicated in column (13). This implies that the cuprous cyanide complex is the dissolution product. The main drawback of this system is that no copper was deposited at the carbon cathode because of low cuprous cyanide concentrations. Addition of cuprous cyanide to the electrolyte results in copper deposition at the cathode; however, it also retards the corrosion of copper at the anode. It appears that the ratio of free cyanide-to-copper content in the electrolyte is an important factor in the overall performance. Further effort is required to determine the optimal ratio for scrap treatment. This preliminary study has, nevertheless, demonstrated that it is technologically feasible to remove copper from scrap steel with a packed-bed electrochemical cell.

ACKNOWLEDGMENT

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Combustion Kinetics in the Modeling of Large, Pulverized Fuel Furnaces: A Numerical Experiment in Sensitivity

A mathematical model of combustion in a utility type of pulverized, coal fired furnace is developed by dividing the furnace into a number of isothermal zones. The method dovetails the combustion rate data available for single char particles with a gas flow pattern to predict local combustion heat release rates and local radiation absorption coefficients, which are used as input to a zoned heat transfer model.

The furnace heat transfer is shown to be insensitive to combustion related parameters such as coal rank and coal fineness. For carbon in ash, local gas temperature, and to a lesser extent local heat flux, significant variations are predicted. It is concluded that for calculation of radiative heat transfer, combustion data are adequate. Further research activity on ignition and combustion stability, together with the radiative properties of fly ash, is recommended.

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SCOPE

Despite the introduction of nuclear power stations and the active research into alternative energy sources, the bulk of electricity generated throughout the world uses conventional water tube boilers burning fossil hydrocarbons as a primary energy source. A large proportion of these boilers burn coal in a pulverized form, and with the increasing restrictions on availability of oil and natural gas, this proportion will surely increase.

Coal fired steam cycles usually operate on the Rankine cycle, most often with superheat and reheat. At present, this cycle has a maximum thermal efficiency of about 40%. This is limited mainly by the temperature to which the

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steam can be heated in present generation furnaces. Increasing cycle efficiency by higher steam temperatures is one obvious way of increasing this efficiency and at the same time decreasing thermal pollution local to power stations. The conventional, essentially empirical, techniques for pulverized fuel furnace design have not shown great promise for extension to the higher duty cycles. The alternative, a detailed numerical analysis of the furnace, has not previously been available.

A program of study of the mathematical modeling of pulverized fuel furnaces has been under way in the Department of Chemical Engineering of the University of Newcastle, N.S.W., for some years. A zoned heat transfer model has been built and tested against the operating furnace and has been shown to be realistic. The model is now being used to explore its own sensitivity to the various data inputs. In this way, future research is directed in the most profitable directions. The particular study presented here develops a zoned combustion model and evaluates the sensitivity of the model to the combustion related parameters.

Mathematical models must be expected to play an important role in the design, assessment, and scale-up of furnaces for the power generation in the future, especially those furnaces fired with the multifuel products from fossil fuel to fuel conversion plants.

CONCLUSIONS AND SIGNIFICANCE

1. For the prediction of heat transfer in the very large pulverized fuel combustion chambers used for electrical power generation, data for the combustion rates of char are entirely adequate.

2. The portion of the pulverized fuel chamber in which combustion proceeds to any appreciable extent is quite small; in the case considered here, 90% of the chamber volume is used for the combustion of 5% of the char. In terms of combustion, the chamber volume could certainly be reduced.

3. The combustion model developed in this paper is completely compatible with the zoned heat transfer model. This allows the construction of a single program to model both combustion and heat transfer in the furnace.

4. A point only briefly considered in this treatment is the release of volatiles. It is not clearly understood how volatiles are released, the composition, and thus the calorific value, or even what weight fraction of the particle is lost to volatiles. From the work reported here, the detail of volatiles combustion appears to have only a second-order effect on heat absorbed in the furnace. It is, however, of more importance in the prediction of peak fluxes in the burner region and, most importantly, is vital for the prediction of flame stability and reliability of ignition. This problem can be also tackled by numerical models. We envisage the use of a mathematical model of the type described in this paper to generate realistic boundary conditions for a more detailed zone model of the region immediately adjacent to the fuel input. There is, however, a need for more detailed information on devolatilization and ignition.

5. The importance of fly ash as an emitter/absorber/scatterer, which until now has received little attention, is worthy of further study. Fly ash scatters radiation as well as absorbing and emitting it, so that the transfer equations become more complex than is usually considered in furnace situations. However, the theoretical background is available, and it remains for the research engineer to establish what assumptions might be made in a scattering medium. For this study, the optical properties of fly ash and their dependence on the composition of ash need first to be evaluated. It is probable that a study on the spectral emission from a pulverized fuel flame, in the spectral regions outside both the triatomic gas bands and soot emission at low wavelengths, will best establish these data. The agglomeration of fly ash on sampling leads us to conclude that data from samples may not be representative of those obtained in-situ.

6. The use of a mathematical model of a real situation can lead to a better understanding of the transfer mechanisms and the most profitable route in further resaerch. Phenomena that dictate transfer on an industrial scale will not necessarily control the laboratory and pilot scale situations.

Many papers discussing the combustion of pulverised fuel have been introduced by statements such as: "A prerequisite for the more efficient design of pulverized fuel combustion equipment is a mathematical treatment accurately describing the rate of burnout of a cloud of coal particles." The development of such a treatment has, until recently, been severely limited by the lack of basic combustion rate data for coal chars under conditions appropriate to pulverized fuel flames.

The publication over the last few years of correlations of combustion rates of pulverized fuel chars against coal rank now allows this statement to be evaluated.

A pulverized, coal fired furnace at the Munmorah Power Station in New South Wales, Australia, has recently been modeled mathematically to good effect, using the zone method (Lowe et at., 1975). This mathematical model is used here to investigate its own sensitivity to variation, or uncertainty, of the combustion related inputs. In this way, the adequacy of the data for the purpose of predicting the performance of the very large combustion chambers used for power generation can be evaluated.

THE COMBUSTION OF PULVERIZED COAL

On injection into a furnace, a coal particle progressively loses volatiles as it heats. The volatiles burn almost instantaneously, and the residue, the char, subsequently ignites and burns away. There is little doubt that ignition can occur before the volatiles have all been evolved, but the modeling of the combustion process generally necessitates a simplified approach whereby ignition follows devolatilization.

Under the very rapid heating experienced in a pulverized fuel furnace (10^4°K/s), the quantity and type of volatiles released are likely to differ from those obtained by the proximate analysis technique. Some relevant experimental data is available (Badzoich and Hawksley, 1970), and on the basis of this work we have allowed a volatiles release of 35% by weight for this coal, compared to 30% by proximate analysis. The calorific value of the volatiles is obtained by subtracting the calorific value of the residual char, taken as carbon plus ash, from the net calorific value of the original coal.

The rate of reaction of a spherical particle of char is established by considering the relative rates of the two mechanisms involved (Field et al., 1967) the diffusion of oxygen through the boundary layer surrounding the particle, and the rate of chemical reaction between oxygen and coal on the particle surface.

If the diffusion rate is very much slower than the reaction rate, then it will control the rate of reduction of the mass of the particle. Per unit external surface area, this will be

$$\frac{dM}{dt} = -K_d(P_g - P_s) \tag{1}$$

where K_d is given by

$$K_d = 1.28 \times 10^{-4}(T_m/1\,600)^{0.75}/d : T_m = \frac{T_g + T_s}{2} \tag{2}$$

for combustion to carbon monoxide at the surface.

With diffusion control, the partial pressure of oxygen molecules at the coal surface p_s will be low, so that Equation (1) reduces to

$$\frac{dM}{dt} = -K_d P_g \tag{3}$$

Alternatively, if the reaction rate is much slower than the diffusion rate

$$\frac{dM}{dt} = -K_s p_s (\equiv -K_s p_g) \tag{4}$$

as the partial pressure of oxygen molecules in the gas and at the coal surface will be the same. Equation (4) takes the reaction to be first order, and in addition K_s may be expected to be of the Arrhenius type:

$$K_s = K_s' \exp(-\Delta E/R\,T_s) \tag{5}$$

If the two rates are of the same order of magnitude, then elimination of p_s from Equations (1) and (4) yields

$$\frac{dM}{dt} = \frac{p_g}{\dfrac{1}{K_d} + \dfrac{1}{K_s}} \tag{6}$$

Equations (2) and (5) give a guide as to the controlling mechanism. For $K_d << K_s$, diffusion controls, and this will occur for large particles and at high temperatures. For small particles and at low temperature, $K_d >> K_s$, and the chemical reaction controls.

Multiplying Equation (6) by the particle surface area, we get the rate of decrease of mass for a particle burning at constant temperature, or in terms of fractional unburnts U

$$\frac{dU}{dt} = \frac{p_g S U}{\dfrac{1}{K_d} + \dfrac{1}{K_s}} \tag{7}$$

where

$$S = \frac{\text{particle surface area}}{\text{mass at time } t}$$

and

$$U = \frac{\text{mass at time } t}{\text{initial mass}}$$

If the char particles are spherical

$$S = \frac{6}{d\rho} \tag{8}$$

Experiment shows (Field, 1970) that pulverized fuel chars burn with both decreasing density and decreasing diameter. The density or diameter after some combustion can be related to the initial values by

$$\left.\begin{aligned} d &= d_o U^{\alpha} \\ \rho &= \rho_o U^{\beta} \end{aligned}\right\} \tag{9}$$

where for constant density combustion $\beta = 0$ and $\alpha = 1/3$, and for constant size combustion $\alpha = 0$ and $\beta = 1$, also by geometry $3\alpha + \beta = 1$. α and β are determined experimentally. Substituting Equations (9) and (8), into (7), we obtain

$$\frac{dU}{dt} = \frac{-p_g}{\dfrac{1}{K_d} + \dfrac{1}{K_s}} \cdot \frac{6U^{(1-\alpha-\beta)}}{\rho_o d_o} \tag{10}$$

For a monosized cloud of pulverized fuel, the particle burnout and the cloud burnout are the same, and the above equations, together with the variation of oxygen particle pressure within the cloud during burnout (Essenhigh, 1961)

$$p_g = p_o\left(\frac{cU + e}{1 + e}\right) \tag{11}$$

enable the progressive burnout to be calculated. For the usual situation where the pulverized fuel covers a considerable size range, for computing, we divide the cloud into a number N of initially equally weighted monosize fractions. Assuming that the sizing of the coal follows a Rosin-Rammler distribution

$$F = 100 \exp(-d/\bar{d})^n \tag{12}$$

we may find the initial diameter of the fractions d_{jo} by substituting

$$F_j = (j - ½) \cdot \frac{100}{N} \quad j = 1, 2, \ldots N \tag{13}$$

into Equation (12) and solving for d_j. If all particles in a given fraction will be combusted to the same extent at any one time, so that Equation (10) gives the rate of reduction of the fractional unburnts of the j^{th} fraction, then

$$\frac{du_j}{dt} = \frac{-p_g}{\dfrac{1}{K_d} + \dfrac{1}{K_s}} \cdot \frac{6u_j^{(1-\alpha-\beta)}}{\rho_o d_{jo}} \tag{14}$$

and

$$U = \sum_{j=1}^{N} \frac{u_j}{N} \tag{15}$$

for N fractions.

Until the early sixties, the experimental work on the coal combustion generally involved captive particles ranging from 300 μm up to 25 mm in size.

For example, the classic experiments of Tu et al. (1934) on 250 mm diameter spheres were the most widely quoted for 30 yr. These data clearly indicate diffusion control. Hottel and Stewart (1940) suggested that for the small particles of pulverized coal size (<100 μm in diameter), diffusion would not be rate controlling, and sophisticated experimental work in the late sixties which followed the kinetics of combustion of pulverized fuel sized char substantiated this. The data were obtained in the BCURA

Industrial Laboratories (Field, 1969, 1970) and the Division of Mineral Chemistry of C.S.I.R.O. (Mulcahy and Smith, 1969), and they allowed the estimated of K_s' and ΔE in Equation (5) for coals of various ranks.

THE ZONE METHOD OF ANALYSIS

For industrial furnaces, where fuels are burnt in flames which do not impinge directly on to the furnace walls, the heat transfer is predominantly radiative. If the walls are not black bodies, the radiation emitted by the flame may undergo a number of reflections before it is fully absorbed. In addition, sections of the furnace (both gas and surface) which are not at the same temperature will exchange thermal radiation, the net exchange being from hot to cold sections.

The geometry of these radiative exchanges is clearly complex, but the problem can be reduced to sets of linear equations if the furnace is divided into gas and surface zones for which direct exchange data are available (Hottel and Sarofim, 1967)

The zone method requires the division of a system into zones, both gas and surface, that may reasonably be considered isothermal. With the gas flows and combustion distribution as inputs, iteration through the nonlinear energy balance for the temperature of each zone (which depends on the temperatures of other zones) in turn, and the convergence of these temperatures, estimates the spatial temperature distribution. The heat flux to the system walls can then be calculated.

The radiative properties of the flame species (coal char, ash soot, triatomic gases) enter this calculation as absorption coefficients. Techniques for the evaluation of these properties are given later.

As has been detailed elsewhere (Wall, 1973), the fitting of the absorption coefficients of these species to a function of the extent of combustion (U) greatly simplifies the procedure.

THE FURNACE AND MODEL

The Munmorah furnace, of 900 MW (thermal input) capacity is a tangent fired, downflow design. There are five burner levels towards the top of the furnace, with full load normally carried on four levels. A dimensional sketch of the furnace is given in Figure 1. An analysis of a typical coal fired at the station is included in Table 1.

For the zoning of the chamber, two alternatives are considered: cubic or cylindrical zones. Cubic zones fit the rectangular cross-section; however, the flow pattern established by the tangential firing is better fitted by cylindrical zones. Also, the cubic system requires more zones. For a simple n zone cylindrical system in plan, n^3 cubic zones give the same pricipal zone dimension.

The cylindrical system was chosen because of computer core limits. This choice allows Erkku's cylindrical direct exchange areas (Hottel and Sarofim, 1967) to be used. Johnson (1973) successfully used a cylindrical model for a rectangular system.

The zoning of an enclosure for the use of the Hottel-Cohen technique should be such that zones are approximately isothermal; for computation ease it is also desirable that gas flow through a maximum of zone boundaries can be neglected. The zoning of Figure 1 conveniently bounds the radiant superheater, flame, plug, and absorbing zones by zone boundaries.

It is assumed that the burners throw pulverized fuel and air into the firing circle zones (14, 17, 20, 23, 26 in Figure 1). The flow out of the firing circle can be either

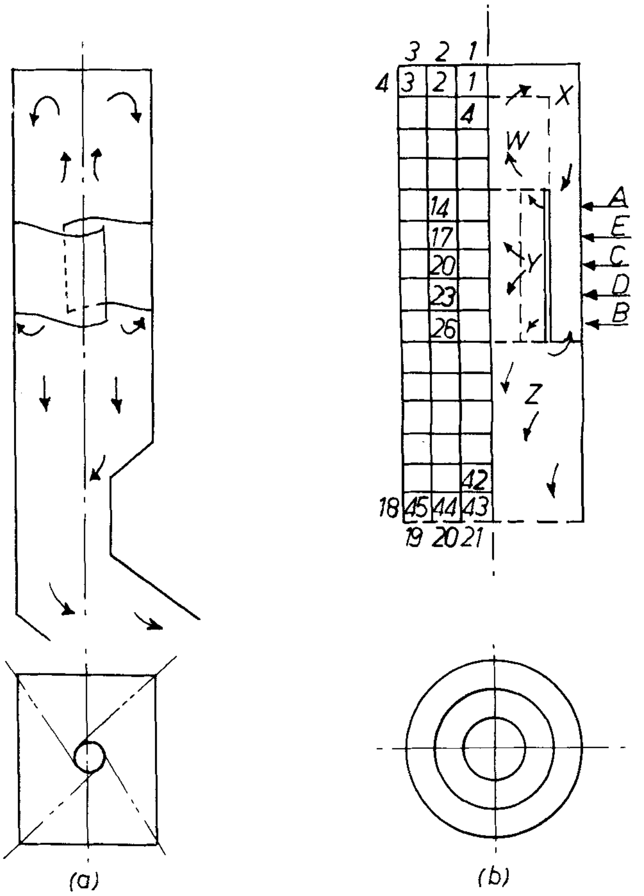

Fig. 1. Comparison between the furnace (a) and the model (b) showing the forty-five gas zones and twenty-one surface zones. The five burners (A, E, C, D, B from the top) inject fuel and air, together with entrained gases into the five firing circle zones Y. Ignition occurs at the ignition plane shown as a double line. Flow is then up through the radiant superheater zones W and the boundary zones X, and also down through the plug flow zones Z.

TABLE 1. BOILER AND FUEL DETAILS

Munmorah No. 2 boiler

Location	Central Coast, N.S.W. Australia
Boiler output, MW (thermal)	900
Unit output, MW (electrical)	350
Steam conditions	
Steam flow kg/h × 10^{-4}	109
Press., MN/m^2	17
Temp., °C	560
Furnace size, m	11.4 × 14.0 × 35 high
Firing arrgt.	Top corner fired 5 burners/corner-arrg'd. vertically—1 mill/burner level —2.5 m firing circle —full load 4 mills
Commissioning year	1968

Coal composition

Proximate analysis		Ultimate analysis	
Moisture	2.0	C	83.0
Volatiles	30.0	H_2	5.2
Ash	18.0	N_2	1.7
Fixed carbon	50.0	S	0.5
C.V. 27 400 kJ/kg		O_2	9.6
C.V. (d.m.m.f.) 33 800 kJ/kg			

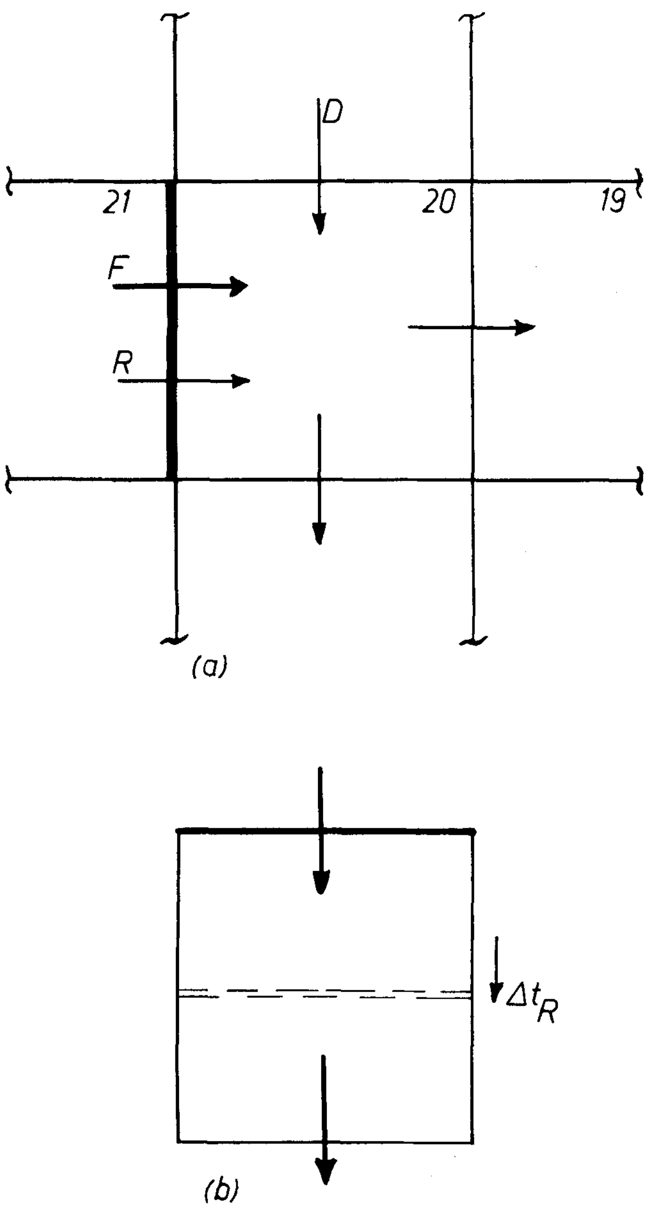

Fig. 2. Sketch showing the simplification of the flows in and out of zones (a) to a single in flow and out flow (b). F denotes feed from burner containing ten particle fractions, R denotes recirculated gas, and may contain fractions from all burners. D denotes downflow and may contain particles from above burners.

up or down; the upflow recirculates through the radiant superheater zones (4, 5, 6, 8, 10, 11) and the absorbing gas (1, 2, 3, 6, 9, 12, 15, 18, 21, 24, 27) zones to be entrained at burner level. The downflow forms the plug zone (28 to 45).

A number of variations of this flow pattern have been tested.

A ZONED FURNACE COMBUSTION MODEL

Ideally, the path of each particle would be tracked, and the partial pressure of oxygen and the temperature at each point on its trajectory would be obtained in terms of the combustion of all other particles in the furnace. This would allow calculation, for example, by Equations (14) and (15), of the instantaneous combustion of that particle as it traverses the furnace. Simultaneous solution for all particles will give the temperature, combustion heat release, and partial pressure of oxygen at each point in the furnace. This approach is, unfortunately, impractical.

Initially, the temperature of each zone is assumed. From a consideration of the gas flow pattern, we can determine the mass of gas, oxidant, and combustibles entering a particular zone. This immediately allows a residence time for the zone to be calculated by

$$t_R = \frac{V}{\dot{m}_g \dfrac{R}{M_g} T} \tag{16}$$

All particles entering the zone are assigned the residence time t_R. As temperature and residence time in the zone are known, combustion heat release in the zone may be calculated from Equations (14) and (15). These equations are solved by taking the zone to be a plug flow combustor and the conditions to be stepwise constant in time. Any one zone may have gas inflow through a number of sides, so inputs are averaged before the burnout calculations are begun. For example, the flow pattern for zone 20 is shown in Figure 2*a*, while the representation of this zone as used in the combustion calculations is seen in Figure 2*b*.

This is considered intuitively to represent the combustion process in the furnace. There is evidence (Juniper, 1973) that the input from each burner tends to retain its identity even through the highly turbulent flame zone adjacent to the burners. Material leaving a burner is seen as flowing through an ill defined but distinct tube to the furnace exit. Only relatively minor intermixing occurs between adjacent tubes. These tubes are represented here by a series of plug flow reactors with the averaging process at the beginning of each zone representing the intermixing between adjacent tubes.

To accommodate the Rosin-Rammler distribution by Equations (12) and (13), each burner in service inputs monosize fractions. At full load there are four burners giving a total input of forty different particle fractions. A given zone may receive input from up to three sides, and, to account for different flow paths, each side may contain fractions from each of the four burners. Then, as in Figure 2*b*, a maximum of 120 particle fractions must be carried through a zone calculation. To prevent the number of fractions growing too large, all fractions are normalized before they leave the zone. This requires that the residues left from a particular fraction are lumped together irrespective of the previous path to the zone. This is done on completion of combustion calculations. The surface area of char particles is calculated by Equation (8) from the unburnts of the fractions leaving the zones. Multiplication of the decrease of fractional unburnts (U) over a zone by thermal input in char gives the combustion heat release for that zone. Substitution of the combustion heat release into the head balance provides a new estimate of the zone temperatures. If the temperature so calculated are markedly different from those initially chosen for the combustion calculations, then a repeat of the combustion calculations using the new zone temperatures must be made.

COMPONENT RADIATION

The components of a pulverized fuel system contribution to its emissivity are large particles (coal, char, ash), small particles (soot), and the triatomic gases (water vapor and carbon dioxide).

The gas emissivity was based on the Hadvig correlation (Hottel and Sarofim, 1967) expressed for our temperature range and $0.47 < (p_{CO_2} + p_{H_2O})L$, m.atm < 0.71 as

$$\epsilon_{Gas} = (490.0[(p_{CO_2} + p_{H_2O})L]^{0.458})/T \tag{17}$$

With the combustion of char represented by the summation of the combustion of N monosize fractions, and taking the char particles as geometric interceptors of radiation, we obtain the absorption coefficient due to char:

$$k_{\text{char}} = \sum_{j=1}^{N} k_{\text{char},j} = \sum_{j=1}^{N} \frac{3}{2} \frac{c_j}{\rho_o d_{jo} \cdot U^{(\alpha+\beta)}} \tag{18}$$

Data from electrostatic precipitators (Sligar, 1972) show that the fly ash sizing is an order of magnitude smaller than the coal sizing. Taking these data as representative of ash size distribution in the furnace at complete burnout ($U = 0$) and dividing into equally weighted fractions, we get

$$k_{\text{Ash},U=0} = \sum_{i} 3pF_{ab}c_i/2\rho d_i \tag{19}$$

Ash particles are not black; experimental values (Street and Twamley, 1971) for their absorption efficiency (F_{ab}) range from 0.2 to 0.65, and here 0.5 has been used.

At the commencement of combustion ($U = 1$), the ash absorption coefficient is due to the extraneous ash, which we have taken as equal to the coal size distribution. The continuous evolution of inherent ash from the char particle during burnout has been assumed to follow a linear variation with $(1 - U)$ so that k_{Ash} is also linear in $(1 - U)$.

Soot distribution is taken as equal to the char component. This approach is supported by previous work (Wall and Stewart, 1973).

Figure 3 illustrates the component absorption coefficients at 1 500°K. The dominance of the ash contribution at moderate and high burnouts for this coal is dramatically obvious from the figure.

The addition of the component contributions by

$$\epsilon = 1 - \{1 - \exp[(k_{\text{ash}} + k_{\text{char}} + k_{\text{soot}})L]\} \cdot (1 - \epsilon_{\text{Gas}}) \tag{20}$$

established curves which allow zone radiative interchange to be calculated.

Equation (10) takes the components to be gray; this is not for soot and the triatomic gases. The limitations of the accuracy of our soot and ash contributions make a more rigorous approach unwarranted.

RANGE OF DATA

Coal varies in rank from the anthracites, which are almost pure carbon plus ash with little included hydrogen, to the lignites, which have a very high proportion of volatile matter and a reduced proportion of fixed carbon. As discussed previously, reaction rate data are available for coals ranging from anthracites to subbituminous coals. The range of these data is shown on Figure 4. It is seen that the data vary by an order of magnitude at any one temperature. It is also seen that there is an approximate correlation between surface reaction rate and coal rank. If we are modeling a particular installation then, from a knowledge of the rank of the coal feed we may estimate the surface reaction rate of that coal. Tabulated correlations of this and other data are given by Field (1970) and Mulcahy and Smith (1969). The amount of scatter one would expect from such an estimation was then taken as the range of our surface reaction rate.

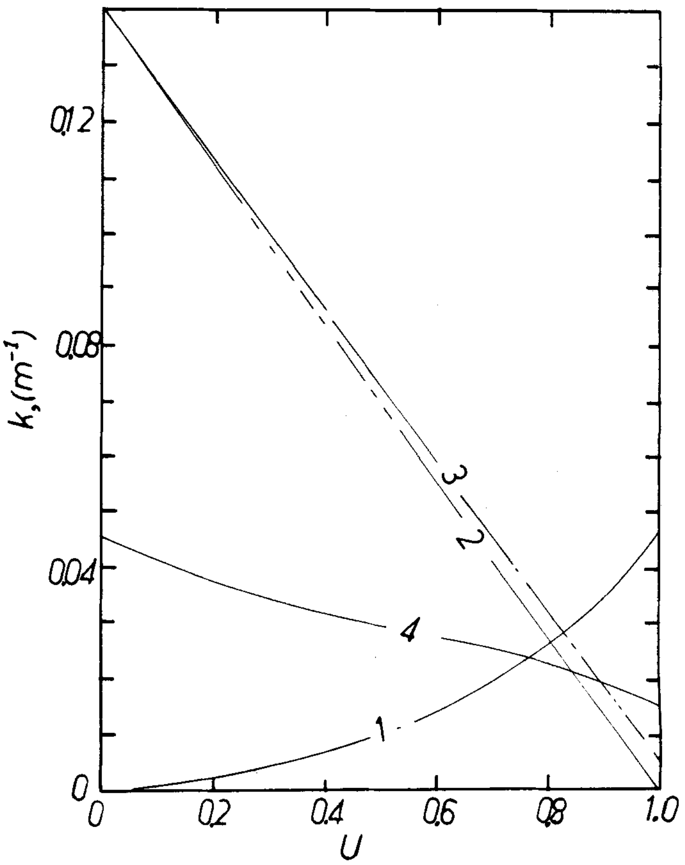

Fig. 3. Component absorption coefficient a 1 500°K. Curve 1: solids absorption coefficient (soot absorption coefficient taken equal to this). Curve 2: ash absorption coefficient without extraneous ash. Curve 3: ash absorption coefficient with extraneous ash. Curve 4: gas absorption coefficient using $k_{\text{gas}} = -\frac{1}{L}\ln(1 - \epsilon_{\text{gas}})$, $L =$ 3m and ϵ_{gas} from Hottel and Sarofim (1967).

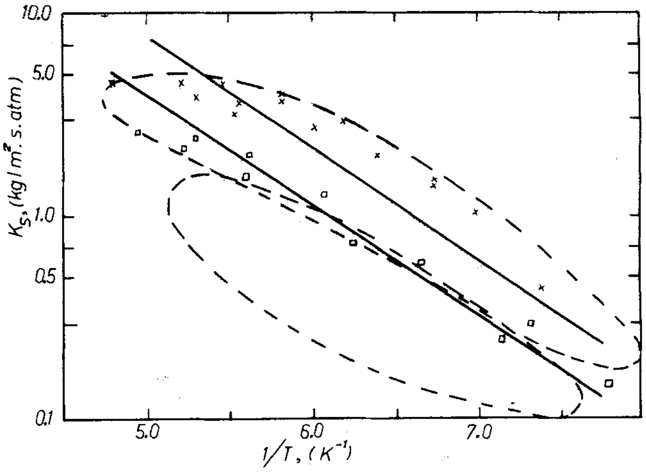

Fig. 4. Arrhenius plot for the surface reaction rate constant for coals of various ranks, from Field (1969, 1970) and Mulcahy and Smith (1969). The top area enclosed by the dashed line is for low rank coals; the bottom is for high rank coals. The crosses and squares are representative of data for different coals. The near parallel lines depict the limits of data for coals of the rank of Munmorah coal and correspond to the range used in the second row of Table 2.

The size distribution of the pulverized coal feed depends on the milling equipment. For a particular set of mills, however, the size range of coal feed is well known. Mill performance, however, decreases relatively rapidly, and it is therefore of interest to appreciate the effect of poor milling on combustion processes.

To represent the coal size distribution by the Rosin Rammler equation [Equation (12)], Field et al. 1967

TABLE 2. EFFECT OF COMBUSTION RELATED PARAMETERS ON PREDICTED FURNACE PERFORMANCE

Run No./parameter	Range	Maximum change in: Unburnts in any gas zone	Maximum change in: Heat flux to any surface zone	Change in total furnace heat absorption
1. Reaction kinetics	$K_s' = 1\,230$ $\Delta E = 8.60 \times 10^4$ to $K_s' = 603$ $\Delta E = 8.55 \times 10^4$ in Equation (5)	1.3%	3.0%	0.8%
2. Coal fineness	$n = 1.2, \overline{d} = 50\ \mu m$ to $n = 0.9, \overline{d} = 65\ \mu m$ in Equation (12)	2.0%	6.0%	1.5%
3. Ignition location	Ignition delay of 0.05 s after ignition plane of Figure 1	5.5%	4.7%	1.0%
4. Particle temperature exceeding gas temperature	From Equation (21)	5.1%	•	•
5. Ash emissivity	$F_{ab} = 0.125$ to $F_{ab} = 0.7$ in Equation (19)	•	37%	27%

• Data not obtained.

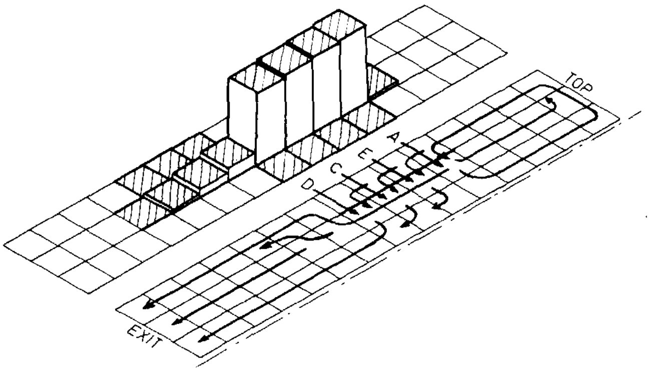

Fig. 5. Isometric histogram showing the extent of char combustion in the gas zones, from Run 1, together with the flow pattern used.

suggest $\overline{d} = 50\mu$ and $n = 1.2$ as representative of good milling practice.

Our field data suggest a coarser grind than this; $\overline{d} = 65\mu$ and $n = 0.9$. These figures are taken as representative of poor milling.

One further combustion related parameter which was studied is the time for heating and devolatilization. This parameter is very largely unknown, and the usual procedure followed is to assume that devolatilization occurs immediately on entry to the chamber. It is considered that a more realistic treatment is to allocate a given time delay to all particles and to specify volatile release and combustion, in a zone other than the entry zone. The effect of delaying devolatilization for 50 ms was determined.

A summary of the various parameter combinations is given in Table 2.

DISCUSSION

Figure 5 depicts in histogram form the heat release profile predicted by Run 1. Note that heat release due to char combustion only is considered and that due to volatile combustion, which occurs in the burner zones, is additional to Figure 5. Of interest in this figure is the large fraction of the furnace volume which is used for a small proportion of the combustion. This explains the rather surprising fact, as seen in Table 2, that combustion heat release profile is insensitive to combustion kinetics data. Most of the small particles in the coal feed burn out within the burner zones, irrespective of the surface reaction rate. This leaves the large particles to burn out, under diffusion control in an atmosphere depleted in oxygen, so producing a large tail of low intensity combustion. Increasing the coal size to the coarse grind sufficiently lengthens the burnout time so that a proportion of unburnts in ash is predicted, although there are only minor changes in the overall combustion pattern.

Ayling and Smith (1972) have measured particle temperatures considerably in excess of the surrounding gas temperature for pulverized fuel sized particles burning under oxygen concentrations of 10 and 20% by volume. Although oxygen levels in the tail of a pulverized fuel flame (when combustion of large particles becomes dominant) are of the order of 3% and particle temperatures must be close to gas temperature, the effect of particle temperature was modeled.

In order that the magnitude of the effect could be easily established, the temperature of each fraction was related to the particle size:

$$T_{pj} = T_g\left(1 + \frac{0.2j}{N}\right) \quad j = 1, 2 \ldots . N \qquad (21)$$

Burning of large particles is controlled predominantly by gas diffusion, with a combustion rate proportional to temperature to the power 0.75, so that the effect is expected to be small. This conclusion was supported by the calculations confirming that a heat balance to predict the temperature of each particle fraction is not warranted.

For the above calculations, it is assumed that volatiles

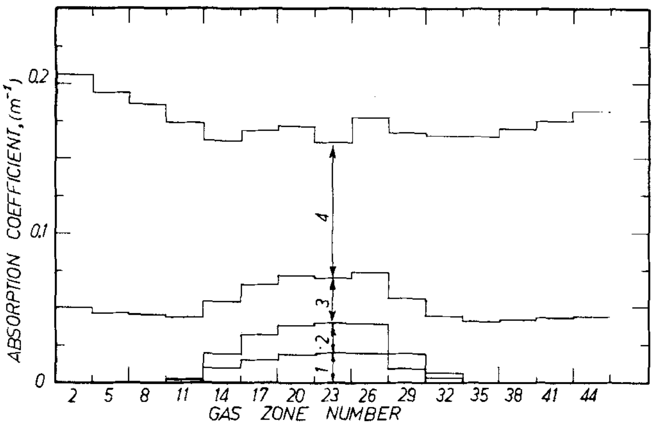

Fig. 6. Cumulative absorption coefficient of inner zones along the furnace. Region 1: absorption coefficient due to char, Region 2: absorption coefficient due to soot, Region 3: absorption coefficient due to tratomic gases (deduced from gas emissivity for 3.0m beam length), Region 4: absorption coefficient due to ash.

were released instantaneously in crossing the ignition plane (see Figure 1). This infers that all particles have been heated to the threshold of devolatilization as they cross the outer burner zone, and that on reaching the burner zones they devolatilize in a short time compared to the residence time of gases in the burner zones. The effect of this assumption was tested, Run 4 of Table 2, by providing a 50 ms period after crossing the ignition plane for devolatilization. No char combustion was permitted during this period. The effect is small.

Local absorption coefficient, a measure of the ability to radiate, is important in the prediction of heat transfer. This was related to burnout for a particular set of conditions in Figure 3. By comparison, Figure 6 shows the variation of absorption coefficient through the inner zones from Run 1. We see the change from radiation by char, soot, combustion gases, and minor quantities of recirculated fly ash in the burner zones, to the ash dominated radiation at complete burnout. The effect of falling temperature increasing gas density towards the furnace exit is also seen. The absorption coefficient was found to be insensitive to combustion related parameters.

In comparison with results described above, the last row of Table 2 depicts the effects of changing the emissivity of ash particles from 0.125 to 0.7, the range of values reported in the literature. It is seen that local heat flux varies by 37%, while total heat absorbed in the furnace changes by 27%. This shows that the level of uncertainty in the model due to assumptions made on radiative property data far exceeds that due to combustion kinetics data.

We draw this conclusion for the high ash coal fired in this furnace. However, our experience with local coals is that lower ash coals tend to give a smaller mean ash particle sizing, and extinction coefficient due to ash will remain high [Equation (19)]. These conclusions have lead us to a study of the absorbing and scattering properties of fly ash and to the fabrication of a spectral pyrometer in order to investigate these properties in the furnace situation.

NOTATION

B = functional zone dimension (m)
c = fraction of stoichiometric air remaining after volatiles combustion
C = mass concentration of particles per unit volume (kg/m^3)
d = diameter of particle (μm)
e = fractional excess air
E_j = black body radiant emission for zone j (W/m^2)
F = cumulative % by weight of particles less than diam d
G_j = j^{th} gas zone
H = volumetric combustion heat release rate (kJ/m^{2}s)
K_d = diffusion rate constant (kg/m^2·s·atm)
K_s = surface reaction rate constant (kg/m^2·s·atm)
K_s' = pre exponential constant (kg/m^2·s·atm)
L = mean beam length (m)
M = mass (kg)
n = exponent in Rosin Rammler equation
p = partial pressure of oxygen or gas designated
$\dot{Q}$ = heat input to zone (kJ/s)
R = universal gas constant
S = surface area per unit mass of char (m^2/kg)
S_i = i^{th} surface zone
t = time (s)
T = temperature (°K)
U = fractional char unburnt
$U = 1$ before combustion begins
$U = 0$ at complete combustion
u_j = fractional char unburnt for j^{th} fraction
ΔE = Arrhenius activation energy (kJ/kg·mole)
ρ = particle density (kg/m^3)

Subscripts

j = j^{th} fraction
g = bulk gas quantity
o = value before char combustion begins
s = value at particle surface

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An Alternate to the Dengler and Addoms Convection Concept of Forced Convection Boiling Heat Transfer

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Current literature describes forced convection, boiling heat transfer as primarily convective heat transfer. The original evidence for this concept, reported by Dengler and Addoms, was reexamined and found misinterpreted. Nucleate boiling data, instead, correlate with their data. Subsequent use of the concept in correlations and models now requires close scrutiny.

SCOPE

The current literature on two-phase, forced convection, boiling heat transfer in tubes describes the phenomenon as primarily convection. Although nucleate boiling may occur near the inlet or at low flow, it is suppressed by the effects of vapor induced forced convection. This concept was first enunciated by Dengler and Addoms (1956) in analyzing the results of experiments with a long vertical tube evaporating water at near atmospheric pressure. Recently, inconsistencies have been noted which have given cause to reexamine the experiments and the basis for the widely held concept.

CONCLUSIONS AND SIGNIFICANCE

Dengler and Addoms tested their hypothesis that convection was dominant by preparing a plot of the log of h/h_L against the log of the reciprocal of the Lockhart-Martinelli, two-phase turbulent flow parameter. They cited a positive slope of a line which gave a reasonable fit as support for the hypothesis. A reexamination shows that the positive slope results from plotting quantities against one another containing the same variables rather than from any effect of convection. The hypothesis must therefore be rejected. Subsequent investigations which have used the same method of correlation must now be reexamined to determine whether the Dengler and Addoms concept is still valid in those individual instances, even though it lacks the support its originators claimed.

A model postulating nucleate boiling does correlate the data of Dengler and Addoms at least as well as nucleate boiling data can be correlated with themselves.

In 1956, Dengler and Addoms published a paper which has had a profound impact on the study of vertical tube evaporators and forced convection boiling heat transfer. No previous investigators had attempted to measure the variation of the heat transfer rate with elevation along the tube. As a result of their investigation, they claimed the mechanism of heat transfer during vaporization in tubes is primarily convective. Nucleate boiling is dominant only under conditions of low liquid velocity and is gradually suppressed by the effects of vapor induced forced convection. The paper continues to be cited frequently. Thirteen papers were found between 1970 and 1975 that referenced the paper.

Recently, the paper has come under scrutiny because of the recognition of superior performance of nucleate boiling in thin liquid films (Mesler, 1976). In a vertical tube evaporator, much evaporation occurs in annular flow where the tube is wet with a liquid film. According to Dengler and