1 SYMBOLS AND ABBREVIATIONS

1 SYMBOLS AND ABBREVIATIONS

1.1 Symbols

Symbol	Description	Units SI	Units British
A	Parameter defined in Section 13.1.5	°C	°F
A_b	Fluidised bed cross sectional area	m^2	ft^2
A_e	Constant in elutriation equation 9.3	-	-
A_t	Total surface area of in-bed tubing for heat transfer: based on tube OD.	m^2	ft^2
A_s	Sorbent additive Reactivity Index	-	-
Ar	Archimedes number	-	-
Ar_{mf}	Archimedes number at minimum fluidising conditions	-	-
Ar_t	Archimedes number at terminal velocity	-	-
A_w	*Flow area of packed bed*	m^2	ft^2
a	Bed area supplied per coal feed point	m^2	ft^2
a_o	Constant	m^{-2}	(ft h)/(gal s)
B	Volume fraction of bed occupied by tube bank	-	-
B_h	Fraction of bed height occupied by tube bank	-	-
B_1	Parameter defined in Section 13.1.5	-	-
b	Index in feed solids size distribution equation	-	-
b_o	Constant	m/s	ft/s
C'	Weight fraction of carbon in fuel	-	-
Ca	*Weight fraction of calcium in sorbent*	-	-
C	Fractional combustion (fraction of potential heat input)	-	-
	C_b combustion occurring in bed		
	C_d datum loss from bed surface		
	C_f combustion in freeboard		

Symbols		SI	British
	C_J loss from the bed surface corrected for the coal mixing parameter		
	C_o total loss from bed surface		
	C_{oc} loss of feed coal from bed surface		
	C'_o total loss from surface of fines burn-up bed		
	C_{of} loss of recycled carbon fines from bed surface		
	C'_c loss from bed surface assuming coal feed only		
	C_t loss in combustor off-gas		
	C_r ratio of recycled carbon fines to carbon in coal feed		
C_D	Drag coefficient	-	-
$C_{N_{ox}}$	NO_x concentration	ppm v/v	ppm v/v
C_{O_2}	Oxygen concentration in the flue gas	% v/v	% v/v
c_b	Specific heat of bed material	J/(kg °K)	Btu/(lb°F)
C_d	Orifice pressure drop constant	-	-
c_g	Mean specific heat of gas and entrained solids (defined in Section 13.1.5)	J/(kg °K)	Btu/(lb°F)
c_i	Percentage of coal in the i th. size fraction	-	-
D	Oil nozzle body inside diameter	mm	in.
D_b	Bubble diameter	m	m
D_d	Diameter of exit holes in air nozzles	mm	ft
D_E	Oil nozzle exit hole diameter	mm	in.
D_i	In-bed heat transfer tubing, inside diameter	mm	inches
D_o	In-bed heat transfer tubing, outside diameter	mm	inches
D_t	Thermal diffusivity	m^2/s	ft^2/h

Symbols		SI	British
D_A	Axial oil tube outside diameter	mm	in.
D_M	Hydraulic diameter of nozzle body flow path	mm	in.
d	Particle size (diameter)	μm	inches
	d_{Mx} maximum particle size defined so that 99% w/w of the sample is smaller than d_{Mx}		
	d_A maximum particle size used in sorbent characterisation test		
	d_c effective particle size below which elutriation is assumed to be instantaneous		
	d_i) d_j) particle size of i th. and j th. fractions		
	d_m particle size where f = 1 for the straight line approximation to the coarse particle size distribution		
	$\bar{d}_p$ surface mean particle size of bed		
	d_r size below which particles pass through the recycle fines collector		
	d_t particle of size having its terminal velocity equal to the operating fluidising velocity		
	d_x mean particle size of x th. fraction	m	ft
E	Activation energy	J/kg mol	Btu/lb mol
E_H	Gross calorific value of fuel	kJ/kg	Btu/lb
E_x	Elutriation rate constant	$kg/(sm^2)$	$lb/(hft^2)$

Symbols		SI	British
e_a	Constant in feed solids size distribution equation	μm^{-1}	$inches^{-1}$
e	Sulphur oxides emission	In appropriate units	See Section 11.3.1.4
e_o	Statutory permissible sulphur oxides emission		
F	Total feed rate of inert bed material	$kg/(sm^2)$	$lb/(h\ ft^2)$
F_n	Fluidisability number = $Ar^{1/3}$	-	-
F_s	Bed temperature as a fraction of the bed to tube temperature difference	-	-
$\bar{F}_s$	Mean bed value of F_s	-	-
F_T	Factor for deviations from counter current flow	-	-
f	Fraction of undersize material:	-	-
	Fanning friction factor	-	-
f_a	Fraction by weight of abraded fines below size d_c	-	-
f_b	Weight fraction of input calcium remaining in the bed	-	-
f_c	Fraction by weight of fine material below size d_c	-	-
f_e	Weight fraction of input calcium elutriated	-	-
f_r	Fraction of material below size d_r, lost through recycle collector	-	-
f_R	Fractional change to new steady state sulphur retention	-	-
f_x	Volume fraction of voids less than particle size d_x also- equals f_b or f_e as appropriate See Section 11.3.4.2	-	-

Symbols		SI	British
G	Mass flow per unit area per unit time	$kg/(s\ m^2)$	$lb/(h\ ft^2)$
	G_A additive flow		
	G_F flow of feed solids below size d_c		
	G_a air flow		
	G_{ac} flow of elutriated particles produced by the abrasion of larger particles to size d_c		
	G_c fuel flow		
	G_e total elutriation rate from bed		
	G_g total gas flow		
	G_h ash flow		
	G_r flow of make-up solids		
	G_x flow of fines elutriated for fraction of size d_x		
	G_1 flow of fines produced by abrasion in recycle stream		
g	Gravitation constant	m/s^2	ft/s^2
H'	Weight fraction of hydrogen in fuel	-	-
H_r	Net heat of reaction of sulphur retention additive	kW	Btu/h
H_{r1}	Heat of sulphation of $CaCO_3$	kW	Btu/h
H_{r2}	Heat of calcination of the $MgCO_3$ content of the sorbent	kW	Btu/h
H_{r3}	Heat of calcination of the $CaCO_3$ content of the sorbent	kW	Btu/h
H_L	Overall heat loss due to sulphur retention sorbent	kW	Btu/h
H_s	Net sensible heat loss due to sulphur retention sorbent	kW	Btu/h
H_{se}, H_{sb}	Sensible heat loss in the spent sorbent in the elutriated solids and overflow bed material streams respectively	kJ/kg	Btu/lb

Symbols		Units SI	Units British
H_6	Sensible heat loss in the CO_2 evolved by the sorbent	kJ/kg	Btu/lb
H_7	Sensible heat loss in the SO_2 and O_2 taken up by the sorbent	kJ/kg	Btu/lb
h	Hydrostatic head, ie depth of bed + height of water level above bed surface	m	ft
h_c	Outside film heat transfer coefficient convection component	J/(s m^2 °K)	Btu/(ft^{2}h °F)
h_i	Inside film heat transfer coefficient	J/(s m^2 °K)	Btu/(ft^{2}h °F)
h_o	Total outside film heat transfer coefficient	J/(s m^2 °K)	Btu/(ft^{2}h °F)
h_r	Outside film heat transfer coefficient, radiation component	J/(s m^2 °K)	Btu/(ft^{2}h °F)
I_1) I_2)	Constants in equation 9.25	-	-
J	Coal mixing parameter	(atm m)	
K	Combustion reaction velocity constant	s^{-1}	s^{-1}
K_A	Abrasion constant	s m/s	h ft/s
K_{am}	Weight mean value of K_A	s m/s	h ft/s
K_{ar}	Recycle abrasion constant	-	-
K_p	Equilibrium constant for reaction 11.65	$(kN/m^2)^{-1/2}$	$(atm)^{-1/2}$
K_s	Ratio of the tube spacing to tube outside diameter	-	-
K_w	Coefficient of water permeability in packed beds	m/day	ft/s
k	Thermal conductivity	J/(m s °K)	Btu/(ft h °F)
k_e	Calcium elutriation constant	See equation 11.33	
k_r	Constant in equation 11.33	See equation 11.33	
k_s	Constant in equation 11.8	-	-
k_o	Datum value of k_s	-	-
k_x	Constant in size reduction rate equation	$(\mu m\ s)^{-1}$	$(in\ h)^{-1}$

Symbols		Units SI	Units British
k_1 to k_5	Reaction velocity constants. See Section 12.	$cm^3/(g\ mol\ s)$	
L	Height of cooled freeboard wall:	m	ft
	Height of heat transfer surface:	m	ft
	Slumped height of bed solids in tapered portion of the bed	m	ft
L_b	Expanded bed height	m	ft
L_{mf}	Expanded bed height at minimum fluidising conditions	m	ft
L_n	Length of oil nozzle	mm	in.
L_s	Packed bed height: Slumped bed height	m	ft
L_1, L_2	Expanded bed heights at two levels in a fluidised bed	m	ft
l	Total immersed length of in-bed tubing	m	ft
l_o	Vertical path of circulating particles in the bed	m	ft
M	Mass flow rate per unit time	kg/s	lb/h
	M_a input air flow		
	M_x fuel flow		
	M_{cs} stoichiometric fuel flow		
	M_g air plus fuel flow		
	M_s sorbent flow		
	M_{sb} flow of spent sorbent retained by the bed		
	M_{se} flow of spent sorbent elutriated		
	M_{1x} to M_{5x} mass flows of calcium sulphate (M_1), magnesium oxide (M_2), calcium oxide (M_3), calcium carbonate (M_4), and inert impurities (M_5) in the elutriated sorbent (x = e), or the sorbent remaining in the bed (x = b).		

Symbols		Units SI	Units British
	M_6 mass flow of CO_2 evolved from the sorbent		
	M_7 mass flow of $SO_2 + O_2$ absorbed by the sorbent		
Mg	Weight fraction of magnesium in the sorbent	-	-
m_e	Mol fraction of sulphur oxides in wet flue gas	-	-
m_d, m_w	Mol fractions of sulphur oxides in the dry and wet combustor off gas respectively assuming that all the sulphur in the fuel enters the gas	-	-
m_{ij}	Fraction by weight of ash prepared from coal in size fraction j which is in size fraction i	-	-
m_{H_2O}	Mol fraction of water	-	-
m_{SO_2}	Mol fraction of sulphur dioxide	-	-
m_{SO_3}	Mol fraction of sulphur trioxide	-	-
N	Number of coal feed points:	-	-
	Number of oil exit holes per nozzle	-	-
Nu	Nusselt number	-	-
n	Maximum number of oil nozzle exit holes per row	-	-
O	Solids overflow rate	$kg/(s\ m^2)$	$lb/(h\ ft^2)$
O'	Weight fraction of oxygen in fuel	-	-
O_x	Fuel oxygen content, wt %	% dmmf	
P	Operating pressure (absolute)	kN/m^2	atm
P_c	Actual carbon dioxide partial pressure	kN/m^2	atm

Symbol	Symbols	Units SI	Units British
P_{ce}	Equilibrium carbon dioxide partial pressure	kN/m^2	atm
P_{O_2}	Partial pressure of oxygen leaving the bed	kN/m^2	atm
P_{SO_2}	Partial pressure of sulphur dioxide leaving the bed	kN/m^2	atm
Pr	Prandtl number	-	-
P_i	Percentage of the total ash occurring in the i th. size fraction	-	-
P	Parameter = (b-1)/b	-	-
P_h	In-bed tubing horizontal tube pitch	mm	inches
P_v	In-bed tubing vertical tube pitch	mm	inches
Q	Heat flow per unit time	J/s	Btu/h
	Q_c due to combustion in bed and freeboard		
	Q_g removed from the bed by the off-gas and elutriated ash at temperature T_b		
	Q_r rate of heat transfer by radiation		
	Q_t rate of heat transfer by in-bed tubing		
	Q_1-Q_6 terms in the freeboard heat balance. See Section 4.3.2.2		
q	Parameter = (bβ - 1)/b	-	-
q_i	Relative proportion of ash in the i th. fraction		
R	Gas constant	cal/(°K g mol)	
R	Ratio, $\frac{\text{(cross-sectional area of tube)}}{\text{total area of holes}}$	-	-
R	Fractional reduction by weight of SO_2	-	-
	R_a by additive		
	R_c by coal ash		
R_e	Reynolds number	-	-

Symbols		Units SI	Units British
Re_{mf}	Reynolds number at minimum fluidising conditions	-	-
Re_t	Reynolds number at terminal velocity conditions	-	-
r	Radius in Section 10.5. Also Decrepitation parameter	mm	inches
r_c	Effective calcium carbonate calcination rate		
r_m	Effective magnesium carbonate calcination rate	See Section 11.3.3.2	
r_o	Effective calcium carbonate calcination rate at zero carbon dioxide partial pressure		
r_r	Sorbent recycle parameter		
S'	Weight fraction of sulphur in fuel		
T	Temperature	°C	°F
	T_a freeboard temperature		
	T_{ai} temperature of slice i of the freeboard		
	T_b bed temperature		
	T_{bo} bed temperature at time zero		
	T_{boo} bed temperature at new steady state		
	T_{bt} bed temperature at time t		
	T_e freeboard exit temperature		
	T_f bulk cooling fluid temperature		
	T_i in-bed tubing inner surface temperature		
	T_p air preheat temperature		
	T_w in-bed tubing outer surface temperature		
	$\bar{T}$ mean bed value of T		

	Symbols	Units SI	Units British
T'	Absolute temperature	°K	°R
	T'_a freeboard temperature		
	T'_b bed temperature		
	T'_d sulphuric acid dew point		
	T'_w tube wall temperature		
	T'_A sorbent characterisation test temperature		
	T'_{IN} Turbine inlet temperature		
t	Time	s	h
t_c	Time constant	s	h
t_f	Mean freeboard gas residence time	s	s
t_g	Superficial gas residence time in the bed: In Section 5 on slumped bed basis	s	s
t_m	Mean residence time needed for the sorbent to achieve a sulphation fraction, κ_a	s	s
t_s	Time taken to reach new steady state conditions	s	s
t_A	Duration of sorbent characterisation test	h	h
U	Overall heat transfer coefficient	$J/(m^2\ s\ °K)$	$Btu/(ft^2\ h\ °F)$
U_b	Bubble rise velocity	m/s	ft/s
U_d	Velocity through exit holes of air distributor nozzles	m/s	ft/s
U_f	Fluidising velocity	m/s	ft/s
U_{mf}	Minimum fluidising velocity	m/s	ft/s
U'_f	Gas velocity in tube bank	m/s	ft/s
U_{sl}	Superficial spray exit velocity	m/s	ft/s
U'_{sl}	Spray limited exit velocity	m/s	ft/s
U_t	Terminal velocity	m/s	ft/s

Symbols		Units SI	Units British
V	Oil flow per oil nozzle:	m^3/s	Imp gal/h
	Water volumetric flowrate through packed beds	m^3/d	ft^3/s
V_a	Inlet air volume at mean bed conditions	m^3/s	ft^3/s
V_{ao}	Air flow per oil nozzle	m^3/s	ft^3/s
V_B	Bubble volume fraction	-	-
V_f	Freeboard volume	m^3	ft^3
V_n	Velocity number = $Re/Ar^{1/3}$	-	-
V_o	Oil flow per oil nozzle exit hole	m^3/s	Imp gal/h
V_t	Tube volume fraction	-	-
V_w	Molar volume		
	specific values are:	m^3/kg mol	ft^3/lb mol
	22.7 m^3 per kg mole at 0°C and 100 kN/m^2		
	22.4 l per g mole at 0°C and 1 atm		
	359 ft^3 per lb mole at 32°F and 1 atm		
	379 ft^3 per lb mole at 60°F and 1 atm		
v	Linear air velocity in nozzle body	m/s	ft/s
W	Total bed weight	kg	lb
W_b	Bed weight per unit area	kg/m^2	lb/ft^2
W_{Ca}	Weight of calcium in the bed at steady-state conditions	kg	lb
W_x	Weight of particles of size d_x in bed per unit area	kg/m^2	lb/ft^2
w	Bed width at base of taper	m	ft
w_a	Stoichiometric moles of air required for combustion of unit weight of fuel	kg mol/kg	lb mol/lb
w_d	Moles of dry gas given by the combustion of unit weight of fuel	kg mol/kg	lb mol/lb

Symbols		Units SI	Units British
w_w	Moles of wet gas given by the combustion of unit weight of fuel	kg mol/kg	lb mol/lb
X	Excess air; % of stoichiometric amount ie $X = \frac{\text{actual air - stoichiometric air}}{\text{stoichiometric air}} \times 100$	%	%
x	Tube thickness in equation 10.3a:	m	ft
	tube length in equation 10.17	m	ft
X_e	Effective excess air; % of stoichiometric amount	%	%
X_s	Excess gas velocity in the dense phase	m/s	ft/s
X_i) x_j)	Weight fraction of i th. and j th. fractions	-	-
x_{ij}	Weight of fraction between sizes d_i and d_j	-	-
y	Variable in error function definition	-	-
Y	Additive Ca/S molar ratio	-	-
Z	Mol ratio $MgCO_3/CaCO_3$ in sulphur retention sorbent	-	-
Z_b	Bed depth correction factor	-	-
Z_n	Nozzle density per unit bed area	m^{-2}	ft^{-2}
Z_t	Bed taper effectiveness factor	-	-
z	Spacing between heat transfer tubing	mm	inches
z_h	Distance above distributor plate	mm	inches

1.2 Greek Symbols

Symbol	Description	Units SI	Units British
α	Additive constant	-	-
β	Parameter defined by equation 9.20		
γ	Fraction by weight of carbon fines leaving the bed that is collected	-	-
δ	Fraction of heat present at a given height in the freeboard which is returned to the bed	-	-
δ_s	Ratio of the observed to the equilibrium value of K_p	-	-
ΔP_1	Pressure differential between two points at depths L_1 and L_2 in a fluidised bed	kN/m^2	atm
ΔP_2	Pressure differential between a point at depth L_2 in a fluidised bed and a point in the freeboard	kN/m^2	atm
ΔP_b	Pressure drop through the bed	kN/m^2	atm (or in. H_2O)
ΔP_d	Pressure drop through the distributor	kN/m^2	atm (or in. H_2O)
ΔP_f	Pressure drop through the freeboard	kN/m^2	atm (or in. H_2O)
ΔT	Logarithmic mean temperature difference	°C	°F
ε_b	Bed emissivity	-	-
ε_h	Emissivity	-	-
ε_{mf}	Voidage at minimum fluidising conditions	-	-
ζ	Fuel type parameter	-	-
η	Overall combustion efficiency	%	%
θ) θ_1) θ_2)	Units change constants	As appropriate	
	Also,		
θ	Angle in cylindrical coordinate system; See Section 10.5	-	-
κ	Fraction of sorbent sulphated	-	-
κ_A	Fraction of sorbent sulphated in sorbent characterisation test	-	-

1.2 Greek Symbols

Symbol	Description	Units SI	Units British
κ_a	Average fraction of sorbent sulphated	-	-
κ_b	Fractional sulphation of the calcium remaining in the bed	-	-
κ_e	Fractional sulphation of the elutriated calcium	-	-
A	Bubble size index	-	-
λ	Fraction of carbon leaving the bed caught by the recycle cyclone	-	-
μ	Gas viscosity	Ns/m^2	lb/(fts)
ζ	Fuel type parameter		
π	Ratio, circumference/diameter of circle	-	-
ρ	Fixed bed bulk density	kg/m^3	lb/ft^3
ρ_f	Fluidised bed mean bulk density	kg/m^3	lb/ft^3
ρ_{mf}	Fluidised bed density at minimum fluidising conditions	kg/m^3	lb/ft^3
ρ_g	Gas density	kg/m^3	lb/ft^3
ρ_s	Particle density	kg/m^3	lb/ft^3
σ	Stefan Botzmann radiation constant	$J/(m^2\ s°K^4)$	$Btu/(ft^2h\ °F^4)$
ϕ	Sphericity of particle	-	-
χ	Sulphation rate constant	-	-
χ'	Sulphation rate constant	-	-
ψ	Variable in error function definition	-	-
Ω	Power in equation 4.4	-	-

1.3 Abbreviations

BCURA	British Coal Utilisation Research Association (now CURL)
BP	British Petroleum Company Limited, including Research Laboratories, Sunbury
CRE	National Coal Board, Coal Research Establishment
CSL	Combustion Systems Limited
CURL	National Coal Board, Coal Utilisation Research Laboratories
NCB	National Coal Board
FBC	Fluidised Bed Combustion
MCR	Maximum Continuous Rating
METR	Maximum Effective Thickness Reduction