ME 6163: Combustion of Solid Fuels

Dr. Md. Zahurul Haq

Professor
Department of Mechanical Engineering
Bangladesh University of Engineering & Technology (BUET)
Dhaka-1000, Bangladesh
http://zahurul.buet.ac.bd/

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Overview

Usual amount excess air supplied to solid fuel-burning equipment[1]

Fuel	Type of furnace or burner	Wt. % excess air
Pulverized coal	Completely water-cooled furnace for slag tap or dry ash removal	15–20
	Partially water-cooled furnace for dry ash removal	15–40
Crushed coal	Cyclone furnace pressure or suction	10–15
	Stoker-fired, forced-draft, B&W chain grate	15–50
Coal	Stoker-fired, forced-draft, underfeed	20–50
	Stoker-fired, natural draft	50–65
Fuel oil	Oil burners, register type	5–10
	Multifuel burners and flat flame	10–20
Natural, coke oven, and refinery gas	Register-type burners	5–10
	Multifuel burners	7–12
Blast furnace gas	Intertube nozzle-type burners	15–18
Wood	Dutch oven (10–23% through grates) and Hofft type	20–25
Bagasse	All furnaces	25–35

T1331

[1] E. Keating (2007). *Applied Combustion*. 2nd ed. Taylor & Francis.

Combustion of Solid Fuels[2]

- Solid fuel particle (pulverized, crushed, chipped, or cut) in a combustion environment undergoes three stages of mass loss:
  1. drying,
  2. de-volatilization (pyrolysis), and
  3. char combustion.
- The rates of these processes depends on the flue type, fuel moisture content, size, and heat and mass transfer to the particle.
- For small particles, drying, de-volatilization, and char burn occur sequentially, while for large particles, these occur simultaneously.
- For small particles, drying is the fastest step, and char burning takes much longer than de-volatilization.
- For large fuel segments such as logs, char burn is the rate-limiting step, and char burn is slowed by the evolution of the moisture.

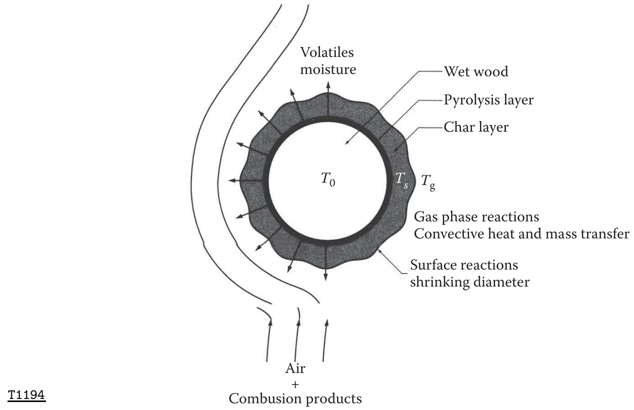
[2] G. Borman and K. Ragland (1998). *Combustion Engineering*. McGraw-Hill.

Drying of Solid Fuels[3]

- Coal and biomass are porous materials with pore sizes ranging from 0.01-30 µm, and fuel moisture may reside in these pores. Lignite coals contain up to 40% water, while bituminous coals have relatively small pores contain small amount water.
- When a pulverized coal or small biomass particle that is inserted into a furnace, water is vaporized and rapidly forced out through the pores of the particle before volatiles are released.
- For relatively large fuel particles, drying initially involves inward migration and outward flow of water vapour. Pyrolysis starts at the outer edge of the particle and gradually moves inward while releasing volatiles and forming char. Moisture release reduces the heat and mass transfer to the particle surface, thus reducing the rate of mass loss of the particle.

[3] G. Borman and K. Ragland (1998). *Combustion Engineering*. McGraw-Hill.

Typical Burning of Wood Log[4]



Cross-section of a reacting log showing char, pyrolysis, & undisturbed wood regions

[4] G. Borman and K. Ragland (1998). *Combustion Engineering*. McGraw-Hill.

De-volatilization of Solid Fuels[5]

- When temperature of a small fuel particle or a zone within a large particle rises to above 250-400°C, fuels begin to decompose releasing volatiles (e.g. H_2, CO, H_2O, hydrocarbon gases etc.). Since the volatiles flow out through the pores, external oxygen cannot penetrate into the particle, and is referred to as the pyrolysis stage. It is a kinetic process which is often modelled as a first-order reaction.
- Pyrolysis products then ignite and form an attached flame around the particle as oxygen diffuses into the products. Flame in turn heats the particle, increasing the rate of de-volatilization. Once all the water vapour is driven out, flame will be hotter.
- Coal pyrolysis begins at 300-400°C, and ignition of the volatiles occurs at 400-600°C. Above 900°C pyrolysis is essentially complete, and the char (fixed carbon) and ash remain.

[5] G. Borman and K. Ragland (1998). *Combustion Engineering*. McGraw-Hill.

Char Combustion[6]

- Char combustion is the final step in combustion of pulverized coal and biomass. Char is a highly porous carbon with small amounts of other volatiles and dispersed mineral matter. Internal surface area of char is on the order of 100 m^2/g for coal char and 10,000 m^2/g for wood char.
- Char surface reaction generates primarily CO and CO then reacts outside the particle to form CO_2. Surface reactions may raise the temperature of the char 100-200°C above the external gas temperature when oxygen is present.
  1. $C + \frac{1}{2} O_2 \longrightarrow CO$
  2. $C + CO \longrightarrow 2\,CO$
  3. $C + H_2O \longrightarrow CO + H_2$
- Reduction reactions (2) and (3) are generally much slower than the oxidation reaction (1), and for modelling reaction (1) is considered.

[6] G. Borman and K. Ragland (1998). *Combustion Engineering*. McGraw-Hill.

Ash Formation[7]

- Mineral matter in biomass ranges from 1-6%, while in coal the mineral matter can range from a few percent to 50% or more for very low-grade coal.
- As the char burns, the minerals are converted to a layer of ash on the char surface.
- In high temperature pulverized coal combustion the ash tends to form hollow glassy spheres called *cenospheres*. At lower temperatures the ash tends to remain softer.
- Ash layer can have a significant effect on heat capacity, radiative heat transfer, and catalytic surface reactions as well as increased diffusive resistance to oxygen, especially late in the char burn stage.

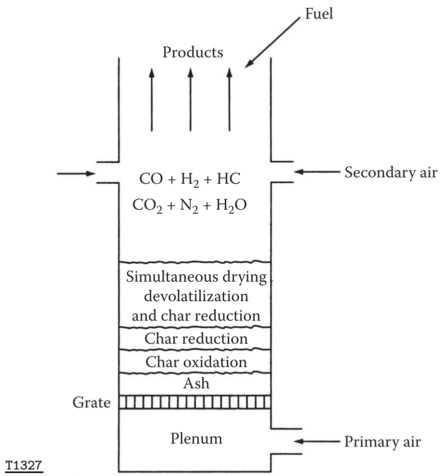
[7] G. Borman and K. Ragland (1998). *Combustion Engineering*. McGraw-Hill.

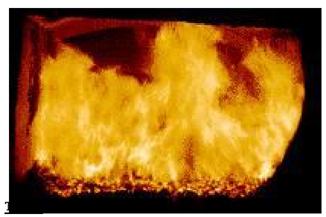
Three Modes of Firing Solid Fuels[8]

1. **Fixed-bed firing**: Fixed bed combustion systems range from simple cook-stoves to large stokers that burn solid fuel on a grate for district heating and electric power generation.
2. **Suspension firing**: Suspension burning furnaces and boilers burn pulverized fuel particles that are blown through burner nozzles into a furnace volume that is large enough to allow burnout of the fuel char. Pulverized coal and biomass are burned separately or together (co-firing). Much of the electricity in the world today is generated by pulverized coal-fired steam power plants.
3. **Fluidized-bed firing**: A fluidized bed is a bed of solid particles that are set into motion by blowing a gas stream upwards through the bed. The velocity of the gas stream must be large enough to locally suspend the particles (fluidize the bed) but small enough to ensure that particles are not blown out of the bed.

[8] G. Borman and K. Ragland (1998). *Combustion Engineering*. McGraw-Hill.

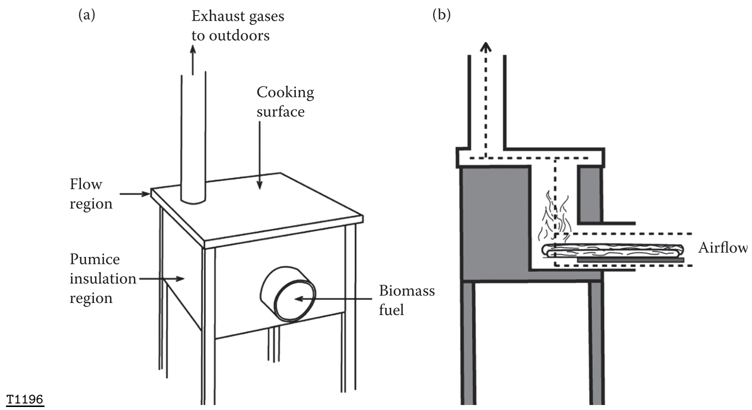
Conceptual Layers in Fixed-bed Combustion[9]





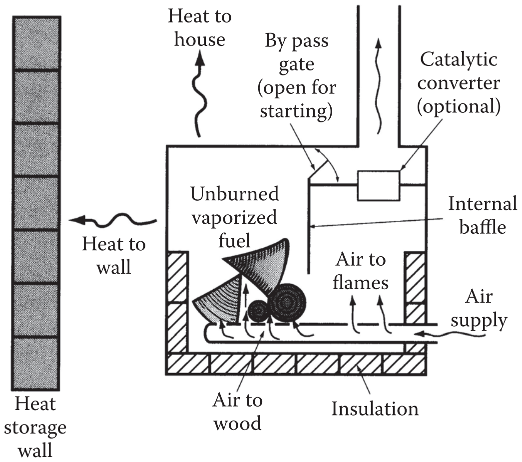
[9] G. Borman and K. Ragland (1998). *Combustion Engineering*. McGraw-Hill.

Enclosed Natural Draft Stick-wood Cookstove[10]



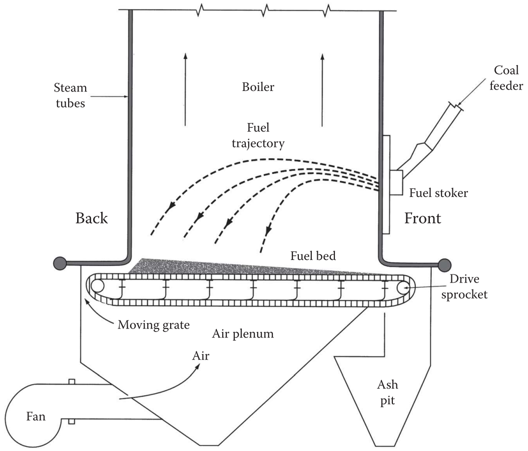
[10] G. Borman and K. Ragland (1998). *Combustion Engineering*. McGraw-Hill.

Residential Space Heating Wood-stove[11]

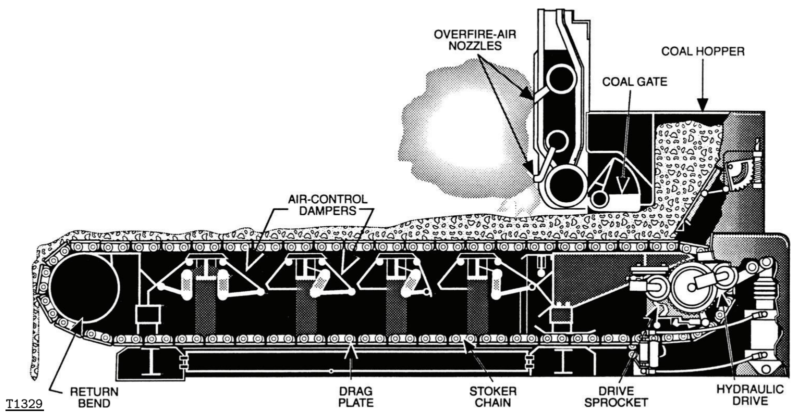


[11] G. Borman and K. Ragland (1998). *Combustion Engineering*. McGraw-Hill.

Spreader-stoker with an Air-cooled Traveling Grate[12]



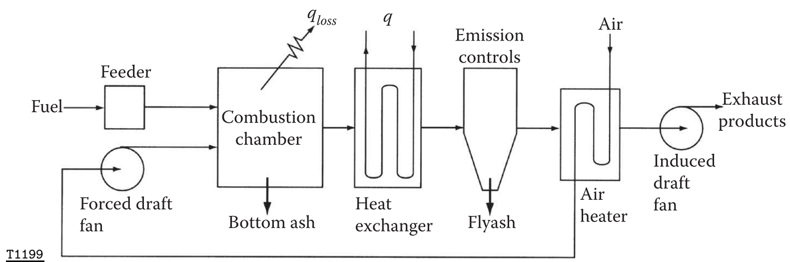
[12] G. Borman and K. Ragland (1998). *Combustion Engineering*. McGraw-Hill.



Stoker-fed coal combustion system schematic[13]

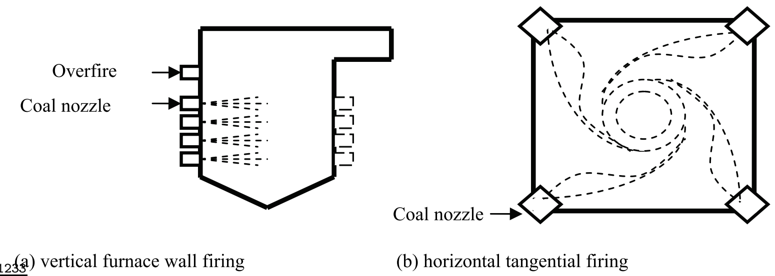
[13] E. Keating (2007). *Applied Combustion*. 2nd ed. Taylor & Francis.

Fixed-bed boiler system[14]



[14] G. Borman and K. Ragland (1998). *Combustion Engineering*. McGraw-Hill.

Suspension Burning



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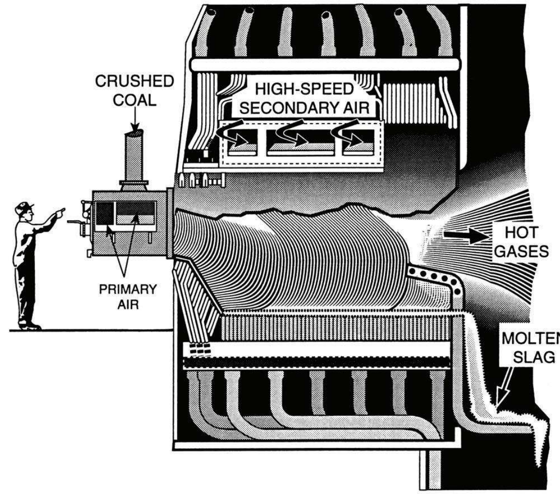
Pulverized coal firing techniques[15]

[15] E. Keating (2007). *Applied Combustion.* 2nd ed. Taylor & Francis.



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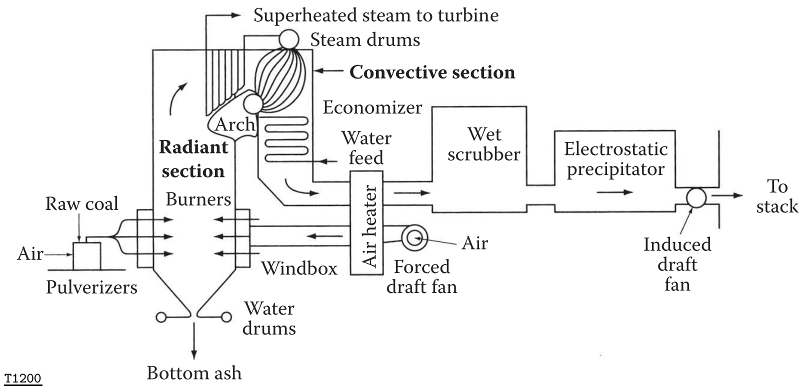
Cyclone combustor schematic[16]

[16] E. Keating (2007). *Applied Combustion.* 2nd ed. Taylor & Francis.

Utility-scale Pulverized Coal Combustion System[17]



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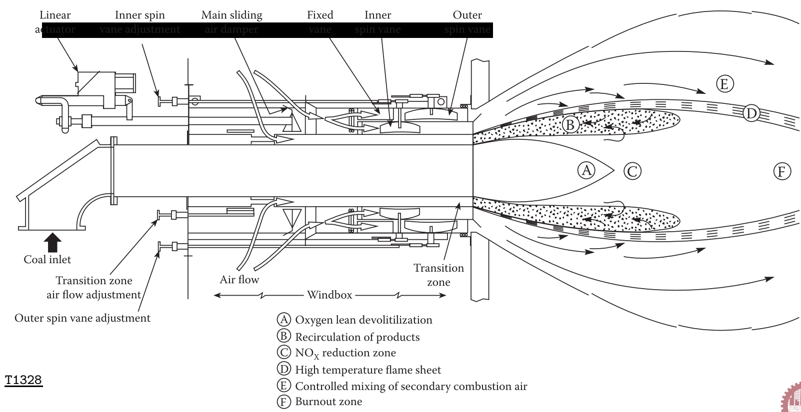
[17] G. Borman and K. Ragland (1998). *Combustion Engineering.* McGraw-Hill.

Low NOx Pulvarized Coal Burner[18]



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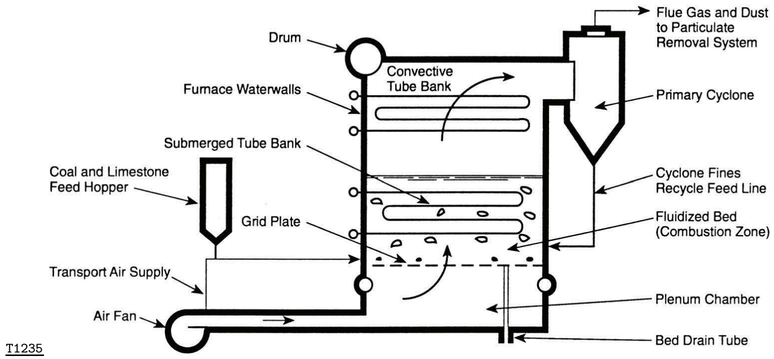
[18] G. Borman and K. Ragland (1998). *Combustion Engineering.* McGraw-Hill.

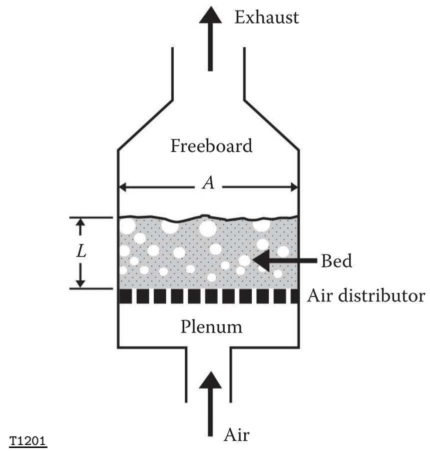
Fluidized-bed Combustion[19]

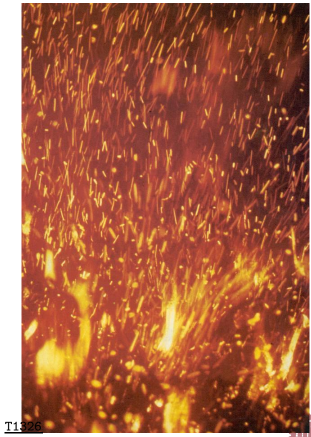


Fluidized bed combustor (FBC) schematic

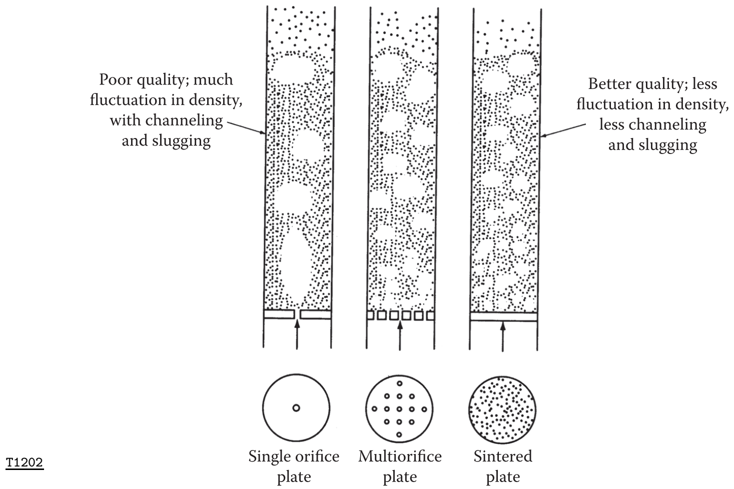
[19] E. Keating (2007). *Applied Combustion.* 2nd ed. Taylor & Francis.

Schematic diagram of a fluidized bed[20]





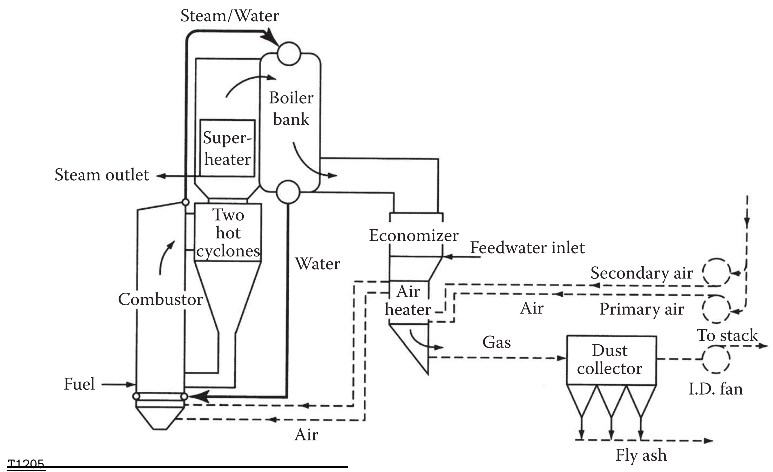
[20] G. Borman and K. Ragland (1998). *Combustion Engineering.* McGraw-Hill.



Quality of fluidization as influenced by the type of air distribution plate[21].

[21] G. Borman and K. Ragland (1998). *Combustion Engineering.* McGraw-Hill.

Circulating fluidized bed combustion system[22]



[22] G. Borman and K. Ragland (1998). *Combustion Engineering.* McGraw-Hill.

Characteristics of Combustion Methods[23]

Variables	Combustion Method: Fixed Bed (stoker)	Fluidized Bed	Suspension
Particle size			
Approximate top size	<2 inches	<0.2 inches	180 µm
Average size	0.25 inches	0.04 inches	45 µm
System/bed temperature	<1,500°F	1,500–1,800°F	>2,200°F
Particle heating rate	≈1°/s	10^3–10^4 °/s	10^3–10^6 °/s
Reaction time			
Volatiles	≈100 seconds	10–50 seconds	<0.1 seconds
Char	≈1,000 seconds	100–500 seconds	<1 second
Reactive element description[a]	Diffusion-controlled combustion	Diffusion-controlled combustion	Chemically controlled combustion

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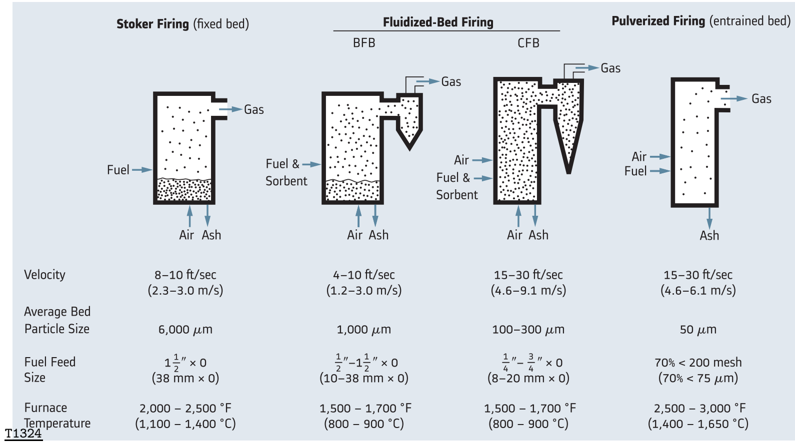
[23] B. Miller (2011). *Clean Coal Engineering Technology*. Elsevier Science.



Relationships between stoker, fluidized bed, and pulverized firing of solid fuels (BFB, bubbling fluidized bed; CFB, circulating fluidized bed)

References I

Borman, G. and K. Ragland (1998). *Combustion Engineering*. McGraw-Hill.

Keating, E. (2007). *Applied Combustion*. 2nd ed. Taylor & Francis.

Miller, B. (2011). *Clean Coal Engineering Technology*. Elsevier Science.