Course Name: Theory of Fire Propagation (Fire Dynamics)

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Week – 11

Lecture – 05

Module 8 – Introduction to dust ignition, dust explosion and forest fires

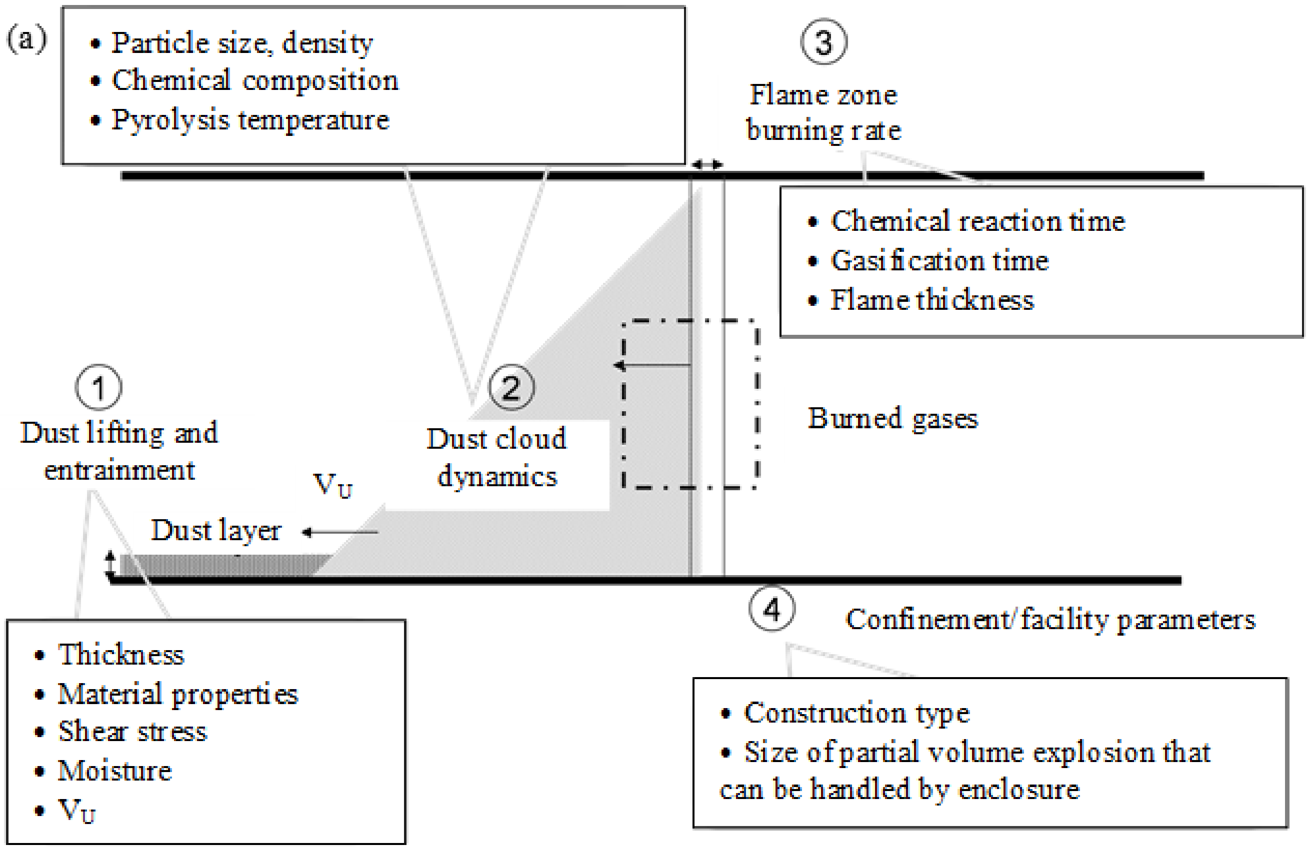
Dust flames:

Dust flames are heterogeneous in nature. Flammable dust (solid) particles interact with hot gaseous ambient to form gaseous fuels (pyrolysis) and leave residues. In case of charring fuels, residue left behind is char (carbon + ash). Gaseous fuel (volatiles) mixes with oxygen from atmosphere and reacts to form gaseous products. When oxygen reaches the hot char surface, oxidation reaction occurs at the solid surface to form gaseous products. Commonly dust flames are seen in coal mines (fine coal particles interact with air or mixture of methane and air) and industries involving fine dusts (chemical, metallurgical and pharmaceutical industries, where the dusts form a combustible cloud during the processes).

Dust flames – controlling factors:

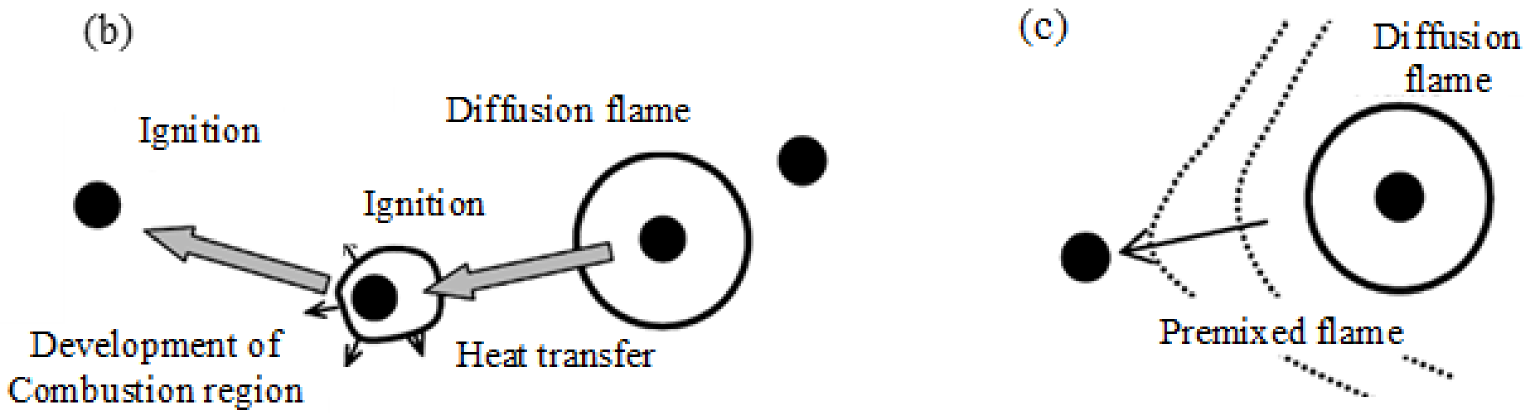
Dust layers deposited in mines (coal dusts deposited over surfaces) or in industries (organic/non-organic dusts deposited on machineries) **lift, entrain and mix** with ambient gas (air and products of combustion) to form a cloud of fine particles (well-mixed particles and gas). Lift an entrainment of dust particles into the cloud depend upon thickness of the deposited layer, viscosity, moisture content, shear stress and material properties. **Cloud dynamics** depends on nature of the gas medium that carries the dust particles; its temperature, oxygen concentration and level of turbulence. Combustion (or deflagration) of dust particles in a cloud depends on pyrolysis time, chemical reaction rate and flame thickness. If combustion occurs in a confinement, its size and material of construction also affect the dust combustion.

Dust flames – deflagration:



Dust flames – modes:

Burning of a dust cloud involves heating of the particles, volatile combustion, char combustion (in case of charring dusts) and ignition of unburned mixture. Based on the dust concentration in the cloud, two modes are generally observed (Sun et al., 2006) as shown in the figure. In the 1st mode, particles have individual diffusion flames, partial premixing of volatile with air occurs and other particles are ignited sequentially. In the 2nd mode, a premixed flame is also present.



Dust flame features:

Earliest work on dust-air premixed flames is provided by Nusselt (1924) and the most up-to-date review on the topic is given by Eckhoff (2003). Several others have analysed different configurations of dust flames. Unlike a premixed gas flame, a mixture of dust and oxidizer involves a multiphase flow, which causes difficulty in both experiments and modelling. Radiation heat transfer also plays a significant role in most cases and is important in dust flames. A premixed dust and air mixture may not be mixed in microscopic (molecular) level. Two types of flames can be analysed: Nusselt flame & volatile flame. In Nusselt flame, strictly **heterogeneous combustion** occurs at the surface of the particles, sustained by oxygen diffusing towards the surface. Volatile flame is homogeneous (gas-phase).

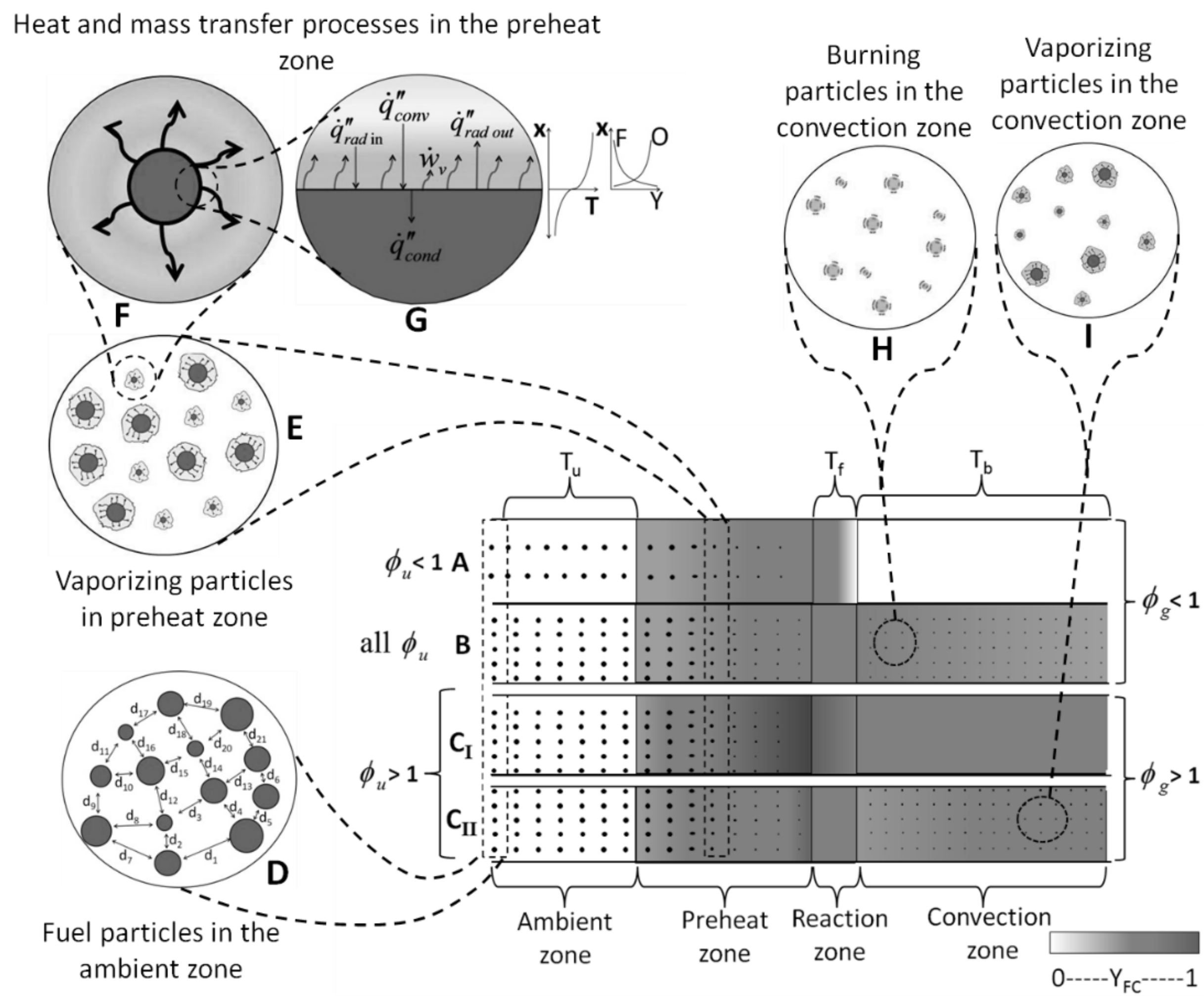
Dust combustion in volatile flame:

As dust particles interact with a volatile flame, further volatiles are released from particles before char combustion. When mixed with air, these volatile gases and/or vapours burn as a premixed gas flame under 3 distinctive mechanisms (Bordon & Fletcher, 1983): For charring fuels, devolatilization and burning of volatiles followed by combustion of char. For certain polymers such as PMMA, melting followed by evaporation and subsequently vapor phase burning. In certain other dusts of oxide forming materials, evaporation through a solid oxide shell followed by combustion of the vapor outside the shell. Four zones are observed: ambient zone, preheat zone, reaction zone and convection zone, as typically in a premixed flame.

Dust combustion in volatile flame – scenarios:

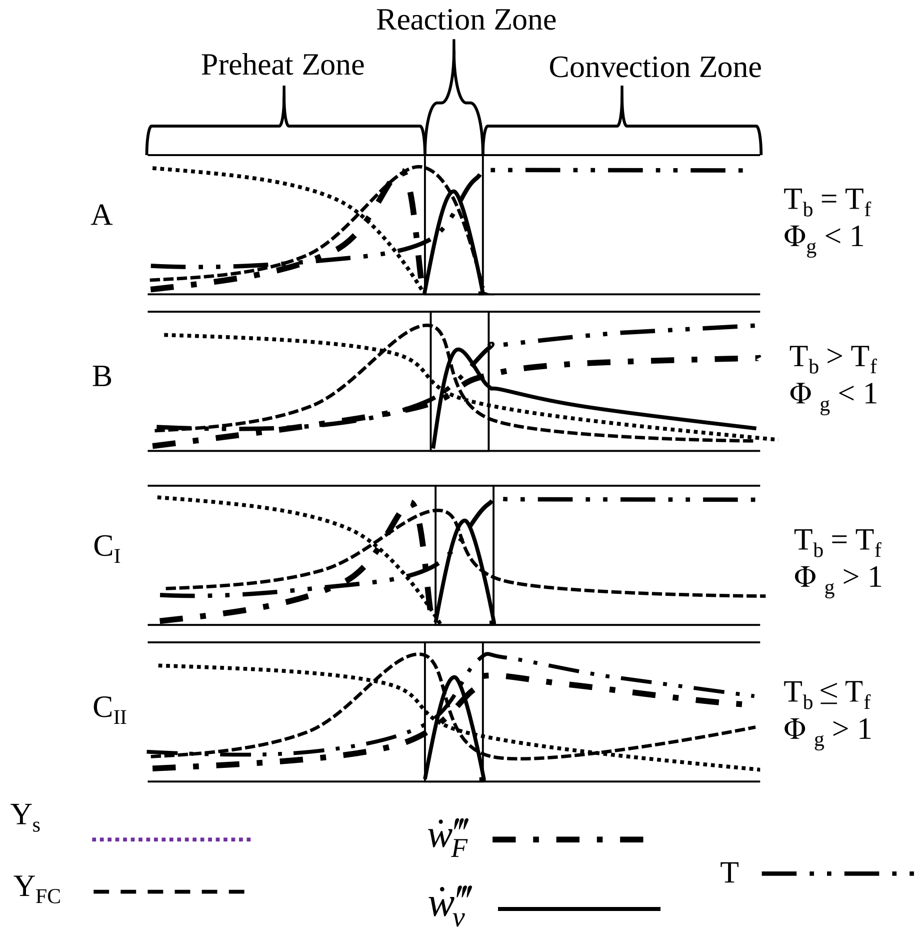
Two equivalence ratios defined: (Rockwell & Rangwala, 2013)

ϕ_u based on total solid fuel in the ambient zone. ϕ_g based on the volatized gas vapor evolved at the end of the preheat zone. ϕ_g changes from reaction to convection zone, based on solid-phase burning.



Heat and mass transfer processes in the preheat zone
$\dot{q}''_{conv}$
$\dot{q}''_{rad\ in}$
$\dot{q}''_{rad\ out}$
$\dot{w}_v$
$\dot{q}''_{cond}$
x
T
x
F
O
Y
F
G
Burning particles in the convection zone
Vaporizing particles in the convection zone
H
I
E
Vaporizing particles in preheat zone
D
Fuel particles in the ambient zone
T_u
T_f
T_b
ϕ_u< 1 A
all ϕ_u B
ϕ_u> 1
C_I
C_{II}
ϕ_g< 1
ϕ_g> 1
Ambient zone
Preheat zone
Reaction zone
Convection zone
0-----Y_{FC}-----1

Dust combustion in volatile flame – structures:



Y_S = mass fraction of solid

Y_{FC} = mass fraction of vaporized fuel

$\dot{W}_F'''$ = reaction rate

$\dot{W}_v'''$ = vaporization rate

T_b = convection zone temp.

T_f = reaction zone temp.

Case A: vaporization is complete in preheat zone & fuel burns in reaction zone.

Case B: particles burn in convection zone also.

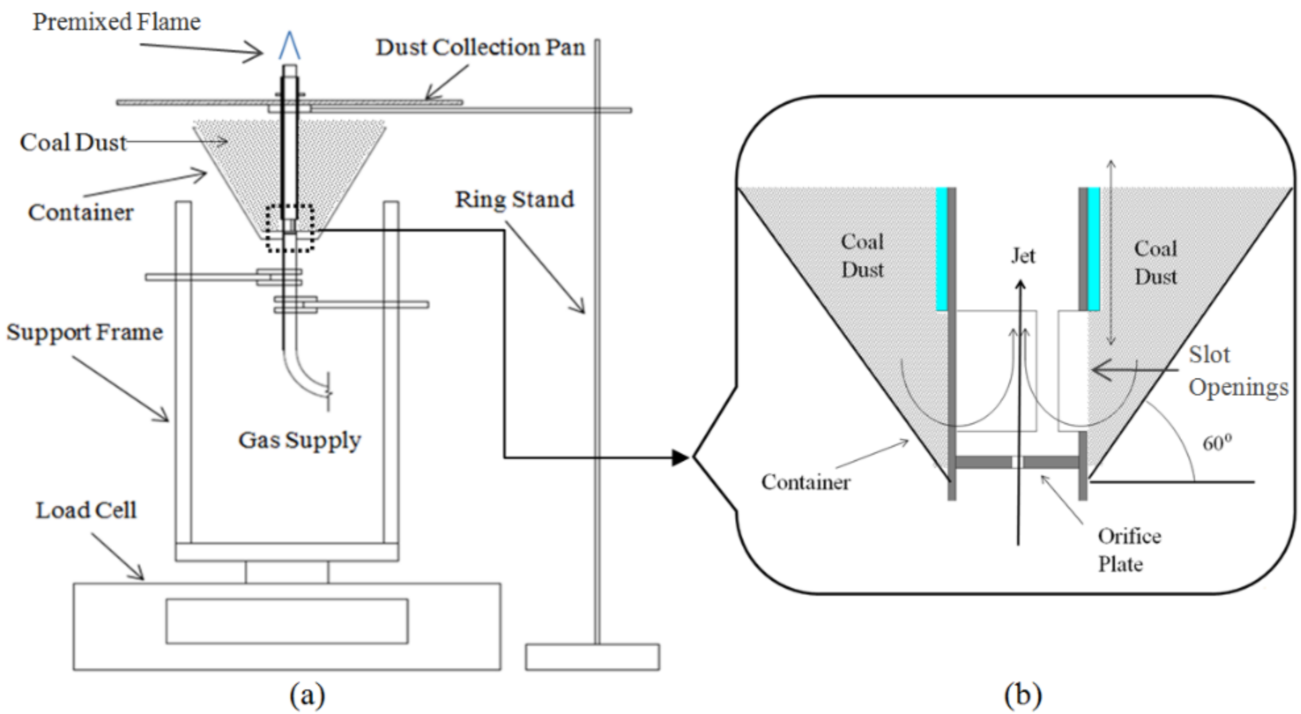
Case C_I: only part of gas fuel burns in reaction zone.

Case C_{II}: Like C_I, O_2 limiting case. Particles convert in convection zone also.

Dust flame – burning velocity:

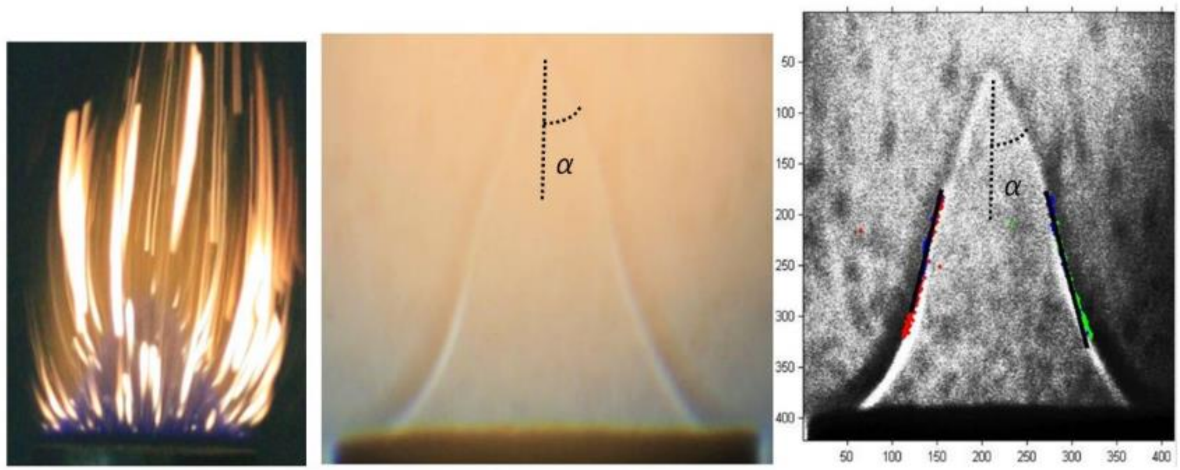
Burning velocity of a premixed particle-air flame is controlled by several parameters such as vaporization (volatile release) rate, particle size, number density (concentration) and so on. For cases A and B, exponent of the vaporization kinetic term (n) and convection zone temperature (T_b) are the most dominant in determining the burning velocity. In scenarios C_I and C_{II}, the activation energy of the gas-phase reaction (E) is the most dominant followed by the frequency factor (B) and the heat of the reaction (Q) in determining the burning velocity. Burning velocity is not sensitive to ϕ_u, in scenarios C_I and C_{II}. Particle size is slightly more dominant for the fuel lean case. Thermal conductivity of the dust is more influential in the case of an oxygen controlled flame front.

Coal dust combustion in premixed flame:



Bunsen burner setup for naturally entrained coal-CH_4-air burner; Xie et al.

Coal dust combustion in premixed flame:



Actual Flame Image (a) | Shadowgraph (b) | Image in Matlab (c)

Coal dust-CH_4-air flame; Xie et al. (2012)