

An Overview of Combustion in Packed Beds

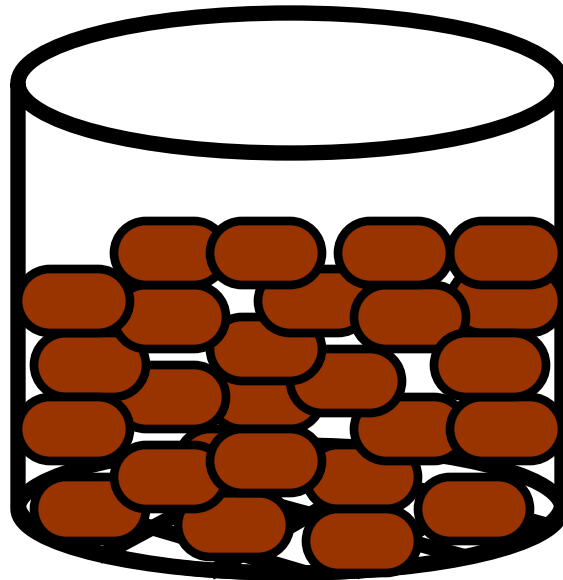
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Talk Outline

- What is a packed bed?
- Flow in a packed bed
- What is combustion?
- Combustion in a packed bed
- Summary

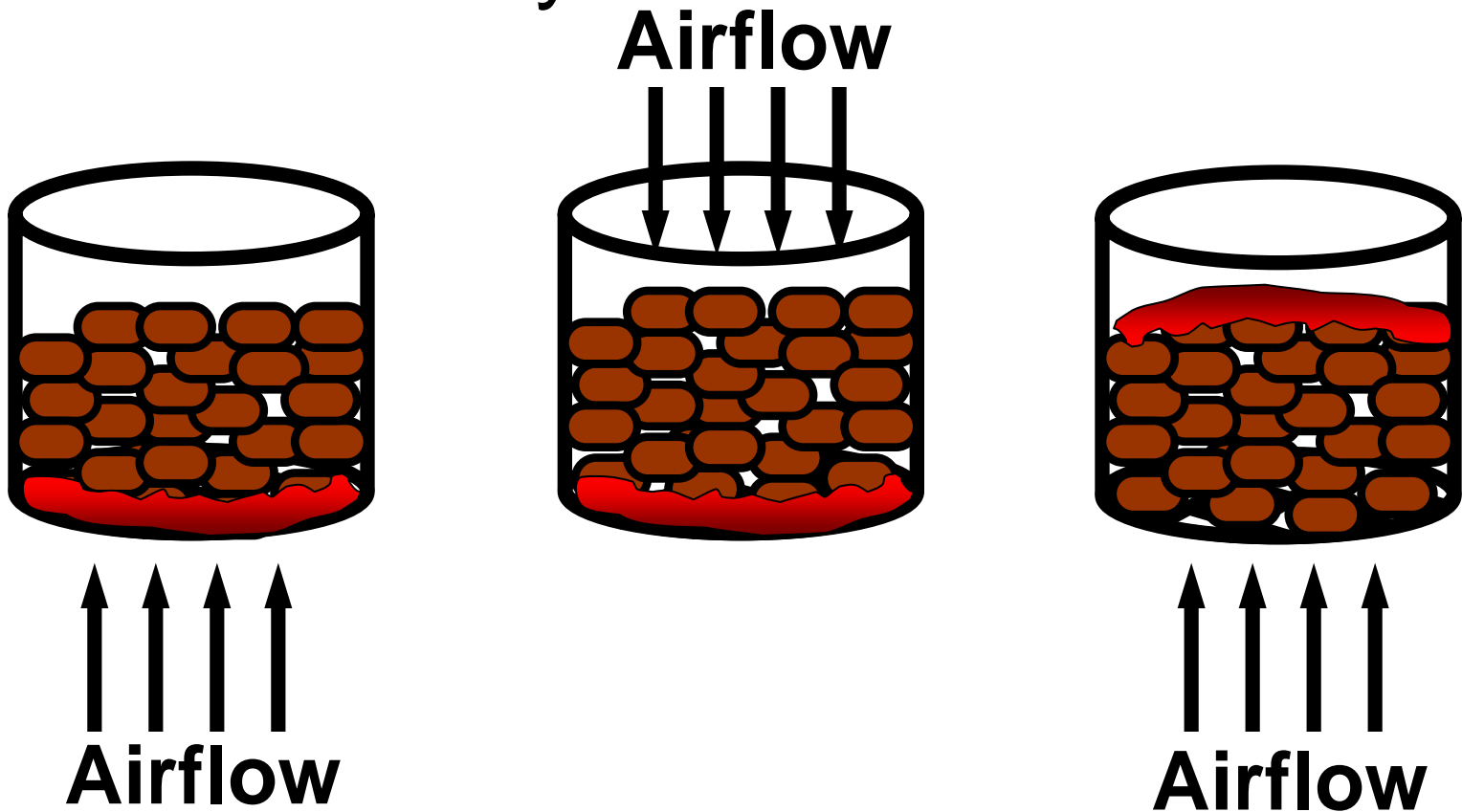
What is a packed bed? :: Definition

A **packed bed** is a pile of fuel particles sitting on top of a grate.



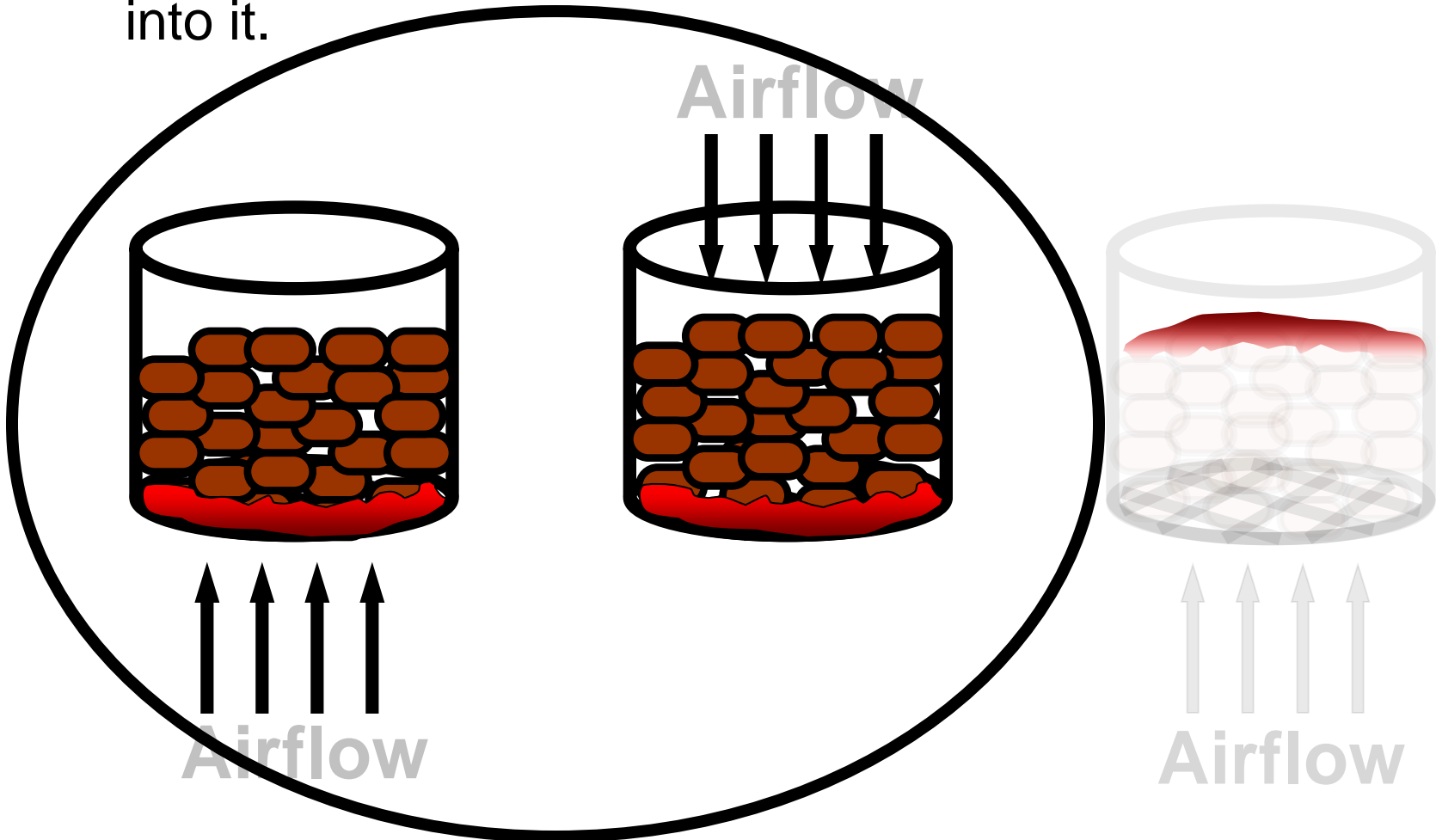
What is a packed bed? :: Types

Packed beds can be operated in three main ways:



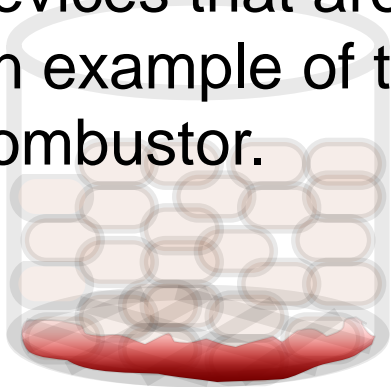
What is a packed bed? :: Types :: Overfeed

Overfeed: Raw fuel is fed in on top of burning fuel. Reaction zone stays near bottom and fuel moves down into it.

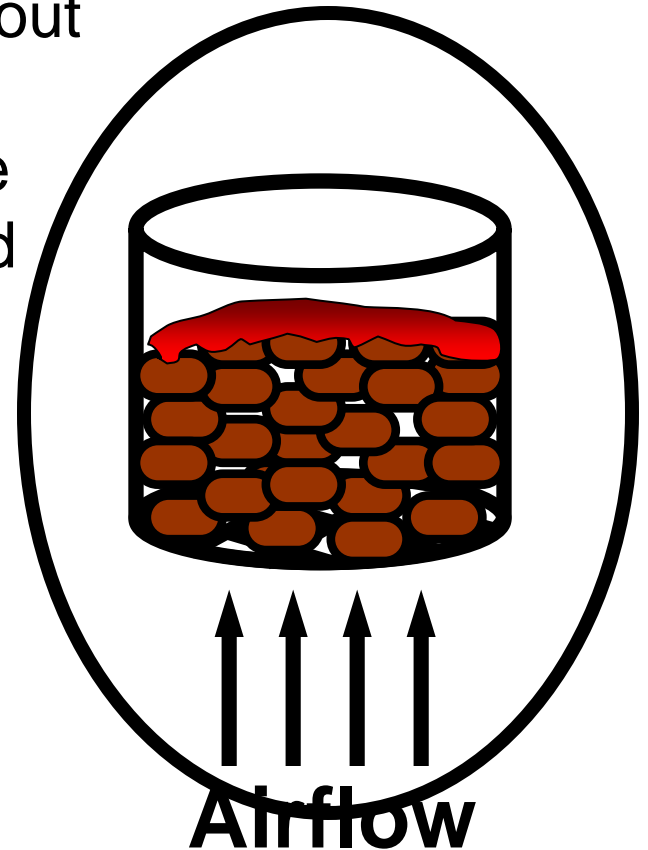
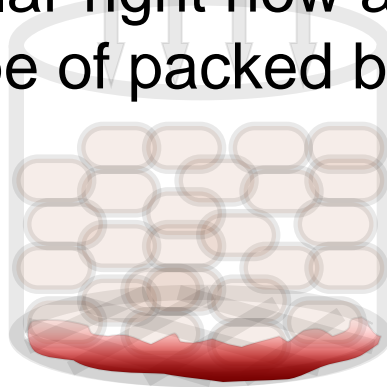


What is a packed bed? :: Types :: Underfeed

Underfeed: Fuel is lit at the top and burns downward. Raw fuel can be added by pushing it up from the bottom, but in many applications the combustor is batch-fed and a single charge of fuel is allowed to fully burn out before more fuel is added. The TLUD devices that are popular right now are an example of this type of packed bed combustor.



Airflow



Airflow

What is a packed bed? :: Types :: Not fluidized

Airflow must be sufficiently low that the majority of the fuel particles do not become suspended in the flow. If that occurs, we no longer have a packed bed, but have a **fluidized bed**. Fluidized beds behave differently.

What is a packed bed? :: Fuel

Packed beds can be used to burn many different solid fuels, but we're mainly interested in chipped or pelletized biomass.

Particle size: anything from rice hulls (~3mm) to small blocks of wood (~35mm) to big chunks of wood (~300mm).

We'll concentrate on the 10mm-50mm range.

Flow through a packed bed :: Void fraction

Flow is sensitive to bed height, particle size, and packing density. Packing density is expressed through the void-fraction, ε , which describes the ratio of the void volume to the total bed volume.

$$\varepsilon = 1 - \frac{\sum_k V_{\text{particle } k}}{V_{\text{bed}}}$$

Flow through a packed bed :: Ergun equation

The pressure drop (and thus the flow rate) can be calculated from the Ergun equation:

$$f_p = \frac{150}{Re_p} + 1.75$$

where

$$f_p = \frac{\Delta p}{L} \frac{D_p}{\rho V_s^2} \frac{\varepsilon^3}{1-\varepsilon} \quad \text{and} \quad Re_p = \frac{D_p \rho V_s}{(1-\varepsilon)\mu}$$

Flow through a packed bed :: Ergun equation cont.

Resistance to flow varies with:

- Bed height

- $\frac{1}{\text{Particle diameter}}$

- $\frac{1}{\text{Void fraction}^3}$

What is combustion? :: Definition

Combustion is the rapid, highly exothermic oxidation of a fuel.

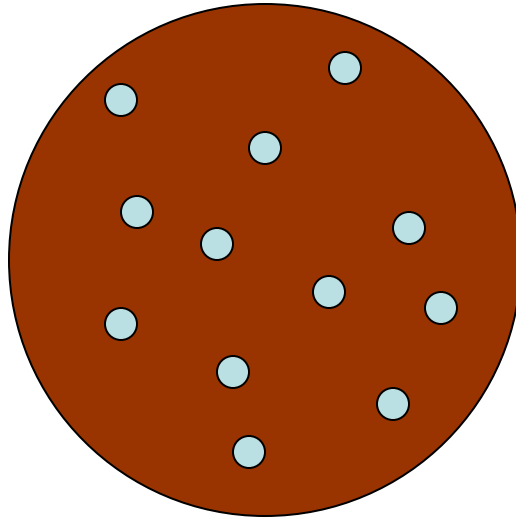
What is combustion? :: Solid Fuels

Combustion of a solid fuel such as wood involves four processes:

1. Drying of the solid fuel
2. Devolatilization of the solid (pyrolysis)
3. Oxidation of the volatiles
4. Oxidation of the fixed carbon

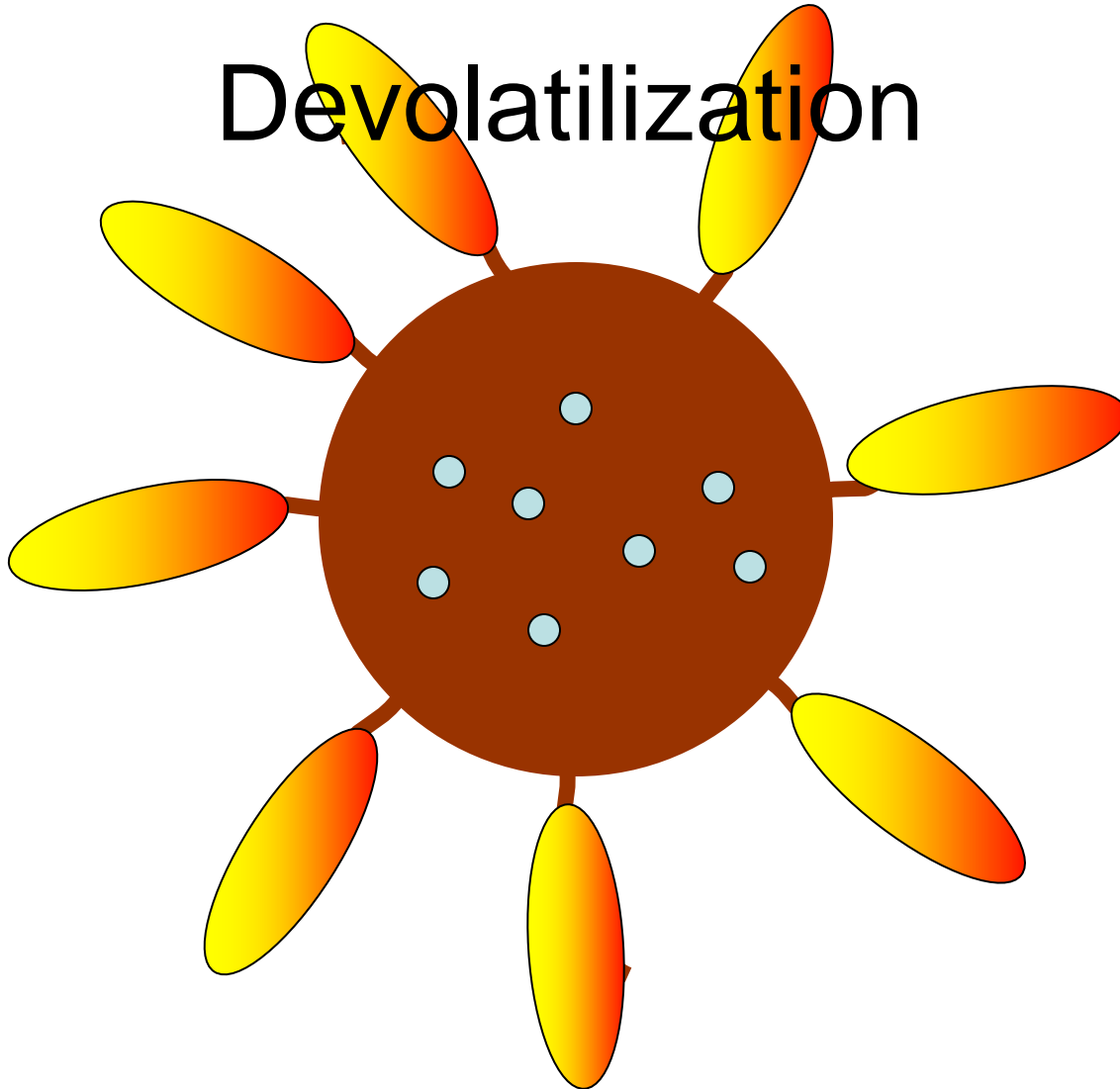
What is combustion? :: Solid Fuels

Drying of the fuel



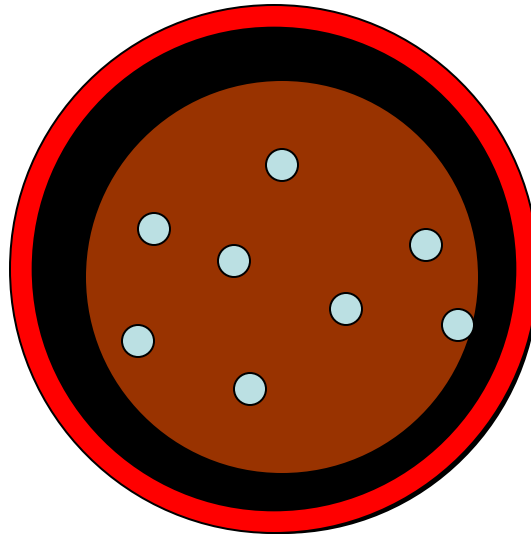
What is combustion? :: Solid Fuels

Devolatilization



What is combustion? :: Solid Fuels

Oxidation of Fixed Carbon



What is combustion? :: Solid Fuels :: Drying

Drying is a mass transfer process that is controlled by

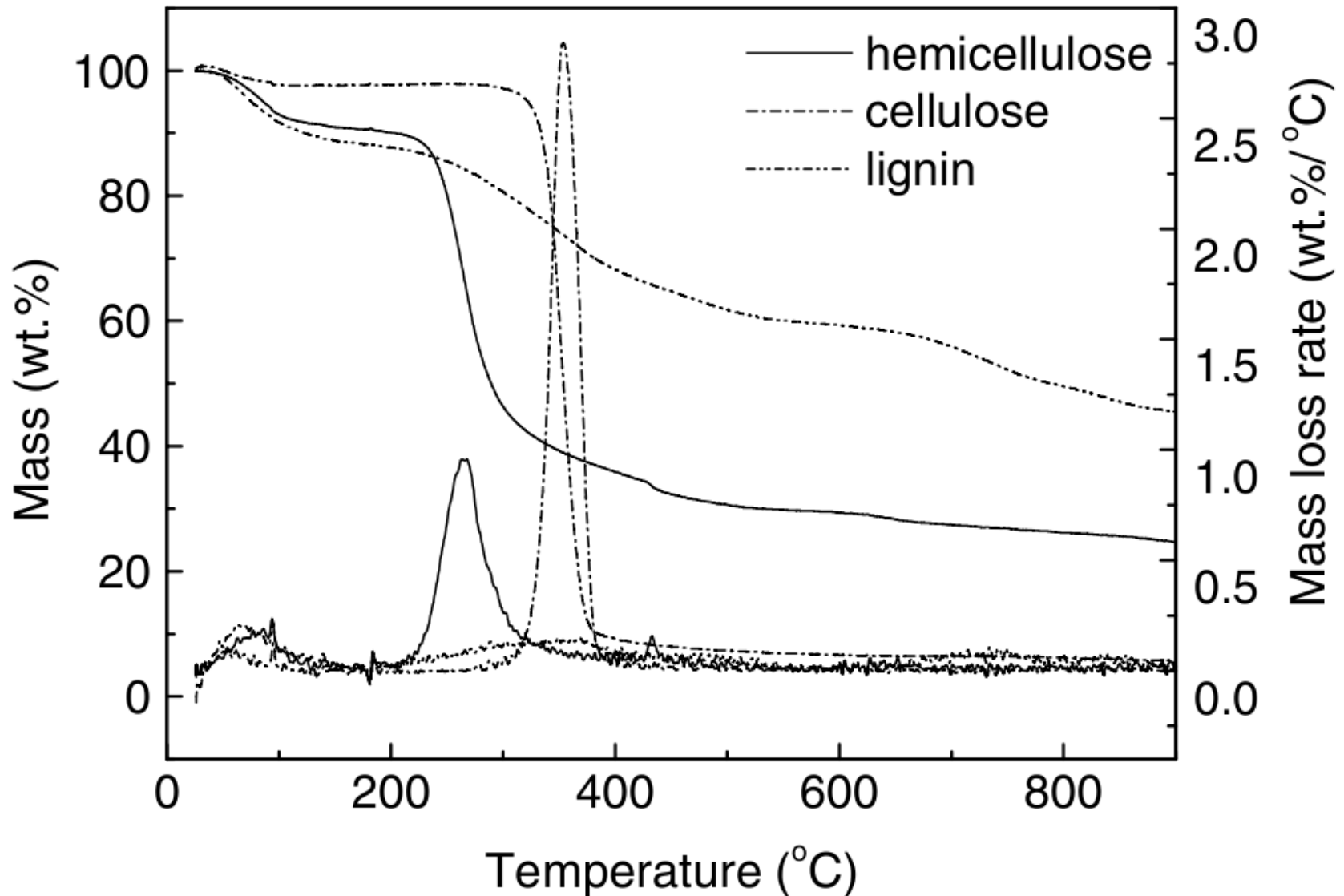
- Surface area of particle
- Gas flow past particle
 - Mass rate
 - Speed
 - Temperature
 - Moisture concentration
- Particle temperature (= moisture temperature)
- Heat of vaporization of water

What is combustion? :: Solid Fuels :: Devolatilization

Devolatilization is a chemical process that is controlled by

- Particle temperature
- Energy requirements of decomposition of constituents
- Physical structure of particle

What is combustion? :: Solid Fuels :: Devolatilization



What is combustion? :: Solid Fuels :: Devolatilization

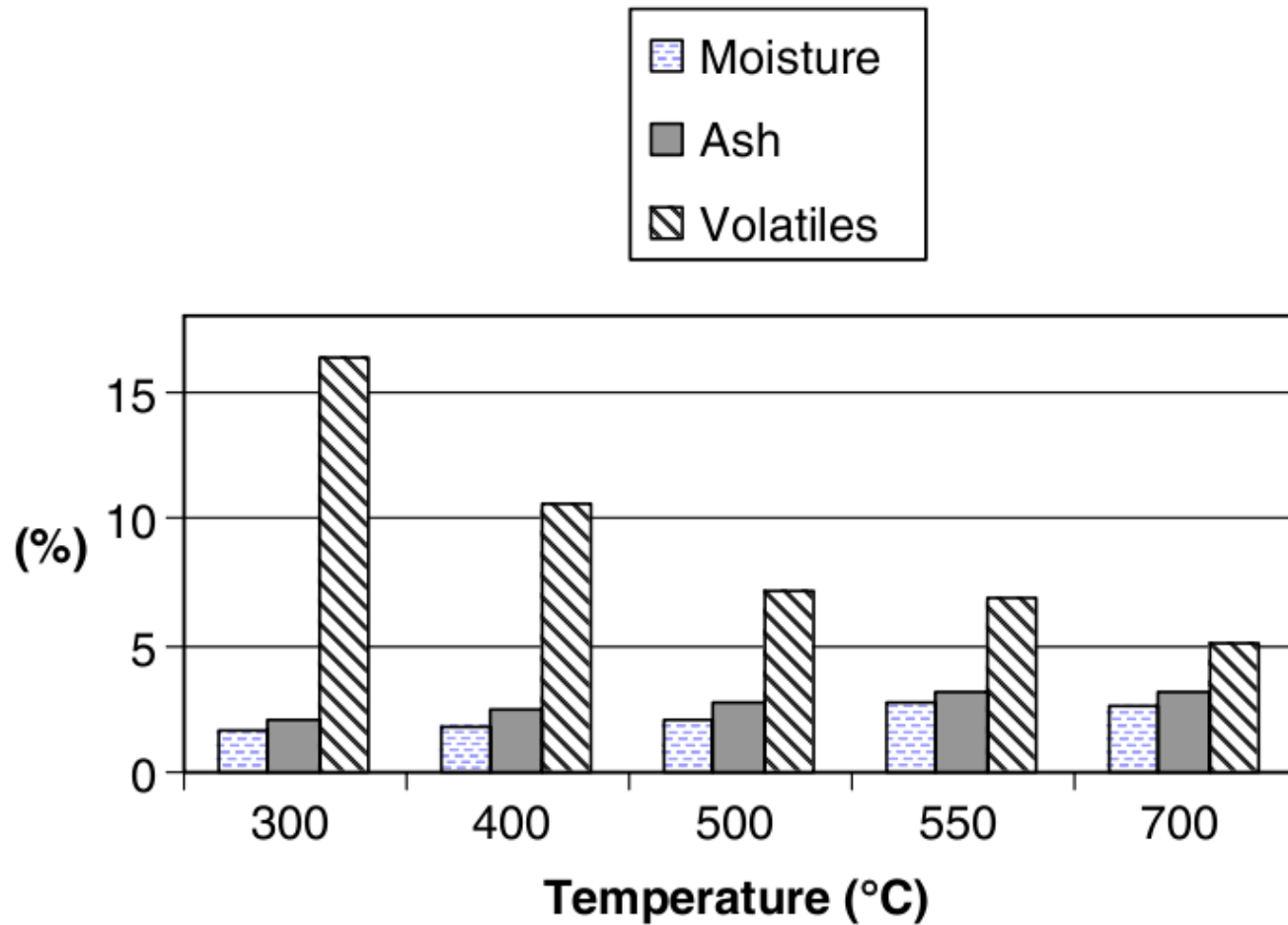


Fig. 6. Proximate analyses of chars at different temperatures.

What is combustion? :: Solid Fuels :: Devolatilization

Pistachio char made at different temperatures under low heat rate. Top-left is uncharred.

Higher temperatures lead to more devolatilization and more surface fissures.

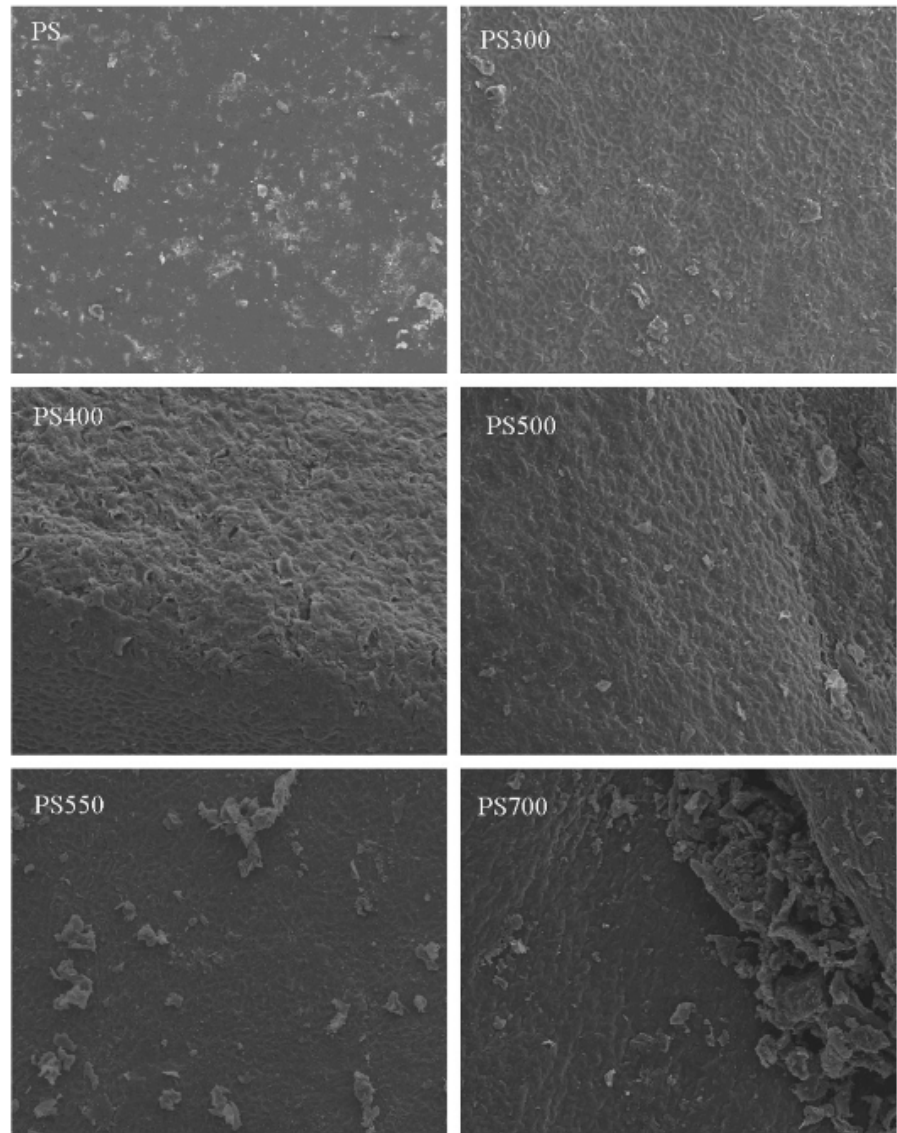


Fig. 9. SEM pictures of pistachio shell and its chars obtained at different temperatures.

What is combustion? :: Solid Fuels :: Devolatilization

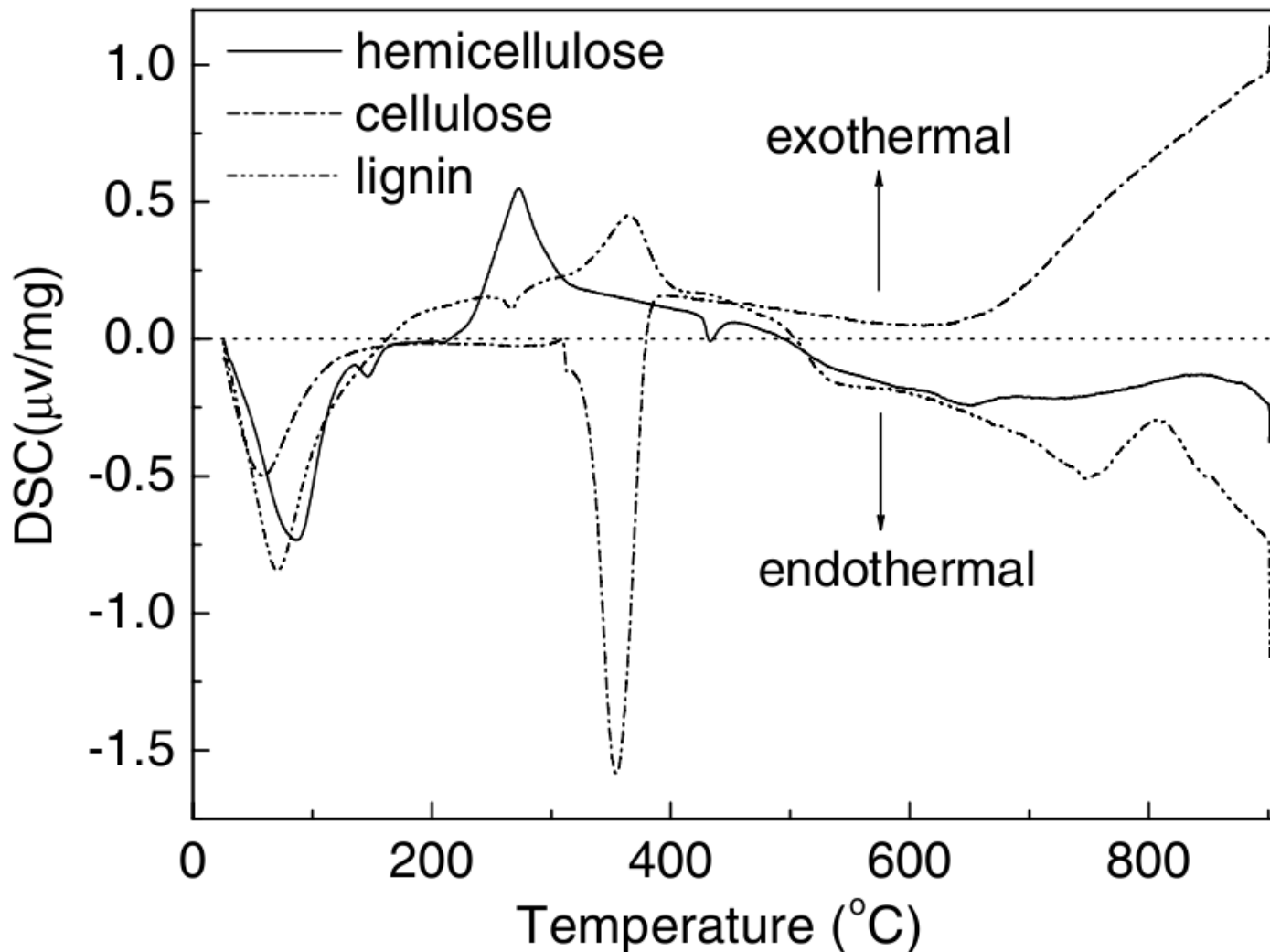


Fig. 3. DSC curves of hemicellulose, cellulose and lignin pyrolysis.

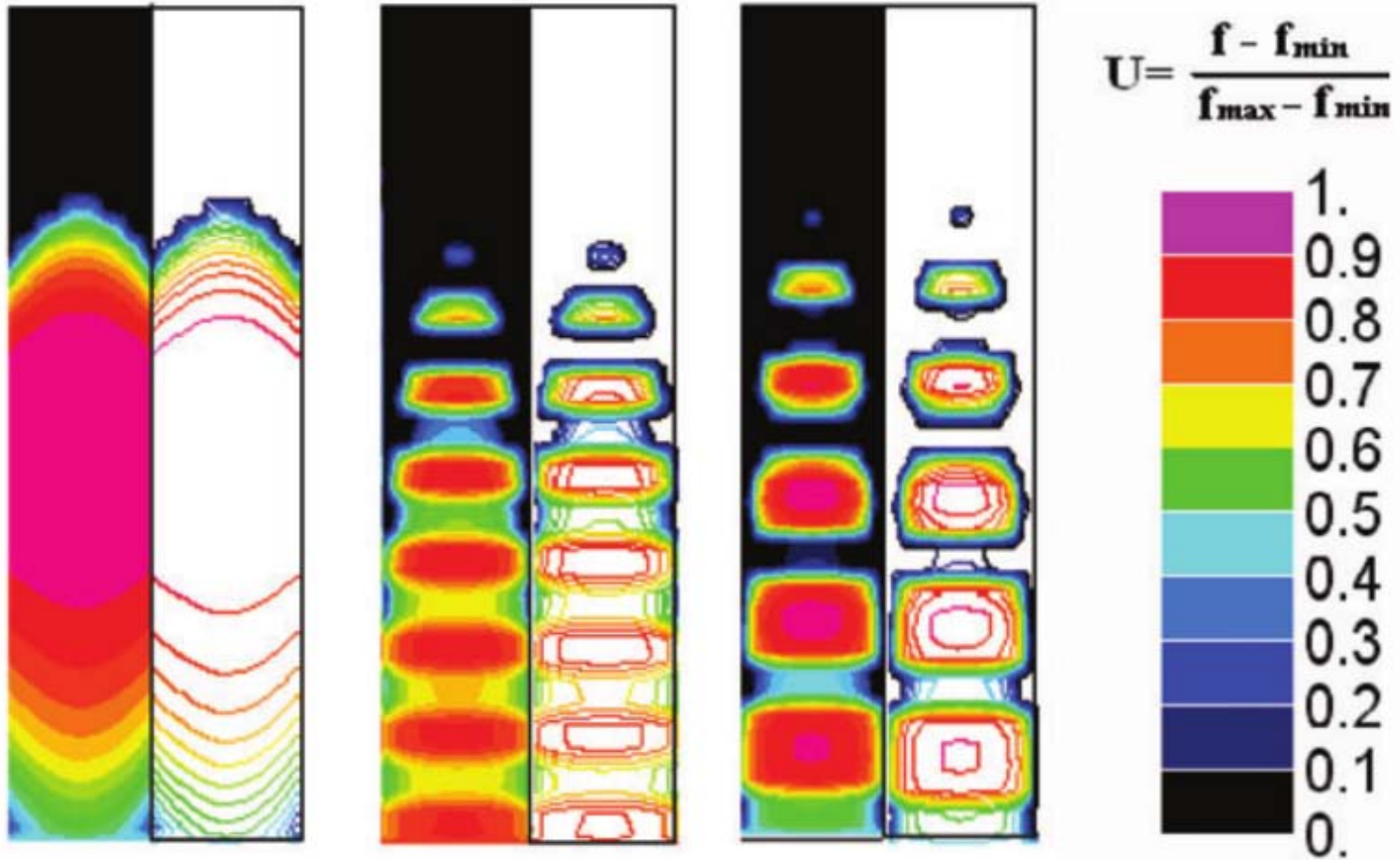
Combustion in a packed bed :: Drying

Fuel drying in a packed bed depends on:

- Airflow
- Particle temperature and internal gradients
- Particle Size
- Void fraction

Combustion in a packed bed :: Drying :: Particle size

Fraction of original moisture



10 mm

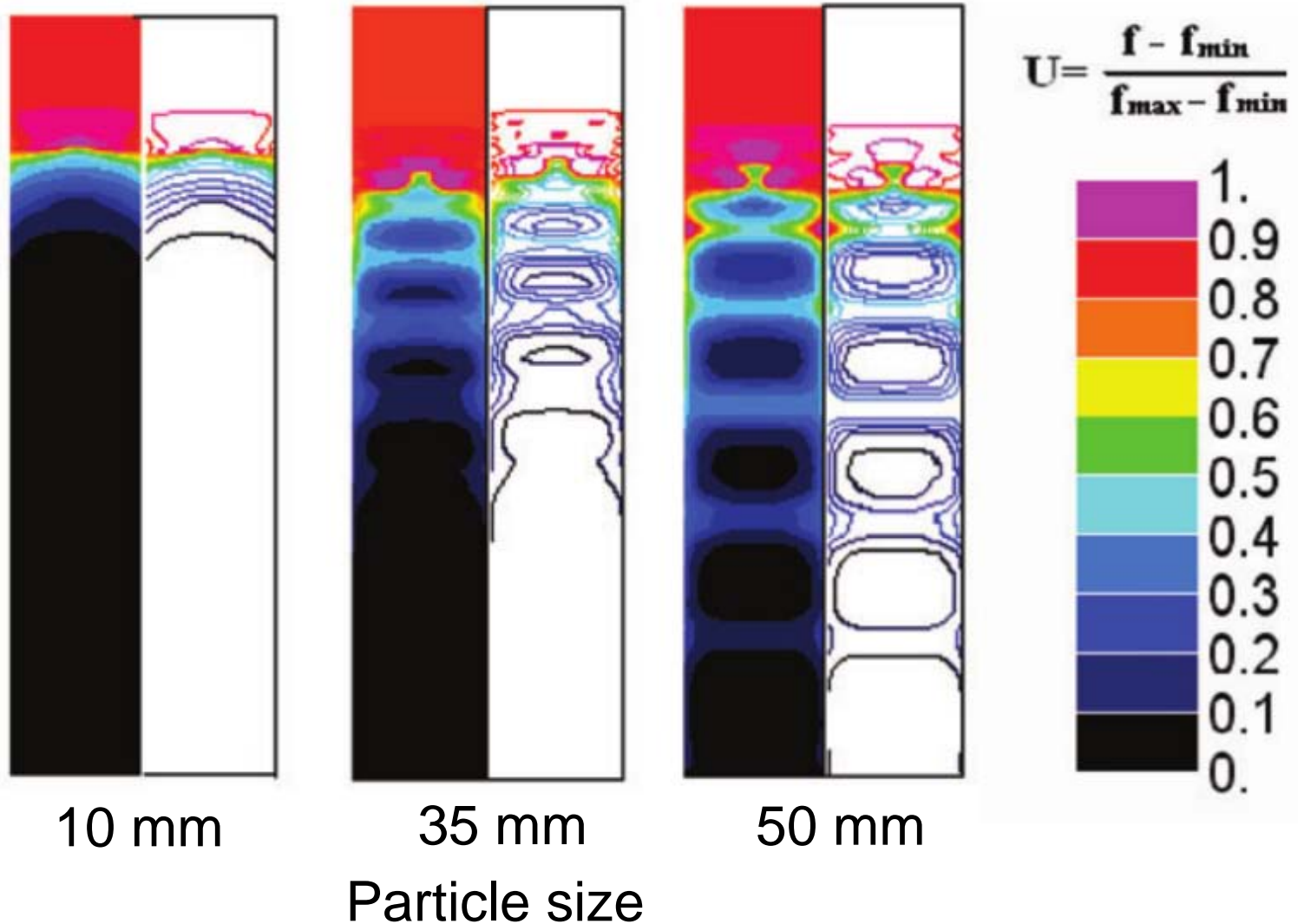
35 mm

50 mm

Particle size

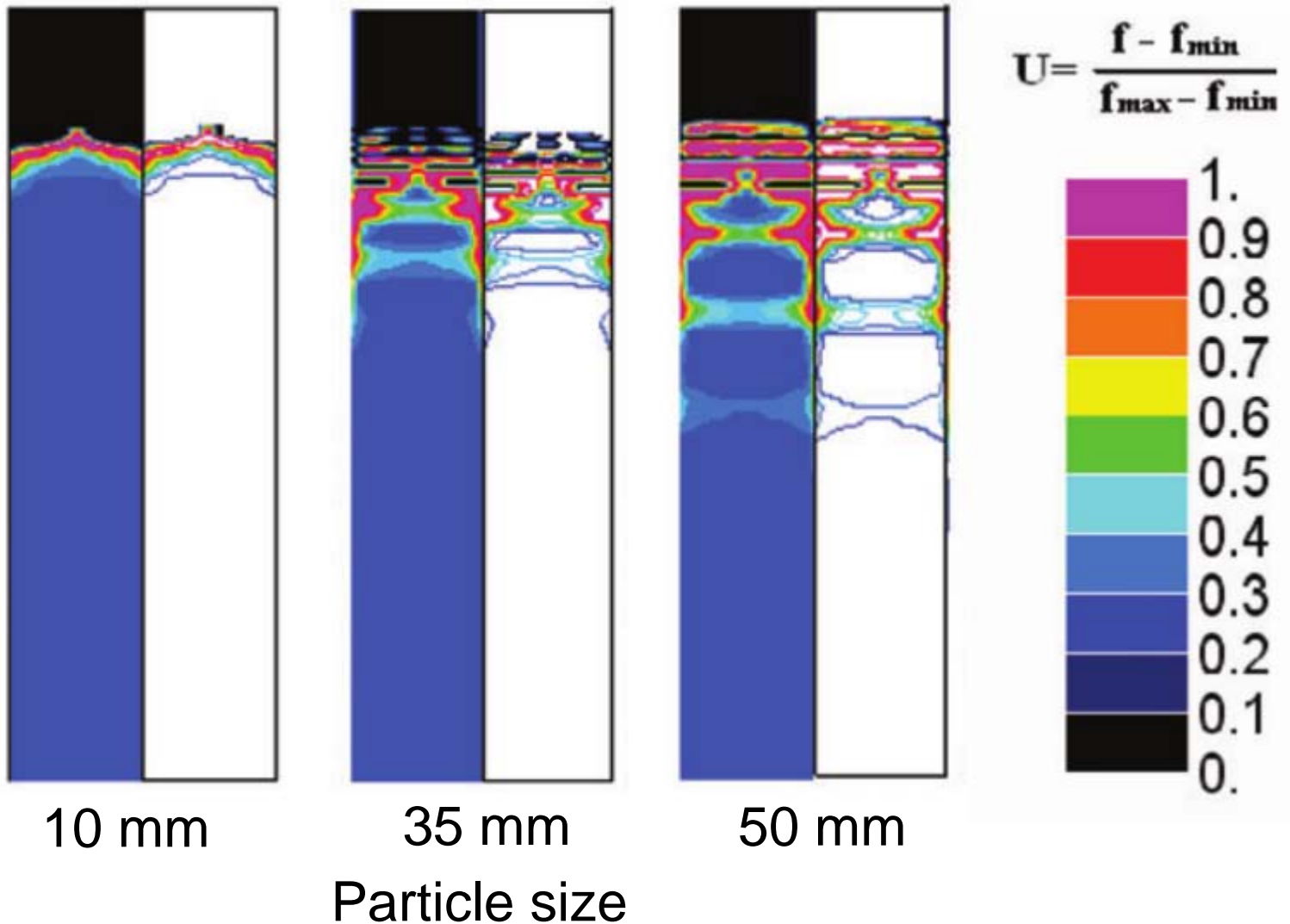
Combustion in a packed bed :: Temp. vs. particle size

Fraction of maximum temperature

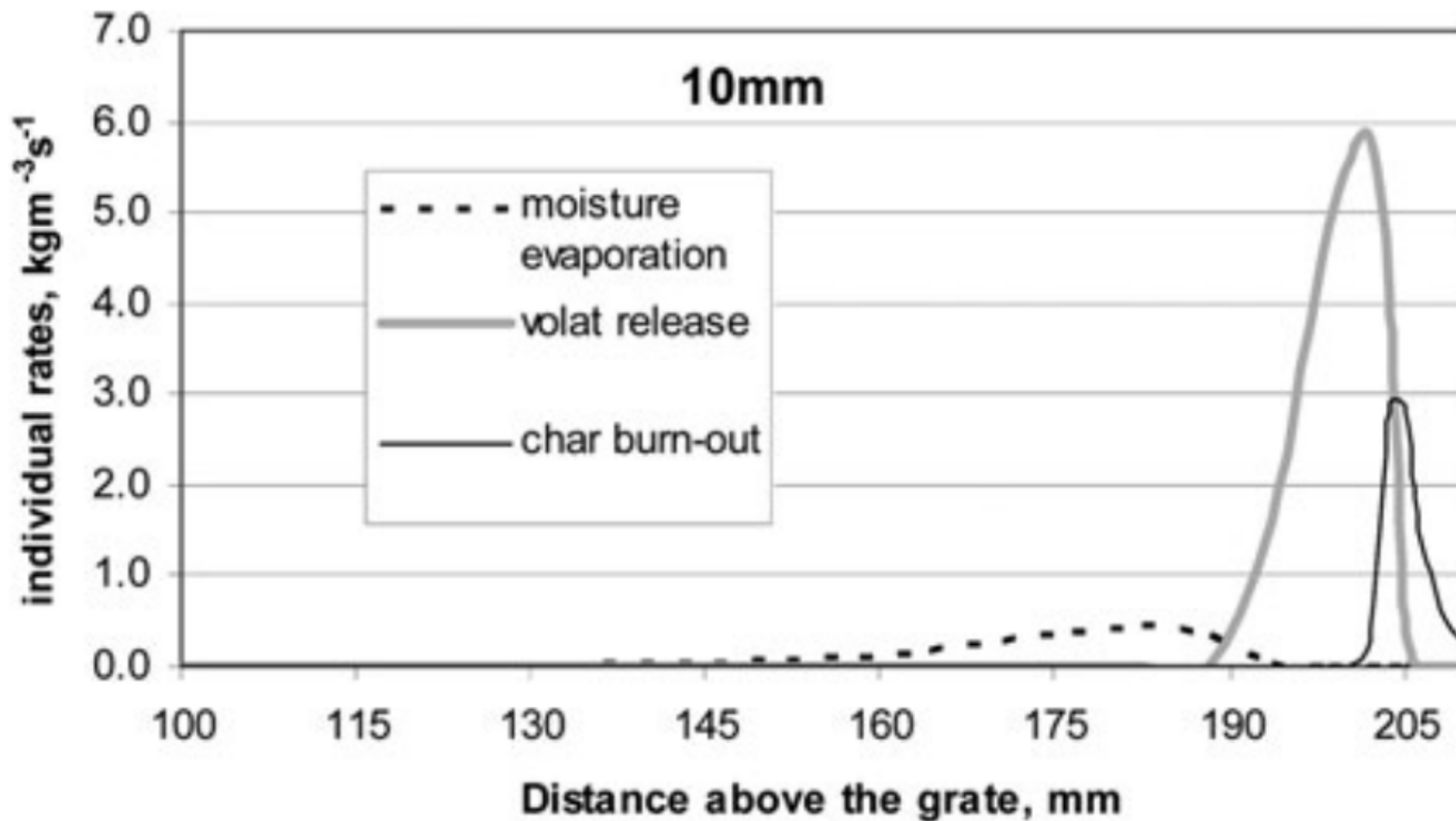


Combustion in a packed bed :: Char vs. particle size

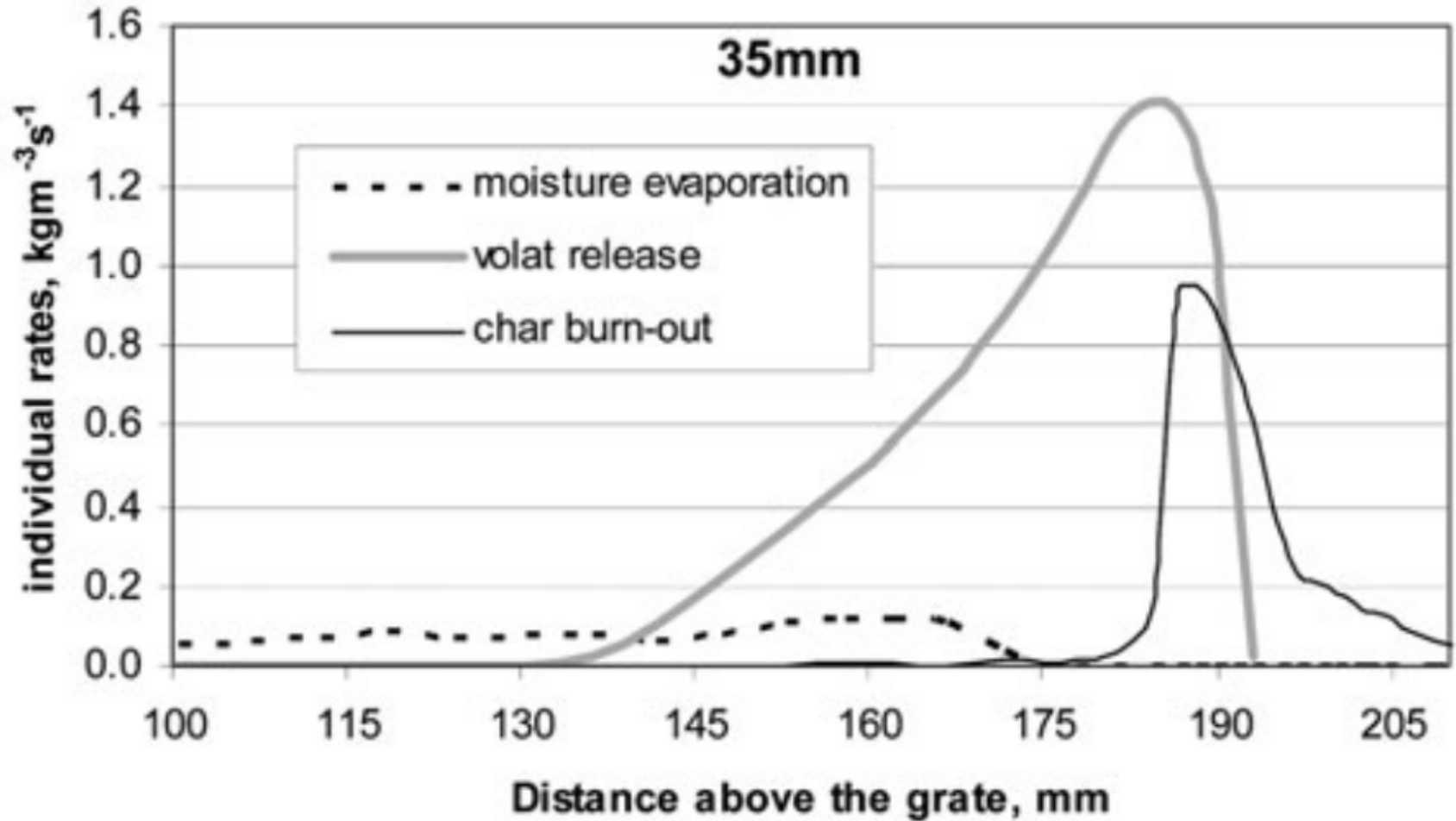
Fraction of total mass due to fixed carbon



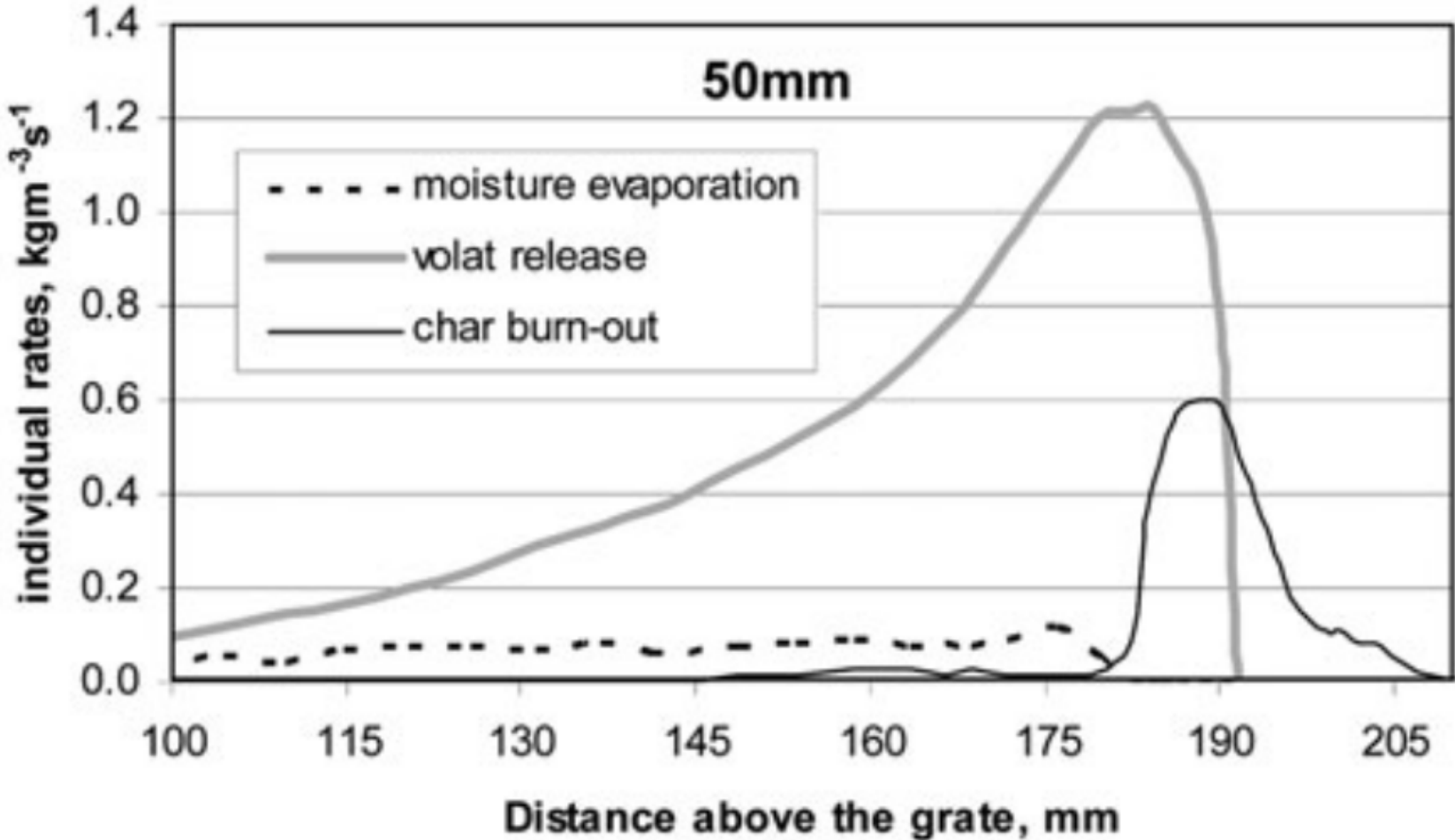
Combustion in a packed bed :: 10mm behavior



Combustion in a packed bed :: 35 mm behavior

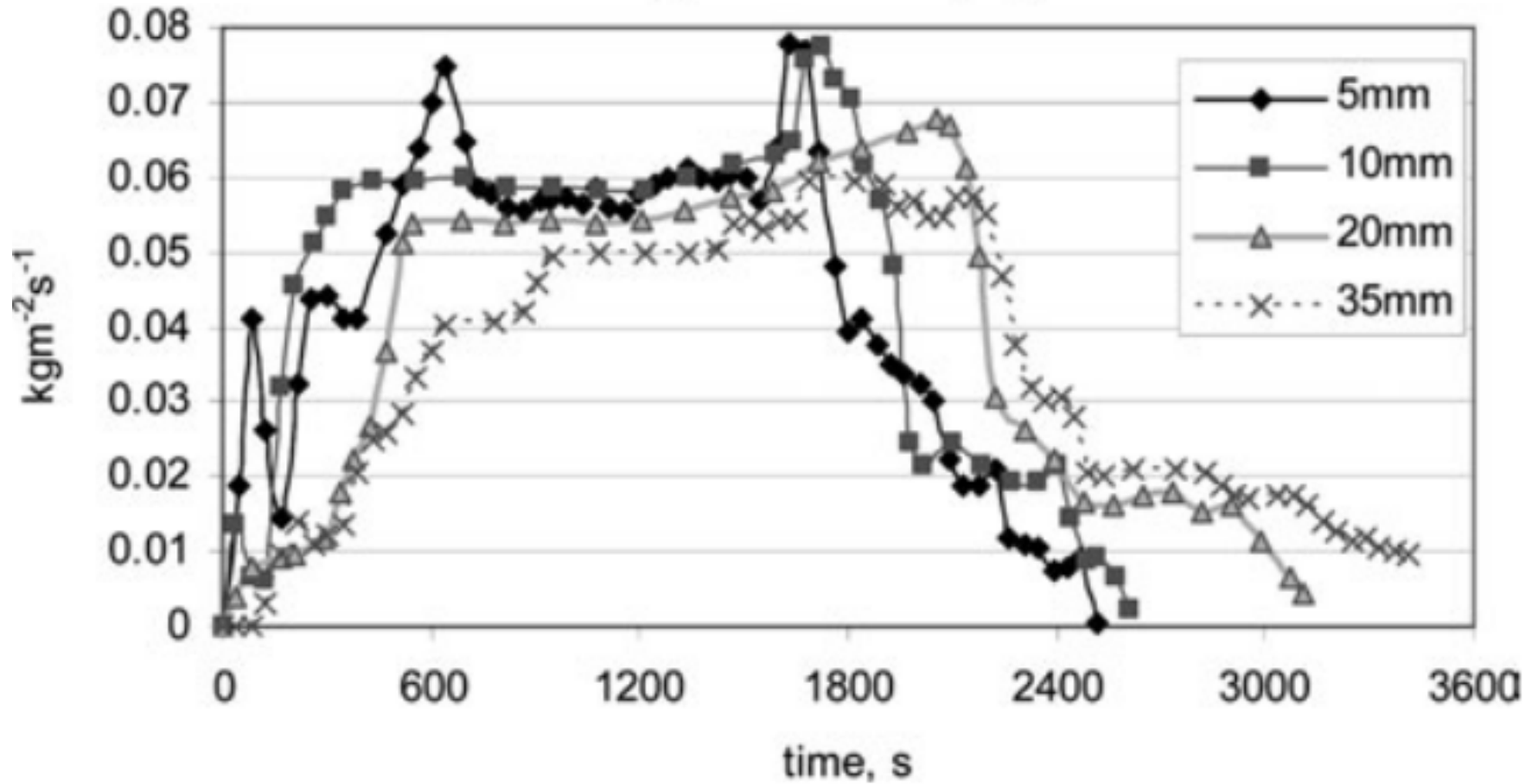


Combustion in a packed bed :: 50mm behavior



Combustion in a packed bed :: Burn rate

Burning rate vs. time (exp)



Combustion in a packed bed :: Heat transfer

- Radiation is major mode of heat transfer in
 - underfeed beds
 - downdraft overfeed beds
- Convection becomes important in updraft overfeed beds

Combustion in a packed bed :: Heat transfer

Smaller particles ->

radiation absorbed quickly ->

radiation does not penetrate as far into bed ->

thinner reaction zone

Larger particles ->

radiation absorbed slowly ->

radiation penetrates farther into bed ->

thicker reaction zone

Combustion in a packed bed :: Heat transfer

Moisture in the fuel affects heat transfer into the bed in three ways:

1. Initially lowers penetration into bed due to surface drying
2. Lowers temperature throughout bed because water vapor in voids absorbs radiation
3. Lowers temperature of char reaction at surface of particles

Summary

- Packed beds come in different types with different properties
- Flow depends on void fraction, particle size, and bed height
- Radiation is the most important heat transfer mechanism inside the bed
- Burn rate and other combustion properties depend on particle size, void fraction, and fuel moisture