Effects of Particle Shape and Size on Biomass Reactivity

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Outline

- Introduction
- Objectives
- Samples
- Experimental Methods
  - Experimental setups
  - Particle Shape Reconstruction
  - Temperature Mapping
- Particle Model Development
- Results and Discussions
- Acknowledgement

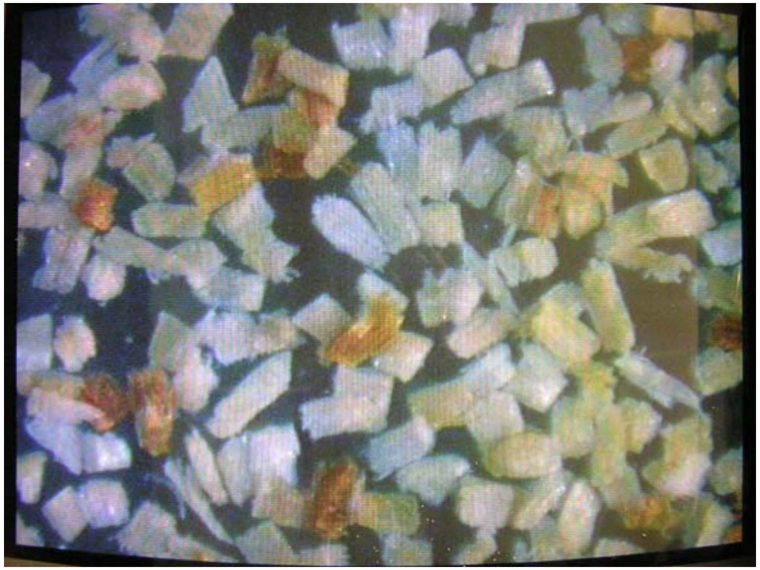
Introduction

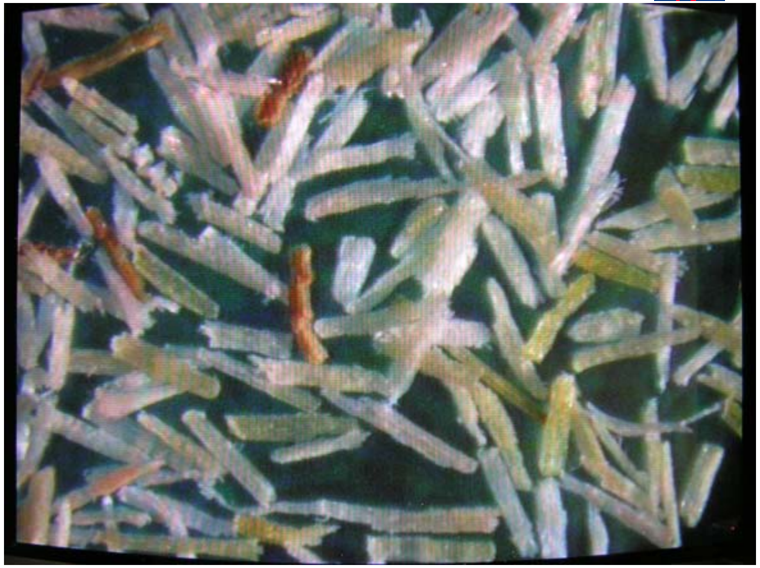
- More cofiring boilers are used in power plants
- Biomass particle shape and size
  - Irregular shapes: typically flake-like and cylinder-like (aspect ratios 2-15)
  - Larger size (1~6 mm)
- Biomass particle surface area
  - Surface area/volume essential to heat, mass, and momentum transfer
  - Sphere is extreme case (lowest surface area to volume ratio of all shapes)
- Comprehensive particle model needed for biomass combustion, which may not be simply approximated by isothermal spheres

Objectives

- **Establish a biomass combustion database for particles with different shapes and sizes**
  - Collecting experimental data for particles with varying shapes and sizes: mass loss, particle volume, surface area, shape, and surface temperature as functions of residence time.
- **Develop a comprehensive biomass particle combustion model**
  - This model should be capable of simulating combustion behaviors of biomass particles with any shape and size.

Samples - sawdust



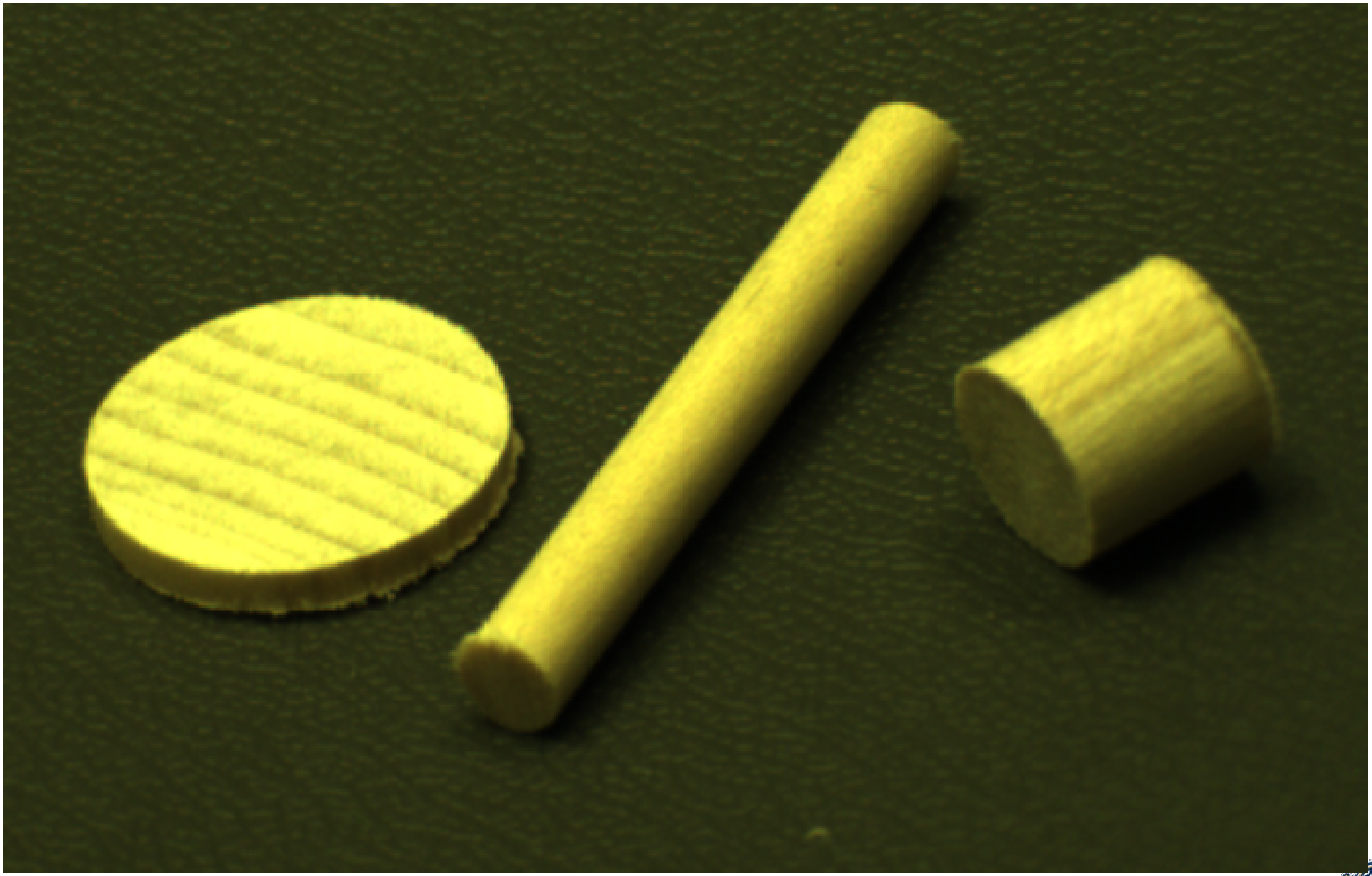


flake-like

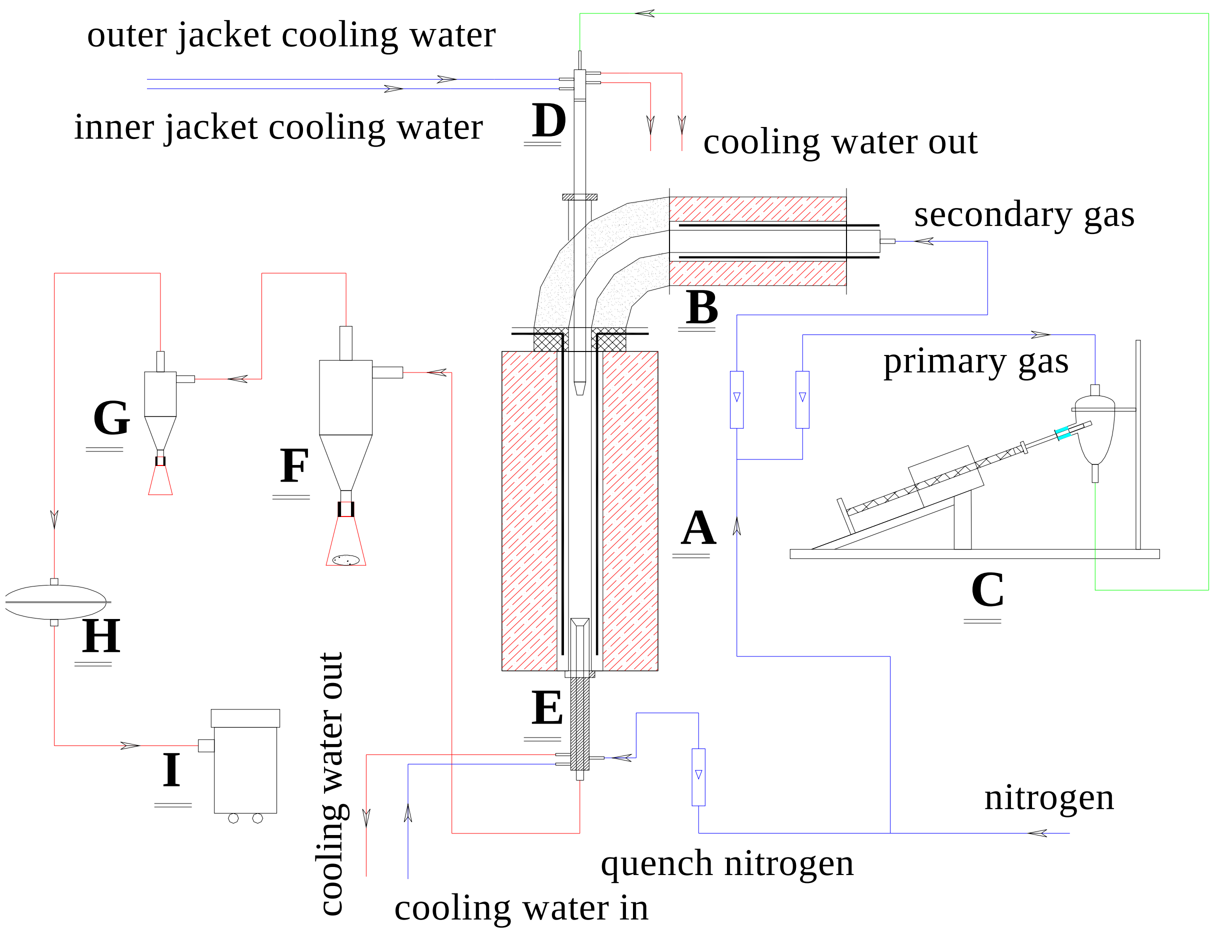
cylinder-like

near-spherical

Samples - poplar



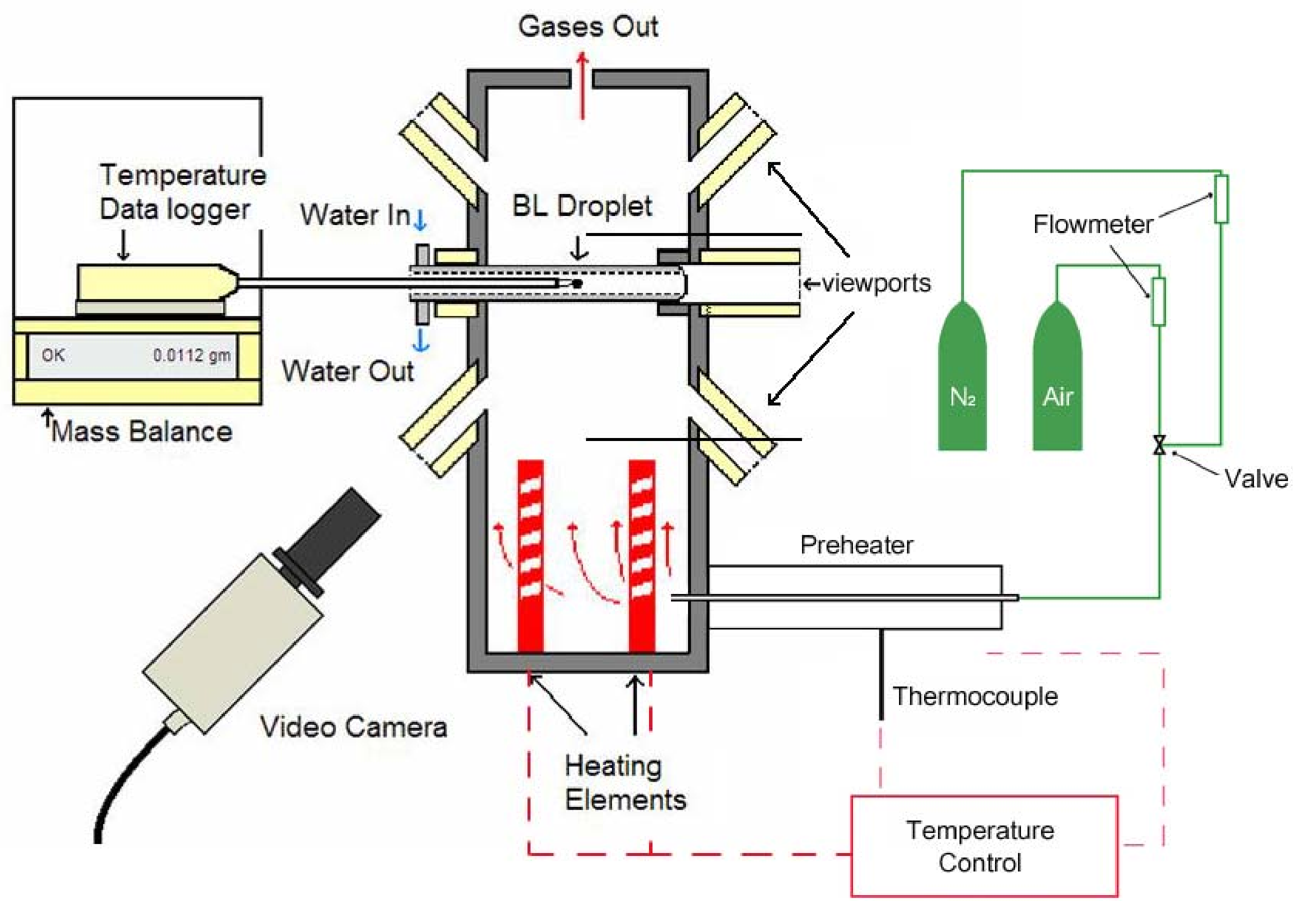
Methods - entrained flow reactor

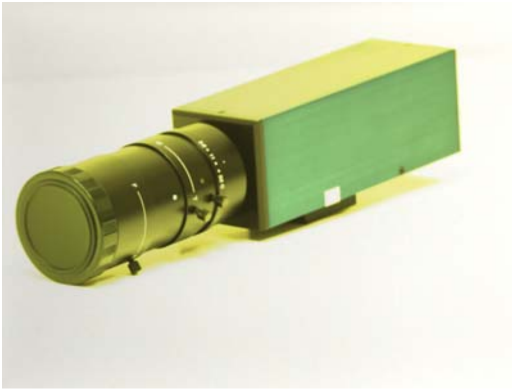


A - entrain flow reactor **B - preheater** **C - syringe feeder**
D - feeding probe **E - collection probe** **F - 1st cyclone separator**
G - 2nd cyclone separator **H - filter** **I - vacuum**

- 0.43m high
- 50mm in diameter
- Electrically heated up to 1600 K
- Feeding rate as low
- as 0.7 gm/hr

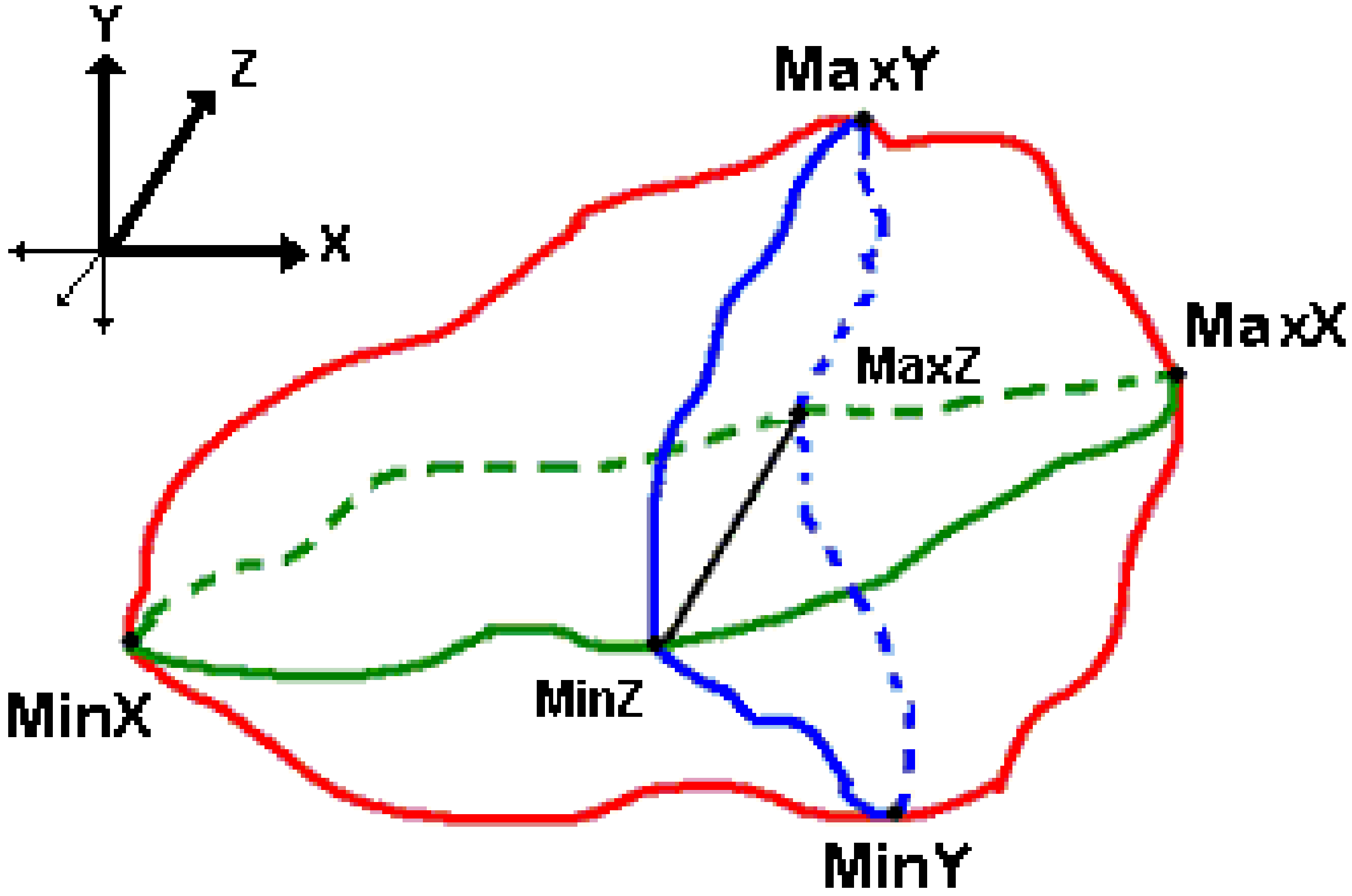
Methods–particle reactor & imaging system





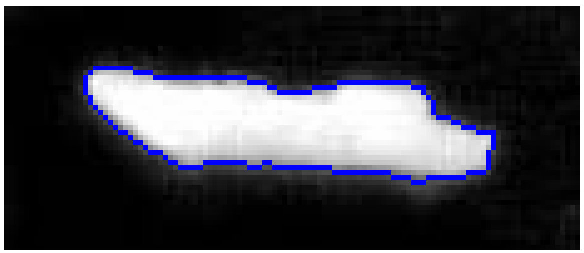
* The three viewports are in three orthogonal direction

Method –shape reconstruction

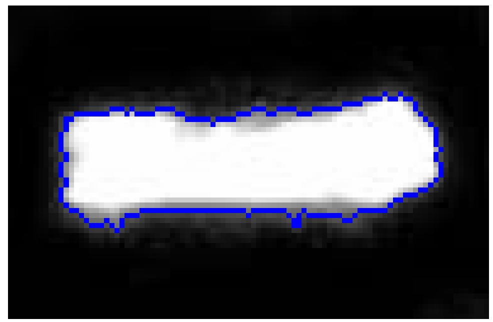


Method – shape reconstruction

- **Image edge detection – walking algorithm**
- **Image alignment and surface points interpolation – IDW**
- **Errors for both Volume and surface area are < 10%**



xy



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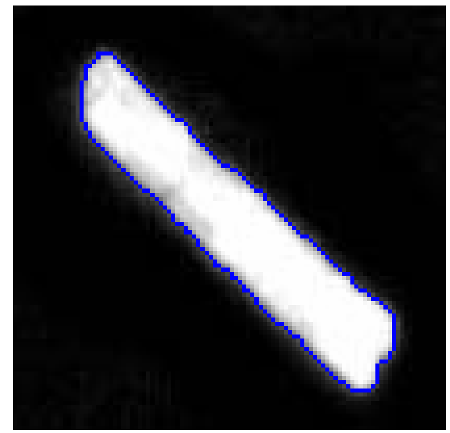

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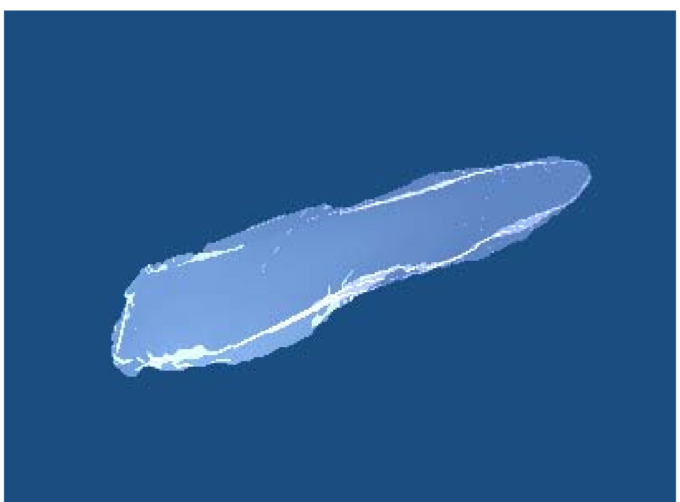
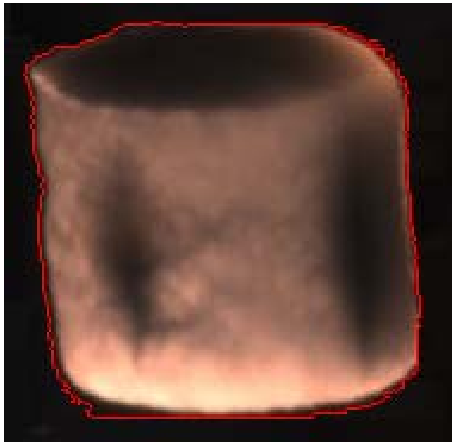
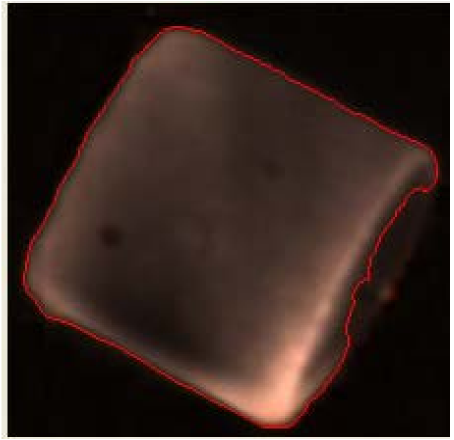


Reconstructed 3D sawdust particle shape

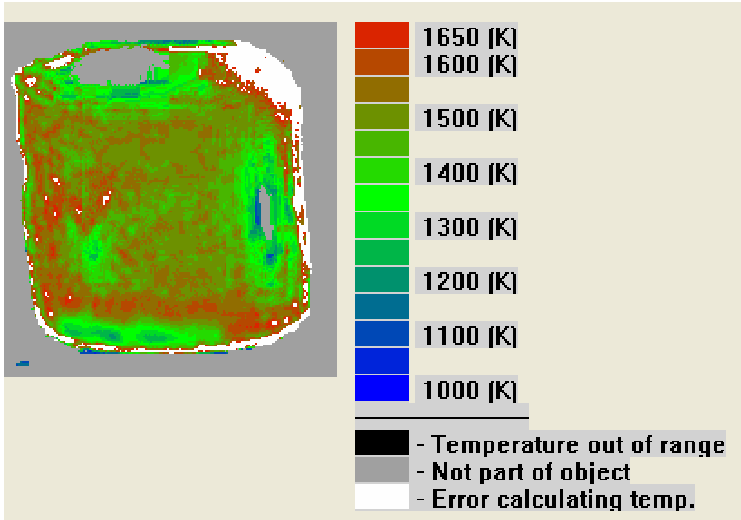
Method – temperature measurement

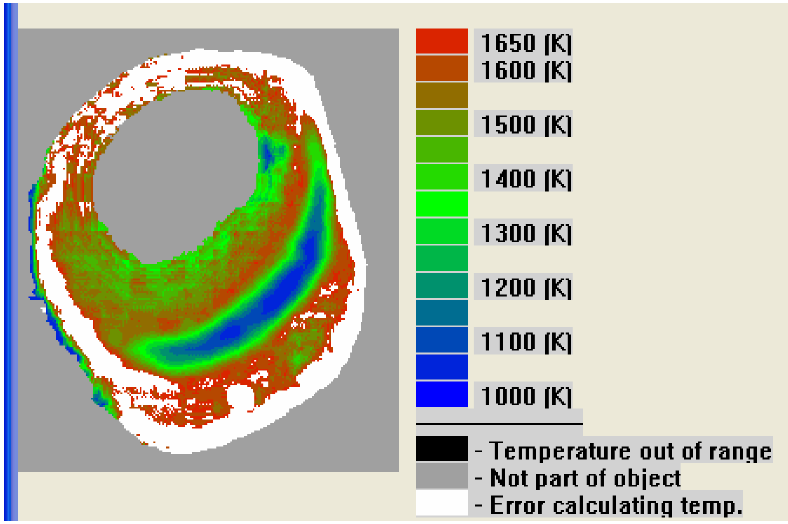
•Thermocouples and cameras were used to measure particle temperature
•Temperature measurement and calculation by color-bands method will be discussed by Dr. Tree in detail

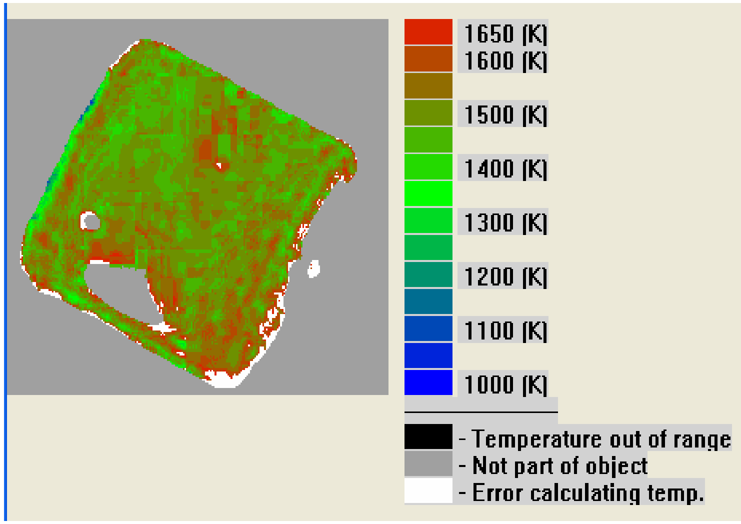


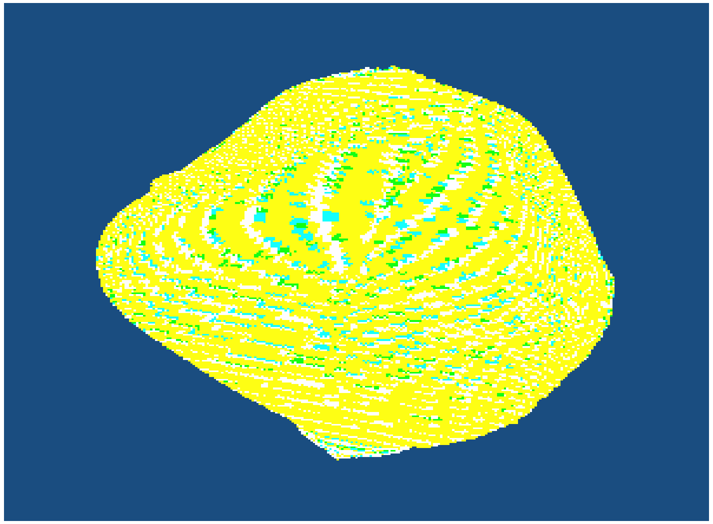


Method- temperature mapping



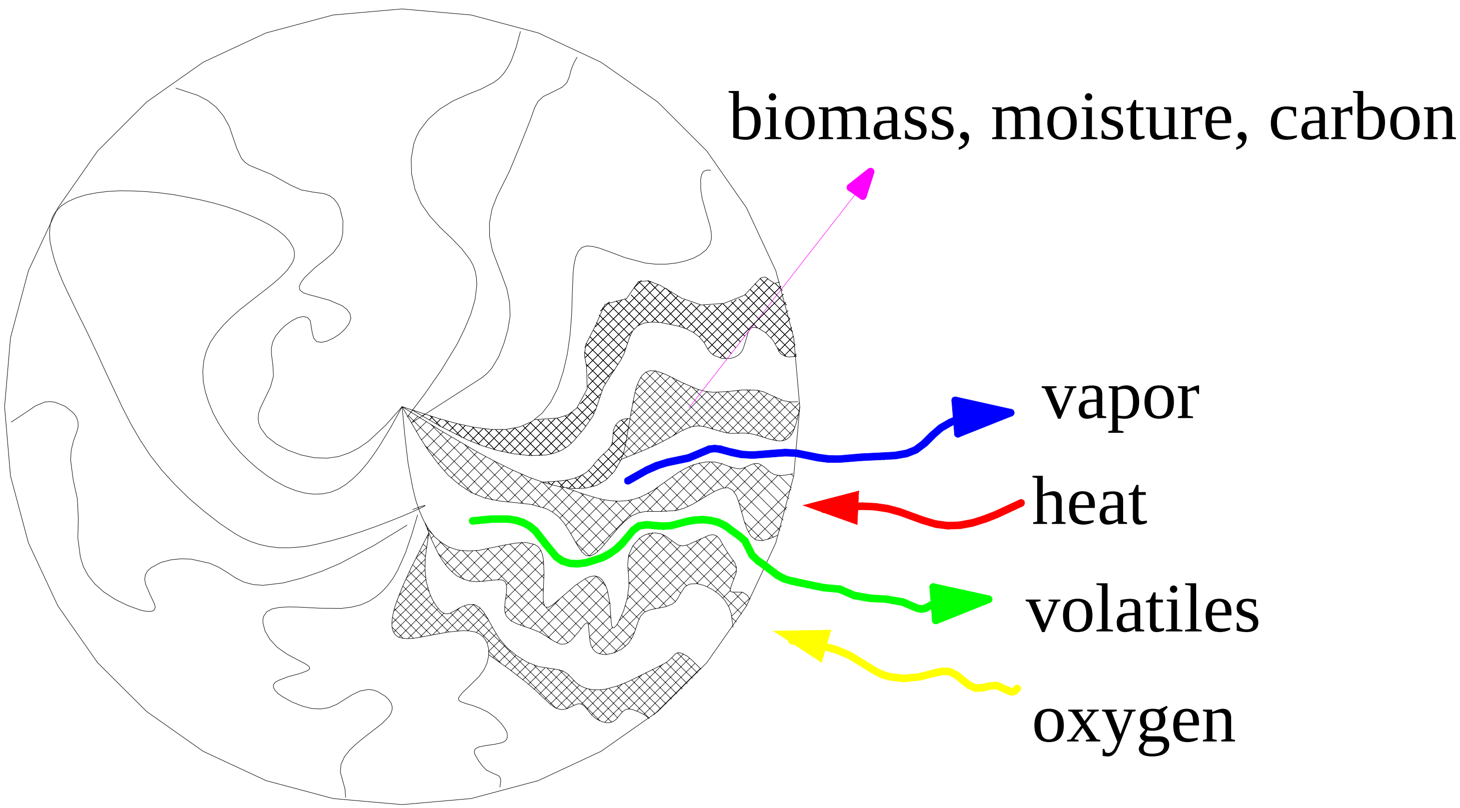






Model Development

- **Physical model**



Model Development

- **Drying Model**
  - **Liquid phase (free water, bound water) diffusion in the particle**
  - **Internal and external evaporation**
  - **Vapor phase diffusion and convection**

$$\frac{\partial \rho_m}{\partial t} = \frac{1}{r^n}\frac{\partial}{\partial r}\left(r^n D_{eff,m}\frac{\partial \rho_m}{\partial r}\right) + S_m$$

$$where, D_{eff,m} = fD_{eff,m,f} + bD_{eff,m,b}$$

$$S_m = -s_a h_{m,pore}(\rho_{v,sat} - \rho_v),$$

s_a is the liquid/gas inferface area in the particle.

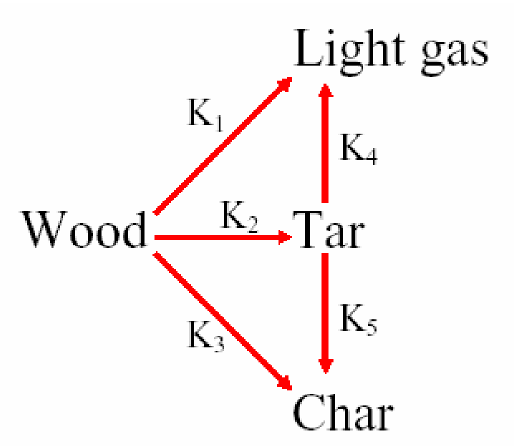
$$\frac{\partial}{\partial t}\varepsilon\rho_g Y_v + \frac{1}{r^n}\frac{\partial}{\partial r}(r^n \varepsilon\rho_g Y_v u) = \frac{1}{r^n}\frac{\partial}{\partial r}(r^n \varepsilon D_{eff,v}\rho_g \frac{\partial Y_v}{\partial r}) + S_v$$

$$where, S_v = s_a h_{m,p}(\rho_{v,sat} - \rho_v)$$

Model Development

- **Pyrolysis model**

$$\frac{\partial \rho_B}{\partial t} = -(r1 + r2 + r3)$$



$$\frac{\partial}{\partial t}\varepsilon\rho_g Y_i + \frac{1}{r^n}\frac{\partial}{\partial r}(r^n \varepsilon \rho_g Y_i u) = \frac{1}{r^n}\frac{\partial}{\partial r}\left(r^n \varepsilon D_{eff,i}\rho_g \frac{\partial Y_i}{\partial r}\right) + S_i$$

where $i = T$ for tar, G for light gas, and I for inert gas

$$\frac{\partial}{\partial t}\varepsilon\rho_g + \frac{1}{r^n}\frac{\partial}{\partial r}(r^n \varepsilon \rho_g u) = S_g$$

n is shape factor: 2-sphere, 1-cylinder, 0-slab

Model Development

- **Char oxidation and gasification model**
  - C+ ½ O2 → CO (6)
  - C + CO2 → 2 CO (7)
  - C + H2O → H2 + CO (8)
  - H2+ ½ O2 → H2O (9)
  - CO + ½ O2 → CO2 (10)

$$\frac{\partial \rho_C}{\partial t} = r3 + r5 - (r6 + r7 + r8)$$

$$\frac{\partial}{\partial t}\varepsilon\rho_g Y_i + \frac{1}{r^n}\frac{\partial}{\partial r}(r^n \varepsilon\rho_g Y_i u) = \frac{1}{r^n}\frac{\partial}{\partial r}(r^n \varepsilon D_{eff,i}\rho_g \frac{\partial Y_i}{\partial r}) + S_i$$

where i = CO2, CO, H2, O2

Model Development

- **Energy balance and momentum balance**

$$\frac{\partial}{\partial t}\left[\left(\rho_B \hat{H}_B + \rho_C \hat{H}_C + \rho_M \hat{H}_M\right) + \varepsilon \rho_g \left(\sum_i Y_i \hat{H}_i\right)\right]$$

$$+\frac{1}{r^n}\frac{\partial}{\partial r}\left[r^n \varepsilon \rho_g u \left(\sum_i Y_i \hat{H}_i\right)\right] = \frac{1}{r^n}\frac{\partial}{\partial r}\left(r^n k_{eff}\frac{\partial T}{\partial r}\right)$$

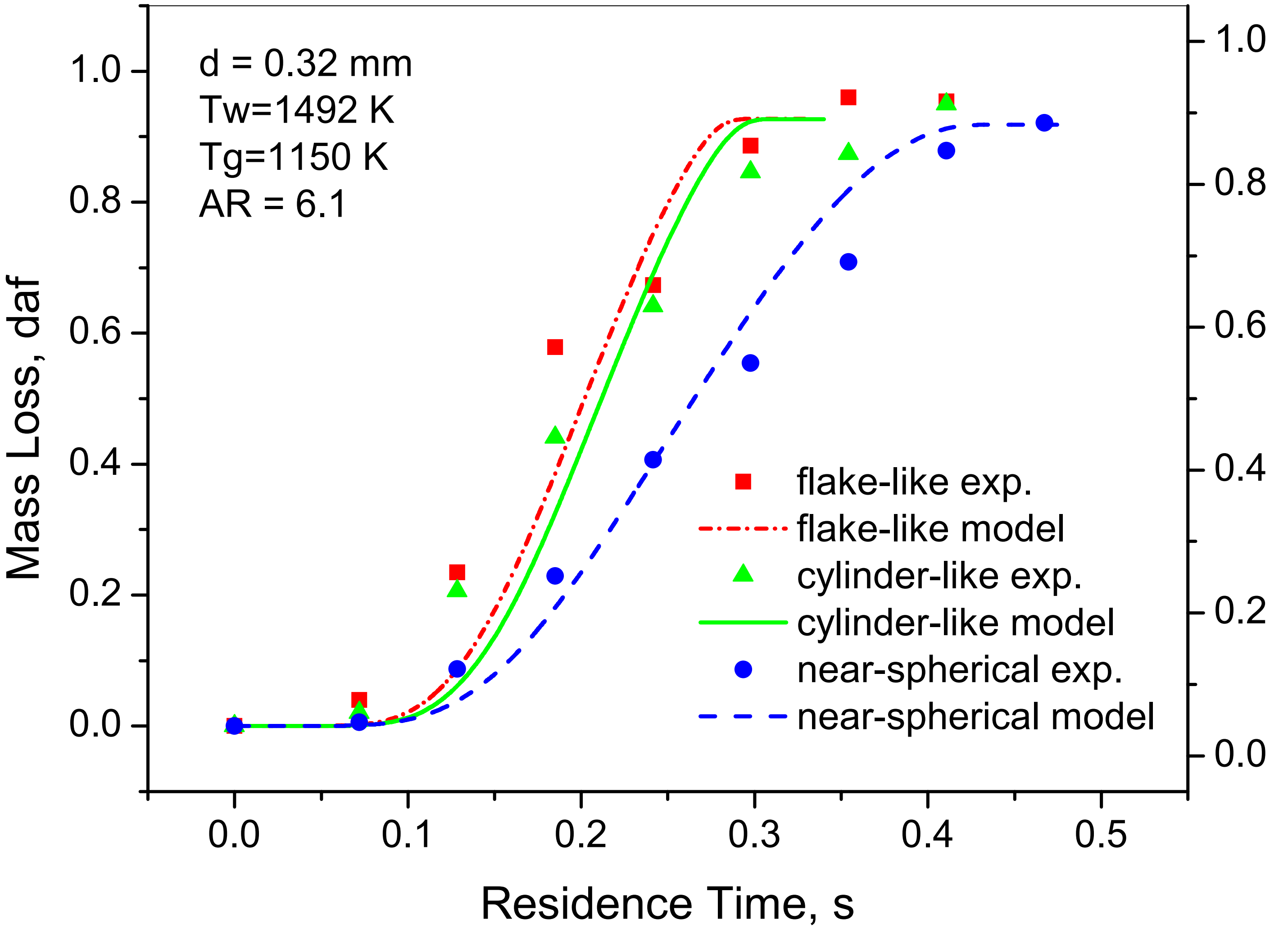
$$+\frac{1}{r^n}\frac{\partial}{\partial r}\left[r^n \rho_g \varepsilon \left(\sum_i D_{eff,i}\frac{\partial Y_i}{\partial r}\hat{H}_i\right) + r^n D_{eff,M}\frac{\partial \rho_M}{\partial r}\hat{H}_M\right]$$

$$u = -\frac{\eta}{\mu}\frac{\partial P}{\partial r}$$

Equations solved by control volume method

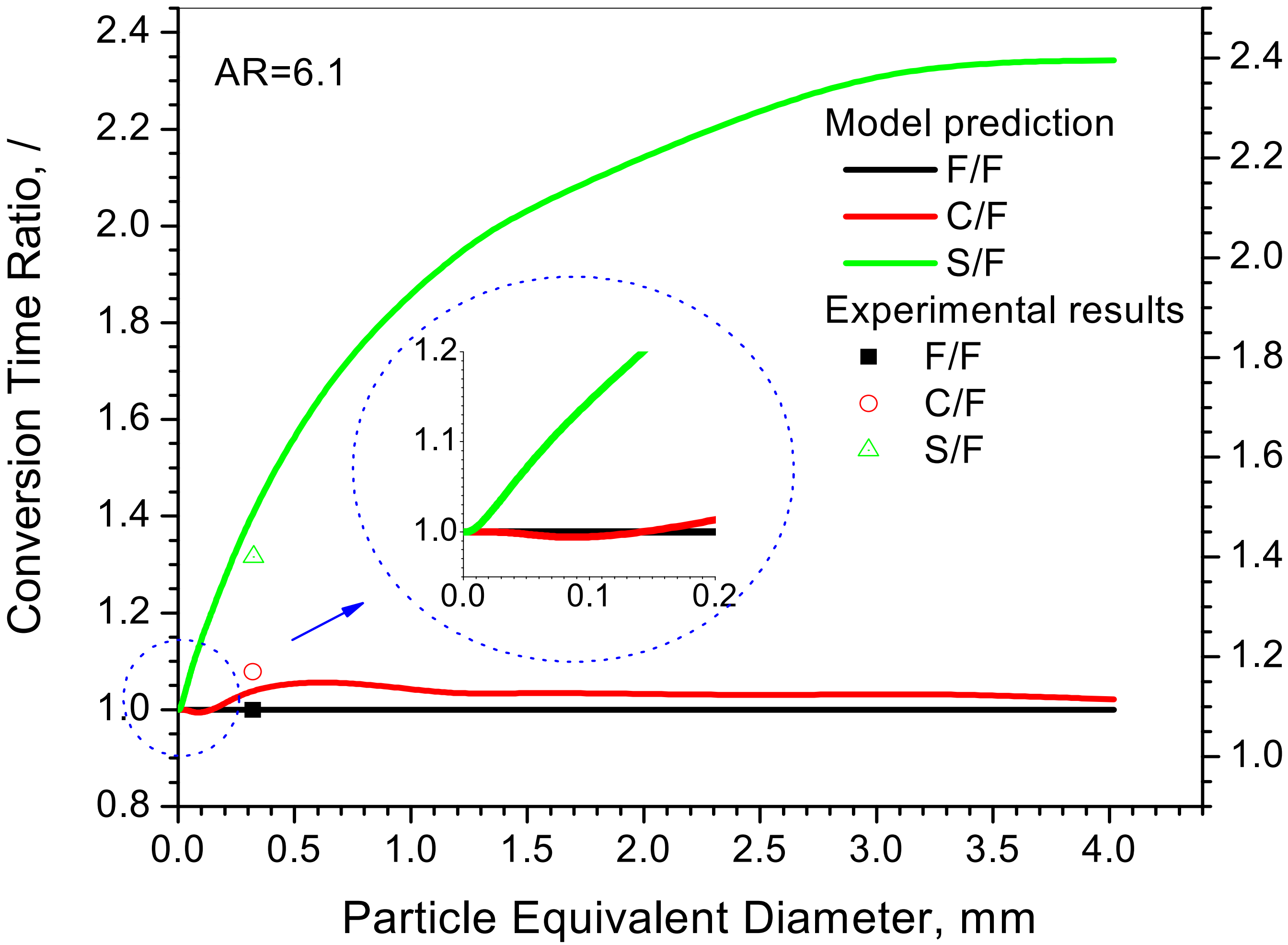
Results and Discussions

- Pyrolysis Mass Loss History –sawdust with various shapes



Results and Discussions

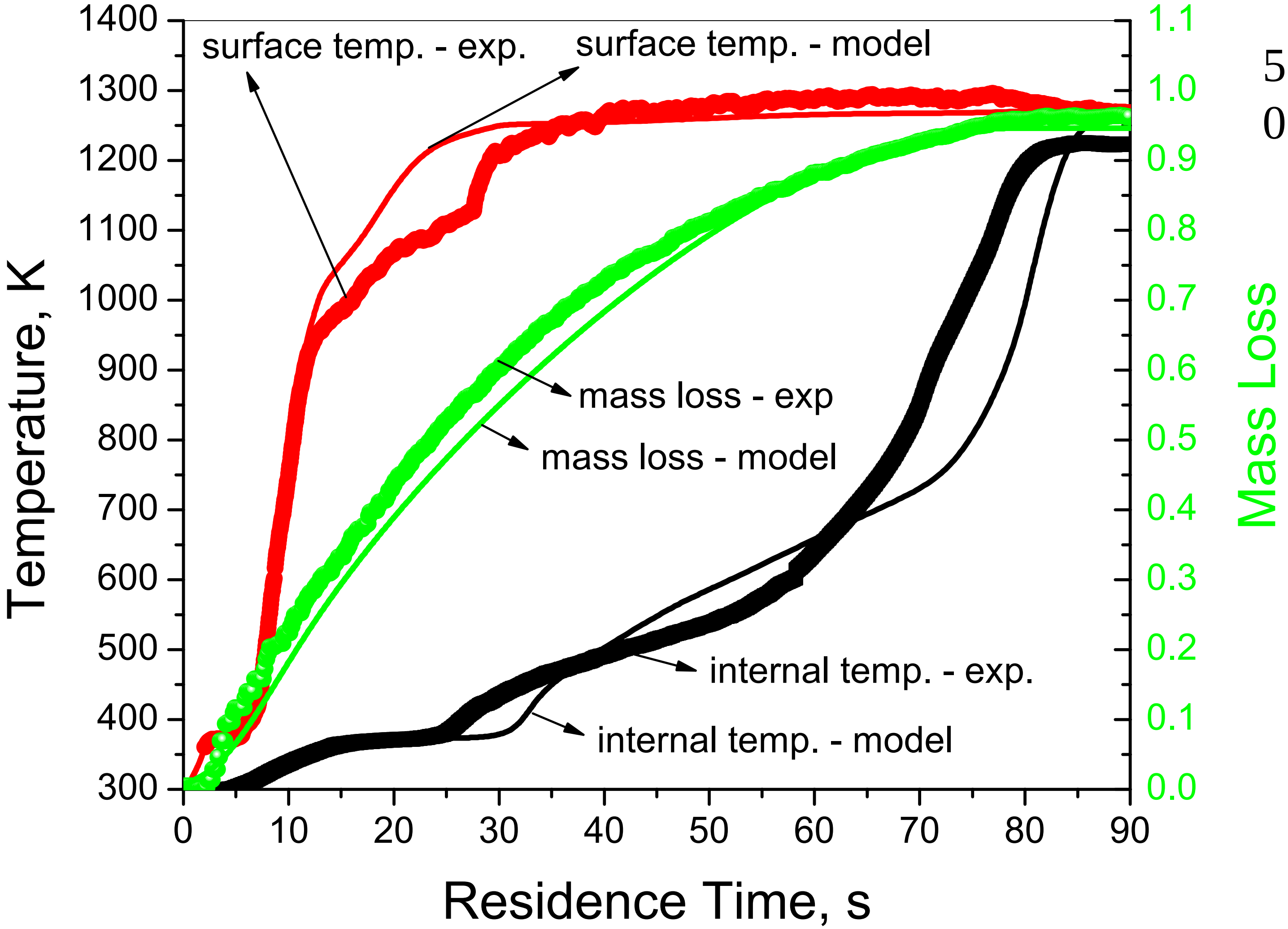
- Pyrolysis conversion time comparison



F - flake-like; C - cyliner-like; S - near-spherical

Results and Discussions

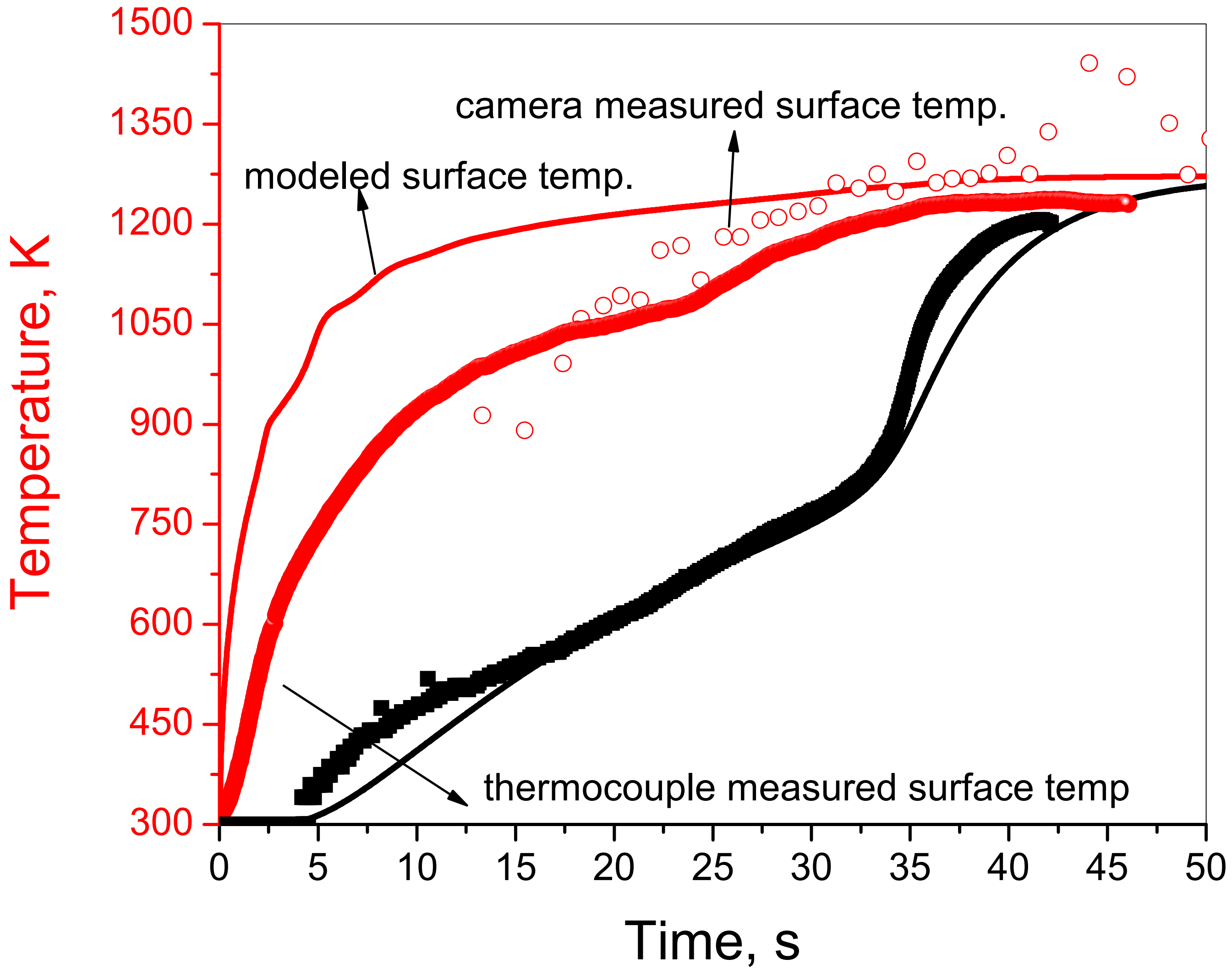
•Drying and Pyrolysis (d=11.5 mm near spherical poplar)



52% moisture
0.5% ash

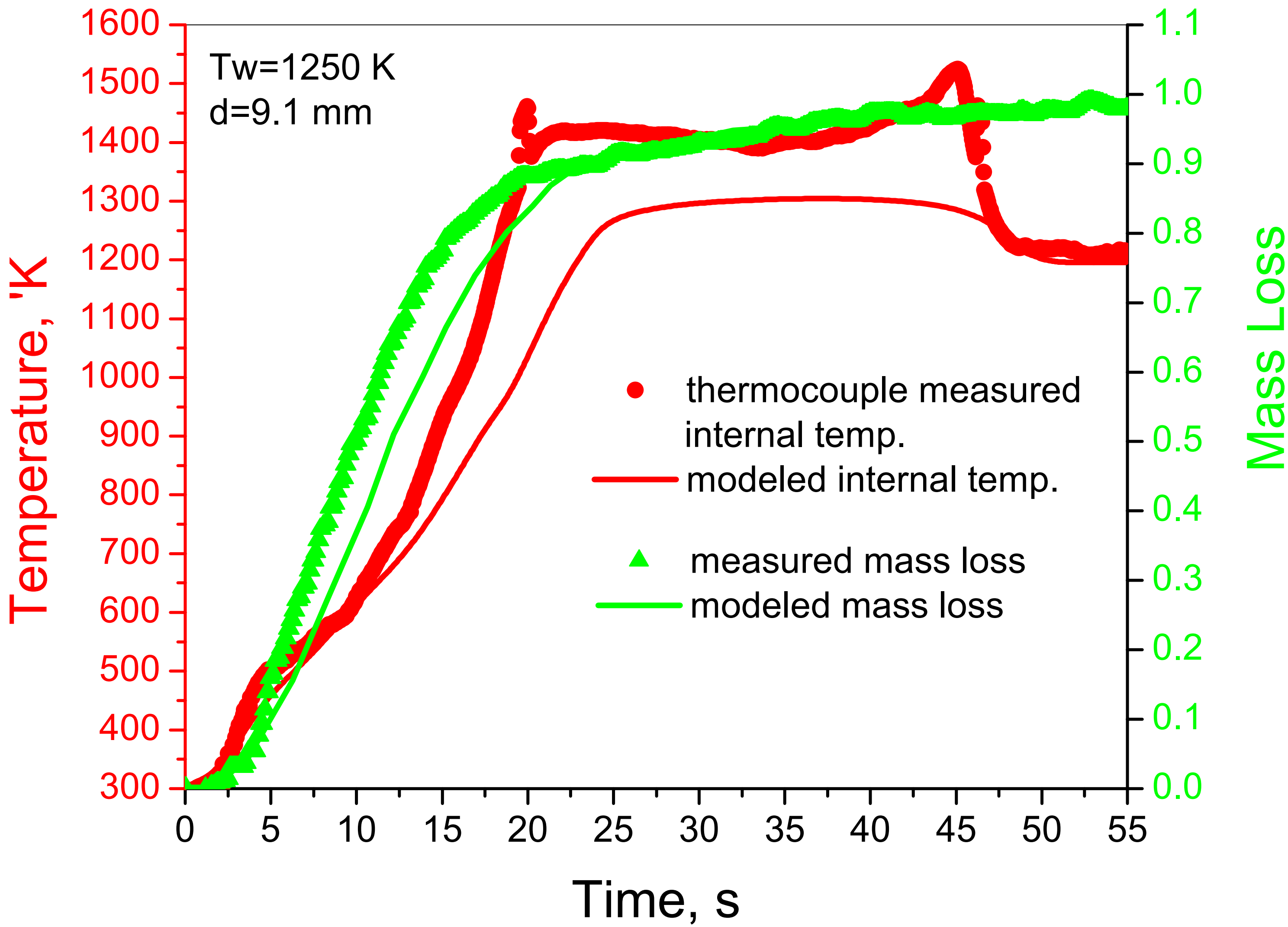
Results and Discussions

• Pyrolysis (d=11.5 mm near spherical poplar)



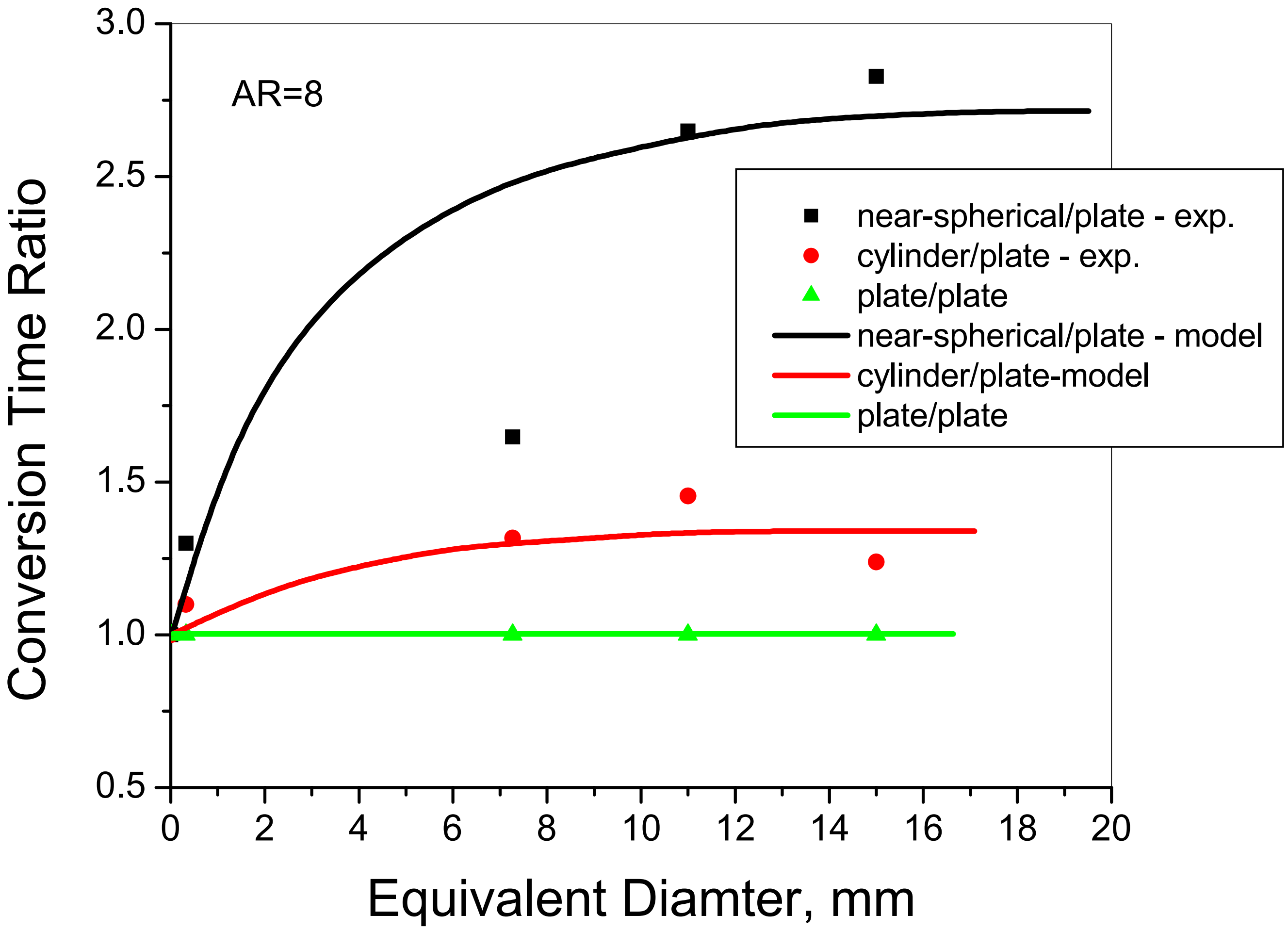
Results and Discussions

•Combustion (near spherical poplar in air)



Results and Discussions

- Pyrolysis conversion time comparison



Conclusions

- A biomass particle combustion model has been developed for fuels have irregular shapes
- Particle shape and size strongly affect conversion time during pyrolysis, consistent with model results
- Near spherical biomass particle was found to lose mass most slowly during pyrolysis, also consistent with theory
- Shape effects impact particle reactions in substantial ways when particles are large (> 300 μm equivalent diameter)
- Irregular particle shape can be reconstructed using three images
- Particle surface temperature can be calculated by the color-band method and mapped to the 3D particle model

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