Particle Shape and Size Impacts on Biomass Reactivity

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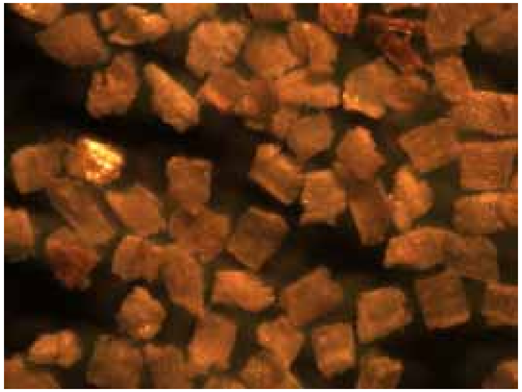
Motivations

- Biomass is the most significant non-hydro renewable energy source.
- Biomass differs from coal
  - Higher volatile
  - Lower density
  - Lower heating value
  - Irregular shape and large size;
  - surface area/volume essential to heat and mass transfer controlled process
  - Sphere is extreme case
  - Poorly approximated by isothermal spheres

— Particle shape and size may play a significant role in combustion and gasification

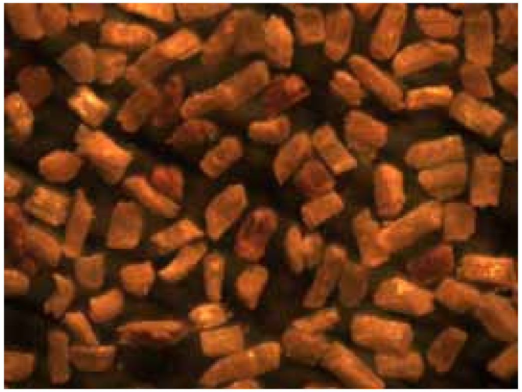
Samples

- Sample I (small wood particles)
  - Size: ~300 micron
  - Shape: flake-like, cylinder-like, and near-sphere



Flake-like

Cylinder-like

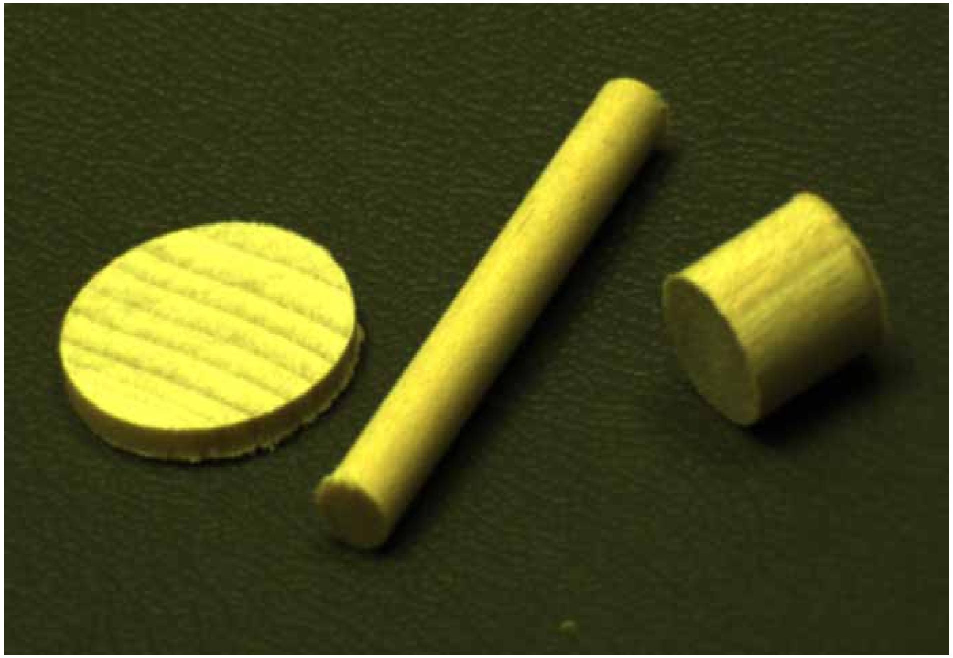


Near-sphere

Shape	Flake-like	Cylinder-like	Near-sphere
Aspect ratio	4	6	1.6
SA ($\times 10^{-7} m^2$)	4.91	4.79	3.44
Volume ($\times 10^{-11}$ m^3)	1.7	1.7	1.8

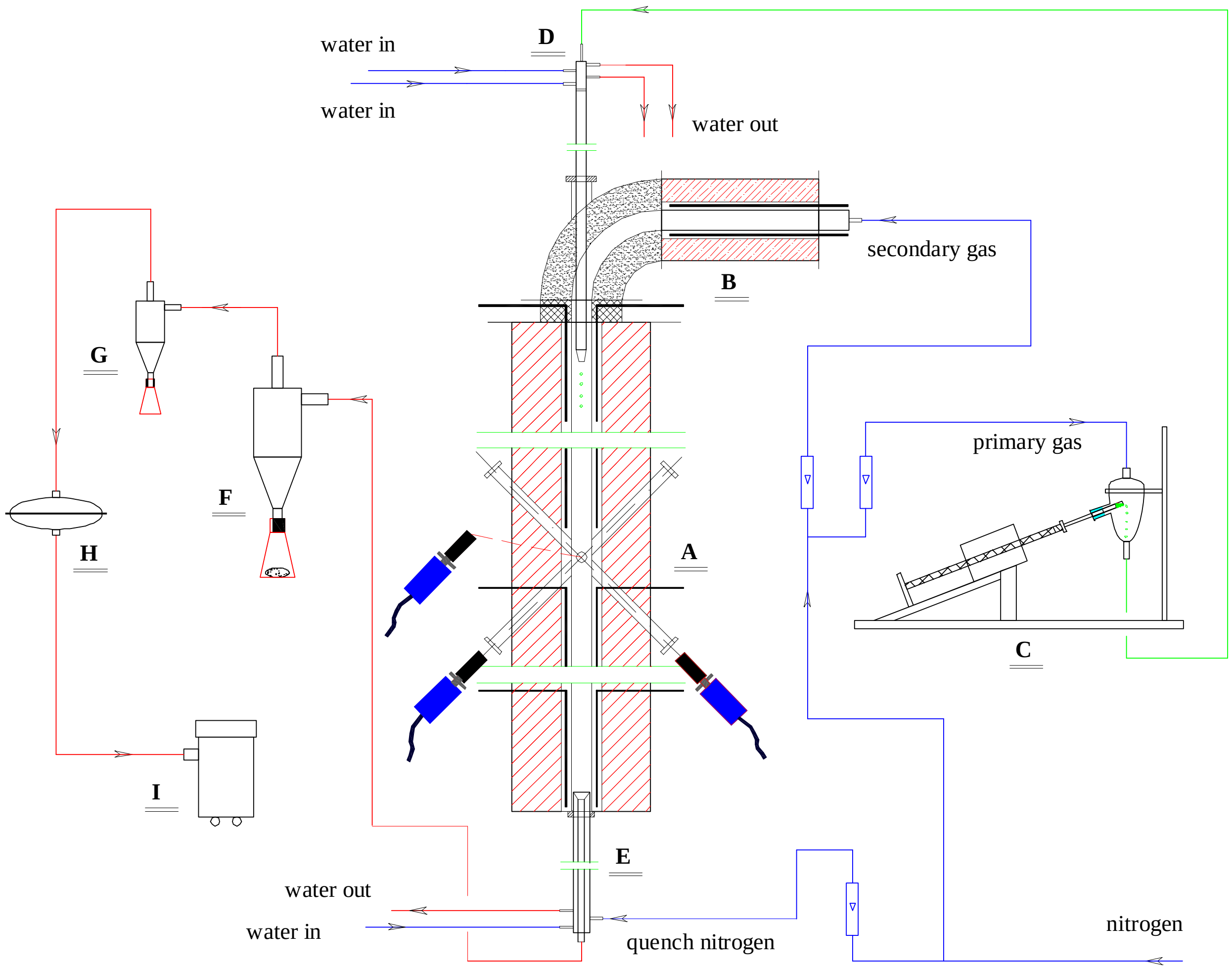
Samples

- Sample II (large wood particles)
  - size: 3 mm to 16 mm
  - shape: disc plate, cylinder, and near-sphere
    - AR = 8 or 5 for both disc and cylinder



Experimental Method

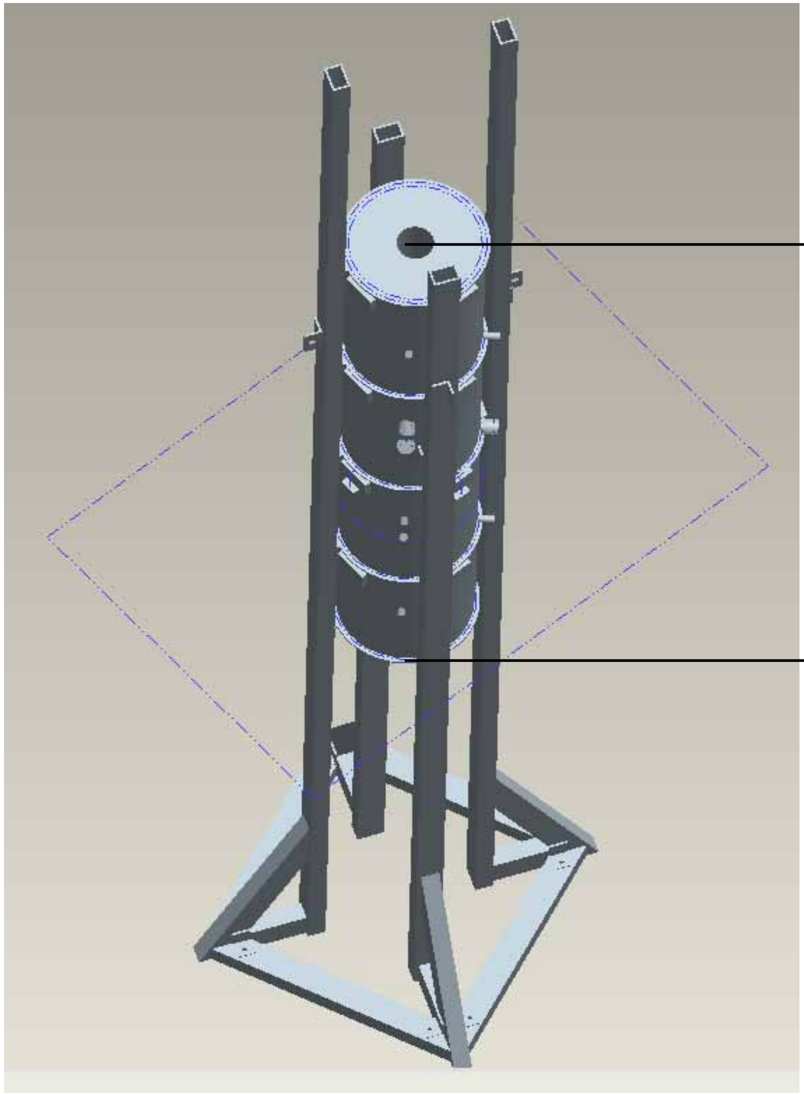
- Entrained-flow reactor system (**EFR**)



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

Experimental Method

- Entrained-flow reactor system (**EFR**)

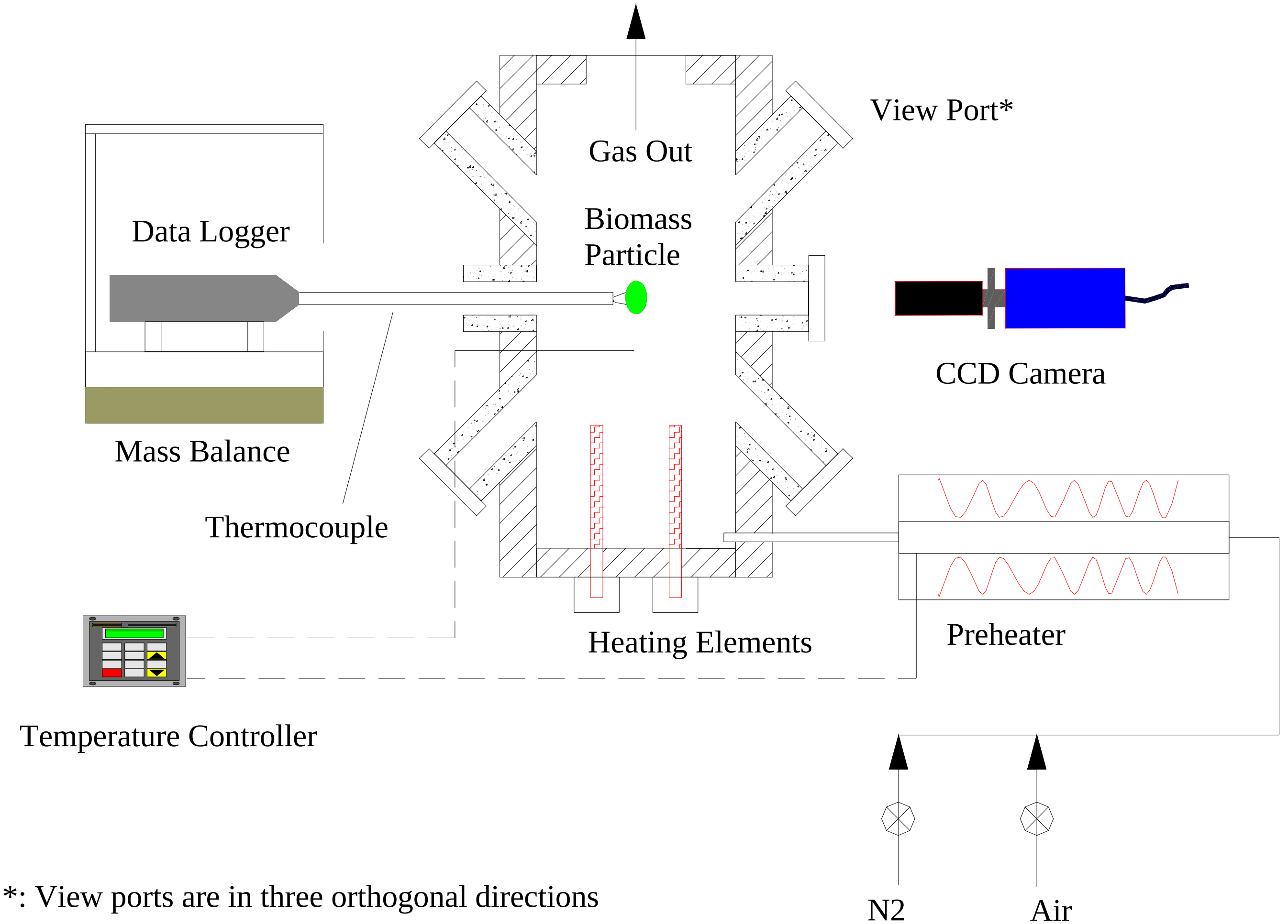


ID=50 mm
OD=0.4 m
T_{max}=1600 K

1.8 m

Experimental Method

- Single-particle reactor (**SPR**)



*: View ports are in three orthogonal directions

Experimental Method

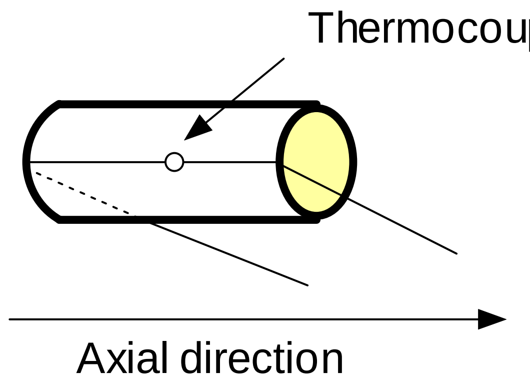
- Single-particle reactor (**SPR**)

Particle combustion video

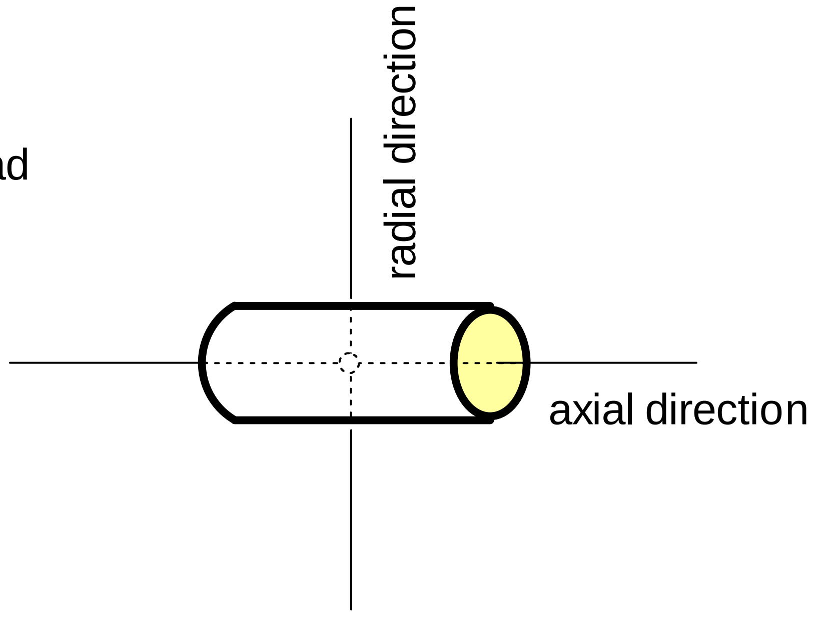
poplar particle burning in the SPR.avi

Experimental Method

- Temperature measurements



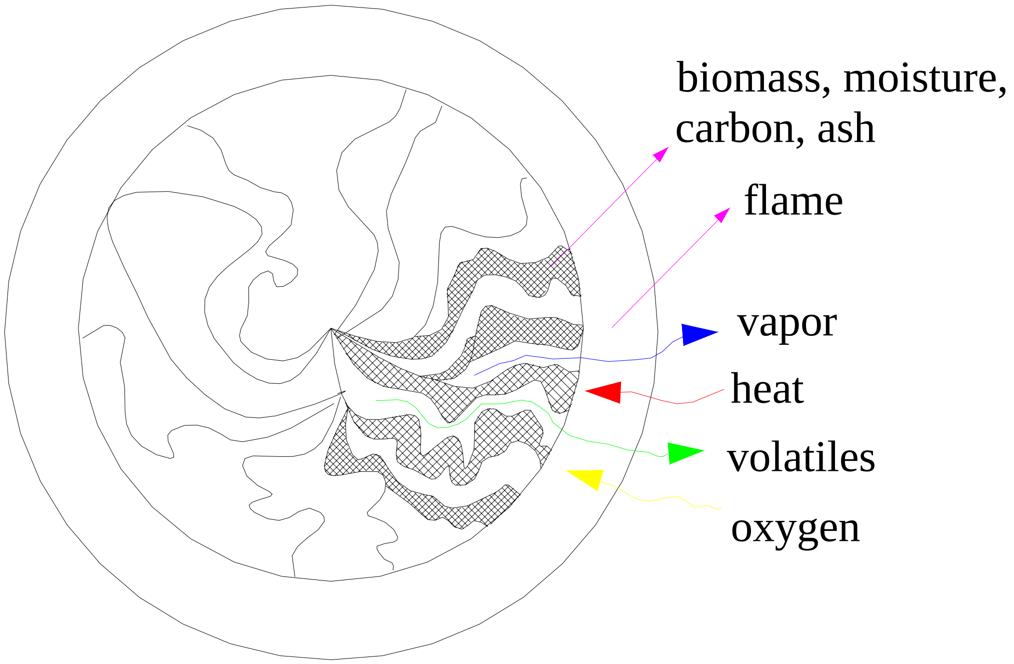
Surface measurement setup



Internal measurement setup

Particle Combustion Model

- Drying, devolatilization, gasification, and oxidation
- 1-D heat, mass, and momentum transfer (intra-particle)
- Three basic shapes: sphere, plate, and cylinder

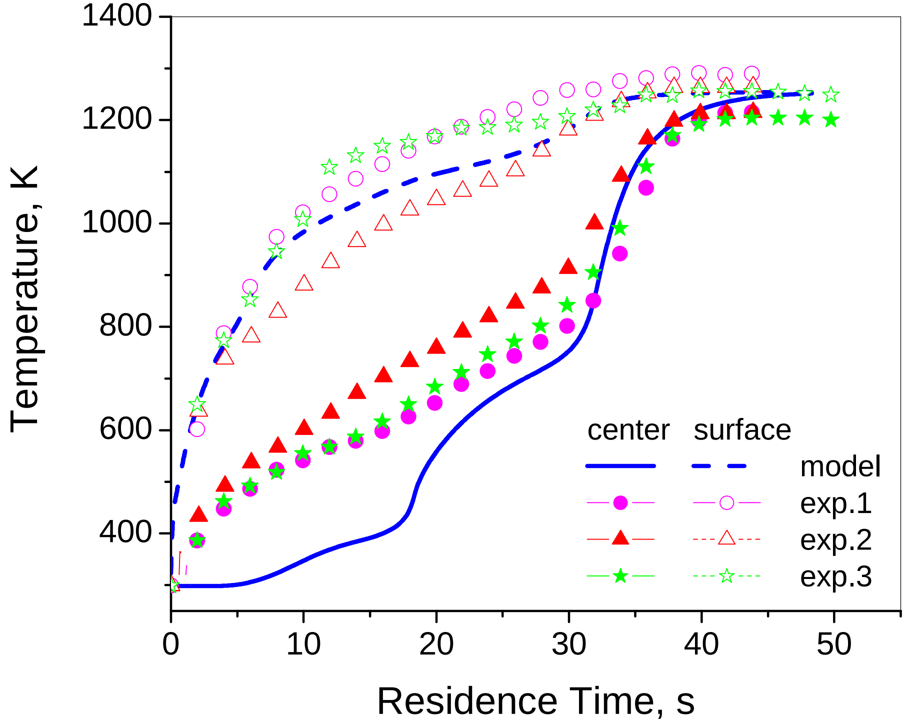


Particle Combustion Model

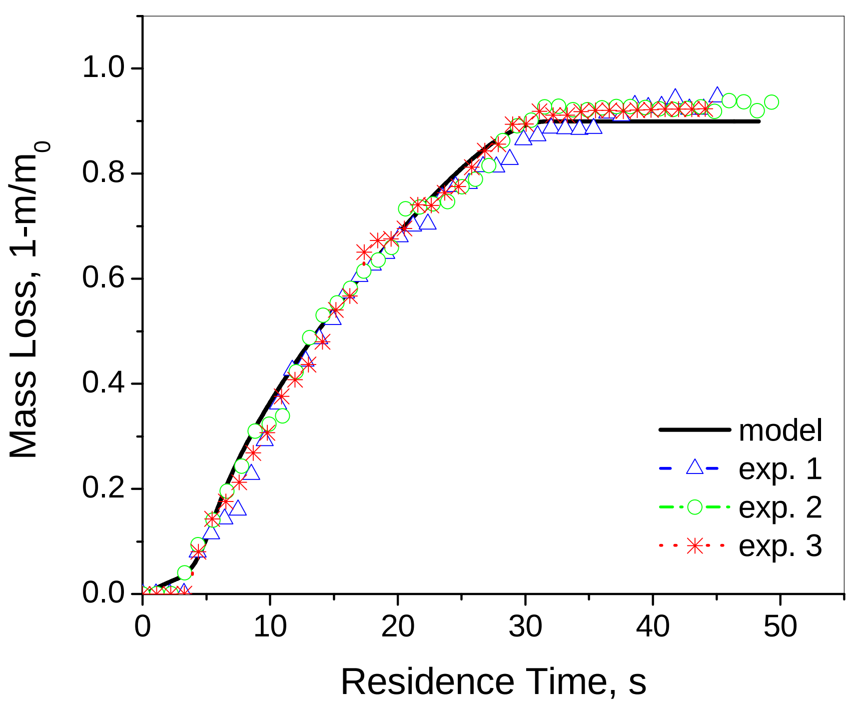
- Conservation equations
  - Species continuity $$\frac{\partial}{\partial t}\varepsilon\rho_g Y_i + \frac{1}{r^n}\frac{\partial}{\partial r}(r^n \varepsilon\rho_g Y_i u) = \frac{1}{r^n}\frac{\partial}{\partial r}(r^n \varepsilon D_{eff,i}\rho_g \frac{\partial Y_i}{\partial r}) + S_i$$
  - Overall continuity $$\frac{\partial}{\partial t}\varepsilon\rho_g + \frac{1}{r^n}\frac{\partial}{\partial r}(r^n \varepsilon\rho_g u) = S_g$$
  - Energy $$\frac{\partial}{\partial t}\left[\sum_i \rho_i \hat{H}_i + \sum_k \rho_k \hat{H}_k + \varepsilon\rho_g \sum_j Y_j \hat{H}_j\right] + \frac{1}{r^n}\frac{\partial}{\partial r}\left[r^n \varepsilon\rho_g u \sum_j Y_j \hat{H}_j\right]$$ $$= \frac{1}{r^n}\frac{\partial}{\partial r}(r^n k_{eff}\frac{\partial T}{\partial r}) + \frac{1}{r^n}\frac{\partial}{\partial r}\left[r^n\left(\rho_g \varepsilon \sum_j D_{eff,j}\frac{\partial Y_j}{\partial r}\hat{H}_j + D_{eff,k}\frac{\partial \rho_k}{\partial r}\hat{H}_k\right)\right]$$
  - Momentum $$u = -\frac{K}{\mu}\frac{\partial P}{\partial r}; \quad P = \frac{\rho RT}{M_W}$$
  - Shrinking/swelling $$\frac{v}{v^0} = 1 + x_M(\beta_M - 1.0) + x_B(\beta_B - 1.0) + x_C(\beta_C - 1.0)$$
  - *n* is the shape factor: 0 – plate, 1 – cylinder, 2 – sphere
  - Partial differential equations solved by control-volume / SIMPLE method

Results

- Model validation (near-spherical particle pyrolysis)



Particle temperature

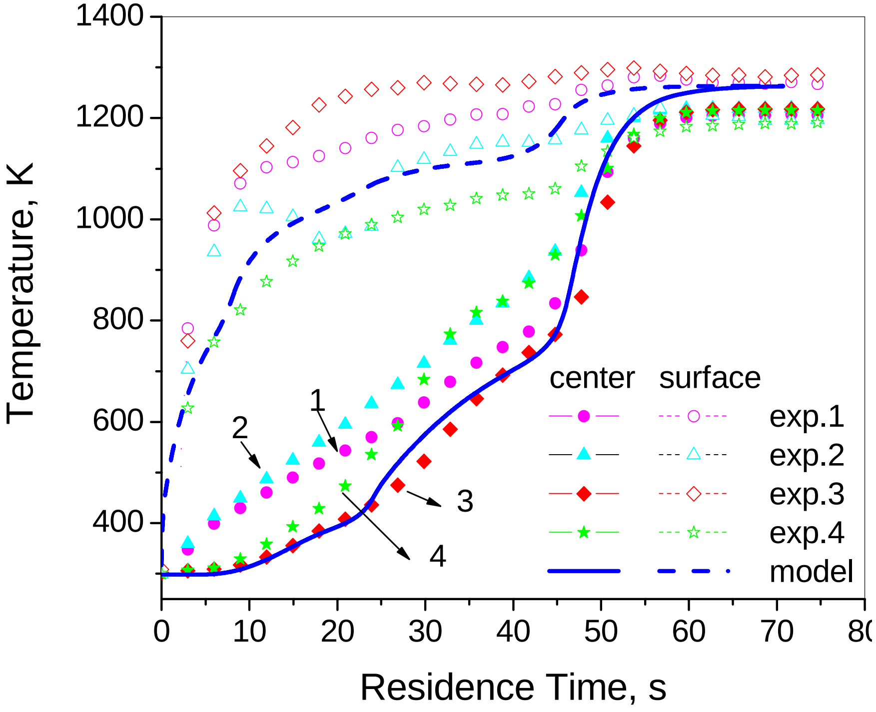


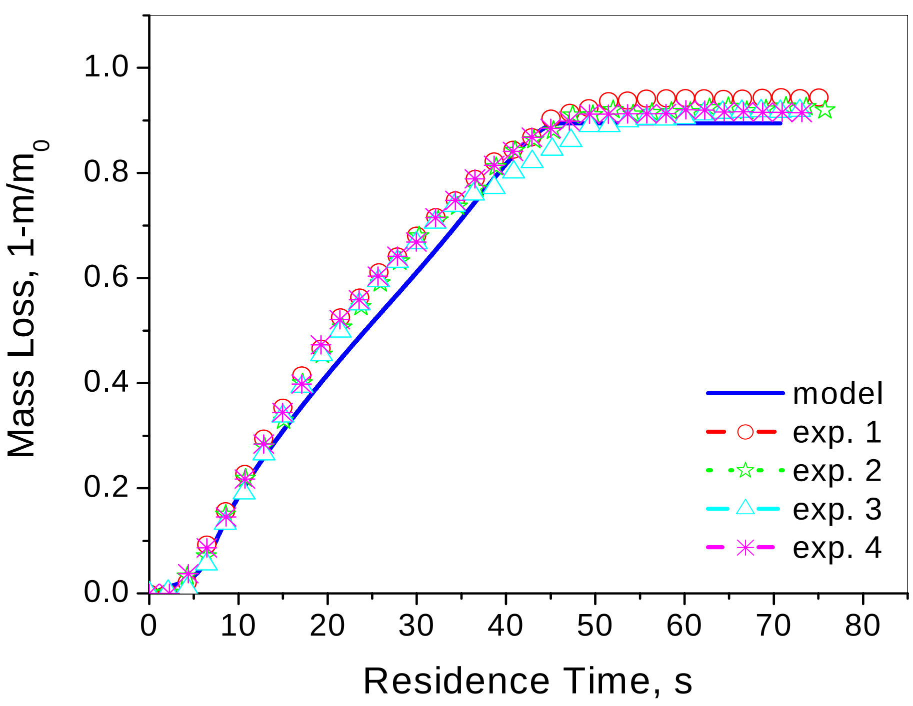
Particle mass loss

N_2, d_{eq} = 11 mm, AR = 1, MC = 6% (wt), T_w=1273 K, T_g=1050 K

Results

- Model validation (cylindrical particle pyrolysis)

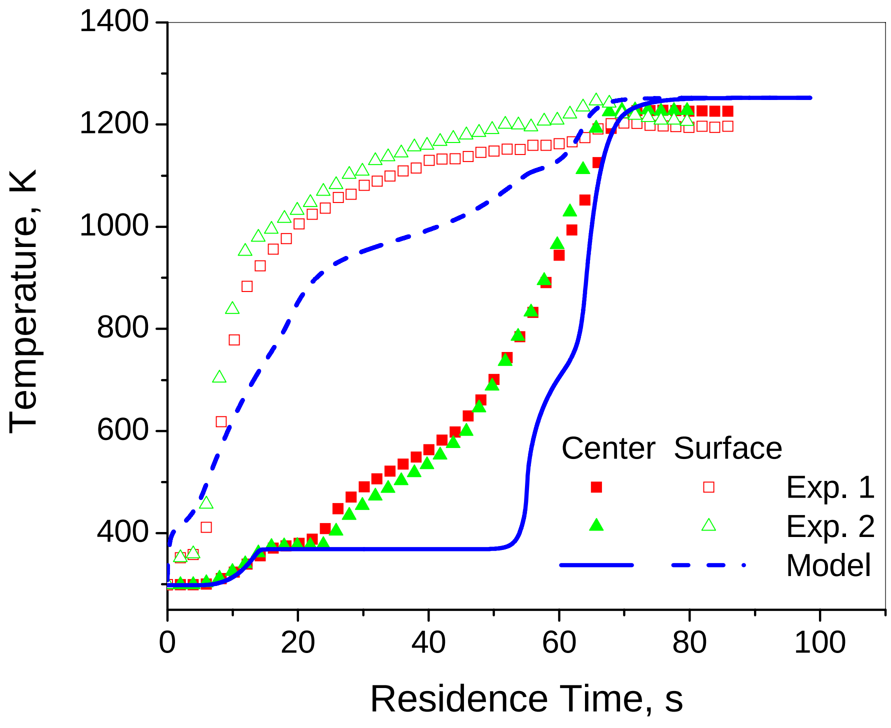


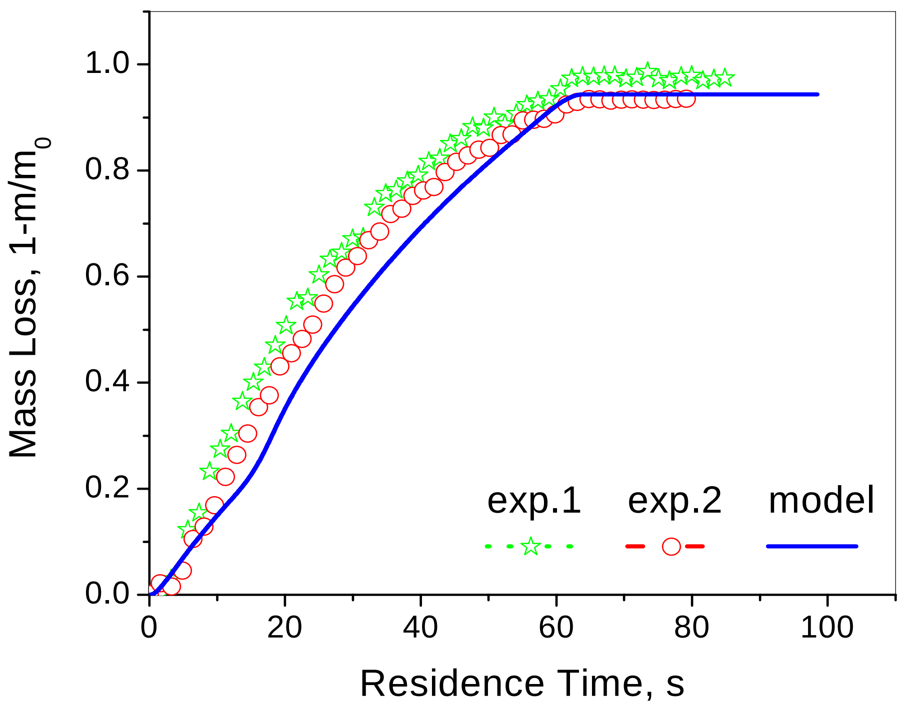


N_2, d_p = 9.5 mm, AR=4, MC = 6% (wt), T_w=1273 K, T_g=1050 K

Results

- Model validation (highly moist near-spherical particle)

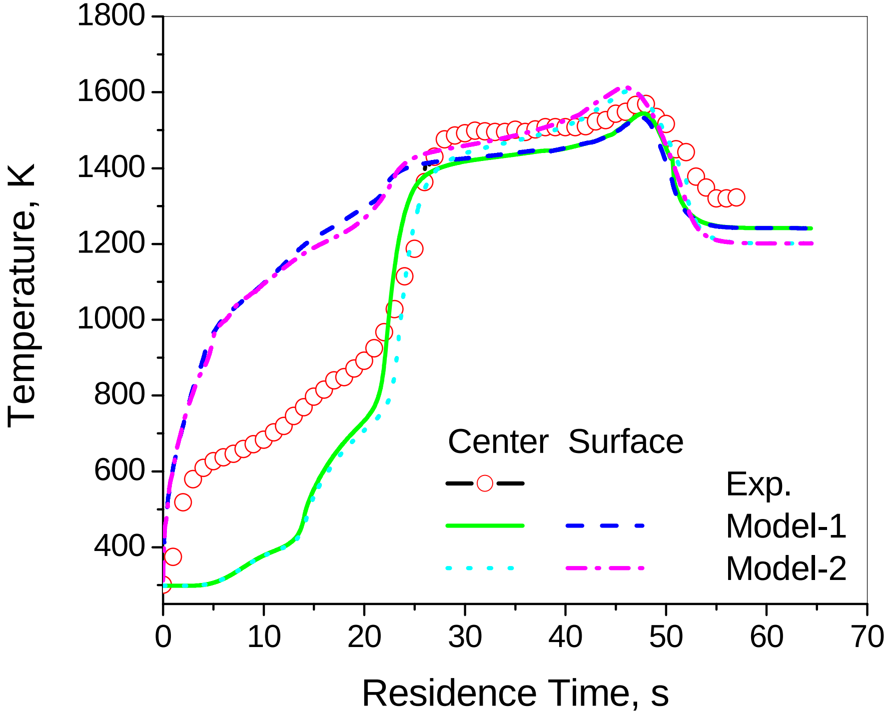


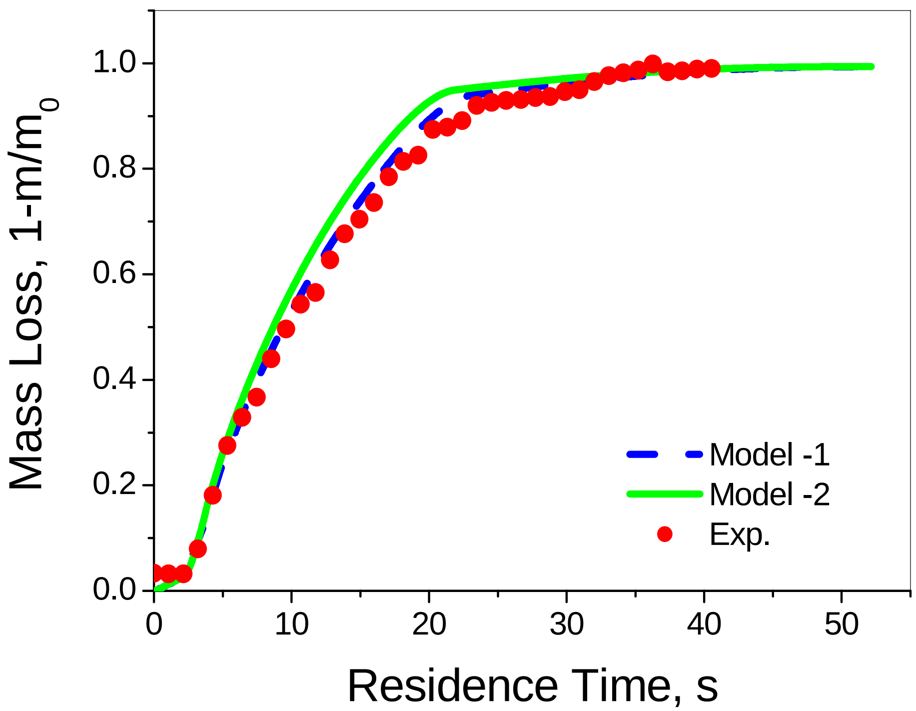


N_2, d = 11 mm, AR=1, *MC* = 40% (wt), Tw=1273 K, Tg=1050 K

Results

- Model validation (char oxidation)



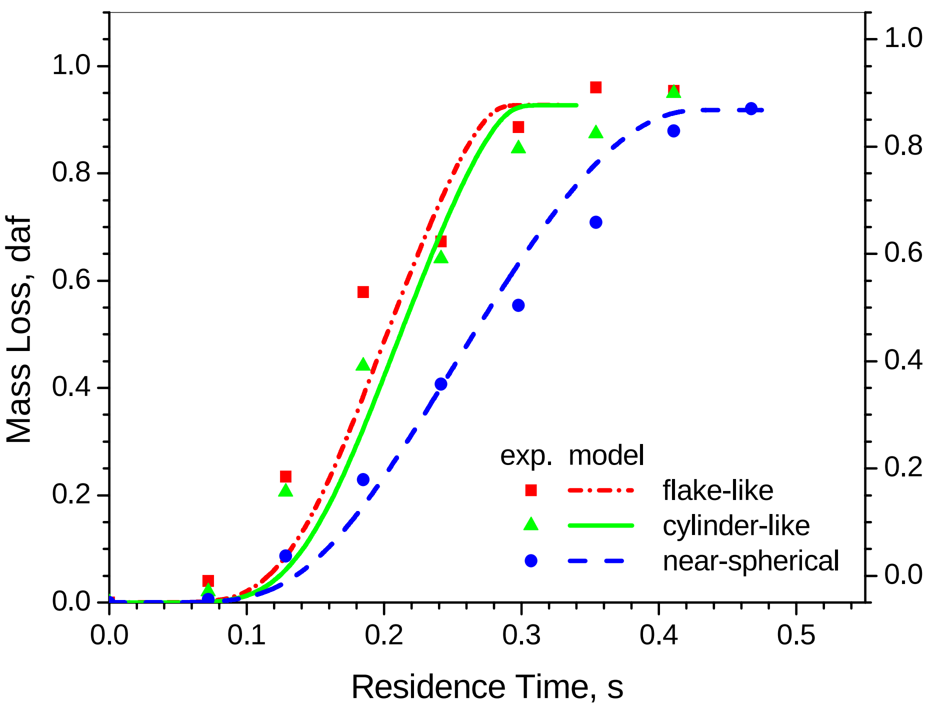


Air, d_{eq} = 11 mm, AR = 1, MC = 6% (wt), T_w=1273 K, T_g=1050 K,

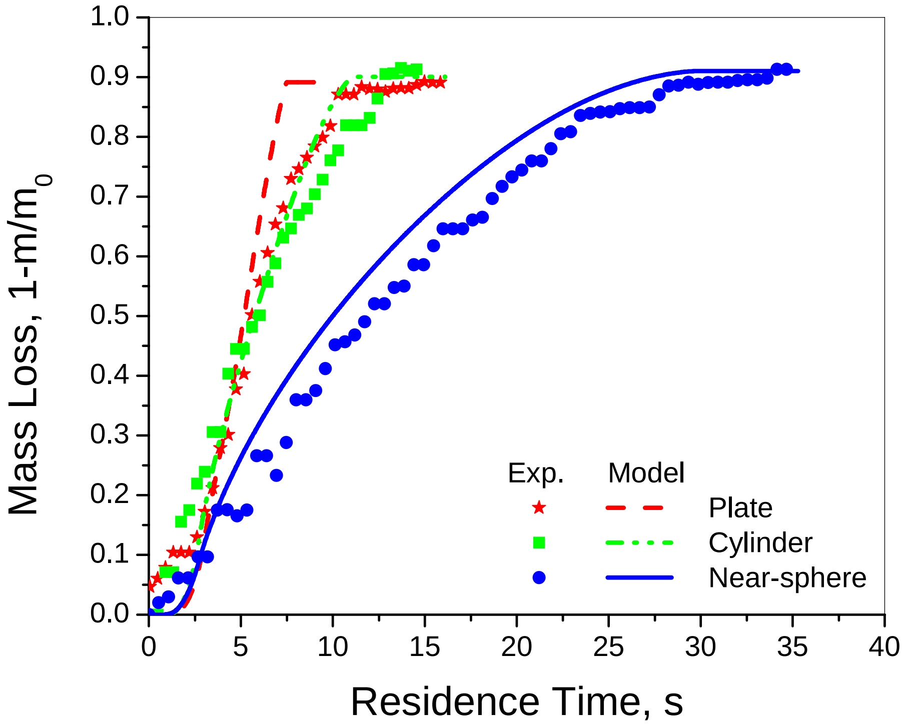
model-1: flame not included; model-2: flame included

Results

- Effects of particle shape on mass loss



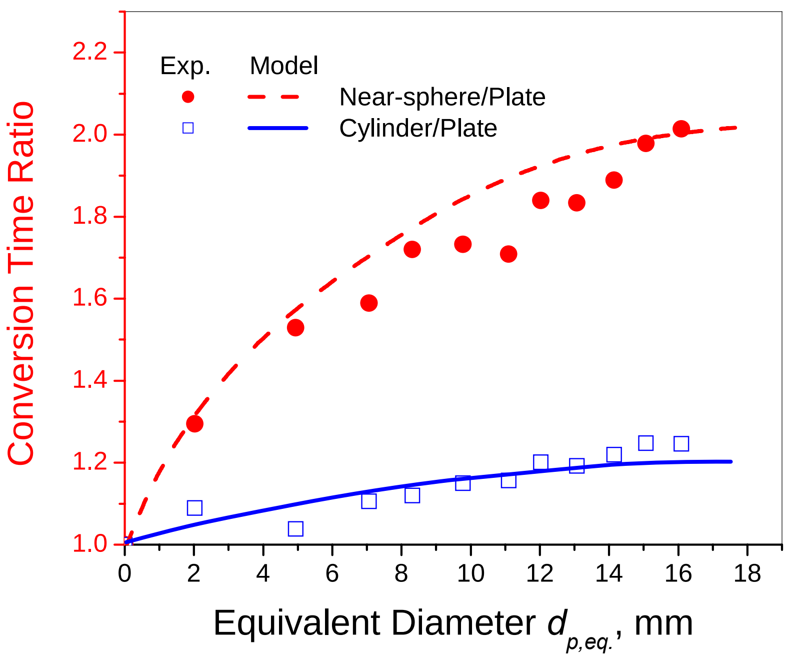
N_2, d_{eq} = 0.32 mm; sample set I,
T_w = 1490 K, T_g = 1295 K



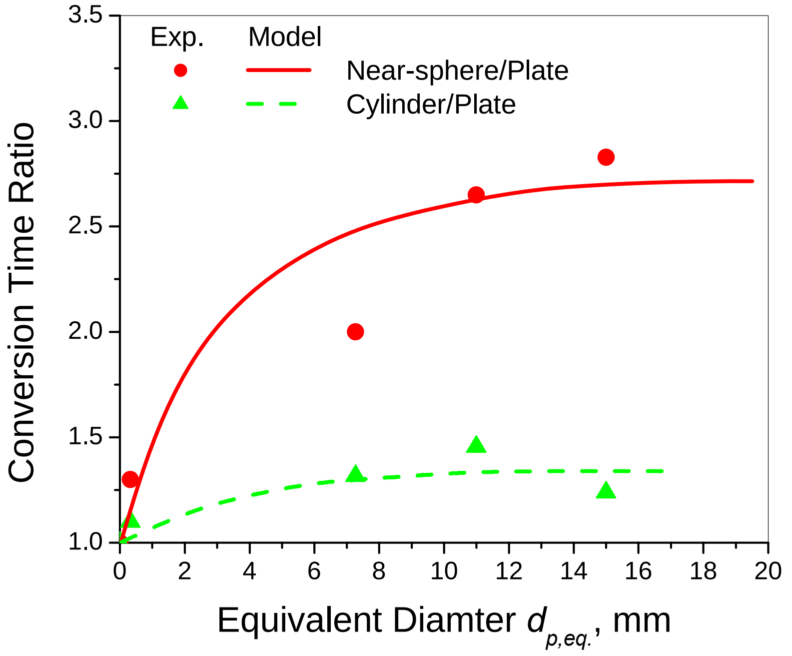
N_2, d_{eq} = 11 mm, *AR* = 8.0, *MC* = 6 % (wt),
T_w = 1273 K, T_g = 1050 K.

Results

- Effects of particle shape and size on conversion time (pyrolysis)



AR=5

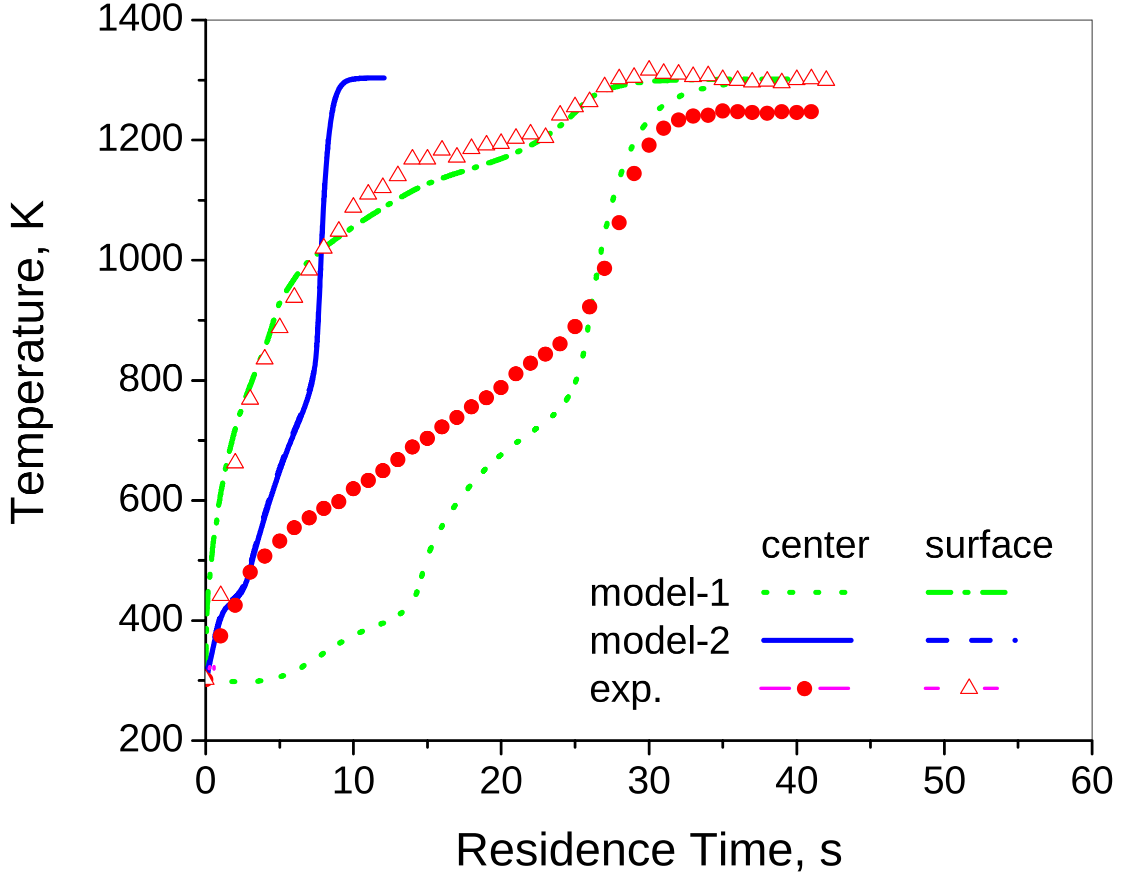


AR=8

Wood particle, T_w=1273 K, T_g=1050 K

Results

- Effects of particle temperature gradient



N_2, d_{eq} = 11 mm, AR = 1, *MC* = 6% (wt), T_w=1273 K, T_g=1050 K,

model-1: non-isothermal particle; model-2: isothermal particle.

Conclusions

1. A comprehensive solid fuel particle combustion model has been developed for particle fuels with any shapes and sizes, which better predicts biomass combustion than isothermal, spherical particle model.
2. Substantial temperature gradient exists for particles with size in mms.
3. Near spherical biomass particle looses mass most slowly during combustion, consistent with theoretical analysis.
4. Data and theoretical models indicate that the impact of shape increases with increasing size and increasing asphericity and is large at sizes relevant to biomass utilization in industry.

Acknowledgement

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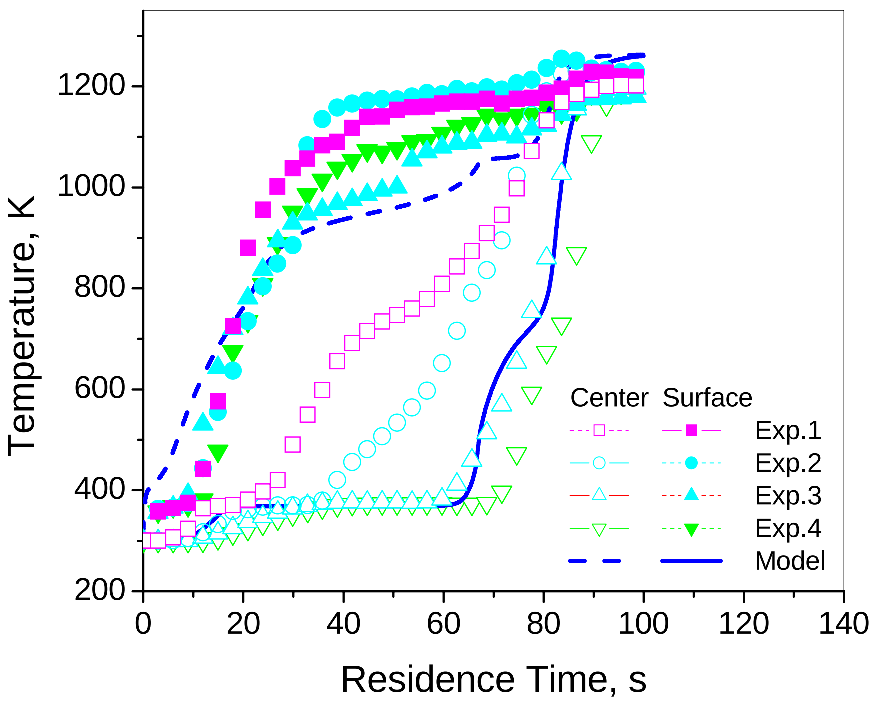
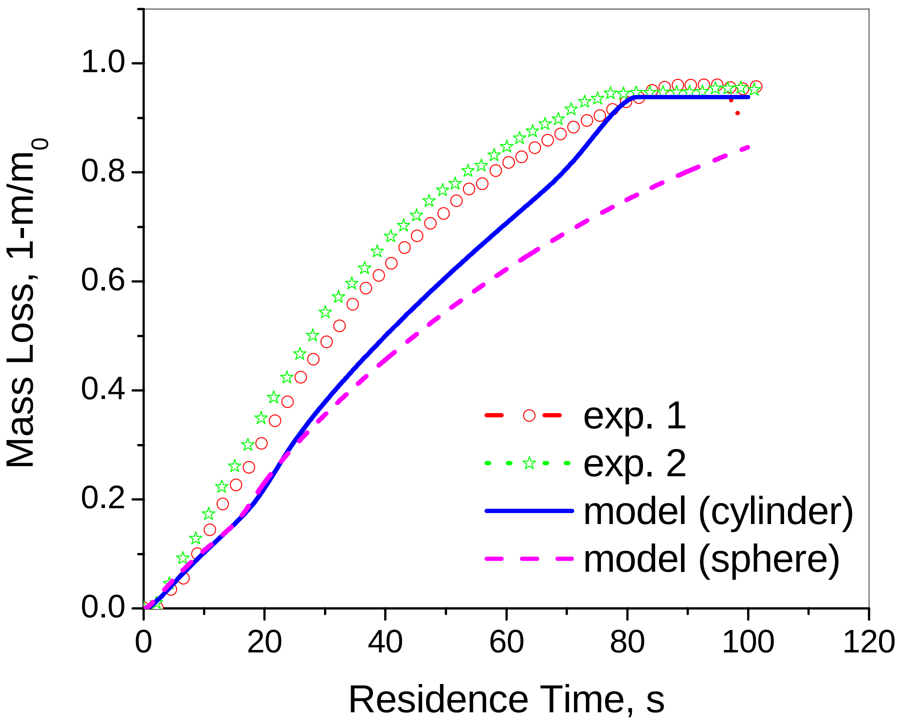
Backup slide

- Model validation (highly moist cylindrical particle)





N_2, d = 11 mm, AR=4, *MC* = 40% (wt), Tw=1273 K, Tg=1050 K