

Investigation of Ash Deposition and Corrosion in Combustion of Bio-fuels and Fuel blends in a Pilot-Scale Facility

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> > by

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Presentation Outline



- Motivation
- Objectives
- Experimental set up
- Theory
- Results
- Conclusions





- CO₂ Neutral fuel.
- Control on toxic emissions.

 Serious ash deposition and corrosion issues.

Focus of the previous research on biomass combustion:

- using biomass in co-firing with coal.
- leaching of biomass prior to combustion.





Fuel interactions of different biofuels

- Ash Deposition To measure the ash deposition rates for pure fuels and fuel blends and use the results in a simplified version of an existing ash deposition model for further comparison between pure fuels and fuels blends.
- Corrosion To perform SEM (Scanning Electron Microscopy) analysis of ash deposits collected from the combustion of pure fuels and fuel blends.



Experimental Setup





Multi-fuel Flow Reactor

- O_2 , CO_2 , CO, SO_2 , NO_x
- LabVIEWTM data acquisition system.



Operating procedure



- Heat up the reactor above 1000 °C with the help of wall CH₄ and excess O₂.
- After achieving steady T- profile, stop wall CH₄ and O₂, lower the primary air (13 kg/hr) and CH₄ (0.75 kg/hr) flow rates to achieve residence time of ~1 s. Natural gas is used in 1:1 ratio of O₂ consumption for flame stabilization.
- Start solid fuel feed; adjust the feed rate to achieve gas concentrations: O₂ ~ 4%, CO<100ppm.
- Wait for the reactor to achieve steady state temperature and gas concentrations under these conditions.
- Insert the probe in the reactor, collect deposit for 30 minutes.
- After the probe is cooled off, scrape the ash off the stationary sleeve, weigh the movable sleeve.



Sample preparation





- Polish the surface of the section. A special polishing oil is used instead of water, to keep water from washing the alkali salts and other solutes from washing away.
- Coat the surface with carbon or gold for conductance (one of the SEM requirements).



Bio-fuels and Fuel Blends







Fuel composition



| % by weight | Straw | Sawdust | Grain screenings | Sunflower shells | Sugar beet pulp | Shea nut shells |
|----------------|--------|---------|---------------------|---------------------|--------------------|--------------------|
| Moisture | 11.0 | 11.0 | 12.5 | 10.1 | 12.3 | 17.0 |
| С | 43.9 | 44.9 | 44.7 | 47.6 | 41.2 | 43.6 |
| н | 5.9 | 5.8 | 6.1 | 6.0 | 5.6 | 5.0 |
| 0 | 38.57 | 38.1 | 34.46 | 35.22 | 39.38 | 31.77 |
| Ν | 0.5 | 0.2 | 2.0 | 0.9 | 1.4 | 2.4 |
| S | 0.13 | < 0.02 | 0.24 | 0.18 | 0.12 | 0.23 |
| Sum | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 |
| CI | 0.52 | 0.016 | 0.26 | 0.054 | 0.037 | 0.079 |
| Ash | 7.52 | 0.39 | 9.02 | 2.59 | 6.02 | 6.06 |
| LHV, MJ/kg | 15.934 | 18.021 | 16.397 | 18.816 | 14.959 | 16.509 |



Ash composition



| Mass % | Straw | Sawdust | Grain screenings | Sunflower shells | Shea Nut shells |
|--------------------------------|-------|---------|------------------|------------------|-----------------|
| SiO ₂ | 52 | 6.4 | 34.4 | 1.1 | 6.6 |
| Al_2O_3 | 0.6 | 2.9 | 2.2 | 0.5 | 1.7 |
| Fe ₂ O ₃ | 1.1 | 0.9 | 2.6 | 0.9 | 2.4 |
| CaO | 9.2 | 45.3 | 15.8 | 16 | 6.4 |
| MgO | 1.8 | 9.8 | 3.9 | 13.1 | 7.9 |
| Na₂O | 0.3 | 3.2 | 1.9 | < 0.2 | 0.4 |
| K ₂ O | 21.9 | 20.6 | 19.2 | 45.1 | 53.3 |
| SO ₃ | 4 | 2.8 | 5.1 | 11.7 | 10.4 |
| P_2O_5 | 3.2 | 2.6 | 11.6 | 10.1 | 9.3 |
| CI | 5.6 | 0.2 | 2.8 | 1.2 | 1.4 |
| Other | 0.3 | 5.3 | 0.5 | 0.3 | 0.2 |
| Sum | 100 | 100 | 100 | 100 | 100 |





Fuel particle size distribution 35 7 Straw Straw Particle size density function Particle size density function Grain screening Grain screening 6 30 Sawdust Sawdust 25 5 Sugar beet pulp Sugar beet pulp - Sunflower shells Sunflower shells 20 3 15 5 0 0 0.2 0.4 0.6 0.8 0.05 0.1 0.15 0.2 0.25 0.3 Average particle size (mm) Average particle size (mm)

The particles size distribution for ash is developed from the fuel particle size distribution. Assumption – Each fuel particle produces 'single' ash particle after combustion.



Ash particle size distribution

Ash deposition model



$$\frac{dm}{dt} = I G + E + T + C + R$$

Capture Efficiency (G) is the fraction of particles that stay on the surface after impaction.

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(I) Inertial impaction

(E) Eddy impaction

(T) Thermophoresis

(C) Condensation

(R) Chemical Reaction

Impaction efficiency: The fraction of particles actually impact on a deposition surface.

$$Stk = \frac{\rho_{p} d_{p}^{2} V_{p}}{9 \mu_{g} d_{c}} \Psi$$
 Stokes Number (Modified Re)

$$\eta(Stk) \cong \left[1 + b(Stk - a)^{-1} - c(Stk - a)^{-2} + d(Stk - a)^{-3}\right]^{-1}$$





m_d= mass deposition rate $m_f = mass$ flow rate of the fuel X_a = mass fraction of ash in the fuel $A_{\rm p}$ = probe projected area η = the impaction efficiency A_r = reactor cross section (cm²)

$$m_{d} = \frac{m_{f} \cdot X_{a} \cdot A_{p} \cdot \eta \cdot G}{A_{r}}$$

Mass of ash deposit = m_d

Mass of ash fed =
$$\frac{m_{f} X_{a} A_{p}}{A_{r}}$$
Collection efficiency
$$C = \frac{m_{d}}{\frac{m_{f} X_{a} A_{p}}{A_{r}}} = \eta \cdot G$$





Measured ash deposition rates of pure fuels



The ratio of maximum to the minimum ~ 130



The ratio of maximum to the minimum ~ 28





Impaction efficiency

Capture efficiency



Density and particle size of fuels

Ash composition of fuels

The ratio of maximum to the minimum capture efficiency ~ 25



Ash deposition of fuel blends



Measured ash deposition rates of Straw blends



Ash deposition rates for the fuel blends are lower by factor of ~ 2.0 than that of pure straw and grain screenings.



Prediction of Ash deposition rates



Straw blends

Grain screenings blends



The differences in the predicted and measured data are large compared to the uncertainty limits.



Results - Corrosion





Straw (100%) - Magnification 200 X

Saw dust (100%) - Magnification 200 X



Results - Corrosion





- Dilution effect
- Fuel interactions!

Straw - Saw dust (50%-50%) - Magnification 1000 X



Results – Corrosion





Figure imported from Report on "Ash deposition and corrosion mechanisms", by Dr. Larry Baxter, Sandia National Lab.



Results – Corrosion





| % w/w | Straw | Sunflower shells | |
|----------|-------|------------------|--|
| Sulfur | 0.16 | 0.19 | |
| Chlorine | 0.64 | 0.065 | |

The complete conversion of chlorides to sulfates requires longer time due to kinetic and transport limitations.



Observations





Contributions from other ash deposition mechanisms are found insignificant as assumed in the deposition model.





- Ash deposition rate is a function of ash content, capture efficiency, and, in instances of small particle size, mechanisms other than impaction.
- Mixing fuels having different capture efficiencies results in lower capture efficiencies thus lowering the amount of deposited ash.
- Alkali and chloride components in fuel contribute to mass accumulation by forming condensate layer and also by reacting with silica to form silicate particles.
- The simple deposition model can accurately predict ash deposition rates to within 20% of actual amounts with exceptions of few over predictions.



Conclusions – II. Corrosion



- The bio-fuels exhibit high corrosion potential due to its high alkali and chlorine content.
- Blends of biomass fuels produce products that react in ways that are not always proportional to the blend ratio.
- The sufficient amount of fuel sulfur can shift the equilibrium to favor sulfates over the chlorides at specified heat transfer surface temperatures.
- The evidence of corrosion initiation through iron oxide formation is detected during investigation of major biofuels.



Recommendations for future work



- Experiments performed for extended time periods.
- Variation of fuel blend ratio other than 1:1.
- Experiments performed with various probe surface temperatures.
- Investigations on the effect of overall stoichiometry (reducing vs. oxidizing conditions) should be conducted, especially with respect to alkali chloride conversion to alkali sulfates.





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