Impact of Oxygen Combustion of Ammonia as a Fuel / Co-fuel on NOx Emissions

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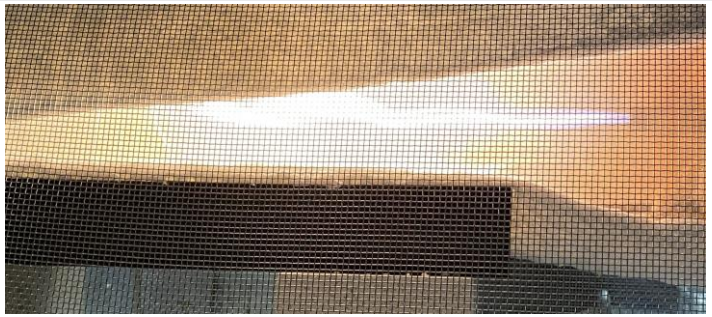
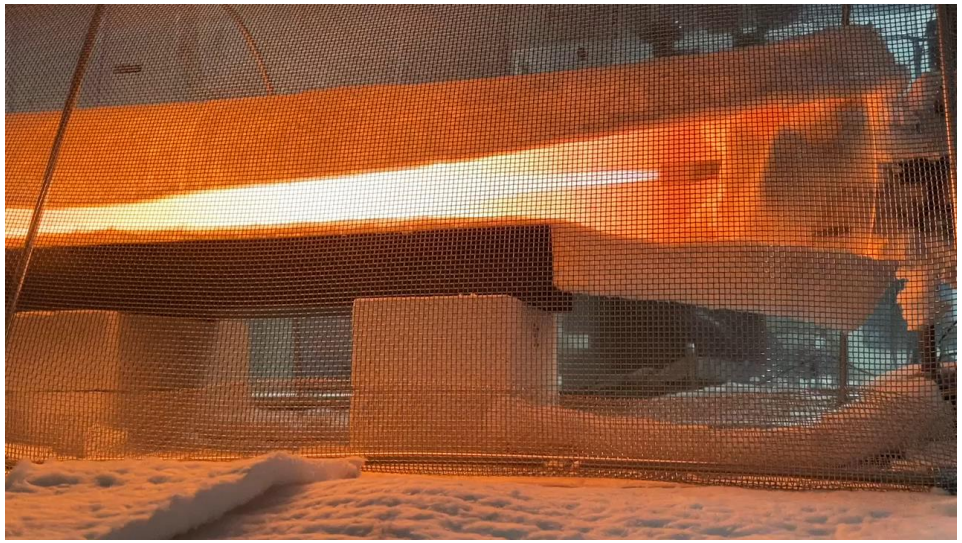
Test Conditions and Visual Observations

NG



NH3

NH3

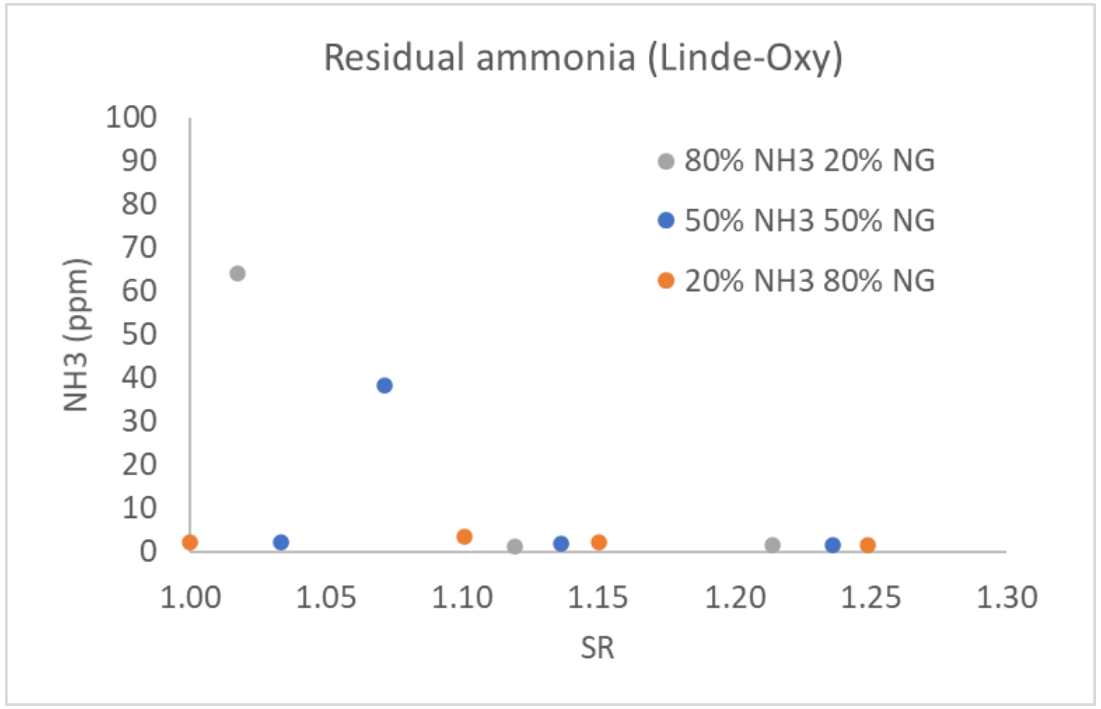


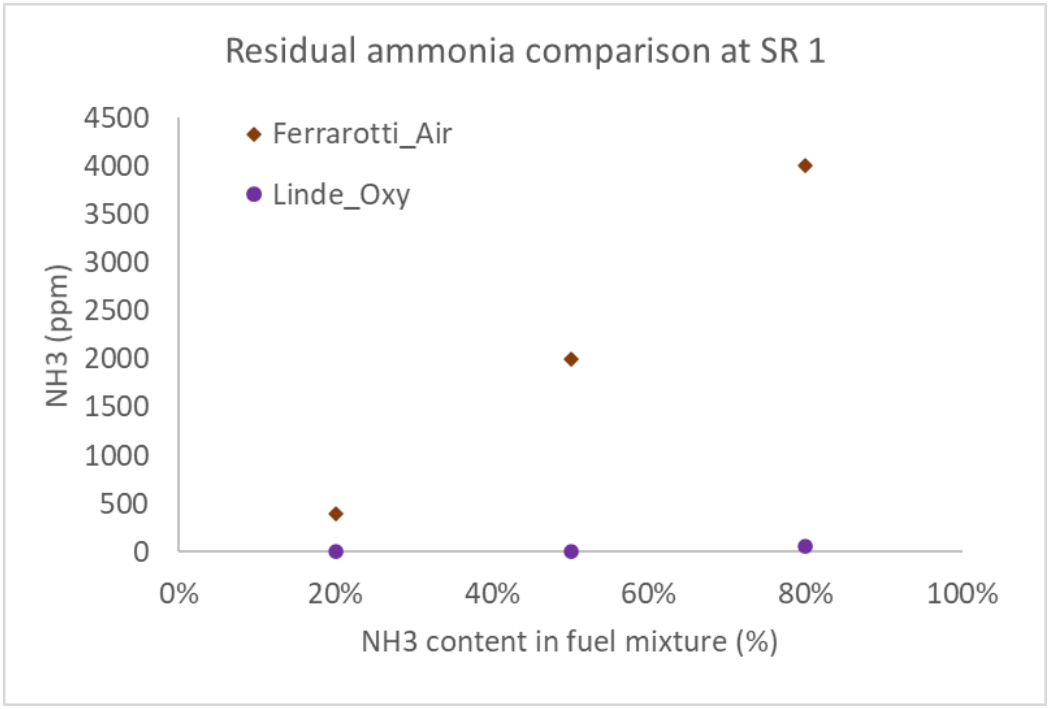
NH_3 (%)	NG (%)	SR
80	20	0.8
50	50	0.9
20	80	0.95
0	100	1 1.05 1.1 1.2
100	0	1.2

- Combustion tests conducted with burner installed inside an insulated quartz tube at 15 KW (50 kBtu/h)
- Flue gas analyzed with FTIR + GC
- 100% oxygen combustion tests were completed for NG-NH_3 mixtures at varying stoichiometric ratios (SRs)
- Easy ignition with oxygen
- Stable flame of ammonia in oxygen

Stable oxygen combustion of ammonia (0-100%) achieved

Residual Ammonia



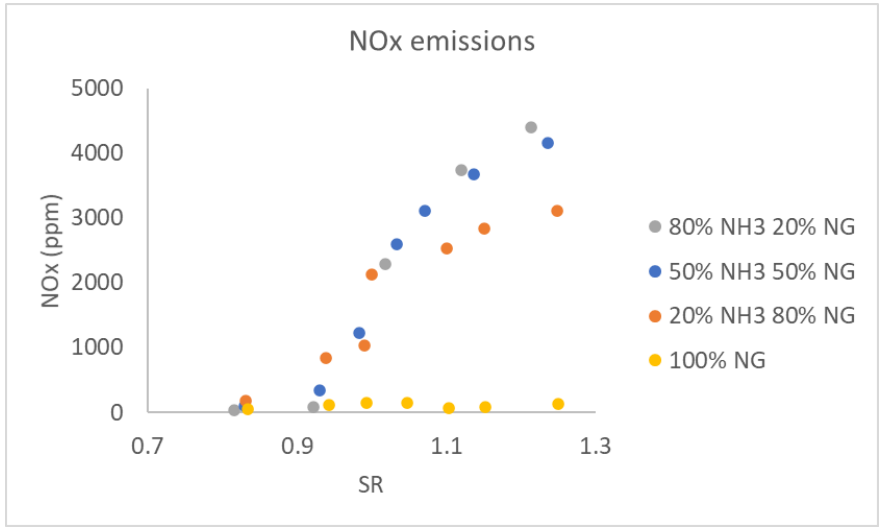


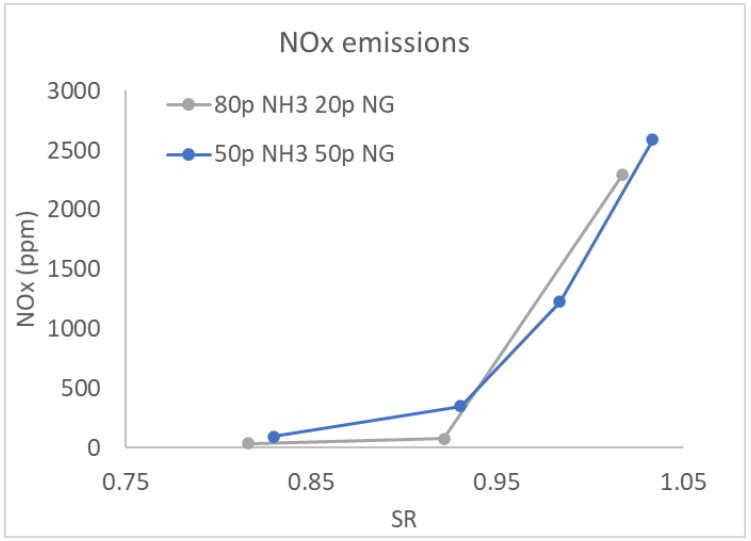
- Very low ppm of ammonia in the product stream at SR 1 and above
- Ferrarotti et al.,[1] showed significant residual ammonia with air combustion
- Kobayashi et al.,[2] reported even higher residual ammonia at 50,000 ppm for 100% ammonia combustion in air
- Very low air ingress – negligible nitrogen for 100% NG run (~0.1%)

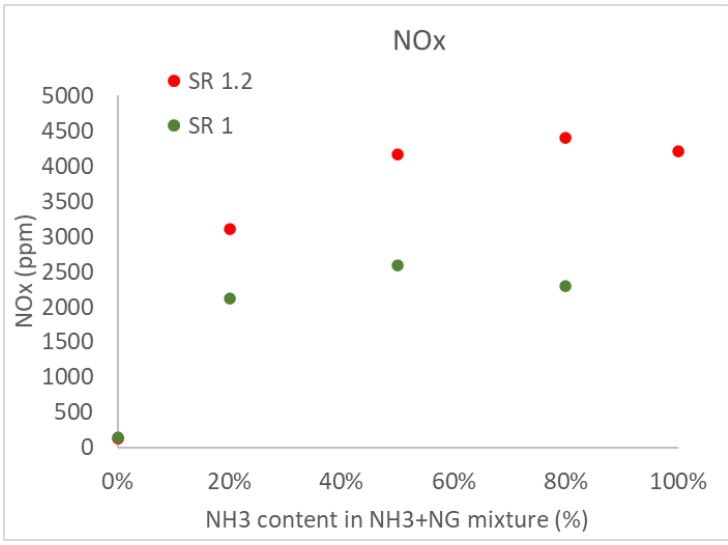
Complete combustion of ammonia with oxygen at all Ammonia-NG mixtures with SR 1 and above

[1]Ferrarotti, M. (2020). Experimental and numerical investigation of fuel flexibility and pollutant emissions in novel combustion technologies using renewable synthetic fuels.
[2]Kobayashi et al., (2019). Science and technology of ammonia combustion. Proceedings of the Combustion Institute, 37(1), 109-133.

NOx Emissions with Oxygen Combustion (wet basis)





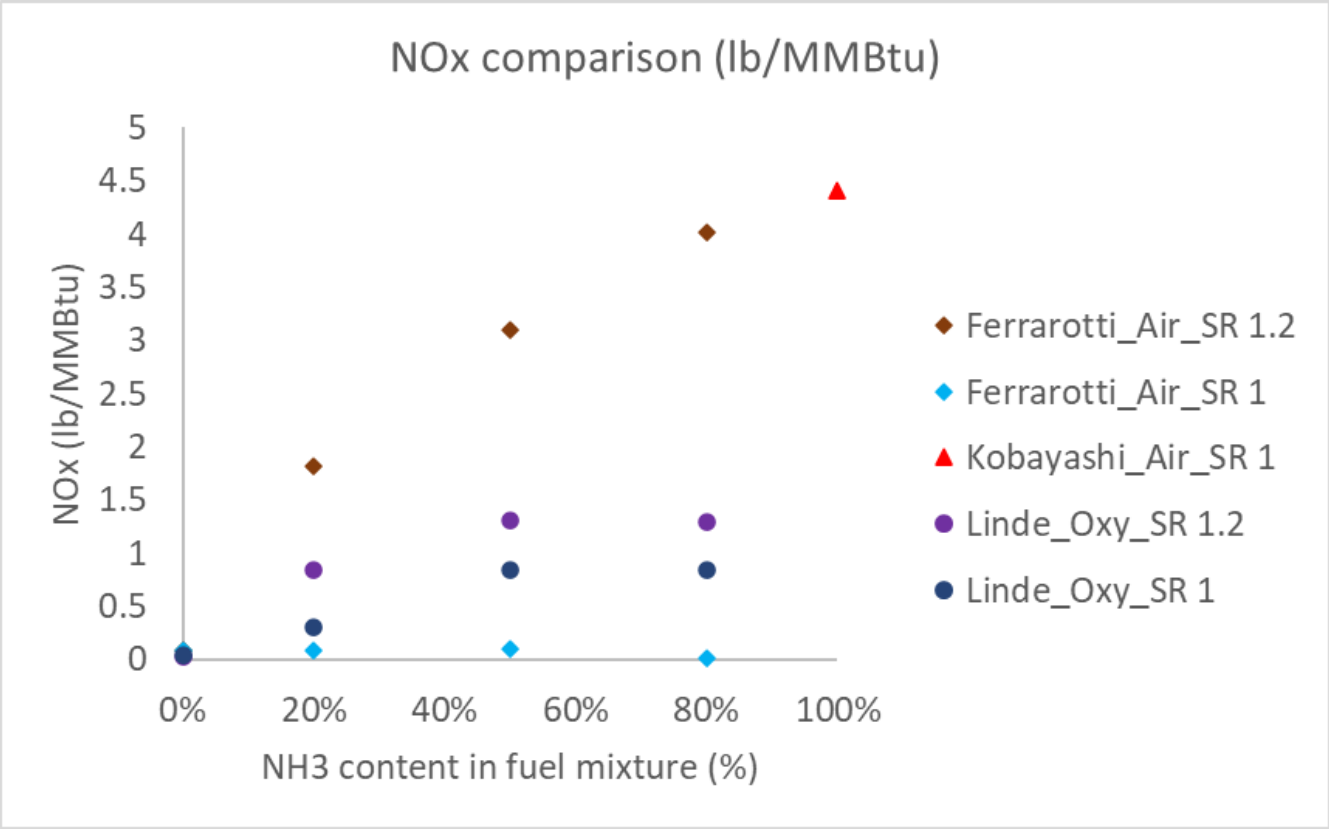


- With increasing ammonia content in the fuel mixture (up to 50% NH_3) –
  - NOx emissions rise
  - NOx reaches a threshold and doesn't increase significantly with increasing NH_3 content thereafter
- With increasing SR –
  - NOx rises
  - NOx saturates at around 4400 ppm at SR 1.2 - Same order of magnitude NOx measured at ULB with air combustion*
- NOx increases significantly between 0.95 and 1.05 SR – Maintaining a slightly lower SR than 1 would reduce NOx considerably

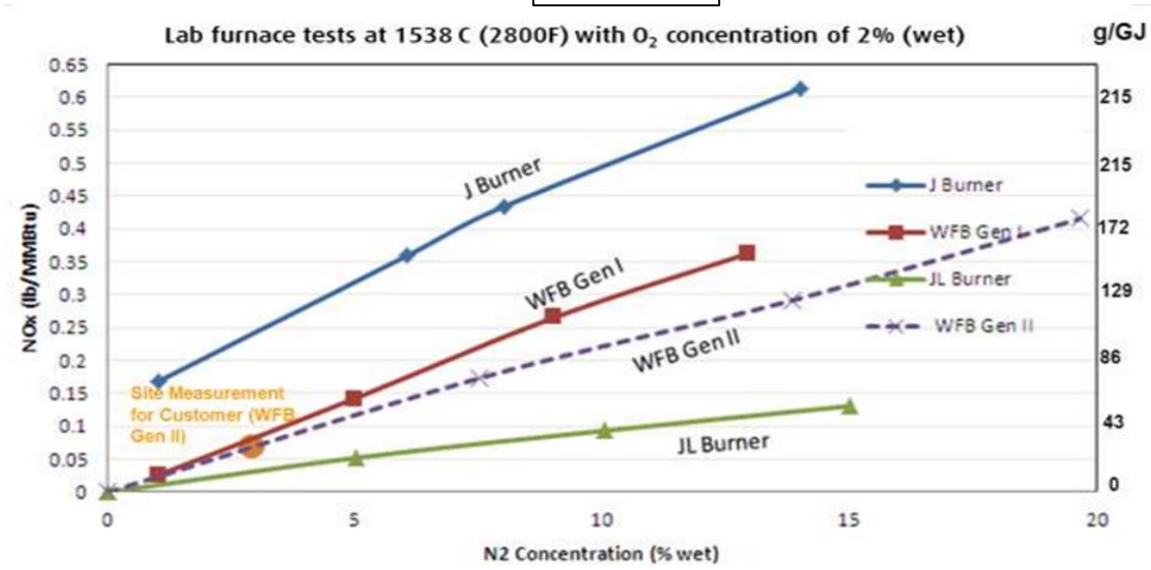
Operating close to stoichiometric ratio will lower NOx significantly

*Ferrarotti, M. (2020). Experimental and numerical investigation of fuel flexibility and pollutant emissions in novel combustion technologies using renewable synthetic fuels.

NOx Emissions in lb/MMBtu



For NG



- Lower NOx generated per MMBtu of fuel fired with Oxygen Vs. Air at SR 1.2
- At SR 1, even though the NOx emissions with air are lower, residual ammonia content is high
- Linde combustion technologies can be strategically designed to further reduce NOx formation while maintaining required combustion chamber temperatures

Conclusion

Advantages of oxygen combustion for ammonia:

- Higher radiation intensity
- Easy ignition
- Stable flame
- Complete combustion – Low ammonia slip
- Lower NOx production (lb/MMBtu) than air combustion at oxygen rich conditions

Thank you