

Microwave-based control of an SCR-based flue gas aftertreatment system for biomass combustion

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Summary:

Selective catalytic reduction (SCR) is essential for reducing NO_x emissions from biomass-fired plants, where fluctuating fuel composition leads to strongly varying raw emissions. Conventional SCR control relies on fixed calibration curves or gas sensors, which can cause inefficiencies and NH₃ slip. This work investigates a radio frequency (RF)-based approach in which the catalyst itself acts as a sensor by monitoring its electromagnetic properties. Experiments show a clear correlation between RF signals and NH₃ storage on commercial vanadia-based catalysts. The results indicate that RF-based control enables more precise and robust SCR operation than conventional gas sensor-based methods.

Keywords:

Flue gas, microwave cavity perturbation, selective catalytic reduction (SCR), ammonia loading, catalyst state-diagnosis, nitrogen oxides

Motivation

Selective catalytic reduction (SCR) is a widely applied technology to remove nitrogen oxides (NO_x) from flue gases produced by combustion processes. It has long been used in coal-fired power plants or waste incineration plants and is increasingly applied in biomass-fired boilers and combined heat and power (CHP) systems. NO_x emissions from biomass combustion arise predominantly from fuel-bound nitrogen. Biomass fuels such as wood chips, bark, straw, and agricultural or biogenic residues often show large variations in nitrogen content, leading to strongly fluctuating NO_x raw emissions [1].

Primary mitigation measures like air or fuel staging, or flue gas recirculation reduce NO_x formation. However, their NO_x reduction potential is often not sufficient to meet the emission limits. Therefore, flue gas aftertreatment systems such as SCR become necessary. The SCR process is based on the catalytic reduction of NO and NO₂ by ammonia (NH₃) to form nitrogen (N₂) and water (H₂O). Ammonia is supplied either directly or generated in-situ from urea-water solutions. SCR reactions occur on an oxide catalyst, mostly based on vanadium-tungsten oxides supported on titanium dioxide (V₂O₅-WO₃/TiO₂, abbreviated VWT) or on zeolite-based materials [2].

For high NO_x conversion and high selectivity (suppression of undesired oxidation reactions),

SCR systems are typically operated between ca. 200 °C and 400 °C. Compared to selective non-catalytic reduction (SNCR), SCR provides substantially higher NO_x removal efficiencies, that exceeds 80%. This is particularly relevant for biomass-fired plants, where variable fuel composition and fluctuating load conditions occur. Here, SCR is the preferred technology when very low emission limits must be met [2].

To date, sensors (NO_x) have been used solely for plant monitoring. The dosing of the reducing agent is generally based on calibration curves, which are suitable only for a narrow range of fuel and operating parameters. If this range is exceeded, increased exhaust emissions occur.

To ensure that the SCR process can always be operated within the optimal range of possible NO_x reduction rates, automated control of reducing agent supply based on the operating conditions is necessary. This simultaneously prevents overdosing with unwanted NH₃ slip. A major general disadvantage of gas sensor-controlled systems is that an overdose is only detected once breakthrough has occurred and NH₃ slip has already taken place. For this reason, the automotive industry has shifted to determine the NH₃ loading of the SCR catalyst based on gas sensor signals and engine operating parameters, and to control it to a defined NH₃ loading [3].

A novel approach utilizes radio frequency (RF)-technology. This involves measuring the electrical properties of the catalyst material using microwaves, thereby using the catalyst itself as a sensor. It has already been demonstrated that RF-based control works for zeolites used as SCR catalysts in automotive exhaust gas [4]. This study investigates whether this is also possible for VWT catalysts, which are typically used for the aftertreatment of biomass flue gases.

Measurement Setup

Generally, the catalyst is installed in an exhaust manifold within a metal casing. This metal casing of the ceramic catalyst acts as a cavity resonator when electromagnetic waves are coupled in (Fig. 1). Using this setup, the loading state of the catalyst can be determined in situ by measuring the dielectric properties of the catalyst material, since NH_3 sorption influences these properties. A frequency shift of the resulting resonance modes (f_0) or an attenuation of the input power occurs. The measurement involves either the reflection of the electromagnetic waves or their transmission through the catalyst material.

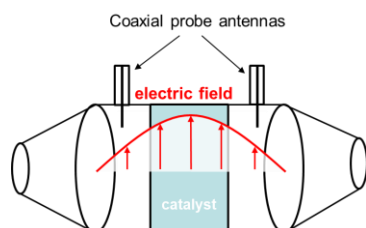


Fig. 1. Basic experimental setup using antennas to measure the electrical properties of the catalyst material within the cavity of the catalyst housing.

The initial measurements in Fig. 2 were performed with a commercial VWT catalyst at around 300 °C using a typical flue gas composition that includes water, CO_2 , O_2 , and N_2 . NO and NO_2 were added as well as NH_3 in concentration that are shown also in Fig. 2 (b) as dotted lines. The FTIR-measured concentrations of NO , NO_2 , and NH_3 downstream of the SCR catalyst are shown in Fig. 2 (b) as drawn lines.

Results and Discussion

Fig. 2 (b) shows the decrease in NO_x concentration when the NH_3 concentration increases. Already in a range where less NH_3 is added than required stoichiometrically for full NO_x reduction, NH_3 is stored in the catalyst. This can be seen in for instance at $t = 100$ min in Fig. 2 (c), where the NH_3 mass is balanced and the stored NH_3 mass in the catalyst is plotted. Both RF-derived data reflect the mass of stored NH_3 very well: the resonant frequency f_0 and the reciprocal quality factor Q_0^{-1} that reflects the attenuation.

Conclusion

This setup seems to be suitable to determine the mass of stored NH_3 , and the RF-parameters may serve as variables to control SCR systems. It is interesting to see that NH_3 storage occurs despite no NH_3 overdosing and no NH_3 slip occurs. This demonstrates that RF-based control may be superior to gas sensor-based control.

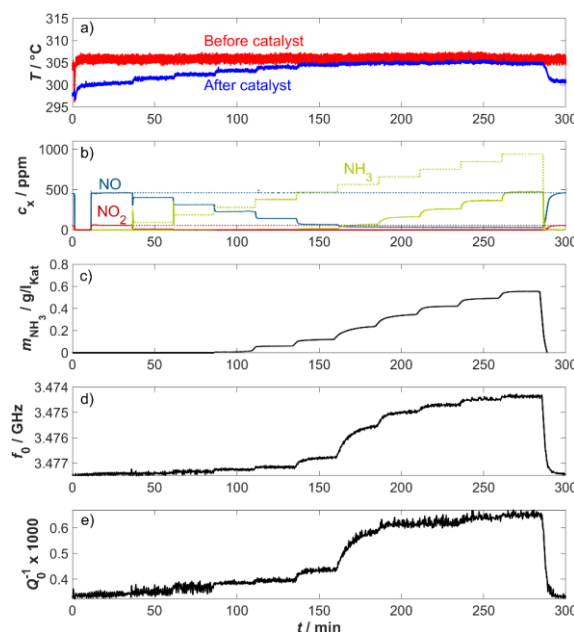


Fig. 2. Experimental Data; (a) temperature of the VWT catalyst, (b) gas concentrations up- and downstream of the catalyst, (c) stored NH_3 mass (derived from b), (d) resonant frequency, and (e) reciprocal quality factor, both measured with a vector network analyzer.

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