Identifying the nature of the active sites in methanol synthesis over Cu/ZnO/Al₂O₃ catalysts

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The heterogeneously catalysed reaction of hydrogen with carbon monoxide and carbon dioxide (syngas) to methanol is nearly 100 years old, and the standard methanol catalyst Cu/ZnO/Al₂O₃ has been applied for more than 50 years. Still, the nature of the Zn species on the metallic Cu⁰ particles (interface sites) is heavily debated. Here, we show that these Zn species are not metallic, but have a positively charged nature under industrial methanol synthesis conditions. Our kinetic results are based on a self-built high-pressure pulse unit, which allows us to inject selective reversible poisons into the syngas feed passing through a fixed-bed reactor containing an industrial Cu/ZnO/Al₂O₃ catalyst under high-pressure conditions. This method allows us to perform surface-sensitive operando investigations as a function of the reaction conditions, demonstrating that the rate of methanol formation is only decreased in CO₂-containing syngas mixtures when pulsing NH₃ or methylamines as basic probe molecules.
The high consumption of fossil fuels causes the emission of greenhouse gases and enhances global warming. Therefore, it is the aim of current research to find alternative energy sources and renewable raw materials. One possible alternative is methanol, which is used in a wide range of applications as a basic chemical, fuel additive as well as energy carrier. It has a high potential to substitute hydrocarbons originating from fossil fuels in many areas. Nowadays, methanol is still industrially produced by the heterogeneous catalysed conversion of syngas, a gas mixture containing CO, CO₂, and H₂ obtained from natural gas or coal, over Cu/ZnO/Al₂O₃ catalysts at elevated temperatures and pressures. For a methanol production with low CO₂ footprint, the mixing of exhaust gases from steel production with sustainably produced H₂ from water electrolysis is a promising route to achieve the gas composition of conventional syngas mixtures. However, many known and unknown impurities in the ppm as well as in the ppb range may be present in such an off-gas-derived syngas, and the effects of most impurities on the catalytic activity, selectivity and stability cannot be predicted with certainty in view of the lack of poisoning studies in literature. These impurities can interact as irreversible poisons, which strongly interact with the active sites, or as reversible poisons, which can be desorbed from the active sites and flushed out of the reactor. In case of reversible poisoning, the poisons can act as selective probe molecules adsorbing on the active sites without irreversible deactivation. Thus, selective poisoning may allow gaining new insight in the nature of the active sites.

The active site for methanol formation of the industrial Cu/ZnO/Al₂O₃ catalyst has been under debate over the last decades. Recent models are the Cu⁰–Zn⁰ surface alloy proposed by the Nakamura and Chorkendorff groups, Zn⁷⁺ species at the defective Cu⁰ surface claimed by the Schlögl group, and the like ZnO like layer on the Cu⁰ particles also suggested by the Schlögl group, and ZnO on the top layer of the Cu⁰ particles postulated by the Rodriguez group. All models are based on strong metal support interactions (SMSI) resulting in Cu–Zn interface sites that are essential for a highly active catalyst, but they differ in the nature of the Zn species in close contact with Cu⁰, which are controversially debated to be metallic or positively charged. The most active site of methanol synthesis is described as metallic Zn species alloyed into defined Cu⁰ sites. Furthermore, it is proposed that high coverages of oxygen-containing intermediates like formate only exist under industrially relevant high-pressure conditions and lead to a partial oxidation of the metallic Zn sites due to the oxophilic nature of Zn compared with Cu. However, there is no characterisation method available for the Cu/ZnO/Al₂O₃ catalyst with CO/CO₂-containing syngas mixtures above 200 °C and at 60 bar. We investigate the reversible poisoning mechanism of NH₃ as well as of different types of methamines and define the corresponding inhibition strength by the non-produced amount of methanol over a defined period of time. Parallel to the reversible poisoning by the amines, we co-feed ethylene into the syngas mixture, which is fast hydrogenated to ethane, we investigate the reversible poisoning mechanism of NO, and we change the syngas mixture from CO₂- to CO-free gas mixtures to clearly confirm that the methanol synthesis catalyst exposes both highly active Cu⁰–Zn⁰ sites and metallic Cu⁰ sites. At the end, the obtained results are discussed in view of the controversial debate on the active site in methanol synthesis demonstrating that the chosen reaction conditions and the time on stream (TOS) control the structure of the catalyst surface.

Results

High-pressure pulse experiment (HPPE). The self-built HPPU enabled us to inject defined amounts of probe molecules as pulses into the syngas stream under methanol synthesis conditions (210 °C, 60 bar). In this way, a variety of valuable kinetic results can be collected in a short period of time without disturbing the main reaction on the surface sites for a too long period of time to minimize possible irreversible structural transformations. When injecting N-containing compounds acting as reversible poisons, the temporary blocking of active sites only occurs when the poison is present in the feed gas stream, which is exemplarily shown for NH₃ in Fig. 1a.

A typical HPPE consists of three steps: First, steady state with clean syngas has to be established. The second step is the injection of the probe molecule as a pulse passing through the catalytic bed, and in the third step the period of time is determined until the initial rate of methanol formation is recovered. The pulsing of pure N₂ (0% NH₃ in Fig. 1a) illustrates that the used low mole fractions of reversible poisons as well as the high inert content in the sample loop lead to a temporary dilution of the product stream. This sharp negative pulse present in every HPPE is neglected for the interpretation of the results. The rising partial pressure of NH₃ leads to an increasing loss of methanol activity after the temporary dilution and to longer regeneration times.

In addition to the methanol mole fraction (black curves), the NH₃ mole fractions (blue curves) were also monitored. For the experiment with 0.05% NH₃, no NH₃ signal was detected, since it is converted to the methylamines monomethylamine (MMA), dimethylamine (DMA) and trimethylamine (TMA) (Supplementary Fig. 10) reacting with oxygen-containing intermediates of methanol synthesis such as formate. This means that the NH₃ signal of the 0.5% HPPE represents the part of the injected NH₃, which does not interact with the catalyst surface, because the position of the signal is equal to the temporary dilution. Obviously, the adsorbed NH₃ species and syngas reactants are part of adsorption equilibria, so that a complete deactivation of methanol synthesis is not possible with a reversible poison in contrast to an irreversible one.

In the same way, MMA (Supplementary Fig. 2), DMA (Supplementary Fig. 3) as well as TMA (Supplementary Fig. 4) were also injected as pulses into the feed gas stream under high-pressure conditions to better understand the reversible poisoning mechanism of NH₃. NO was also used (Supplementary Fig. 5), which is hydrogenated to NH₃ and H₂O (Supplementary Fig. 11). All investigated N compounds act as reversible poisons, and for the comparison of the different poisoning strengths the relevant methanol mole fractions were integrated to obtain the non-produced amount of methanol ∆Methanol during the required synthesis over an industrial Cu/ZnO/Al₂O₃ catalyst with CO/CO₂-containing syngas mixtures above 200 °C and at 60 bar. We investigate the reversible poisoning mechanism of NH₃, as well as of different types of methamines and define the corresponding inhibition strength by the non-produced amount of methanol over a defined period of time. Parallel to the reversible poisoning by the amines, we co-feed ethylene into the syngas mixture, which is fast hydrogenated to ethane, we investigate the reversible poisoning mechanism of NO, and we change the syngas mixture from CO₂- to CO-free gas mixtures to clearly confirm that the methanol synthesis catalyst exposes both highly active Cu⁰–Zn⁰ sites and metallic Cu⁰ sites. At the end, the obtained results are discussed in view of the controversial debate on the active site in methanol synthesis demonstrating that the chosen reaction conditions and the time on stream (TOS) control the structure of the catalyst surface.
period of regeneration time (Supplementary Note 1, Supplementary Fig. 6). The correlation of the calculated values $\Delta n_{\text{MeOH}}$ with the different mole fractions of the reversible poisons is shown in Fig. 1b. The $\Delta n_{\text{MeOH}}$ values for every corresponding poison correlate linearly with the mole fraction of the poison for values below 0.2% under the investigated conditions. Above this mole fraction, the poisoning strength reaches a stationary regime due to the limited deactivation effect of reversible poisons, exemplarily shown for NH$_3$ (injection of 0.4 and 0.5%). The linear trend of the curves in Fig. 1b can be easily predicted with a one-parameter function through the origin. Here, the slope is defined as the inhibition strength $a$, and the corresponding values are shown in Fig. 1b. When comparing the determined values for the individual inhibition strengths, the following sequence is obtained, in which NH$_3$ is the strongest reversible poison and TMA the weakest:

$$\text{NH}_3 > \text{NO} > \text{DMA} \approx \text{MMA} > \text{TMA}. \quad (1)$$

The consecutive reaction of NH$_3$ to TMA is one reason for this correlation. NH$_3$ requires the highest number of methylation steps until the final product TMA is formed, resulting in the longest blocking of active sites as well as in the highest consumption of oxygen-containing intermediates$^{26,27}$. In contrast, TMA only blocks the active sites by adsorption, since no further methylation is possible (Supplementary Fig. 10b), leading to the shortest residence time on the surface and the lowest inhibition strength. In principle, MMA should be a stronger poison than DMA, but Fig. 1b shows that the inhibition strength of DMA is only slightly higher. Thus, it can be assumed that the methylation steps are fast and a clear distinction between both methylamines is difficult to identify at 210 °C and not observable at 250 °C (Supplementary Fig. 10b). The inhibition strength of NO should also be higher than that of NH$_3$ due to the additional hydrogenation step, but the poisoning by NH$_3$ and NO proceeds in different ways as explained in Fig. 2.

**Probing the presence of two different active sites.** From the first HPPEs, it can be seen that different types of N compounds interact with the active sites of the Cu/ZnO/Al$_2$O$_3$ catalyst resulting in the observed decrease of methanol formation. Therefore, our work was focused on the identification of the nature of these active sites and on answering the question as to whether other surface sites play an important role. For these investigations, only the probe molecules NH$_3$ as reacting N compound (Fig. 2) and TMA as blocking N compound (Supplementary Fig. 12) were considered. The freshly reduced Cu/ZnO/Al$_2$O$_3$ catalyst has various types of Lewis and Bronsted acid

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**Fig. 1 High-pressure pulse experiments and the determined inhibition strengths.** a Recorded methanol (black curves) and NH$_3$ (blue curves) mole fractions during the injection of pulses with different NH$_3$ partial pressures over the Cu/ZnO/Al$_2$O$_3$ catalyst (conditions: 210 °C, 60 bar, 13.5% CO, 3.5% CO$_2$, 73.5% H$_2$, 9.5% N$_2$). b Correlation of the determined $\Delta n_{\text{MeOH}}$ (non-produced amount of methanol over a defined period of time) values (Supplementary Note 1) with the injected mole fractions of the investigated N compounds (NH$_3$ red squares and line, NO black points and line, monomethylamine (MMA) blue triangles and line, dimethylamine (DMA) violet stars and line, trimethylamine (TMA) orange diamonds and line). The corresponding pulse experiments are shown in Supplementary Figs. 1–5. $a$, the slope of the corresponding linear interpolation, is defined as the inhibition strength.
sites with different acid strengths. Actually, the Cu/ZnO/Al2O3 catalyst developed for industrial reactors is a multi-site system. According to its composition, three different types of adsorption sites can be present: metallic Cu0 sites, grey area = Zn0 sites, and sites exposed by ZnO. In addition, every type of exposed surface is non-uniform due to the presence of vacancies, steps and kinks. In general, the Cu:Zn ratio as well as the synthesis route is chosen in such a way that an intimate contact between Cu and ZnO is achieved to maximize the number of Cu–Zn oxide interface sites. A significant influence of pure ZnO sites under the conditions of the low-temperature methanol synthesis can be neglected, and the absence of acidic OH groups on the structural promoter Al2O3 is also excluded due to the absence of acid-catalysed products such as dimethyl ether (Supplementary Note 3). For Al2O3, it is generally accepted that it acts as physical spacer to enhance the lifetime as well as the surface area of the Cu/ZnO catalyst maintaining economical methanol production rates over several years. No evidence can be found in literature that Al2O3 is involved in the reaction mechanism of methanol formation or in the formation of the active sites.

The hydrogenation of ethylene and NO was analysed in detail (Fig. 2a, b) to identify the presence of different Cu sites, which has already been claimed in several publications. Figure 2a shows that the continuous dosing of ethylene into the syngas stream leads to its nearly complete hydrogenation to ethane without influencing the rate of methanol formation. Thus, the two reactions are catalysed by two different active sites. Obviously, unpromoted metallic surfaces like Cu0 are highly suitable for the hydrogenation of unsaturated hydrocarbons. It is known from literature that Cu0 can act as adsorption site for hydrogenation reactions such as the hydrogenation of esters. Furthermore, the high hydrogen content in the syngas is sufficient to ensure that ethylene hydrogenation can proceed without disturbing the formation of methanol on the Cu–Zn interface sites. Adding 0.05, 0.1 and 0.2% of NH3 as pulses leads to the expected reversible poisoning of methanol formation, but not to a lowering of the produced amount of ethane neglecting the temporary dilution.

As a result, it seems that NH3 does not prefer unpromoted metallic Cu0 as adsorption site, which was also the outcome of NH3 adsorption studies on Cu0 single crystals. To confirm this hypothesis, the syngas mixture was switched from CO/CO2/H2 to CO/H2 and back to CO/CO2/H2 at 210 °C and 60 bar coupled with HPPEs with NH3. Here, the resulting methanol (black curve) and NH3 (green curve) mole fractions in the product gas stream are shown. The images visualize the oxidative effect of CO2 in the syngas mixture and the corresponding interaction of NH3 with the catalyst surface. Orange area = Cu0 sites, blue area = Zn0+ / ZnO sites, grey area = Zn0- sites.
from the formate pathway to the formyl pathway, which is kinetically not preferred on Zn-promoted Cu\(^0\) surfaces\(^{17}\). The adsorbates of the formyl mechanism such as CO\(_{\text{ads}}\) and HCO\(_{\text{ads}}\) bind through their C atoms to the catalyst surface, and no oxidising effect is induced due to the absence of CO\(_2\) and H\(_2\)O in contrast to the formate pathway. Therefore, the combination of this experiment with HPPE shows no reversible poisoning and no conversion of NH\(_3\) in the CO/H\(_2\) mixture. Thus, the composition of the syngas mixture controls the oxidation state of the catalyst surface, which can be changed reversibly under low-temperature conditions as confirmed in many studies\(^{11,16,24}\). In summary, all experiments shown in Fig. 2 indicate that metallic Cu\(^0\) or Cu\(^0\)–Zn\(^0\) sites are not the adsorption sites for NH\(_3\), implying that the observed reversible NH\(_3\) poisoning in the presence of CO\(_2\) must selectively proceed on positively charged Cu\(^0\)--Zn\(^{\delta^+}\) interface sites due to the oxidising effect of the oxygen-containing adsorbates.

The role of CO\(_2\). It was already shown that adsorbates like formate or other oxygen-containing species originating from CO\(_2\) play not only a crucial role in the methylation of amines, but also in the partial oxidation of Zn species in contact with metallic Cu\(^0\) sites\(^{12,13}\). This type of oxidation is favoured for Zn due to its higher oxophilicity compared with Cu\(^{13,17}\). Providing evidence for this hypothesis requires that the corresponding investigations must be performed under high-pressure methanol synthesis conditions to generate the necessary adsorbates on the surface. For methanol synthesis over Cu/ZnO/Al\(_2\)O\(_3\), the high-pressure pulse method combined with selective poisons as probe molecules enables us to analyse the oxidation effect under working conditions. For the investigation of the adsorbate-induced surface oxidation, the CO\(_2\) content in the feed gas was increased from 0 (CO hydrogenation) to 100% (CO\(_2\) hydrogenation) to generate different coverage degrees of the reaction intermediates, and for every gas mixture the normalized \(\Delta n_{\text{MeOH}}\) values (Supplementary Note 2) were determined by pulsing NH\(_3\) and TMA (Fig. 3).

Adding small amounts of CO\(_2\) in the syngas feed results in a strong increase of the methanol production rate, which further increases with rising CO\(_2\) content, because CO\(_2\) is much faster hydrogenated to methanol than CO\(^{17}\). In general, it is accepted that the highest production rate is achieved at low CO\(_2\) mole fractions around 2–4\(^{\%}\). This statement is only valid for high degrees of syngas conversion and high methanol and H\(_2\)O mole fractions (Supplementary Fig. 13). In the differential kinetic regime, product inhibition effects by H\(_2\)O are not significant enough to lower the rate of methanol formation strongly\(^{17,36}\).

In addition to the increasing production rate of methanol, Fig. 3 illustrates that the observed poisoning strengths of NH\(_3\) and TMA increase linearly as a function of the CO\(_2\) content in the syngas mixture. Therefore, higher CO\(_2\) mole fractions lead to increasing coverages of the resulting oxygen-containing adsorbates exemplary shown as formate, and these adsorbates create more Cu\(^0\)--Zn\(^{\delta^+}\) interface sites. In this way, the adsorption capacity of TMA is enhanced, and more NH\(_3\) molecules can be adsorbed and further converted.

On the basis of the presented results and of different literature reports, we assume that the initial reduction of the catalyst surface induces the migration of metallic Zn species onto the metallic Cu\(^0\) particles forming the Cu\(^0\)--Zn\(^0\) surface alloy\(^{11}\). This state of the surface seems to be stable under the conditions of CO hydrogenation, but not in the presence of CO\(_2\), which leads to the oxidation of the metallic Zn species forming Zn\(^{\delta^+}\) species on the Cu\(^0\) surface\(^{13}\). It cannot be clarified if all Zn sites in contact with Cu\(^0\) are oxidized in the CO/H\(_2\) gas mixture, but the majority of the sites should have a positively charged nature. The models of the active site of the Cu/ZnO/Al\(_2\)O\(_3\) catalyst of the Nakamura and Schlögl groups are rather similar proposing a Cu\(^0\)--Zn\(^0\) surface alloy\(^{11}\) and Cu steps with Zn alloyed into it\(^{13}\), respectively. Behrens et al.\(^{13}\) assumed the partial oxidation of the metallic Zn species, which cannot be neglected under industrially relevant coverage degrees. In contrast, the assumptions of the Nakamura and Chorkendorff groups\(^{11,12,19}\) are mainly based on results obtained under atmospheric pressure or ultra-high vacuum, which
result in low degrees of conversion and coverages. Thus, the fraction of oxidized Zn sites compared to the metallic ones is small, and the oxidation effect is hardly observable. For example, most characterization methods like our pulse experiments at 1 bar (Supplementary Fig. 9d) provide an averaged result over the whole Cu surface area, which is mainly metallic. However, the Cu\(^0\)-Zn\(^0\) surface alloy model\(^{11}\) provides a highly suitable description of the catalyst surface after reduction and presumably for methanol synthesis from CO.

**Discussion**

We analysed the rate of methanol formation reaction mainly from CO/CO\(_2\)-containing syngas mixtures over an industrial Cu/ZnO/Al\(_2\)O\(_3\) catalyst, which can be reversibly deactivated by NH\(_3\), which initializes the consecutive methylation reactions. The step-by-step methylation with presumably oxygen-containing intermediates like formate seems to be the major factor determining the inhibition strength of the animes, because NH\(_3\) is the strongest inhibitor. Both reactions selectively take place on the positively charged Zn species, which are formed by the diffusion of ZnO\(_x\) species onto the metallic Cu\(^0\) particles creating additional interface sites. The unpromoted Cu\(^0\) sites act as hydrogenation sites for ethylene as well as NO, and sites exposed by ZnO nanoparticles are not active under the low-temperature conditions. For the hydrogenation products of NO, the re-adsorption of NH\(_3\) and H\(_2\)O is favoured under the high-pressure conditions. In addition, we showed that the CO\(_2\) content in the syngas is essential to achieve the optimum oxidation state of the interface sites, which are less active and more metallic in the absence of CO\(_2\). The resulting adsorbate-induced oxidation of surface sites by formate and the importance of Lewis acids on metallic Cu\(^0\) for the formation of methanol were also observed in recent studies\(^{39,40}\).

Actually, the statement that CO\(_2\) is important for the oxidation state of the surface goes back to Klier et al.\(^{41}\), who assumed erroneously that Cu\(^+\) is the active site. Figure 4 illustrates that all newer models can be applied to describe the structural evolution of the Cu/ZnO/Al\(_2\)O\(_3\) catalyst as a function of TOS.

The strong loss of \~50% of the initial activity in the first weeks is inevitable for Cu-based catalysts developed for industrial reactors due to thermal sintering and restructuring\(^4\). Therefore, the Cu/ZnO/Al\(_2\)O\(_3\) catalyst is a dynamic system with a continuously changing structure, so that true steady state for a couple of days cannot be reached even under industrial timescales as illustrated by the extrapolated curve. We propose the following structural changes as a function of TOS from left to right in Fig. 4:

At the beginning, highly reduced ZnO\(_x\) species migrate onto the metallic Cu\(^0\) nanoparticles during reduction forming a finely dispersed Cu\(^0\)-Zn\(^0\) alloy according to Nakamura et al.\(^{11}\). The change to a CO\(_2\)-containing syngas mixture initializes the formation of different oxygen-containing adsorbates as well as the oxidation of the metallic Zn species to Zn\(^{5+}\) species at the defective Cu\(^0\) surface according to Behrens et al.\(^{13}\). The migration of further Zn species results in the formation first of a graphitic-like ZnO\(_x\) layer on Cu\(^0\) according to Lunkenbein et al.\(^{14}\) and then a more crystalline and stable thick ZnO layer or particles according to Kattel et al.\(^{15}\). The formation of thick ZnO layers due to segregation from the metallic Cu\(^0\) phase were observed in recent long-term studies\(^{18,23}\). Clarifying that the SMSI process is thermodynamically preferred, but kinetically slow. Under industrially relevant conditions our results clearly confirm the presence of highly active Cu\(^0\)-Zn\(^{5+}\) interface sites embedded in the structurally constantly changing matrix provided by the Cu/ZnO/Al\(_2\)O\(_3\) catalyst. Thus, by applying our developed high-pressure pulse method, we were able to identify the nature of these interface sites, which has not been possible by other characterization methods lacking the combination of surface sensitivity and industrially relevant reaction conditions.

**Methods**

**Activation and aging of the Cu/ZnO/Al\(_2\)O\(_3\) catalyst.** All measurements in this work were performed with the same industrial Cu/ZnO/Al\(_2\)O\(_3\) catalyst provided by Clariant Produkte (Deutschland) GmbH, using a standard high-pressure flow.
set-up including mass flow controllers (MFC, Bronkhorst Deutschland Nord GmbH) for the adjustment of the necessary volume flows, shutdown (Swagelok Company) and multi-port (VICI Valco Instruments) valves, one tubular 1/4-inch stainless-steel reactor mounted in a 1-zone oven (HTM Reetz GmbH) and equipped with an internal thermocouple in order to achieve the desired reaction temperature in the catalyst bed, a back pressure regulator (BPR, Equilibr Precision Pressure Control) connected to a process pressure controller (PC, Bronkhorst Deutschland Nord GmbH) for the reaching of high-pressure conditions (up to 60 bar) in the reactor and a unique self-built HPPU. In addition, all stainless-steel tubes and parts, which were contaminated by the corrosive reversible poisons used in this work, were coated with SilcoNert 2000® provided by SilcoTek GmbH and heated up to 150 °C to minimize any kind of adsorption phenomena. For the formed in this work was in the acceptable range of 100% ± 1%.

The calibrations of both analytics were validated and the carbon balance (C-balance) of every kinetic experiment performed for recording the chromatograms. The spectrometer offers two different types of detectors for recording IR spectra: The thermal DTGS (deuterated triglycine sulfate) and the liquid nitrogen cooled MCT (mercury cadmium telluride) detectors. In the case of the Micro GC device, a pump, a micro-machined thermal conductivity detector were used for recording the chromatograms. The calibrations of both analytics were validated and the carbon balance (C-balance) of every kinetic experiment performed in this work was in the acceptable range of 100% ± 1%.

\[
C - \text{balance} = \frac{Y_{\text{CO}2,\text{out}} + Y_{\text{CO},\text{out}} + Y_{\text{HCO}2,\text{out}}}{Y_{\text{CO}2} + Y_{\text{CO}} + Y_{\text{HCO}2,\text{in}}}. \quad (3)
\]

Here, the ratio between the mole fraction of all carbon-containing compounds (CO, CO₂, CH₃OH) in the product gas stream \(Y_{\text{out}}\) and the mole fraction of all carbon-containing compounds (CO, CO₂) in the feed \(Y_{\text{in}}\) yields the C-balance. For the reduction of the catalyst precursor, the temperature was increased to 175 °C with a heating rate of 1 °C min⁻¹ using a gas flow rate of 500 Nml min⁻¹ g₄cat⁻¹ diluted H₂ (2% H₂ (99.999%)) in N₂ (99.999%) for 15 h. In a second step, the temperature was increased to 240 °C with 1 °C min⁻¹ and held for 30 min. After the second increase of the temperature, the reduced catalyst was ready for methanol synthesis.

To reach steady-state conditions in a relatively short period of time, the catalyst was aged before performing the kinetic experiments. The reaction temperature was increased to 250 °C at 60 bar to establish equilibrium-controlled conditions ensuring a reproducible deactivation by exposing the whole catalyst bed to the same gas composition at high degrees of conversion according to the study by Fichtl et al.ⁱ⁸. As standard syngas mixture, the following composition was used: 13.5% CO (99.997%), 3.5% CO₂ (99.998%), 73.5% H₂ (99.999%) and 9.5% N₂ (99.999%). All measurements in this study were performed in the differential regime with the necessary syngas flow rate.

High-pressure pulse experiment (HPPE). For the HPPE, a self-built HPPU was developed to inject probe molecules as pulses under high-pressure conditions, which is schematically shown in Fig. 5.

The HPPU consists of one 6 port, 2 position valve equipped with a 1 ml sample loop and two identical back pressure regulators (BPR1 and BPR2) coupled with one process PC. BPR2 is integrated in the reactor line between the reactor outlet and the analytics and BPR1 in the pulse line between the sample loop and the exhaust. For the method for the injection of a pulse over the catalyst bed in the reactor under high-pressure conditions is as follows: The BPRs consist of two parts, which are separated from each other by a Kapton® membrane. The upper parts are connected with PC and the other parts with the incoming gas flow from the reactor or the sample loop on the inlet sites and on the outlet sites with the analytics or exhaust. The task of the PC is to reach the same pressure level in both back pressure regulators. It consists of two valves and a pressure sensor PI. For the setting of pressure values up to 60 bar, 65 bar of Ar (99.999%) must be connected on the inlet valve. When a pressure value is set in the program of the PC, the inlet as well as outlet valve is opened and closed until the pressure sensor measures the given value. Consequently, the pressure in both upper parts of BPR1 and BPR2 increases and so the membranes are pressed down. At this moment, the gas flows are stopped and the pressure in the reactor line and pulse line builds up until the same pressure level is reached like in the upper parts. Then, the membranes are lifted up to the starting positions and the gas mixtures can flow again. If both pressure sensors PI in the reactor and pulse line show the same pressure value, then the valve can be switched to inject the first pulse into the syngas stream.

The results of the validation are shown in Fig. 6. Here, 200 mg of a-Al₂O₃ (sieve fraction: 250–355 µm, Südchemie GmbH) were placed in the isothermal zone of the sample loop on the inlet sites and on the outlet sites with the analytics or exhaust. Consequently, the pressure in both upper parts of BPR1 and BPR2 increases and so the membranes are pressed down. At this moment, the gas flows are stopped and the pressure in the reactor line and pulse line builds up until the same pressure level is reached like in the upper parts. Then, the membranes are lifted up to the starting positions and the gas mixtures can flow again. If both pressure sensors PI in the reactor and pulse line show the same pressure value, then the valve can be switched to inject the first pulse into the syngas stream.

The dashed red line in Fig. 6a represents the injection point of the pulses at time 0. Increasing the pressure leads to longer \(A_{\text{pulse}}\) and increasing \(A_{\text{pulse}}\). In this case, only the blue curve (\(A_{\text{pulse}}\)) in Fig. 6b goes through the origin and not the red curve (\(t\)). The reason for this is the constant operation of the analytics under atmospheric pressure and so the expansion of the pulses after the BPR2 (Fig. 5). In general, the volume flow \(V\) of gaseous compounds is reduced by increasing the pressure level \(p\) according to the ideal gas law (Eq. (4)), since the molar flow \(n\) (due to a constant

\[
\frac{V}{p} = \frac{n}{RT} \quad (4)
\]
mass flow provided by the used MFC at every pressure level), the gas constant $R$ and the temperature $T$ (due to small changes in the pressure level) can be seen as constant:

$$p = \frac{h \cdot R \cdot T}{V} = \text{const.} \cdot \frac{1}{V} \quad (4)$$

$$\tau = \frac{V}{\text{const} \cdot p} \quad (5)$$

In contrast, the resulting retention time or residence time $\tau$, which is defined as reactor volume $V$ divided by the volume flow $\dot{V}$ of the pulses, is proportional to the applied pressure. The corresponding value for the constant in Eq. (3) is equal to the slope $m$ of the lines in Fig. 6b.

The linear behaviour of both functions (Fig. 6b), the absence of steps in the recorded pulses and the acceptable tailing at higher pressures (Fig. 6a) demonstrate a successful validation of the HPPU. Consequently, significant pressure drops and backmixing of the probe molecules can be excluded. In addition, the small error bars (every measurement was repeated five times) in Fig. 6b underline the reproducibility of the pulse method.

For a typical HPPE, 100 mg of the industrial Cu/ZnO/Al2O3 catalyst (sieve fraction 250–355 μm) were placed in the tubular reactor. In the first step, the initial methanol mole fraction in the standard syngas mixture at 210 °C and 60 bar was recorded under differential controlled conditions. Then, the different N compounds were injected as pulses from the corresponding gas cylinder: 0.5% NH3 (99.999%) in N2 (99.999%), 0.2% NO (99.5%) in N2 (99.999%), 0.2% monomethylamine (MMA, 99.5%) in N2 (99.999%), 0.2% dimethylamine (DMA, 99.5%) in N2 (99.999%), 0.2% trimethylamine (TMA, 99.5%) in N2 (99.999%). The mole fraction in the sample loop was set at 0, 0.01, 0.025, 0.05, 0.075, 0.1 and 0.2%. The measurement with 0% corresponds to a pulse with pure inert gas N2 (99.999%). In the case of NH3, additional HPPEs were performed with 0.4 and 0.5%. In addition, 0.05, 0.1 and 0.2% NH3 were injected at 230 and 250 °C at constant 60 bar as well as at 1, 10, 30 and 60 bar at constant 210 °C.

**Co-feeding of NH3, NO, MMA, DMA and TMA.** The continuous dosing experiments with various N compounds were performed over 200 mg (sieve fraction 250–355 μm) of the industrial methanol catalyst. For the dosing of 0.05% NH3 (from 0.5% NH3 (99.999%) in N2 (99.999%)) and 0.2% NO (from 2% NO (99.3%) in N2 (99.999%)), the reaction temperature and pressure were set at 210 °C and 60 bar. In the case of dosing of 0.051% NH3, 0.0153% MMA (from 0.2% MMA (99.5%) in N2 (99.999%)), 0.0170% DMA (from 0.2% DMA (99.5%) in N2 (99.999%)) and 0.0157% TMA (from 0.2% TMA (99.5%) in N2 (99.999%)), the reaction temperature was increased to 250 °C. After achieving a constant initial methanol mole fraction applying the standard syngas mixture, the corresponding N compound was continuous dosed over the catalyst bed for a defined period of time by replacing the internal standard N2 in the standard syngas mixture. At the end, the gas stream of the N compounds was switched off to measure the methanol activity in pure syngas.

**Co-feeding of ethylene coupled with HPPE with NH3/TMA.** The combination of methanol synthesis in the presence of ethylene coupled with HPPEs with NH3 and TMA were performed with 100 mg of the industrial Cu/ZnO/Al2O3 catalyst (sieve fraction 250–355 μm) mounted in the tubular reactor. In the first step, the initial methanol mole fraction was determined with the standard syngas mixture at 210 °C and 60 bar. Then, 1% of the internal standard N2 was replaced by ethylene (from 20% ethylene (99.995%) in N2 (99.999%)) and after a defined period of time, the feed was switched back to the standard syngas mixture. During the adding of ethylene, 0.05%, 0.1% and 0.2% of NH3 (from 0.5% NH3 (99.999%) in N2 (99.999%)) and TMA (from 0.2% TMA (99.5%) in N2 (99.999%)) were injected as pulses.
Syngas switching experiments coupled with HPPE with NH3/TMA. The combination of syngas switching experiments under methanol synthesis conditions with HPPEs with NH3 and TMA were performed with 100 mg of the Cu/ZnO/Al2O3 catalyst (sieve fraction 250–355 μm). Here, the syngas feed was changed from the standard mixture containing CO/CO2 to 17% CO (99.997%), 73.5% H2 (99.999%), 9.5% N2 (99.999%) and back to the standard mixture. At each instant, methanol was produced at 210 °C and 60 bar. In addition, pulses containing 0.2% of NH3 (from 0.5% NH3 (99.999%) in N2 (99.999%)) and TMA (from 0.2% TMA (99.5%) in N2 (99.999%)) were injected as pulses. Every measurement was repeated five times to determine the corresponding error bars.

Long-term measurement. The procedure of the long-term measurement was adapted from Fichtl et al., and is shown in Fig. 7. Three hundred milligrams of the industrial methanol synthesis catalyst (sieve fraction 250–355 μm) were mixed with 1800 mg purified α-Al2O3 (sieve fraction 510–750 μm) in the tubular reactor. To prevent the formation of hot spots, so that a homogeneous temperature profile over the entire catalyst bed was obtained. After the standard activation procedure, the gas stream was changed to the standard syngas mixture. The reaction temperature was constant at 210 °C and 60 bar and the CO2 content in the syngas feed was changed from 0 to 17% (0, 0.3, 5, 10, 17%) by substituting or adding CO to maintain the carbon mole fraction at constant 17% (CO + CO2). For every new syngas mixture, the methanol productivity was recorded and 0.2% NH3 (from 0.5% NH3 (99.999%) in N2 (99.999%)) as well as TMA (from 0.2% TMA (99.5%) in N2 (99.999%)) were injected as pulses. Every measurement was repeated five times to determine the corresponding error bars.

Data availability. The data sets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

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**Author contributions**
M.M. and H.R. conceived the idea. D.L. designed and built the flow set-up with the unique HPPU under the guidance of M.M and H.R., carried out all catalytic tests and pulse experiments, and performed the data analysis. All authors discussed the results and contributed to the manuscript.

**Competing interests**
The authors declare no competing interests.

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