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Water Vapor does not Catalyze the Reaction between Methanol and OH Radicals

Wen Chao,^[b] Jim Jr-Min Lin,^[b] Kaito Takahashi,^[b] Alexandre Tomas,^[c] Lu Yu,^[d] Yoshizumi Kajii,^[d] Sébastien Batut,^[a] Coralie Schoemaeker^[a], and Christa Fittschen*^[a]

Abstract: Recent works [Jara-Toro *et al.*, *Angew. Chem. Int. Ed.* **2017**, 56, 2166 and PCCP **2018**, 20, 27885] suggest that the rate coefficient of OH reactions with alcohols would increase by up to 2 times from dry to high humidity. This finding would have an impact on the budget of alcohols in the atmosphere and that it may explain differences in measured and modeled methanol concentrations. The results were based on a relative technique carried out in a small Teflon bag, which might suffer from wall reactions. We have re-investigated this effect using a direct fluorescence probe of OH radicals, and no catalytic effect of H₂O could be found. Experiments in a Teflon bag were also carried out, but we were not able to reproduce the results of Jara-Toro *et al.* Further theoretical calculations show that the water-mediated reactions have negligible rates compared to the bare reaction and that even though water molecules can lower the barriers of reactions, it cannot make up for the entropy cost.

Methanol (CH₃OH) is one of the most abundant oxygenated volatile organic compounds (OVOC) in the atmosphere^[1, 2]. Direct emissions are the main source, but some oxidation pathways of methane also contribute to its abundance, especially in the remote troposphere^[3, 4, 5]. Concentrations range from 1-15 ppbv in the continental boundary layer and up to 1 ppbv in the remote troposphere^[6, 7]. Despite numerous efforts, global atmospheric chemical models are presently unable to reconcile the modeled and measured methanol concentrations^[7, 8, 9].

The atmospheric degradation of CH₃OH is governed by its reaction with OH radicals, which proceeds by abstraction of H-atoms from either the methyl or the hydroxyl site^[10]. The rate coefficient shows a non-Arrhenius behavior and increases at

temperatures below 200 K, due to enhanced stabilization of a pre-reactive H-bonded complex that can undergo tunneling^[10]. The rate coefficient at room temperature (298 K) has been measured many times^[11, 12] and is recommended^[13] to be $k_1 = 9.0 \times 10^{-13} \text{ cm}^3 \text{ s}^{-1}$.

Very recently, Jara-Toro *et al.*^[14] reported that the reaction of OH with CH₃OH is significantly catalyzed by water (enhanced by a factor of 2 between 20 to 95% of relative humidity) even at 294 K. The same group also reported the water catalysis effect on reactions of OH with ethanol and n-propanol^[15]. Their results are based on a well-known relative method, where the consumption of the alcohol is measured relative to the consumption of a reference compound (C₅H₁₂) following their simultaneous reactions with OH radicals. The reactions took place in a 80 liter Teflon bag, and OH radicals were generated continuously from the 254 nm photolysis of H₂O₂. The ratio of the consumption of CH₃OH versus the consumption of C₅H₁₂ gives the ratio of the rate coefficients, $k_{\text{CH}_3\text{OH}+\text{OH}} / k_{\text{Ref}+\text{OH}}$. This type of experiments was carried out at different relative humidity (RH) up to 95%, and it was found that the ratio increased with increasing RH. Under the assumption that the rate of the OH reaction with unpolar C₅H₁₂ is independent on RH, this increased ratio was assigned to an increased rate of OH reaction with CH₃OH due to water catalysis. More surprisingly, they found a quadratic dependence of the rate enhancement with RH, and speculated that this effect was dismissed in earlier works, because earlier experiments were commonly carried out under low RH, where the water effect would be too weak to observe. Accompanying theoretical work proposed a mechanism of reaction barrier lowering by adding H₂O. However, no rate coefficient has been calculated to estimate the impact of this lowering in the reaction barrier heights.

Using the rate coefficients taking into account the water catalytic effect could decrease the atmospheric lifetime of CH₃OH by a factor of 2 in tropical region with high RH, which would have a non-negligible effect on the global CH₃OH budget. It is therefore important to verify this new finding by using different methods. Indeed, the experiments of Jara-Toro *et al.* have been carried out in a relatively small Teflon bag, where heterogeneous consumption of CH₃OH on the walls may take place. This effect may increase with RH and may become complicated when photochemistry occurs (which produces radicals and radical reactions may change the wall property). They did not vary the surface to volume ratio to quantify this effect.

In this work, we have reinvestigated the influence of H₂O on the rate coefficient of OH reaction with CH₃OH using a direct method: laser photolysis coupled to a time-resolved detection of OH radicals by laser induced fluorescence (LIF) after gas expansion (FAGE - Fluorescence Assay by Gas Expansion)^[12, 16]. We have also repeated experiments using the same relative method as Jara-Toro *et al.*, and in addition to varying RH, we

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have also largely varied the gas volume in the Teflon bag in order to vary the surface to volume ratio. Finally, theoretical calculations have been carried out for a refined analysis of possible H₂O catalysis pathways.

The FAGE technique, initially developed for the quantification of OH radicals in the atmosphere, allows following OH concentrations in a selective and sensitive way even under atmospheric conditions, i.e. high O₂ and H₂O concentrations, which proves difficult with in-situ LIF due to strong quenching of OH fluorescence by O₂ and H₂O. Here, FAGE has been coupled to a laser photolysis reactor (Figure 1) [16, 17] for a pulsed initiation of the reaction between OH and CH₃OH. Briefly, OH radicals were generated by pulsed photolysis of a mixture of ozone and water (O₃ + *hν* → O(¹D) + O₂; O(¹D) + H₂O → 2OH). The 266 nm photolysis laser beam (4th harmonic of Nd:YAG Laser, Quantel Brilliant, ~20 mJ) was expanded to a diameter of ~5 cm before entering the photolysis cell. The photolysed gas mixture was continuously expanded from near atmospheric pressure within the photolysis cell to around 1 Torr into the FAGE cell through a pinhole (1 mm diameter). OH radicals were resonantly excited at high repetition rate by the probe laser (308 nm, Sirah Dye laser, 5000 Hz, ~3.5 mW). The LIF signal of OH was detected in a time resolved manner by a channel photomultiplier tube (Perkin Elmer) and recorded by a National Instrument DAQ card and computer. This way, temporal OH profiles were recorded from each photolysis shot with time stamps every 200 μs and, depending on the signal intensity, individual profiles were added from 30 up to 480 photolysis laser shots. We further binned 5 data points together (final time bin is 1 ms) to enhance the signal-to-noise ratio.

Figure 1. Schematic view of the FAGE set-up

Water vapour was added to the reaction mixture by bubbling a fraction of the main flow (composed of synthetic air) through a glass bottle containing high purity water (TOC < 10 ppb). The H₂O concentration was varied by changing the fraction of the main flow passing through the water bottle. A minimum H₂O concentration of 1×10¹⁷ cm⁻³ (RH ≈ 17%) was necessary to generate enough OH radicals, the highest H₂O concentration (6.1×10¹⁷ cm⁻³, RH ≈ 92%) was reached by passing the entire air flow through the water bottle. The H₂O concentrations were measured at the exit of the photolysis cell using a commercial dew point hygrometer (Mitchel S8000 Integrale).

Test experiments were carried out using CO as a reaction partner for OH. Different concentrations of CO were added to the main flow through calibrated flow meters and a rate constant of (2.3±0.3)×10⁻¹³ cm³s⁻¹ was obtained, in good agreement with literature data [13] and no dependence on the water concentration was observed. See SI for more details.

The rate coefficient for the reaction of CH₃OH with OH was then measured at RH up to 92%. Figure 2 shows typical OH decay profiles in the presence of different CH₃OH concentrations. The OH loss in the absence of CH₃OH (black symbols in Figure 2) is due to reaction of OH with impurities (trace amounts in the synthetic air or in the water) as well as through diffusion/dilution of OH into the non-photolysed volume.

Figure 2. Typical OH decay profiles in the presence of different CH₃OH concentrations. [H₂O] = 5.7×10¹⁷ cm⁻³. Solid lines represent a fit to an exponential decay between 0.015 and 0.4 s.

The OH decays can be described as the sum of these losses:

$$-\frac{d[\text{OH}]}{dt} = (k_{\text{loss}} + k_1[\text{CH}_3\text{OH}])[\text{OH}]$$

with *k*₁ being the rate coefficient for the reaction between OH radicals and CH₃OH. With [CH₃OH] being in large excess over [OH], [CH₃OH] can be considered as constant and the OH decay can be described by an exponential decay, with the observed decay rate being

$$k_{\text{obs}} = k_{\text{loss}} + k_1[\text{CH}_3\text{OH}].$$

Plotting the decay rates of Figure 2-type signals as a function of [CH₃OH] leads to a straight line, with the slope being the rate coefficient *k*₁, and the intercept *k*_{loss} representing the sum of all other losses. Figure 3 shows the decay rates of 6 series of experiments (see SI for detailed results) at different H₂O concentrations (RH between 18 and 92%), where the CH₃OH concentration has been varied for each RH between 2 – 9 × 10¹³ cm⁻³.

It can be seen that the intercepts slightly differ for different series. This can be explained by the synthetic air gas cylinders of different quality used during the period of experiments, which lasted for weeks. However, the slopes are the same for all RH, which means that the rate coefficient obtained for conditions with different H₂O concentrations are the same, no dependence of *k*₁ on [H₂O]. This is illustrated in Figure 4, where the slopes of the linear regressions from Figure 3 are plotted as a function of the RH.

Figure 3. Plot of OH decay rates k_{obs} as a function of CH_3OH concentration for different RH. Error bars show statistical uncertainty only, full lines correspond to linear regression.

Figure 4. Plot of the rate coefficient k_1 such as obtained from the linear regression in Figure 3 as a function of RH. Error bars show statistical error only (95% confidence interval). Dashed line represents linear regression through all data points.

Additional series of experiments have been carried out by keeping the CH_3OH concentration stable and varying the H_2O concentration. Figure 5 shows the normalized OH decays for 3 different RH between 36 and 83 %, no systematic increase in the OH decay rate can be observed.

Teflon bag experiments have been carried out in order to try to reproduce and understand the water effect in the bag experiments such as observed by Jara-Toro *et al.* Experiments have been carried out in a 400 liter Teflon bag^[18] using the relative rate method with n-pentane as reference compound: CH_3OH has been quantified by FTIR spectroscopy, while n-pentane was quantified by GC/FID, OH radicals have been generated by the photolysis of CH_3ONO , a common precursor for OH radicals in chamber experiments. Compared to H_2O_2 (which has been used by Jara-Toro *et al.*), NO (and NO_2 from the oxidation of NO) is a by-product of this precursor. However, it is not expected to influence the result of this study, as neither NO nor NO_2 will react with CH_3OH or with C_5H_{12} . The bag was filled with either 400 liters or with 100 liters in order to vary the surface to volume ratio, and experiments with 3 different RH have been carried out: dry air (RH<5%), 40 and 90%.

Figure 5. Normalized OH LIF intensities as a function of time for 3 experimental conditions with identical CH_3OH concentrations ($5.4 \times 10^{13} \text{ cm}^{-3}$), but different RH. Decay rate was obtained by fitting traces to an exponential decay between 0.01 and 0.2 s.

Figure 6 summarizes the results: the upper graph shows the plot of the consumption of CH_3OH versus the consumption of C_5H_{10} for the 6 different experiments, the lower graph shows the slopes of the linear regressions. The average of all experiments yields a slope of 0.26, leading with the rate coefficient of $k_{\text{C}_5\text{H}_{12}+\text{OH}} = 3.8 \times 10^{-12} \text{ cm}^3 \text{ s}^{-1}$ to a rate coefficient $k_1 = 9.9 \times 10^{-13} \text{ cm}^3 \text{ s}^{-1}$, in agreement with literature. This slope would increase with increasing RH if k_1 increases with RH, however in our experiments we observed, if anything, a small decrease with increasing RH. We also do not see any effect when changing the surface to volume ratio by a factor of 4, indicating that our results are not affected by heterogeneous processes in our Teflon bag. No explanation can be given why Jara-Toro *et al.* observed an increase in the ratio.

Figure 6. Upper graph: plot of the decay of CH_3OH ($\ln([\text{CH}_3\text{OH}]_0/[\text{CH}_3\text{OH}]_t)$) versus the decay of C_5H_{12} ($\ln([\text{C}_5\text{H}_{12}]_0/[\text{C}_5\text{H}_{12}]_t)$) for different gas volumes and different RH. Lower graph: slopes of the linear regression of the experiments in the upper graph. Error bars represent 95% confidence interval.

Quantum chemistry calculations (CCSD(T)/aug-cc-pVTZ//UMP2/aug-cc-pVTZ) and transition state theory (with vibrational perturbation theory including semiclassical tunneling model using the Multiwell program^[19]) were used to simulate the rate coefficients for the $\text{CH}_3\text{OH}+\text{OH}+n\text{H}_2\text{O}$ reactions. The obtained potential energy surfaces are very similar to those reported by Jara-Toro *et al.*; both showed lowering of the reaction barriers with increasing n (see SI for details). We obtained rate coefficients of $2.7\times 10^{-12}\text{ cm}^3\text{ molecule}^{-1}\text{ s}^{-1}$, $1.4\times 10^{-32}\text{ cm}^6\text{ molecule}^{-2}\text{ s}^{-1}$, and $4.4\times 10^{-52}\text{ cm}^9\text{ molecule}^{-3}\text{ s}^{-1}$, for the $n = 0, 1$, and 2 reactions, respectively at 298 K. Even at $[\text{H}_2\text{O}] = 6\times 10^{17}\text{ cm}^{-3}$ (RH = 92% at 298 K), the effective bimolecular rate coefficient for $\text{CH}_3\text{OH}+\text{OH}$ reaction with $n=1$ will be $8.4\times 10^{-15}\text{ cm}^3\text{ molecule}^{-1}\text{ s}^{-1}$, and that for $n=2$ is $1.6\times 10^{-15}\text{ cm}^3\text{ molecule}^{-1}\text{ s}^{-1}$, which are still orders of magnitude smaller than the $n=0$ rate. That is, even though the reactant complexes are stabilized with the addition of water molecule(s), the decrease in enthalpy at the transition states is not large enough to overcome the large entropic effect of water complexation (for $n=1, 2$) at room temperature. Similar reports on negligible water effect has been found for a number of OH reactions^[20, 21], it would require either low temperature^[20, 22] or large stabilization in enthalpy^[23] to observe significant water enhancement. For theoretical predictions and interpretations, it is important to calculate the reaction rates; only showing the electronic energy on the reaction path could often be misleading if one does not consider the associated entropy change.

It is interesting to mention that the reaction between CH_3OH and OH in liquid water has been well studied and is evaluated to be $9.7\times 10^8\text{ M}^{-1}\text{ s}^{-1}$ ($1.6\times 10^{-12}\text{ cm}^3\text{ s}^{-1}$) at 298 K and 1 atm^[24], which is close to the gas phase value, suggesting the water solvation does not enhance the rate dramatically.

In summary, our direct kinetic experiments, our relative rate measurements as well as the theoretical rate calculations all find that water catalysis in the $\text{OH} + \text{CH}_3\text{OH}$ gas-phase reaction is insignificant at room temperature. No explanation can be given about the origin of the contradictory observations made by Jara-Toro *et al.*, but it can be speculated that unidentified heterogeneous reactions biased their results. This highlights the need of different approaches for getting reliable results.

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Conflict of interest

The authors declare no conflict of interest.

Keywords: Alcohols • Atmospheric chemistry • Radical reactions • Reaction mechanism • OH radicals

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Entry for the Table of Contents

COMMUNICATION

The reaction of OH radicals with CH₃OH is the major removal path for CH₃OH from the atmosphere. In recent works it was found, that this reaction is substantially catalyzed by water. Using direct methods, we re-investigated the influence of H₂O on the reaction, and did not find any measurable influence of H₂O on the rate coefficient.

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