Visible light-induced photocatalytic degradation of gas-phase acetaldehyde with platinum/reduced titanium oxide-loaded carbon paper†

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Visible light-induced degradation of gas-phase acetaldehyde (CH₃CHO) is investigated using O-deficient reduced TiO₂ₓ-loaded carbon paper. The carbon paper is synthesized by the pyrolysis of a filter paper, and the reduced TiO₂ₓ is prepared by the magnesiothermic reduction of commercial anatase TiO₂. The surface areas of the non-carbonized filter paper and carbon papers obtained by carbonization at 400, 600, 800, and 1000 °C are 4.31 m² g⁻¹, 13.57 m² g⁻¹, 466.81 m² g⁻¹, 461.60 m² g⁻¹, and 26.28 m² g⁻¹, respectively. Although the as-prepared carbon papers possess much lower specific surface areas than that of commercial activated carbon (2200 m² g⁻¹), the carbon papers show better adsorption capabilities. The O-deficient reduced TiO₂ₓ samples exhibit strong visible-light absorption, and the reduced TiO₂ₓ-loaded carbon papers induce rapid degradation of CH₃CHO and simultaneous generation of CO₂ in both closed-circulation and continuous-flow modes under visible light irradiation (λ > 420 nm), attributed to the efficient adsorption of gas-phase CH₃CHO by the carbon paper and the rapid and complete degradation of CH₃CHO to CO₂ by the active reduced TiO₂. This strongly suggests that the reduced TiO₂ₓ-loaded carbon paper is an efficient composite photocatalyst for the visible light-induced photocatalytic degradation of gas-phase CH₃CHO.

1. Introduction

TiO₂ photocatalysis has been extensively studied in applications for air and water purification. Photocatalytic reactions are initiated by the absorption of ultraviolet (UV) photons, which concurrently generate conduction-band (CB) electrons and valence-band (VB) holes in the TiO₂ lattice. The VB holes are strong oxidants and react with surface -OH groups to produce 'OH radicals. The remediation power of TiO₂ photocatalysts is largely attributed to the strong oxidation potential of these 'OH radicals. However, the wide band gap of TiO₂ limits the range of solar light wavelengths that can be utilized for catalysis. Several strategies have been investigated to enhance the solar light absorption of TiO₂, including metal and non-metal doping, coupling of low-band gap materials, and dye sensitization.

Many researchers focus on the photooxidation of gas-phase acetaldehyde (CH₃CHO), a prevalent volatile organic compound that causes sick-house syndrome. The complete degradation of gas-phase CH₃CHO to CO₂ can be achieved with TiO₂ or Au-loaded TiO₂ under UV irradiation. Recently, the visible light-induced photocatalytic removal of gas-phase CH₃CHO was also investigated using visible light-responsive modified photocatalysts including zeolite/WO₃-Pt hybrids, Mn-doped TiO₂, and N-doped TiO₂.

For air purification, photocatalysts immobilized on support materials are usually employed. The surface area and activity of the catalyst are often reduced by immobilization. Therefore, support materials with high surface areas are preferred for photocatalyst immobilization. The composite materials generated can show synergistic effects on adsorption and photocatalysis. Activated carbon is one such commonly used support material; it has a high surface area that can enhance adsorption and photocatalytic activity. Previously, we prepared TiO₂-embedded carbon nanofibers (CNFs) and core–shell-structured CNF–TiO₂ nanotubes for the photocatalytic oxidation of gaseous CH₃CHO. CNF mats prepared by electrospinning and subsequent carbonization did not adsorb gas-phase CH₃CHO, but the convenient application of CNF mats suggests that mats with improved adsorption of gas-phase CH₃CHO could be widely used.

Recently, O-deficient black or reduced TiO₂ₓ samples have attracted great attention as new photocatalysts for light-induced water splitting towards H₂ production. The reduction of TiO₂ generates many surface defects, Ti³⁺ species, and O vacancies,
which contribute to improved light absorption.\textsuperscript{28,29} We also investigated a new approach for a defect-induced TiO$_{2-x}$ solar photocatalyst for H$_2$ production from water and CO$_2$ reduction to fuel.\textsuperscript{30,31} However, the approach has not yet been applied to the degradation of environmental pollutants.

In this study, carbon paper was synthesized by the simple pyrolysis of a filter paper, and O-deficient reduced TiO$_{2-x}$ was prepared by the magnesiothermic reduction of commercial anatase TiO$_2$. Then, Pt-deposited reduced TiO$_{2-x}$ (Pt/rT) nanoparticles were loaded on the as-prepared carbon papers. The physicochemical properties of the Pt@reduced TiO$_{2-x}$-loaded carbon paper (Pt/rT-FPC) were measured. The adsorption of gas-phase CH$_3$CHO by the filter paper carbon (FPC) or Pt/rT-FPC and the visible light-induced photocatalytic oxidation of adsorbed CH$_3$CHO over the Pt/rT-FPC were investigated.

2. Experimental details

2.1. Preparation of carbon paper from filter paper

Carbon paper was prepared from a filter paper (Hyundai Micro Co., Ltd.). The filter paper was carbonized at 400, 600, 800, or 1000 °C for 2 h under continuous-flow Ar gas. The temperature was increased at the rate of 5 °C min$^{-1}$. The prepared samples are hereinafter denoted as FPC-x where x indicates the carbonization temperature. For comparison, two different carbon materials of CNFs prepared by a previously reported method\textsuperscript{32} and commercial activated carbon (MSC, MSC-30, Kansai Coke and Chemicals Co., Ltd, Japan) were also used as substrates.

2.2. Synthesis of reduced TiO$_{2-x}$ and preparation of reduced TiO$_{2-x}$-FPC

O-deficient reduced TiO$_{2-x}$ was synthesized by a magnesiothermic reduction of commercial anatase TiO$_2$ as previously reported.\textsuperscript{30,31} A 4 g sample of commercial anatase TiO$_2$ (CT, particle size <25 nm, Sigma Aldrich) was mixed with the desired amount of Mg powder. The mixed powder was placed in a tube furnace and heated at 500 °C for 8 h under flowing 3% H$_2$/Ar. After annealing, the Mg-treated sample was stirred in 2.0 M HCl solution for 1 day and then washed with distilled water and ethanol to remove MgO and other Mg impurities. The washed Mg-free reduced TiO$_{2-x}$ samples were dried at 80 °C. Different reduced samples prepared with 0.5 and 0.75 molar ratios of Mg per molar amount of CT are denoted as rT-0.5 and rT-0.75, respectively. For comparison, a commercial photocatalyst of P25 TiO$_2$ (P25, Aerioxide) was also used.

Pt/rT photocatalysts were synthesized through the well-documented photodeposition method.\textsuperscript{33} The reduced TiO$_{2-x}$ photocatalyst (0.5 g L$^{-1}$) was dispersed in 10 vol% methanol, and a proper amount of x mole chloroplatinic acid hexahydrate solution was added dropwise to this dispersion under vigorous stirring for 30 min. The Pt : photocatalyst weight ratio was 0.005 : 1. The suspension was illuminated with UV light (300 W Xe arc lamp, Newport) through a 10 cm infrared (IR) water filter and a UV cutoff filter (\(\lambda > 325\) nm) for 30 min. The suspension was filtered using 0.45 μm polytetrafluoroethylene (PTFE) filters (Millipore), washed with methanol solution, and dried at 80 °C in an oven to obtain Pt/rT. The photocatalyst was then loaded on the FPC. A 5 mL suspension of photocatalyst in distilled water was pipetted onto the center of each FPC specimen. After the dispersion of the suspension, the FPC was dried at 80 °C in an oven. The mass of the photocatalyst (Pt/rT-FPC or Pt/rT) in the sample holder was approximately 10 mg for each loading.

2.3. Characterizations

Surface morphology images were obtained using a field-emission scanning electron microscope (FE-SEM, Hitachi S4-8020, Japan). Transmission electron micrographs were obtained on a high-resolution transmission electron microscope (HR-TEM, Hitachi HF-3300, Japan). X-ray diffraction (XRD) patterns were obtained with an X-ray diffractometer (Panalytical, Empyrean, 40 kV, 30 mA) using Cu K$_\alpha$ radiation (\(\lambda = 0.154178\) nm) and a quartz monochromator. Raman spectra of the samples were analyzed by a Raman spectrophotometer (Thermo Scientific, Nicolet Almega XR) in the wavenumber range of \(\sim 100\) to 4000 cm$^{-1}$ using a 532 nm laser. The Brunauer–Emmett–Teller (BET) surface areas were determined from the N$_2$ adsorption–desorption isotherms obtained at 77 K (ASAP 2020 Micromeritics). The surface compositions were measured by X-ray photoelectron spectroscopy (XPS, Thermo Scientific, Escalab 250Xi) using the Mg-Kz line (1253.6 eV) as the excitation source. The light absorption was analyzed by UV-visible diffuse reflectance spectroscopy (DRS) using a Cary series spectroscope (Cary 5000, Agilent Technologies).

2.4. Visible light-induced gas-phase CH$_3$CHO oxidation

Photocatalytic oxidation experiments were performed by two different methods of closed-circulation mode and continuous-flow mode. In closed-circulation mode, the photocatalytic oxidation of gaseous CH$_3$CHO was determined in a closed circulating stainless steel reactor with a volume of 150 cm$^3$ that could be divided into two parts (upper and lower) by a control valve, similar to the reactor in a previously reported experiment.\textsuperscript{34} The gases used were CH$_3$CHO (300 ppmv N$_2$) as a CH$_3$CHO standard, O$_2$ (99.99999%), and Ar (99.9999%) as the carrier gas. The concentrations of CH$_3$CHO and O$_2$ were 80 ppmv and 20%, respectively. A sample of reduced TiO$_{2-x}$-loaded FPC was placed in the lower reactor. Each sample weighed approximately 15 mg. The mixed gas passed through the empty upper reactor, and the concentration of CH$_3$CHO in the exit stream was monitored until it reached a constant value. The gas was then circulated in the reactor by the pump. Next, the circulated gas was passed through the lower reactor by using the valve to make contact with the surface of the sample in the lower reactor. After adsorption equilibrium with the surface of the sample was established in the dark, the sample was illuminated with UV light (150 W Xe arc lamp, Abet Technologies). The distance between the sample and the lamp was 15 cm, and a cut-off filter (\(\lambda > 295\) nm for UV irradiation or \(\lambda > 420\) nm for visible irradiation) was used. The removal of CH$_3$CHO was monitored using a gas chromatograph (GC, HP6890, Agilent) equipped with a Porapak Q column, a flame ionization detector.
(FID), a CO2 methanizer (Ni catalyst), and a gas-sampling valve. In the continuous-flow mode, the photocatalytic oxidation of gaseous \(\text{CH}_3\text{CHO}\) was performed in the same 150 cm\(^2\) stainless steel reactor without division. The mixed gas was fed to the reactor at the total flow rate of 100 mL min\(^{-1}\). The concentrations of \(\text{CH}_3\text{CHO}\) and \(\text{O}_2\) were 60 ppmv and 20\%, respectively. The gas residence time in the reactor was 1.5 min. All other experimental conditions were the same as those in the closed-circulation experiments.

3. Results and discussion

3.1. Characterization of FPCs

Fig. 1 shows photographs and SEM images of the filter paper and the FPC-600. The filter paper is obviously transformed to carbon paper, as shown in Fig. 1a and c. The filter paper and the FPC-600 both contain fibers with some degree of variation in diameter. The diameters of the fibers are not strongly affected by the carbonization, but do show slight shrinkage.

Fig. 2a shows the XRD patterns of the filter paper, FPC-600, and FPC-800. The filter paper pattern exhibits two major peaks, a weak diffraction peak centered at 15.1\(^{\circ}\) and a strong diffraction peak centered at 22.5\(^{\circ}\), which are consistent with previously reported results.\(^{24}\) The FPC patterns each exhibit one broad peak centered at 23\(^{\circ}\), indicating amorphous carbon.\(^{25}\) The intensities of the diffraction peaks are increased as the temperature of carbonization is increased. Fig. 2b shows the Raman spectra of the filter paper and the FPCs. The FPC spectra show two characteristic peaks centered at 1350 cm\(^{-1}\) and 1580 cm\(^{-1}\) corresponding to the D and G bands, respectively.\(^{26}\) These characteristic peaks become sharper and more intense with increased carbonization temperature. The D and G bands are associated with the vibrations of sp\(^2\) carbon atoms with dangling bonds; the integrated intensity ratio (I\(_D\)/I\(_G\)) corresponds to the degree of graphitization. The I\(_D\)/I\(_G\) ratios for FPC-400, FPC-600, FPC-800, and FPC-1000 are 0.62, 0.65, 0.89, and 0.96, respectively. This implies increasing structural order in the FPC with increasing carbonization temperature, consistent with the results reported for other cellulose materials.\(^{27}\) The XRD patterns and Raman spectra obviously demonstrate that graphitized carbon forms during carbonization, with increasing formation at higher carbonization temperatures.

The \(\text{N}_2\) adsorption–desorption isotherms of the filter paper and FPCs are shown in Fig. S1.\(^{†}\) The BET surface areas of the filter paper, FPC-400, FPC-600, FPC-800, and FPC-1000 were 4.31 m\(^2\) g\(^{-1}\), 13.57 m\(^2\) g\(^{-1}\), 466.81 m\(^2\) g\(^{-1}\), 461.60 m\(^2\) g\(^{-1}\), and 26.28 m\(^2\) g\(^{-1}\), respectively. The surface areas increase significantly for papers carbonized at temperatures of 400 and 800 \(^\circ\)C, and then decrease with the increase of temperature from 800 to 1000 \(^\circ\)C. The release of volatile compounds favors the formation of pores, which create the high surface areas of FPC-600 and FPC-800. At 1000 \(^\circ\)C, structural ordering and merging of pores decreases the surface area of the FPC.

3.2. Gas-phase \(\text{CH}_3\text{CHO}\) adsorption on FPCs

The capability of FPCs to adsorb gaseous \(\text{CH}_3\text{CHO}\) was compared with those of commercially available activated carbon (MSC), CNF, and non-carbonized filter paper. Fig. 3a shows that the dark adsorption of gaseous \(\text{CH}_3\text{CHO}\) on filter paper and CNF does not occur at all, whereas MSC exhibits strong dark adsorption of \(\text{CH}_3\text{CHO}\). However, FPC-800 shows better \(\text{CH}_3\text{CHO}\) adsorption than MSC does. The \(\text{CH}_3\text{CHO}\) adsorption may be influenced by the carbonization temperature. Therefore, the carbonization temperature-dependent adsorption of \(\text{CH}_3\text{CHO}\) is analyzed as shown in Fig. 3b. The FPCs, except FPC-1000, exhibit strong \(\text{CH}_3\text{CHO}\) adsorption. Fig. 3c shows the relationship between the amount of adsorbed \(\text{CH}_3\text{CHO}\) and the BET surface area. The dark adsorption capacity of \(\text{CH}_3\text{CHO}\) follows the order of FPC-600 > FPC-800 > FPC-400 > MSC > FPC-1000. Although the specific surface areas of FPCs are much lower than that of MSC, the adsorption capacities of FPCs, except that of FPC-1000, exceed that of MSC. The adsorption of \(\text{CH}_3\text{CHO}\) on the surfaces of the carbon materials depends on the surface chemistry as well as the microporosity.\(^{27}\) The atomic ratio of O in the FPCs is higher than that in MSC (Fig. S3\(^{†}\)). Therefore, enhanced adsorption of \(\text{CH}_3\text{CHO}\) appears in FPCs bearing O-containing functional groups. These results were obtained in the closed-circulation system. Similar tendencies were more clearly observed in the continuous-flow system during the photocatalytic oxidation experiments. Additionally, \(\text{CH}_3\text{CHO}\) showed no oxidation under UV irradiation on FPCs without photocatalyst.

3.3. Visible light-induced activity of reduced \(\text{TiO}_2\)\(_x\)

The visible light-induced photocatalytic oxidation of gas-phase \(\text{CH}_3\text{CHO}\) was further investigated using Pt/rT-FPC. Previously, reduced \(\text{TiO}_2\)\(_x\) exhibited high activity for the visible light-induced production of \(\text{H}_2\) (ref. 30) and photocatalytic reduction of \(\text{CO}_2\).\(^{31}\) In Fig. 4a, the reduced \(\text{TiO}_2\)\(_x\) samples clearly illustrate extended absorbance in the visible region as well as the UV region compared to that of commercial pristine \(\text{TiO}_2\)
which shows only UV-region absorption. Our previous work revealed that visible light absorption is related to the presence of Ti$^{3+}$. The absorption of light increases as the amount of Mg used in the reduction increases, as observed for rT-0.5 and rT-0.75; this is also reflected in the color change of the samples from white to yellow and gray for pristine TiO$_2$, rT-0.5, and rT-0.75, respectively. The XRD patterns of the different samples are presented in Fig. 4b. Despite the color changes, the reduced samples still show predominantly anatase-phase TiO$_2$. Although the XRD analysis indicates no major structural changes during Mg reduction, the Mg treatment probably induces modifications on the surfaces of the reduced TiO$_{2-x}$ particles, as reflected in the enhanced light absorption and color changes of the reduced samples. The magnesiothermic reduction of TiO$_2$ follows the reaction shown below. The strong reduction powder of Mg causes the pristine TiO$_2$ to lose the framework of O on the surface of the TiO$_2$ particles, generating reduced O-deficient TiO$_{2-x}$ and MgO. The light absorption in the visible region is increased, and the color darkens because of the increased surface modification of the reduced samples with increased amounts of Mg. In the given reaction conditions, this modification occurs only on the surface of the reduced sample;
thus, the inner part of the reduced sample has the anatase TiO₂ structure, as indicted by the XRD patterns in Fig. 4b.

\[ \text{TiO}_2 + \text{Mg} \rightarrow \text{TiO}_{2-x} + \text{MgO} \]  

(1)

The photocatalytic oxidation of CH₃CHO by reduced TiO₂₋ₓ under visible light was performed in continuous-flow mode. Fig. 5a shows the photocatalytic oxidation of CH₃CHO on reduced TiO₂₋ₓ and P25 TiO₂. The dark adsorption capacities on the surfaces of the reduced TiO₂₋ₓ and P25 TiO₂ are much lower than those of reduced TiO₂₋ₓ immobilized on the FPCs. Under visible irradiation, the concentration of CH₃CHO is only slightly reduced and CO₂ production is negligible. Under UV irradiation, however, the CH₃CHO is degraded and CO₂ immediately produced. The concentrations of CH₃CHO and CO₂ reach steady-state levels after several minutes, indicating that establishing adsorption–desorption equilibrium under UV illumination requires a long time. Meanwhile, the concentration of CO₂ on rT₋₀.₇₅ is higher than that on either P25 or rT₋₀.₅. This implies that the photocatalytic oxidation of CH₃CHO is faster on rT₋₀.₇₅. The CH₃CHO degradation and the CO₂ production under UV irradiation remain almost identical throughout repeated cycling. However, although the reduced TiO₂₋ₓ absorbs visible light, the visible light-induced photocatalytic oxidation of CH₃CHO occurs on neither rT₋₀.₅ nor rT₋₀.₇₅. This can be attributed to the rapid recombination of the electron–hole pairs produced under visible irradiation. Therefore, Pt must be photodeposited onto the reduced TiO₂₋ₓ surface for the efficient separation of the photo-generated electron–hole pairs.

Fig. 6 shows HR-TEM images of Pt/P25, Pt/rT₋₀.₅, and Pt/rT₋₀.₇₅. In all cases, Pt is deposited similarly. The photocatalytic oxidation of CH₃CHO on Pt-deposited P25 and reduced TiO₂₋ₓ was also investigated. As shown in Fig. 5b, under visible irradiation, the CH₃CHO is degraded with simultaneous CO₂ production on Pt/rT₋₀.₅. The concentrations of CH₃CHO and CO₂ do not reach a steady-state level because of the offsets of the adsorption and the photocatalytic oxidation of CH₃CHO. This implies that Pt deposition inhibits the recombination of charge carriers created by absorbing visible light and thereby enables visible light-induced CH₃CHO degradation. The photocatalytic reaction of CH₃CHO oxidation into CO₂ can be written as follows:

\[ \frac{\text{Pt/TiO}_2{-x}}{+} \text{hv} \rightarrow \hat{h}^+\text{(Pt/TiO}_2{-x}) + e^-\text{(Pt/TiO}_2{-x}) \]  

(2)

\[ \text{CH}_3\text{CHO} + 10\hat{h}^+\text{(Pt/TiO}_2{-x}) + 3\text{H}_2\text{O} \rightarrow 2\text{CO}_2 + 10\text{H}^+ \]  

(3)

\[ 2.5\text{O}_2 + 10e^-\text{(Pt/TiO}_2{-x}) + 10\text{H}^+ \rightarrow 5\text{H}_2\text{O} \]  

(4)

(\text{Total}) \text{CH}_3\text{CHO} + 2.5\text{O}_2 \rightarrow 2\text{CO}_2 + 2\text{H}_2\text{O} \]  

(5)

On Pt/rT₋₀.₇₅, the CH₃CHO is degraded but no CO₂ is observed, which could be attributed to the production of some undetected intermediates by the visible light-induced
degradation of CH$_3$CHO. Meanwhile on Pt/P25, CH$_3$CHO is not degraded under visible irradiation. The photocatalytic degradation rates of CH$_3$CHO on Pt/P25, Pt/rT-0.5, and Pt/rT-0.75 under UV irradiation are much higher than those under visible irradiation. Compared to the results obtained in the absence of Pt, the photocatalytic activities for CH$_3$CHO degradation under UV irradiation are not significantly enhanced. This implies that UV light-induced charge separation occurs efficiently on P25, rT-0.5, and rT-0.75, so the effect of Pt deposition is not significant. Moreover, the CH$_3$CHO degradation and the CO$_2$ production under UV irradiation remain almost identical throughout repeated cycling, as with the results obtained in the absence of Pt.

3.4. Visible light-induced gas-phase CH$_3$CHO oxidation

The visible light-induced photocatalytic oxidation of gas-phase CH$_3$CHO using reduced TiO$_2$-x-loaded FPC was investigated. Based on the above results, we investigated visible light-induced gas-phase CH$_3$CHO oxidation using the Pt-deposited photocatalysts and FPC-600. We observed cross-sectional SEM images and analyzed the elemental composition of the Pt/rT-0.5 loaded on the FPC-600 by energy-dispersive X-ray spectroscopy (EDS) mapping, as shown in Fig. 7a and 8b. The Pt/rT-0.5 is well loaded and easily distinguishable on the FPC-600. The amount of Pt/rT-0.5 nanoparticles on the surface of the FPC-600 is indirectly calculated from the thermogravimetric analysis (TGA) results (Fig. S2†). Fig. S2a† shows that the decomposition of Pt/rT-0.5 loaded on FPC-600 begins at approximately 400 °C and stops at 500 °C. The weight loss of Pt/rT-0.5 loaded on the FPC-600 is approximately 47%.

Fig. 8 shows the photocatalytic oxidation of CH$_3$CHO on Pt/rT-0.5, Pt/rT-0.75, and Pt/P25 loaded on FPC-600 in closed-circulation mode. All cases show strong dark adsorption of
CH$_3$CHO, similar to the dark adsorption of CH$_3$CHO on the FPC without Pt/rT-0.5, Pt/rT-0.75, or Pt/P25. Upon visible irradiation, the Pt/rT-0.5 loaded on the FPC-600 shows rapid degradation of CH$_3$CHO and simultaneous generation of CO$_2$. The photocatalytic oxidation of CH$_3$CHO on Pt/rT-0.5-FPC-600 is also performed in continuous-flow mode under repeated experiments, as shown in Fig. 9. The photocatalytic oxidation of CH$_3$CHO to CO$_2$ is strongly dependent on the flow rates of 25, 50, and 100 mL min$^{-1}$, which relate directly to the residence times of 6, 3, and 1.5 min, respectively. For all cases, the concentration of CH$_3$CHO does not reach steady-state levels within 30 min. At the highest flow rate, CO$_2$ production is rapidly saturated and its concentration remains constant under repeated experiments. However, at the lowest flow rate, the concentration of CO$_2$ does not reach a steady-state level but CO$_2$ production from the photocatalytic oxidation of CH$_3$CHO is dramatic, possibly because of the longer residence time. The photocatalytic oxidation of CH$_3$CHO to CO$_2$ was repeated up to six times. The result demonstrates the good stability of Pt/rT-0.5-FPC-600. Investigations to improve the operation conditions are needed for photocatalytic oxidation applications. Even with a small amount of Pt/rT-0.5, the photocatalytic oxidation of CH$_3$CHO under visible irradiation occurs in a few minutes. The FPC-600 efficiently adsorbs the CH$_3$CHO, and Pt/rT-0.5 rapidly and completely degrades the CH$_3$CHO to CO$_2$, even under visible irradiation. It is also possible that some electrons are transferred to the carbon paper, which would promote electron–hole pair separation; this implies that the carbon paper could function as an electron-transfer mediator as well as a support material. A schematic of the visible light-induced photocatalytic degradation of gas-phase CH$_3$CHO using reduced TiO$_2$-x-loaded FPC is shown in Fig. 10.

Fig. 9 Dark adsorption and photocatalytic oxidation of CH$_3$CHO on the Pt/rT-0.5-FPC-600 under visible irradiation in continuous-flow mode.

Fig. 10 Schematic of the visible light-induced photocatalytic degradation of gas-phase CH$_3$CHO using reduced TiO$_2$-x-loaded carbon paper.
4. Conclusion

In this work, visible light-induced gas-phase CH\(_3\)CHO degradation on Pt/reduced TiO\(_2\)\(_x\)-loaded FPC was examined for the first time. The FPC was synthesized by the simple pyrolysis of filter paper; its surface area was strongly affected by the carbonization temperature. Although the specific surface areas of the FPCs were much lower than that of commercial MSC, the adsorption rate and capacities of FPCs outperformed those of MSC. The O-deficient reduced TiO\(_2\)-x prepared by the Mg-H\(_2\) reduction of commercial anatase TiO\(_2\) showed increased visible light absorption; it was successfully utilized as the active material for visible light-induced photocatalysis. The reduced TiO\(_2\)-loaded FPC showed rapid degradation of CH\(_3\)CHO and simultaneous generation of CO\(_2\) in both closed-circulation and continuous-flow modes under visible irradiation, clearly demonstrating that the reduced TiO\(_2\)-x-loaded FPC described in this work is a suitable candidate for the visible light-induced photocatalytic degradation of gas-phase CH\(_3\)CHO.

Conflicts of interest

There are no conflicts of interest to declare.

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