

## Article

# Experimental Investigation on the Reaction Characteristics between Ozone and Vehicle Cabin/Furniture Materials

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**Abstract:** Volatile organic compounds (VOCs) emitted from building and vehicle cabin materials seriously affect indoor and in-cabin air quality, as well as human health. Previous studies revealed that some VOCs from building materials could react with ozone to affect the concentration levels of the indoor environment, but seldom refers to vehicle cabin materials. In this study, we performed experimental investigation for two kinds of vehicle cabin materials (car carpet, sealing strip) and one furniture material (medium-density fiberboard) by conducting small-scale chamber tests under two different conditions, with ozone (about 110  $\mu\text{g}/\text{m}^3$ ) and without ozone (about 10  $\mu\text{g}/\text{m}^3$ ), to explore the effect of in-cabin chemistry on VOC emissions. We observed the VOC concentration changes in the two scenarios and found that ozone had a significant impact on the concentrations of aldehydes and ketones while having little impact on the concentrations of benzene series. We introduced a gain ratio to quantitatively reflect the concentration changes in the presence of ozone. The gain ratio for aldehydes and ketones is greater than one, while that for the benzene series is basically around one with a small fluctuation range. This study demonstrates that ozone can react with VOCs containing unsaturated carbon-carbon bonds or carbon-oxygen bonds emitted from varied materials to produce aldehydes and ketones, which will further reduce indoor and in-cabin air quality.

**Keywords:** ozone; vehicle cabin material; furniture material; volatile organic compounds (VOCs); in-cabin air quality



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## 1. Introduction

People spend about 87% of their time indoors, with an average of about 1.5 h a day in cars. Indoor and in-cabin air quality has an important impact on people's comfort, health, and work efficiency [1–5]. More than 100 volatile organic compounds (VOCs) have been detected in the indoor environment [6], and the VOCs emitted from building materials are responsible for poor indoor air quality. The VOCs with high concentrations and adverse health effects mainly include benzene, toluene, xylene, ethylbenzene, styrene, formaldehyde, acetaldehyde, acrolein, and some other pollutants stipulated in the Chinese national standard GB/T 27630 [7]. According to the statistics of the World Health Organization in 2015, about 4.3 million people die every year worldwide due to indoor and in-cabin air pollution, which is comparable to that of outdoor pollution [8,9]. Formaldehyde has a strong irritating odor, and its toxicity is mainly manifested in the nervous system and respiratory system symptoms. When indoor formaldehyde level reaches 0.1  $\text{mg}/\text{m}^3$ , it can cause throat discomfort or pain, and when the concentration is higher, it can cause nausea, vomiting, and even death [10]. Therefore, conducting in-depth research on VOCs in indoor and in-cabin environments is of great importance to control and improve air quality.

The VOCs in indoor environments not only come from the physical emissions of materials [11] but also are related to the chemical reactions of other substances in materials with strong oxidizing compounds such as ozone and hydroxide [12–14]. Observing and

understanding indoor chemical reactions is very important for studying indoor air quality. Previously, some scholars conducted in-depth research on ozone/body chemistry [15–23]. Ozone, hydroxyl, and other substances can react with squalene and unsaturated fatty acids on indoor people's skin to generate VOCs, which pose great risks to human health [15,16]. Among them, ozone is a very powerful oxidizing agent that can react rapidly with certain classes of organics, especially those containing unsaturated carbon–carbon bonds and carbon–oxygen bonds [24]. These reactions result in the emergence of a series of volatile oxidation products. Some researchers performed experimental studies on the reaction between ozone and building materials and recorded the ozone removal rate on the surface of different materials, as well as the primary and secondary VOC emissions [25–27]. Nicolas et al. [28] selected carpet, gypsum board, and pine wood board as reaction materials and placed them, respectively, in environmental chambers in the presence and absence of ozone, and found that the concentrations of some VOCs, e.g., formaldehyde and nonanal, increased significantly when exposed to ozone. Schripp et al. [29] reported the emission amounts of monoterpenes, organic acids, and aldehydes in a series of wood-building products, paints, and exotic wood samples, and observed that the emission amounts of VOCs varied in different degrees.

The prior experimental studies mentioned above are mainly focused on the reaction between indoor building materials and ozone, while very few studies refer to the reaction between vehicle cabin materials and ozone. Although people spend less time in cabins than indoors, the concentration levels of VOCs in the in-cabin environment are generally higher than those in the indoor environment [30,31]. Especially in the hot summer season, when the vehicle is exposed to the sun, the VOC emissions will increase significantly. The in-cabin environment has become a special microenvironment that cannot be ignored [32–34]. It should be noted that the air quality in the vehicle also has an important impact on people's health. Therefore, it is still necessary to study the reaction of ozone with vehicle cabin materials.

In view of this, this study performs an experimental observation on the reaction of ozone with two kinds of vehicle cabin materials (car carpet and seal strip), as well as one kind of furniture material (medium-density fiberboard), to examine the emissions of aldehydes and ketones, and benzene series. We further analyze the VOC concentration levels emitted from each material and explore the reaction behaviors of ozone with each material, to provide some data for the in-depth mechanism study of reactions in the in-cabin environment.

## 2. Experiments and Methods

### 2.1. Tested Materials

Three materials were selected for the experiments, i.e., two vehicle cabin materials (car carpet, sealing strip), and one wood-based material used for manufacturing furniture (medium-density fiberboard, MDF). Before the experiment, these materials had been wrapped with plastic wrap and placed in airtight bags for some time, to maintain uniform internal concentration. In addition, five sides of the tested materials were sealed with tin foil so that VOCs could be released just from one side, forming a one-dimensional diffusion within it, as shown in Figure 1. The detailed material dimensions and experimental conditions are summarized in Table 1.



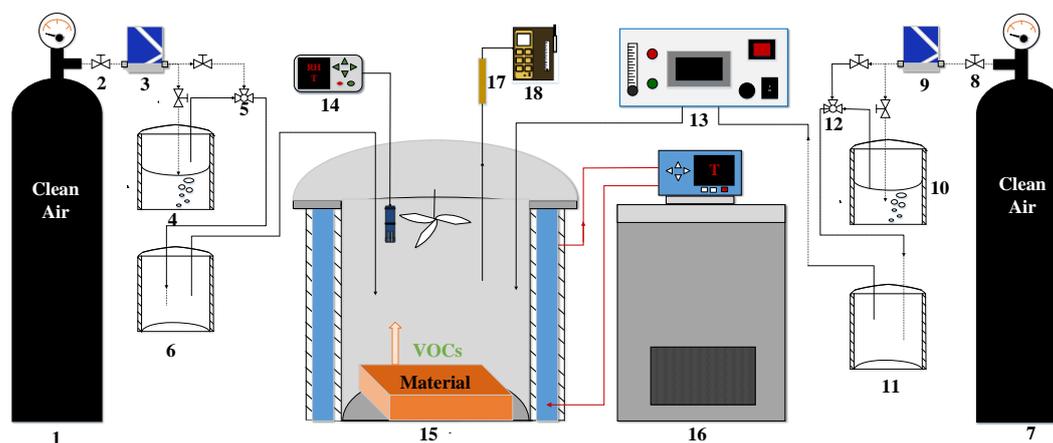
**Figure 1.** Schematic of the wrapped sealing on five sides of the tested material.

**Table 1.** Detailed test material dimensions and experimental conditions.

Tested Materials	Temperature	Relative Humidity	Dimensions (cm × cm)
Car carpet	23.6 °C	50%	15 × 12
Sealing strip	25.0 °C	50%	12 × 8
Medium-density fiberboard (MDF)	25.0 °C	50%	10 × 10 (3 pieces)

## 2.2. Experimental System

The experimental system mainly includes the following parts: a 30 L stainless steel chamber, flowmeter, temperature and humidity control system, temperature and humidity sensor, gas cylinder, and ozone generator. According to standard of the American Society for Materials and Testing (ASTM), the chamber was made of stainless steel with fully polished internal wall, to minimize the adsorption and desorption effect of VOC gas molecules onto the inner wall of the chamber. To make the gas evenly distribute in the chamber and simulate the indoor/in-cabin environment to a great extent, a fan was installed in the chamber during the whole experiment. To ensure the tightness of the chamber under working conditions, the cover of the chamber was tightly fitted on the chamber with bolts and rubber rings. A schematic diagram of the experimental system is shown in Figure 2.



**Figure 2.** Schematic of the volatile organic compounds (VOCs) emission and reaction testing system. 1: gas cylinder; 2: valve; 3: mass flow controller; 4: humidification tank; 5: three-way valve; 6: empty tank; 7: gas cylinder; 8: valve; 9: mass flow controller; 10: humidification tank; 11: empty tank; 12: three-way valve; 13: ozone generator; 14: temperature and humidity sensor; 15: chamber; 16: water bath; 17: sampling tube; 18: sampling pump.

The 30 L chamber meets the standards of ISO 16000-9 and ASTM D5116-97. The inner chamber is 430 mm in height, 300 mm in diameter, and made of 304 stainless steel. After polishing, it can effectively avoid the influence of VOC wall adsorption on concentration monitoring. The chamber is divided into two parts: chamber cover and chamber body. There is a fan at the top of the cover. Through the agitation of the fan blade, the concentration of VOC in the chamber is uniform. There is an empty cavity area outside the chamber body for water bath circulation, and the two interfaces of the cavity are symmetrical and are connected with the water bath by the rubber hose. During the experiment, we used the water bath to control the temperature and use the humidity control system (humidification tank, three-way valve, and empty tank) to control the humidity in the chamber, so as to avoid the influence of temperature and humidity changes on VOC concentration.

## 2.3. Procedures of Experiments and VOC Analysis

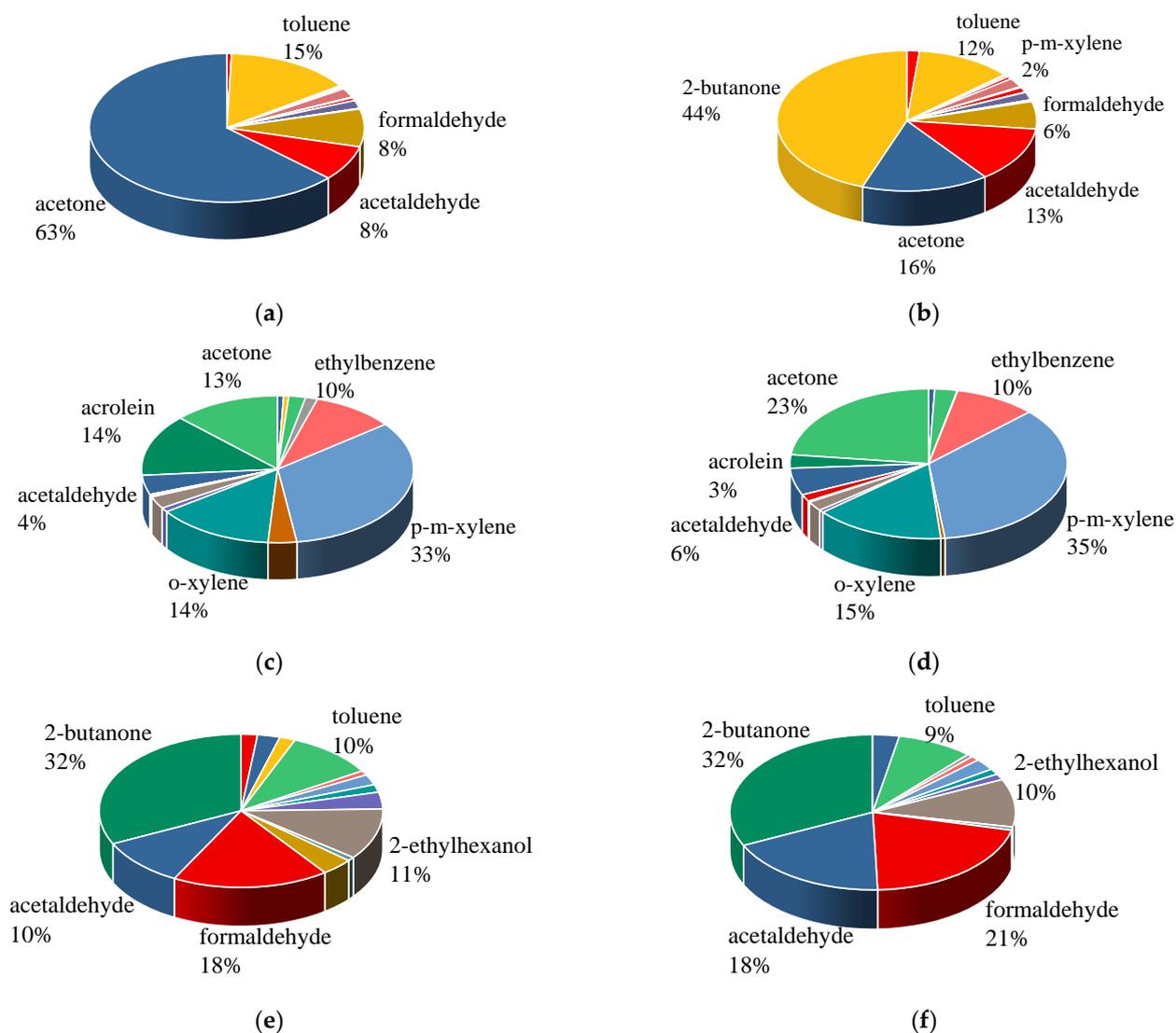
The experimental process includes two stages: airtight condition and ventilated condition. Firstly, the tested material, as the VOC emission source, was put inside the airtight chamber to emit for 13 h. According to the results of pre-experiments, the VOC concen-

tration in the airtight chamber basically reached an equilibrium in about 13 h. When the VOC concentration reached equilibrium, clean air was introduced into the chamber. For the experimental group without ozone, the VOC emission from material is a physical process, and the concentration will show a downward trend. The chamber was ventilated at a constant air exchange rate (AER). The AER is an important factor affecting in-cabin air quality. Chaudhry et al. [35] conducted experiments on a school bus parked outdoors, and found that when the school bus was stationary with windows closed, the AER was between 2.10 and 6.71/h. Ott et al. [36] observed that when the vehicle speed was between 32–116 km/h and the ventilation system was closed, the AER was less than 7/h. Therefore, an AER of 4/h is selected in this study. For the ventilated condition, two groups of parallel experiments were designed to compare the emission of VOCs due to reaction. For one group (ozone-free), 99.9% pure air was introduced into the chamber, and for the other group (ozone-present), air containing constant ozone generated by a portable ozone generator (CH-ZTW) was introduced into the chamber. For the ozone-free group, the airflow rate was 2 L/min. For the ozone-present group, the flow rate of pure air from the cylinder was 1.5 L/min air, which was then mixed with ozone (flow rate was 0.5 L/min). In the ozone-free experiments, the ozone concentration was between 7.9 and 11.8  $\mu\text{g}/\text{m}^3$  for the three materials, and the average concentration was 9.9  $\mu\text{g}/\text{m}^3$ . While in the ozone-present experiments, the ozone concentration was between 97.1 and 134.2  $\mu\text{g}/\text{m}^3$ , and the average concentration was 109.6  $\mu\text{g}/\text{m}^3$ . The reason for selecting these levels of ozone concentration was that a field test on a realistic vehicle, conducted by us [37], found that the ozone concentration was around 10  $\mu\text{g}/\text{m}^3$  when the car was stationary with closed windows, and was around 107  $\mu\text{g}/\text{m}^3$  when the car was ventilated with windows open.

An ozone monitoring instrument (2B-205) was used to measure the ozone concentration at the outlet of the chamber at the time of 0 h, 1 h, 2 h, 3 h, 4 h, 5 h, 7 h, 9 h. After 9 h of ventilation, the VOC concentration level in the chamber was very low, so there might be a large measurement uncertainty if sampling continued. Therefore, sampling concentration within 9 h of the ventilation condition was selected for analysis and discussion. Subsequently, Tenax-TA (for VOCs excluding aldehydes) or DNPH (for aldehydes) tubes were connected to the outlet of the chamber to sample the gas-phase VOCs using a sampling pump. These sampling tubes were analyzed using gas chromatography/mass spectroscopy (GC-MS, Agilent Technologies, 7890A/5975C) or high-performance liquid chromatography (HPLC, Shimadzu, LC-15C) to obtain concentration data of VOCs in the chamber. For HPLC sampling tube, the detection limit of single compound concentration was 0.002  $\text{mg}/\text{m}^3$ . The Tenax-TA tube collected two samplings at each time point and took the average value of the two samplings as the concentration of VOCs in the gas phase.

### 3. Results and Discussion

The VOC concentrations in different experiments were analyzed. The target VOCs include benzene series, aldehydes, and ketones. The benzene series include n-hexane, benzene, trichloroethylene, toluene, octene, butyl acetate, ethylbenzene, p-m-xylene, nonane, o-xylene, styrene, 2-ethylhexyl alcohol, undecane, tetradecane, and cetane. Aldehydes and ketones include formaldehyde, acetaldehyde, acrolein, acetone, propionaldehyde, butenal, 2-methacrolein, 2-butanone, butyraldehyde, benzaldehyde, valeraldehyde, m-methylbenzaldehyde, and hexanal. The results are shown in Figure 3. It can be seen that for different materials, the main type of emitted VOCs is not the same. This is due to the difference in the raw material for each tested material: the main raw material of the car carpet is leather and polyester sponge; the main raw material of the sealing strip is rubber; the main raw material of the MDF is wood fiber and resin glue.



**Figure 3.** Comparison of experimental data for (a) car carpet under ozone-free condition; (b) car carpet under ozone-present condition; (c) sealing strip under ozone-free condition; (d) sealing strip under ozone-present condition; (e) medium-density fiberboard (MDF) under ozone-free condition; (f) MDF under ozone-present condition.

### 3.1. VOC Compositions of Different Materials

For the car carpet shown in Figure 3a, the top four VOCs of the ozone-free group are acetone, toluene, formaldehyde, and acetaldehyde, accounting for 94% in total (the average gas-phase concentration of the sampled data within 9 h is used). As shown in Figure 3b, the top six VOCs of the ozone-present group are 2-butanone, acetaldehyde, acetone, toluene, formaldehyde, and p-m-xylene. It accounts for 93% of the total. VOC concentrations increased from  $734.75 \mu\text{g}/\text{m}^3$  in the absence of ozone to  $1039.27 \mu\text{g}/\text{m}^3$  in the presence of ozone by 41.4%. Aldehyde and ketone concentrations accounted for 79% of the total amount under both the ozone free and present conditions, which has a greater effect on the overall concentration change. Since the temperature and humidity of the two groups of experiments are the same, the material is cut from the same material, and the material size and the emission area are the same, the initial emission concentration of the two groups can be approximately considered to be the same. The change in the total amount indicates that the presence of ozone does have a significant impact on the concentration levels of VOCs in the environmental chamber. The most obvious changes are two VOCs, 2-butanone and acetone.

For the sealing strip, the change in the total amount also indicates that the presence of ozone greatly affects the concentration level of VOCs in the chamber. For the ozone-free group, as shown in Figure 3c, the top six VOCs are p-m-xylene, acrolein, o-xylene, acetone, ethylbenzene, and acetaldehyde, taking up 88% in total. For the ozone-present group, as shown in Figure 3d, the top six VOCs are p-m-xylene, o-xylene, acetone, ethylbenzene, acetaldehyde, and acrolein, taking up 92% of the total. VOC concentrations increased from 1339.69  $\mu\text{g}/\text{m}^3$  for the ozone-free group to 1454.73  $\mu\text{g}/\text{m}^3$  for the ozone-present group, with an increase of 8.6%. The levels of benzene and benzene series took up 68% and 67% of the total concentrations under the ozone free condition and the ozone present condition, respectively. The reaction between ozone and the material can be characterized by a Criegee mechanism, which is reflected in the reaction between ozone and carbon–carbon double bond [38,39]. For the benzene series, the number of double bonds is small, and the amount of reaction is relatively small, so the change in VOC concentrations is not obvious for the sealing strip.

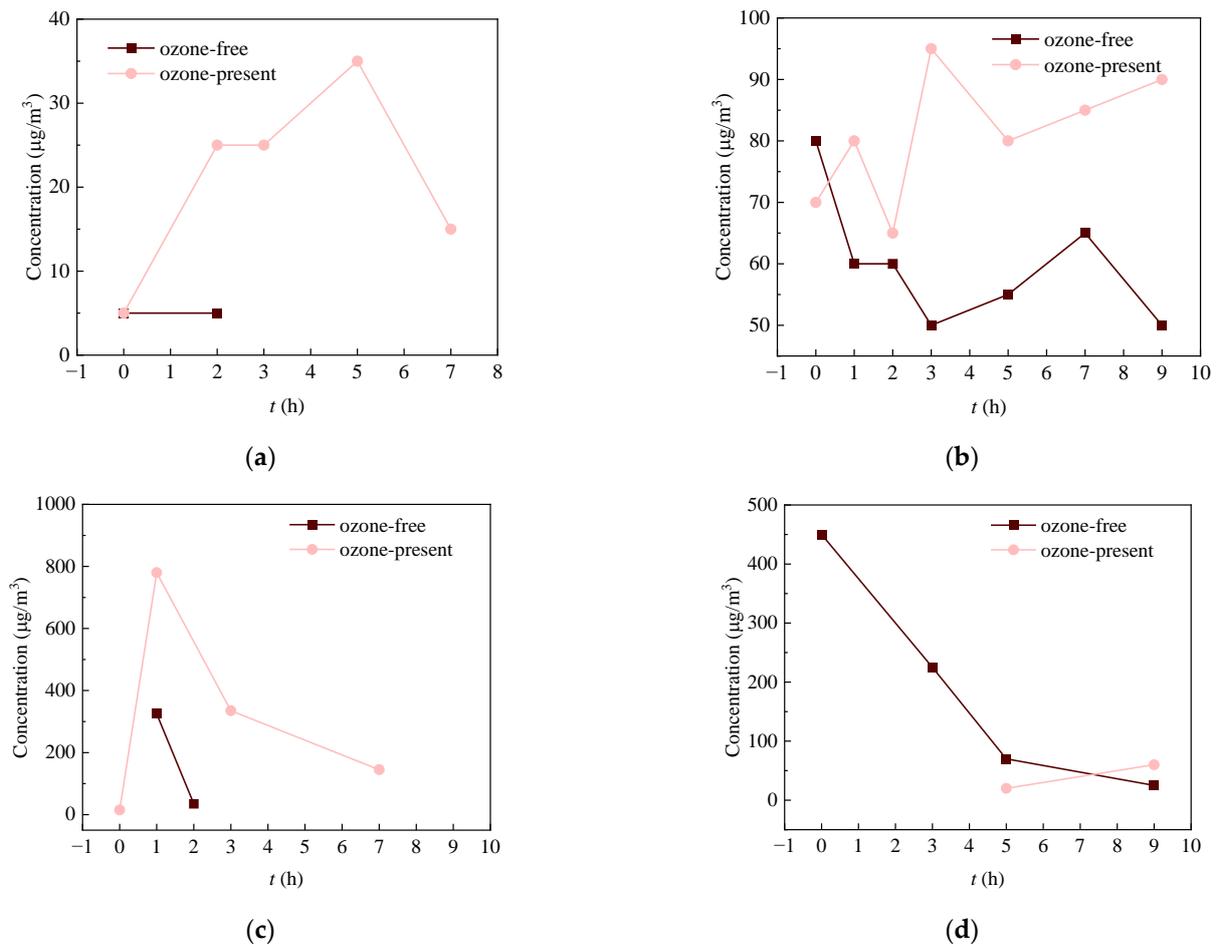
For MDF, in the ozone-free scenario shown in Figure 3e, the top five VOCs are 2-butanone, formaldehyde, acetaldehyde, 2-ethylhexanol, and toluene, accounting for 81% of the total. In the ozone-present scenario shown in Figure 3f, the top five VOCs are 2-butanone, formaldehyde, acetaldehyde, 2-ethylhexanol, and toluene, accounting for 90% of the total. VOC concentrations increased from 365.15  $\mu\text{g}/\text{m}^3$  in the absence of ozone to 384.25  $\mu\text{g}/\text{m}^3$  in the presence of ozone by 5.2%. The relatively small variation implies that the sensitivity of MDF to ozone is low. Aldehyde and ketone concentrations accounted for 60% of the total amount in the absence of ozone and 71% in the presence of ozone, respectively. The increase in the total amount reveals that the presence of ozone does impact the concentration level of VOCs in the chamber, meaning ozone-initiated chemistry happens.

### 3.2. Comparative Analysis of Concentration Changes for Some Typical Aldehydes and Ketones in Different Tested Materials

#### (1) Sealing strip

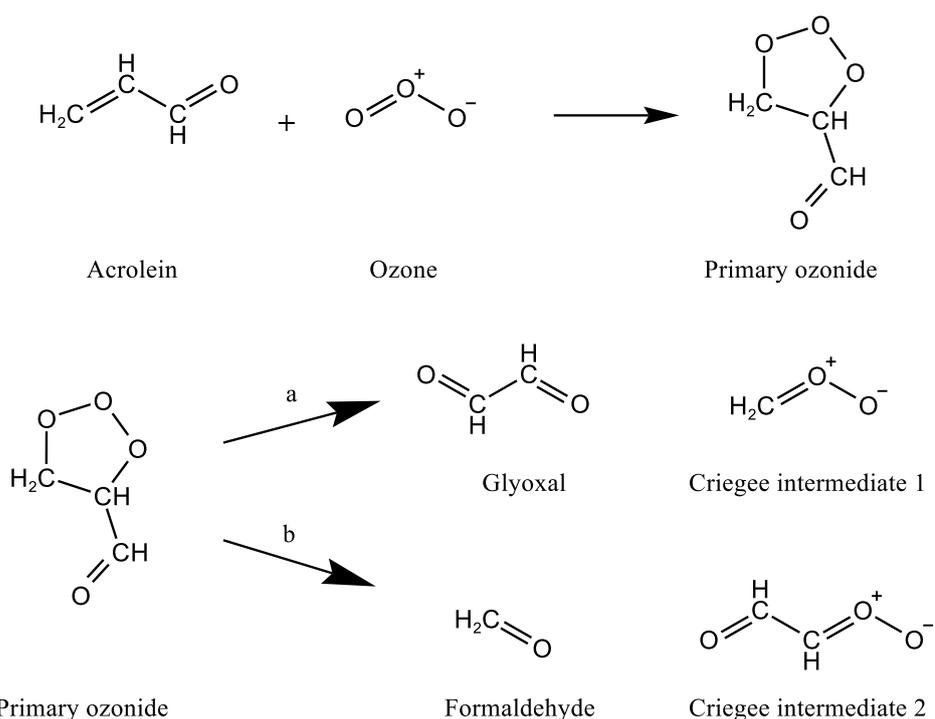
Since the tested material was put inside the airtight chamber and emitted for 13 h before it was changed to the ventilated condition, the concentration of pollutants at the beginning of ventilated condition was not zero. For the ozone-free group (average ozone concentration of 11.8  $\mu\text{g}/\text{m}^3$ ), the formaldehyde concentration level is very low (about 5  $\mu\text{g}/\text{m}^3$ ), as shown in Figure 4a. For the ozone-present group (average ozone concentration of 97.1  $\mu\text{g}/\text{m}^3$ ), Figure 4a shows that the formaldehyde concentration is low at the beginning, but then increases significantly with the introduction of ozone, reaching the highest 35  $\mu\text{g}/\text{m}^3$ , and then decreases. The change tendency for acetaldehyde is given in Figure 4b. As can be seen in this figure, at the initial stage, there is little difference in the gas-phase concentration under the two conditions. With time by introducing ozone, the acetaldehyde concentration for the ozone-present scenario is significantly higher than that for the ozone-free scenario.

In Figure 4c, the concentration of acetone in the sealing strip is higher in the presence of ozone, and lower in the absence of ozone. It can be seen from Figure 4d that the concentration of acrolein is extremely low at high ozone concentration. However, in the case of no ozone, the concentration is high at the initial stage and then decreases with the flow out of the chamber through ventilation. In both cases, the difference in acrolein concentration may be due to the carbon–carbon bond and carbon–oxygen bond in the structure of acrolein, which can be easily oxidized by ozone to produce new substances.



**Figure 4.** Comparison of experimental data for ozone reaction with sealing strip (a) formaldehyde; (b) acetaldehyde; (c) acetone; (d) acrolein.

According to the Criegee ozonation reaction [38–42], ozone can react rapidly with olefins in the material. The change in acrolein concentration in the present study was comparable to the previous studies in the atmospheric chemistry community [43]. As shown in Figure 5, the acrolein-ozone reaction is triggered by the electrophilic addition of ozone to the unsaturated carbon–carbon bond, which then breaks down the 1,2,3-trioxane adduction monomolecular into two carbon groups, formaldehyde and glyoxal, and two Criegee intermediates (CIs).  $\text{CH}_2\text{OO}$  can be combined with the carbon–carbon bond and carbon–oxygen bond of acrolein to form a five-membered cycloadd mixture, and the most competitive reaction channel is  $\text{CH}_2\text{OO}$  on the carbon–oxygen bond to form a secondary ozonide (SOZ) [44]. At low pressure, some of SOZ decompose into formic acid + acrolein or formaldehyde + acrylic acid. Based on these reactions, the concentration of formaldehyde and other VOCs in the chamber increased.

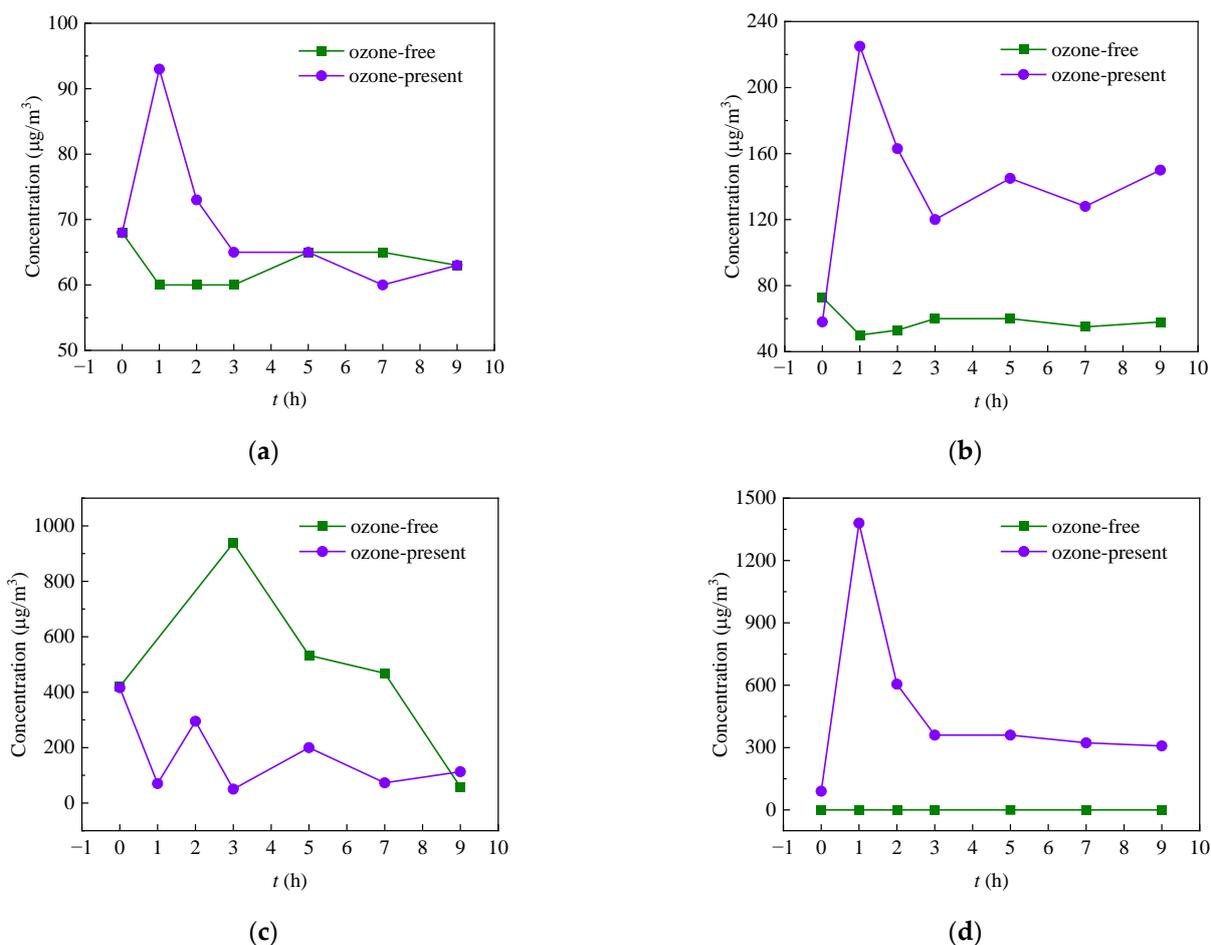


**Figure 5.** Possible reaction pathway of acrolein with ozone, and a and b represent two possible combinations of a carbonyl and a biradical.

## (2) Car carpet

Through the detection of ozone concentration at each sampling point, we observed that the average ozone concentration within 9 h (ventilated condition) in the chamber with pure air was 10.0 µg/m<sup>3</sup>. At such a low ozone concentration, the formaldehyde concentration does not change significantly over time, as shown in Figure 6a. The reason may be that the formaldehyde emitted by the material is roughly the same as the amount of formaldehyde leaving the chamber. In the ventilated chamber with the presence of ozone, the average ozone concentration within 9 h is 134.2 µg/m<sup>3</sup>. At such a high ozone concentration, the formaldehyde concentration shows a trend of first rising and then falling. Formaldehyde concentration reaches its maximum after 1 h of ventilation. It is preliminarily inferred that the upward trend may be due to the reaction of ozone with certain compounds containing carbon–carbon double bonds (terminal) to produce formaldehyde, which may subsequently be similar to the low ozone concentration level because of the reduction of the initial reactant and less production rate than the ventilation loss rate (AER of 4/h).

For the ozone-present group shown in Figure 6b, acetaldehyde concentration also shows a trend of rising first and then stabilizing, which clearly demonstrates the influence of ozone on these typical pollutants in vehicle cabins. Formaldehyde and acetaldehyde are typical products of the reaction between ozone and unsaturated VOCs emitted from car carpets. Therefore, their concentrations are expected to increase in the presence of ozone. By comparing Figure 6a,b, we can see that the increase in the concentration of acetaldehyde is more significant than that of formaldehyde. This suggests that a major precursor is a compound with a double bond at the 2 sites.



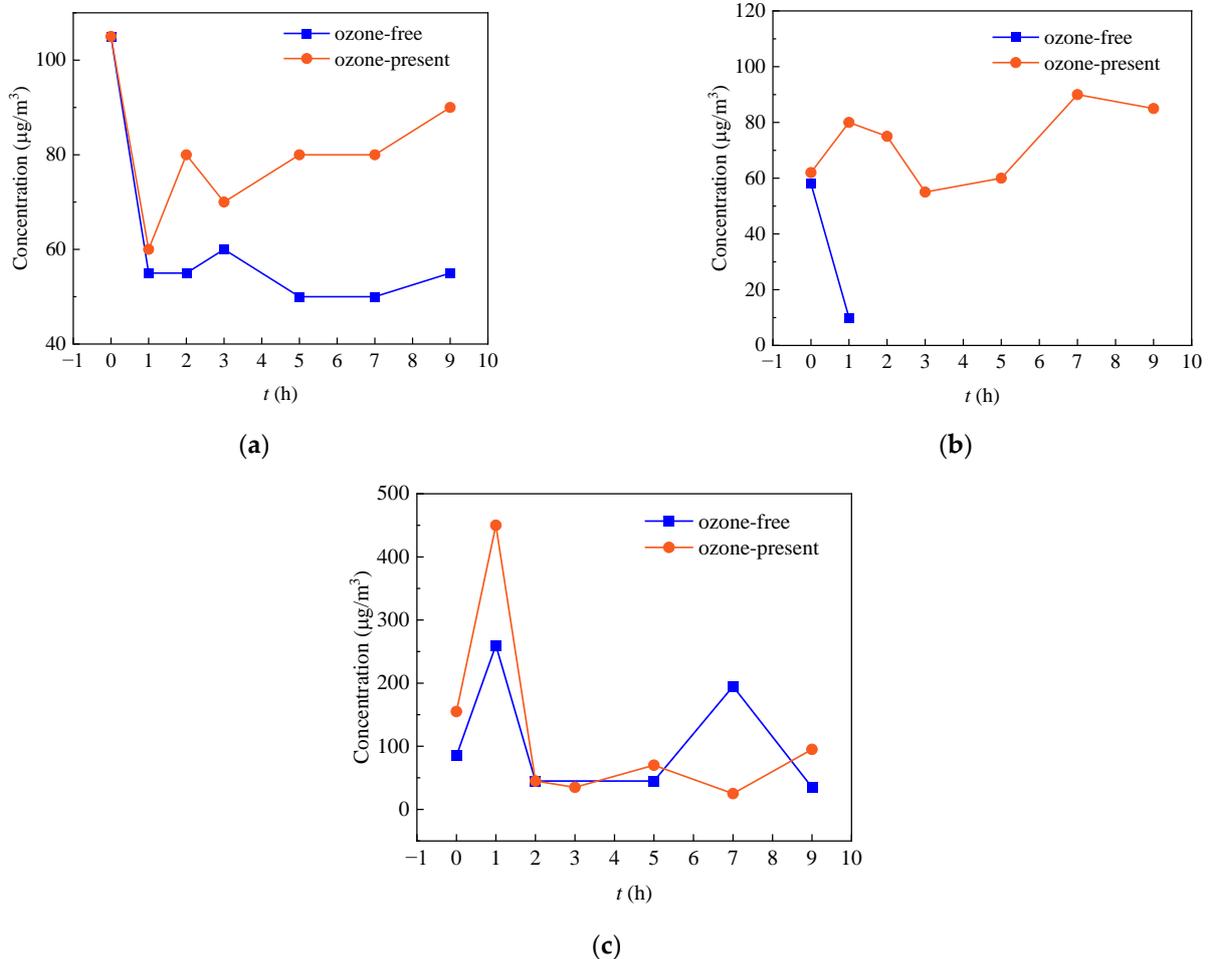
**Figure 6.** Comparison of experimental data for ozone reaction with car carpet (a) formaldehyde; (b) acetaldehyde; (c) acetone; (d) 2-butanone.

For acetone, its concentration showed different changes, as shown in Figure 6c. In the presence of ozone, the concentration of acetone was relatively low, while in the absence of ozone, the concentration was relatively high. The change in 2-butanone concentration in Figure 6d more vividly shows the effect of ozone on the concentration of gaseous pollutants. In the absence of ozone, the concentration of 2-butanone was near zero in the outlet gas. However, in the presence of ozone, a certain level concentration of 2-butanone was detected at the initial point. The preliminary conclusion may be that the reaction produced less 2-butanone because the ozone was just injected for a short time. Subsequently, the yield of 2-butanone was roughly equal to the loss of ventilation, and the concentration showed a slow decline.

### (3) MDF

Different from the vehicle cabin materials, the main emitted aldehydes and ketones of the MDF for manufacturing indoor furniture are formaldehyde, acetaldehyde, and some other pollutants with very low concentrations. As can be seen from Figure 7a, there is little difference in formaldehyde concentration between the two ozone concentrations in the first 2 h after ventilation begins, while formaldehyde concentration increases by about 60% at high ozone concentration after ventilation begins. At a high ozone concentration ( $97.3 \mu\text{g}/\text{m}^3$ ), the overall concentration of formaldehyde is higher. At low ozone concentration ( $7.9 \mu\text{g}/\text{m}^3$ ), acetaldehyde concentration decreases gradually as shown in Figure 7b. At high ozone concentration, acetaldehyde concentration increases to about  $90 \mu\text{g}/\text{m}^3$ . Figure 7c gives the results for 2-butanone. The concentration of 2-butanone of MDF is slightly higher in the presence of ozone than that in the absence of ozone, and the average

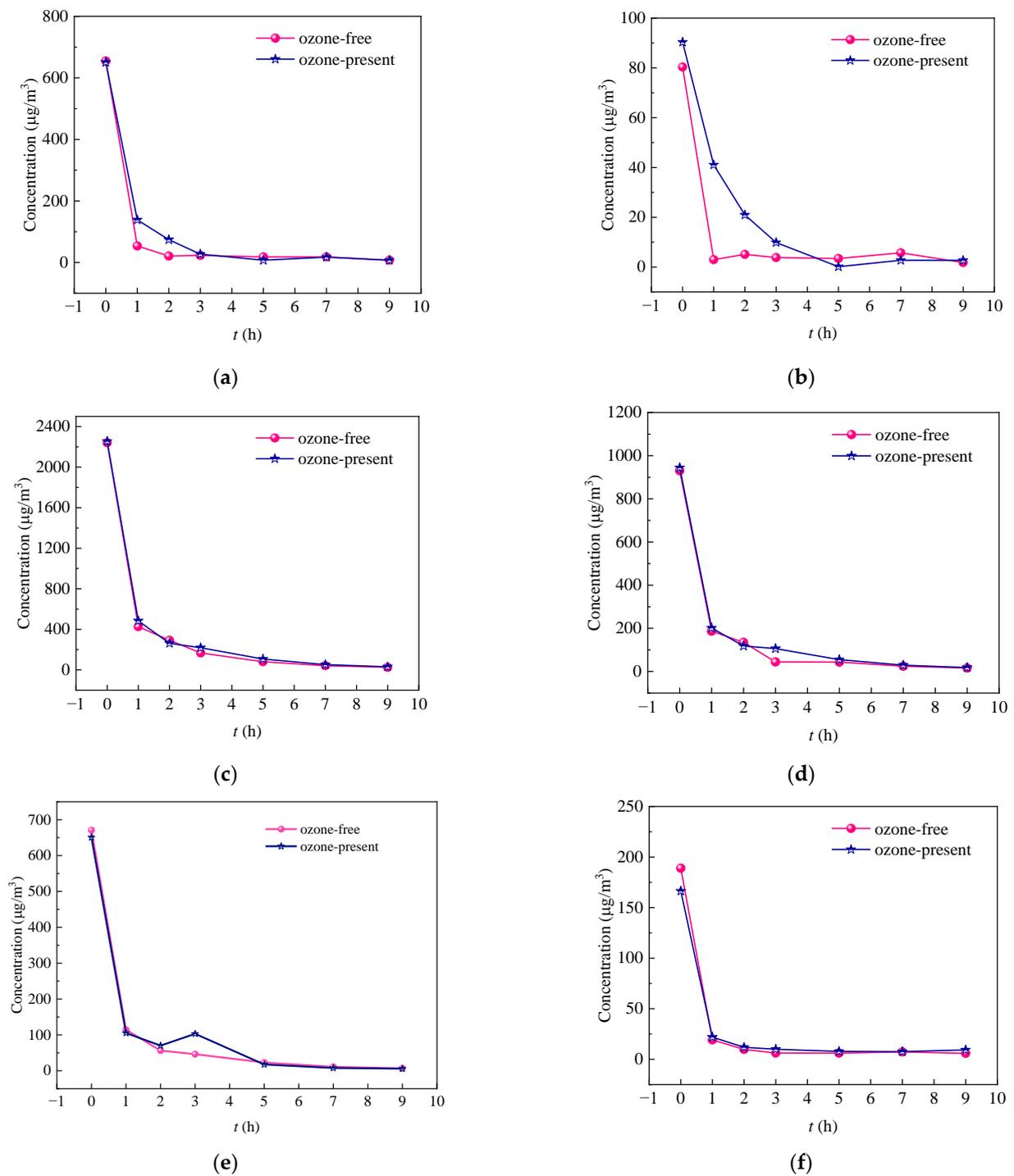
concentration of ventilation is 12.8% higher than in the presence of ozone. In addition, in the presence of ozone for 1 h, its concentration is 73% higher than that in the presence of ozone.



**Figure 7.** Comparison of experimental data of for ozone reaction with MDF (a) formaldehyde; (b) acetaldehyde; (c) 2-butanone.

### 3.3. Comparative Analysis of Concentration Changes for Benzene Series in Different Tested Materials

The benzene series was also tested in the experiments. We found that ozone had little influence on the benzene series selected in our experiment. Figure 8 shows the results for different material-VOC combinations. For car carpets, toluene and p-m-xylene are selected for analysis, since their concentrations are at relatively high levels compared with other compounds. For these benzene series, there is little difference between the ozone-present case and the ozone-free case, which may be related to the structure of the benzene series. Benzene rings are exceptionally stable, which is not easy to react with ozone and is unlikely to be the reaction product of some precursor substances with ozone. For the combinations of sealing strip and MDF with some typical benzene series, the change patterns are almost the same due to similar reasons.



**Figure 8.** Comparison of experimental data for different material/VOC combinations (a) car carpet/toluene; (b) car carpet/p-m-xylene; (c) sealing strip/p-m-xylene; (d) sealing strip/o-xylene; (e) sealing strip/ethylbenzene; (f) MDF/toluene.

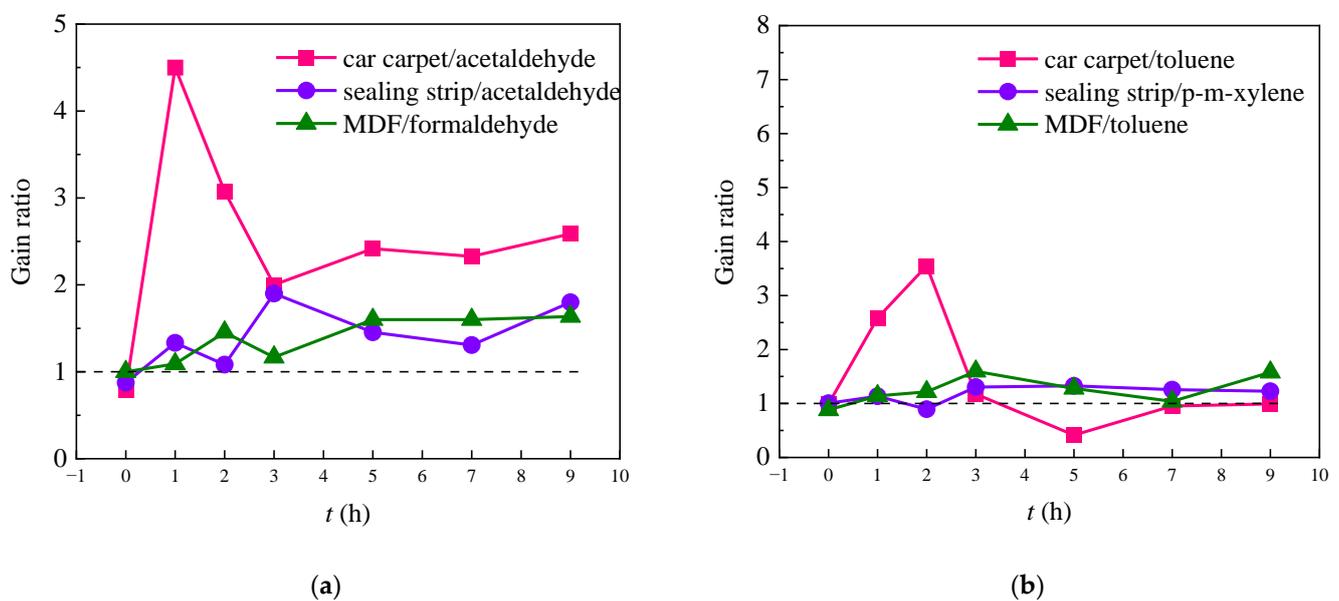
### 3.4. Calculation of Gain Ratio for the Oxidized Products

In order to quantitatively describe the influence of ozone on VOC concentrations in the tests, we introduce a gain ratio for analysis. It is defined as the ratio of VOC concentrations in the presence of ozone to that in the absence of ozone ( $\varphi$ ), which is expressed as:

$$\varphi = \frac{C_{\text{ozone-pre}}}{C_{\text{ozone-abs}}} \quad (1)$$

where  $C_{\text{Ozone-pre}}$  is the VOC concentrations in the presence of ozone,  $\mu\text{g}/\text{m}^3$ ;  $C_{\text{Ozone-abs}}$  is the VOC concentrations in the absence of ozone,  $\mu\text{g}/\text{m}^3$ .

Several VOCs with obvious concentration changes among the three tested materials were selected for calculation, e.g., acetaldehyde of car carpet, acetaldehyde of sealing strip, and formaldehyde of MDF. Figure 9a gives the results for aldehydes and ketones, which indicates that the  $\varphi$  values are greater than one during the whole ventilated stage. In Figure 9b, the  $\varphi$  values of the benzene series are listed. It can be seen from this figure that the  $\varphi$  values are all basically around one with a small fluctuation range, implying that the benzene series are not sensitive enough to the change in ozone concentration. This quantitative analysis effectively demonstrates that the increase in the concentration of aldehydes and ketones is related to the reaction between ozone and precursor substances containing unsaturated carbon–carbon bonds or carbon–oxygen bonds, and ozone is not easy to react with benzene series or to form benzene series with some precursor substances.



**Figure 9.** The gain ratio of different VOCs in the three tested materials (a) aldehydes and ketones; (b) benzene series.

It should be noted that this study just performed a preliminary experimental investigation on the reactions between ozone and vehicle cabin/furniture material. According to previous studies on the physical emission of VOCs from materials [45,46], temperature, humidity, air exchange rate, and loading ratio will impact the VOC concentration levels in the chamber or indoor environment. Some researchers explored the relationship between temperature, humidity, and indoor concentration (or emission rate, or key emission parameters) [11]. Some other experimental studies showed that increasing air exchange rates and controlling the type of building materials used in home construction could decrease indoor formaldehyde concentrations in new homes [47,48]. The humidity (water vapor) might also impact the fates of some reactions [49]. For the present study, although we just examined the reactions between ozone and material in a certain temperature and humidity (a specific case), the methods and procedures could be used to explore the reaction characteristics under other environmental conditions.

#### 4. Conclusions

In this study, we made an experimental observation to explore the reaction behaviors of ozone with varied materials in in-cabin and indoor environments. Two kinds of vehicle materials (car carpet, sealing strip) and one kind of indoor furniture material (MDF) were selected for the tests. Results indicate that, for different materials, the main VOCs released are not completely the same. For car carpets and MDF, the main VOCs are aldehydes and

ketones, while there are benzene series for the sealing strip. We observe that the concentrations of various aldehydes and ketones are greatly affected by the concentration of ozone, while the concentrations of benzene series containing only carbon atoms and hydrogen atoms do not change under the condition of different ozone levels. Some possible reaction mechanisms are applied to analyze the different change phenomena. Future research will examine the impact of some environmental factors (e.g., temperature, humidity, AER) on the reaction characteristics, deeply and quantitatively uncover the reaction mechanism and process principle, as well as model the reaction process between ozone and various vehicle cabin materials.

**Author Contributions:** Conceptualization, Y.G. and J.X.; methodology, Y.G., H.W. and J.X.; formal analysis, H.W.; investigation, Y.G. and M.Z.; writing—original draft preparation, Y.G.; writing—review and editing, M.Z., H.W. and J.X.; visualization, Y.G. and H.W.; funding acquisition, J.X. All authors have read and agreed to the published version of the manuscript.

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