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Theoretical study on the generation of Criegee intermediates from the ozonolysis of trifluoropropene (CF₃CH=CH₂)

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The O₃-initiated degradation mechanisms of trifluoropropene (CF₃CH=CH₂) were studied using density functional theory (DFT). Three types of mechanisms were observed for the title reaction, namely, addition/elimination, H-abstraction and substitution. The computations showed that O₃ with a C=C bond undergoes a 1,3-cycloaddition reaction to generate a primary ozone intermediate (POZ) with a relatively low free energy barrier, which then dissociates to generate an aldehyde group and carbonyl oxide, known as Criegee intermediates (CIs). Detailed analysis was conducted on the subsequent reactions of CIs. It is found that when a new type of CI-containing halogenated alkyl groups reacts with NO, NO₂, CH₂O, SO₂, H₂O and O₂, its reaction pathway is singularly analogous to that of the general CI. The degradation total rate coefficient and the estimated lifetime are in accordance with the experimental results. The current calculation results are of great significance for the atmospheric chemistry of the ozone oxidation of unsaturated halogenated compounds.

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1. Introduction

The international community has realized that chlorofluorocarbons (CFCs) can have adverse effects on stratospheric ozone and induce greenhouse effects, urging researchers to work towards finding environmentally friendly alternatives to these compounds.^{1,2} Due to the absence of chlorine atoms in hydrofluorocarbons (HFCs), they are not conducive to the establishment of a good chlorine-based catalytic ozone-depletion cycle.³ Therefore, saturated hydrofluorocarbons (HFCs) have proven to be the extensively employed alternatives to CFCs. Unsaturated HFCs are latent alternatives to CFCs and saturated HFCs. The oxidation of the unsaturated HFCs could be induced by reactions with OH,⁴⁻⁶ O₃ (ref. 7–10) and NO₃ (ref. 9, 11 and 12) radicals in the atmosphere. Ozone decomposition in the atmosphere is one of the common oxidation channels for unsaturated hydrocarbons, which plays a significant role in both the city and the countryside.¹³ The reaction between O₃ and unsaturated HFCs has been proven to involve the addition of double-bond systems to generate an ozonide, which rapidly dissociates to generate carbonyl oxides (Criegee intermediates (CI)) and aldehyde

compounds. The reactions involving propylene and halogenated propylenes have recently attracted substantial experimental attention.¹⁴⁻²² Only one research group has investigated the kinetics of the reaction of CF₃CH=CH₂ with O₃. In 2005, Sulbaek Andersen *et al.*¹⁷ investigated the kinetics and mechanism of the reaction of CF₃CH=CH₂ with O₃ in an N₂ atmosphere at 296 K by employing long-path-length FT-IR-smog chamber techniques. The measured rate constant of CF₃CH=CH₂ with O₃ at 1 atm and 298 K is $k_{\text{CF}_3\text{CH}=\text{CH}_2+\text{O}_3} = (3.50 \pm 0.30) \times 10^{-19} \text{ cm}^3 \text{ per molecule per s}$. The atmospheric lifetime of CF₃CH=CH₂ is approximately 70 days due to the reaction with O₃. Unfortunately, thus far, the reaction between O₃ and CF₃CH=CH₂ has not been well established theoretically. In the present work, to assess the oxidation reaction of CF₃CH=CH₂ induced by ozone, the reaction mechanism and the secondary pathways in the presence of NO, NO₂, CH₂O, H₂O, SO₂ and O₂ are investigated by employing theoretical methods, which have been extensively employed in the environmental area.²³⁻³¹ The rate constants of primary reaction pathways are predicted using the Rice–Ramsperger–Kassel–Marcus (RRKM) theory³² to forecast the atmospheric lifetime.

Up to date, very little is known about the final products and mechanisms of O₃ with trifluoropropene (CF₃CH=CH₂). Moreover, the data on the Criegee intermediates with an aldehyde group and a trifluoromethyl group are scarce. Hence, we investigate the ozonolysis of trifluoropropene using quantum chemical methods. This work provides a comprehensive study on the reaction between trifluoropropene and ozone, which contributes to the literature on the mechanism of the primary step of ozone decomposition and the further reaction of CI. The research data in this work can help us evaluate the impact of these compounds on the atmosphere.

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2 Computational methods

All the electronic structure computations for the $\text{CF}_3\text{CH}=\text{CH}_2 + \text{O}_3$ reaction were performed using the Gaussian 09 program.³³ The geometries of all stable points (including reactants, complexes, transition states, intermediates, and products) were

optimized using the M06-2X³⁴ method in combination with the 6-311++g(d,p) basis set,^{35,36} and the vibrational frequency analysis computations were performed at the same level. All the minima have real frequencies, while the transition states have only one imaginary frequency. Intrinsic reaction coordinate (IRC)^{37,38} computations were carried out to determine the

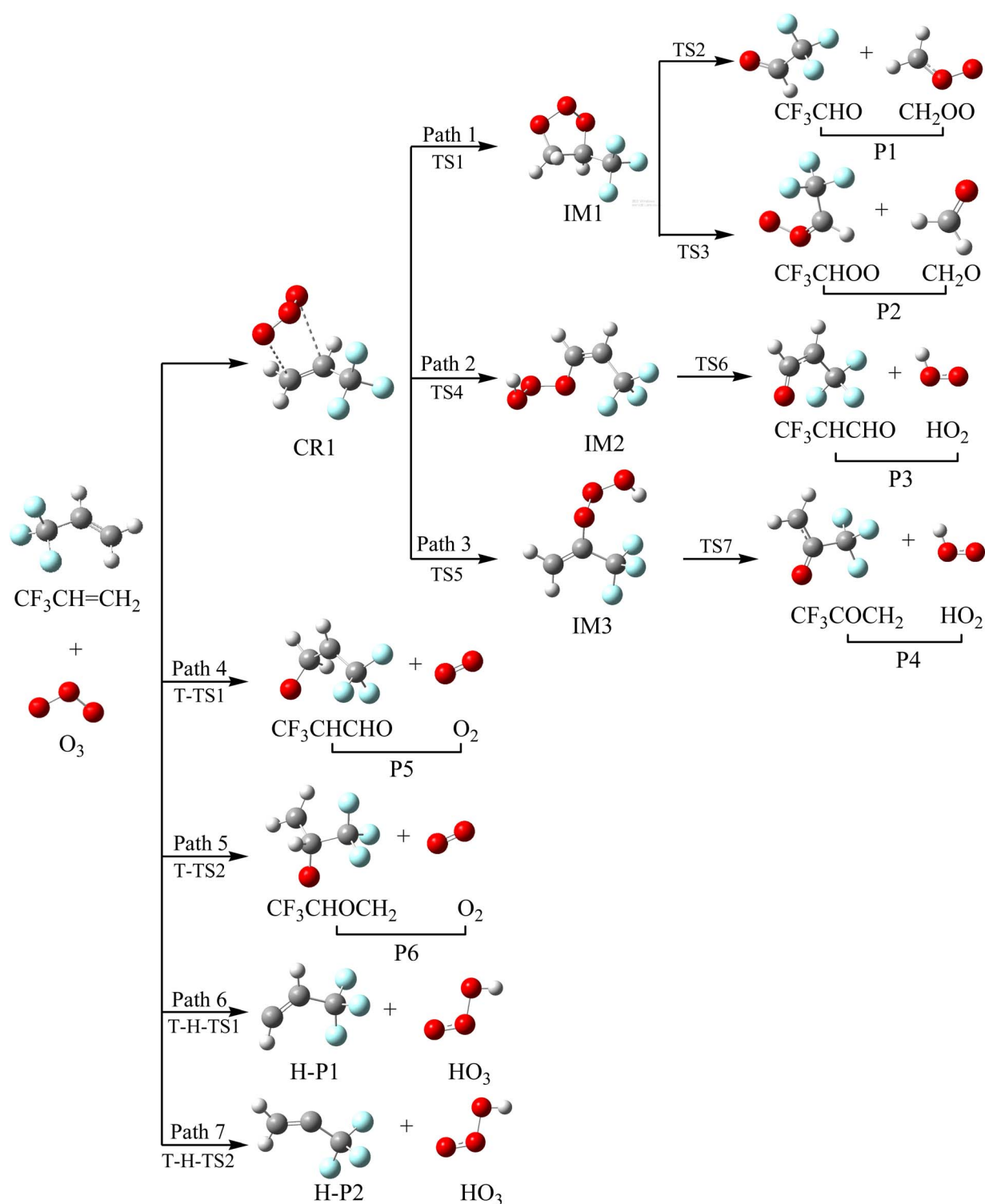


Fig. 1 Optimized geometries and reaction schematic of the trifluoropropene ($\text{CF}_3\text{CH}=\text{CH}_2$) with ozone reaction.



transition states connecting the corresponding reactants and products. The CCSD(T)³⁹//cc-pVTZ method was employed for all the species involved in the CF₃CH=CH₂ + O₃ reaction to obtain accurate single-point energies.

3 Results and discussion

Taking the reaction between trifluoropropene and ozone as an example, we describe the generation mechanism of POZ (primary ozone intermediate) and CIs (Criegee intermediates). All the optimized structures of the reactants, products and intermediates and the reaction schematics for the trifluoropropene with ozone reaction are presented in Fig. 1. All the transition states involved in the CF₃CH=CH₂ + O₃ reaction at the M06-2X/6-311++g(d,p) level of theory are presented in Fig. S1. As can be seen from Fig. 1, the reaction of CF₃CH=CH₂ with O₃ has a total of seven pathways, which mainly include three reaction mechanisms, namely addition/elimination, substitution and hydrogen abstraction. The potential energy surface (PES) of the CF₃CH=CH₂ + O₃ reaction is presented in Fig. 2, and R in Fig. 2 represents the CF₃CH=CH₂ + O₃. Table 1 summarizes the relative energies, reaction enthalpies and

Gibbs free energy of all the species involved in the trifluoropropene with ozone reaction.

3.1 Reaction mechanism of addition/elimination

As seen from Fig. 1, the two terminal oxygen atoms of the ozone molecule can simultaneously interact with the C=C bond in CF₃CH=CH₂ to generate the pre-complex (CR1). The relative energy of CR1 is -28.47 kcal mol⁻¹, and the ΔG is -18.50 kcal mol⁻¹. Subsequently, CR1 surmounts a free energy barrier of 9.61 kcal mol⁻¹ through a transition state (TS1) to generate the primary ozone intermediate, a five-membered ring structure (IM1). The lengths of the two generated C-O bonds in TS1 are 2.20 and 2.22 Å. The two generated C-O bonds in IM1 have equal bond lengths of 1.41 Å. The generation of the intermediate (IM1) released a large amount of heat (81.84 kcal mol⁻¹). The energy-rich intermediate (IM1) (80.50 kcal mol⁻¹) could overcome the free energy barriers of 20.30 and 27.45 kcal mol⁻¹ to generate P1 (CF₃CHO + CH₂OO (CI1)) and P2 (CF₃CHOO (CI2) + CH₂O), respectively. The transition states corresponding to the above two direct decomposition processes are TS2 and TS3, respectively. The lengths of the broken C-C and O-O bonds in TS2 and TS3 are 1.952 and 2.032 Å and 1.971 and 2.079 Å, respectively. The energies of P1 and P2 are lower

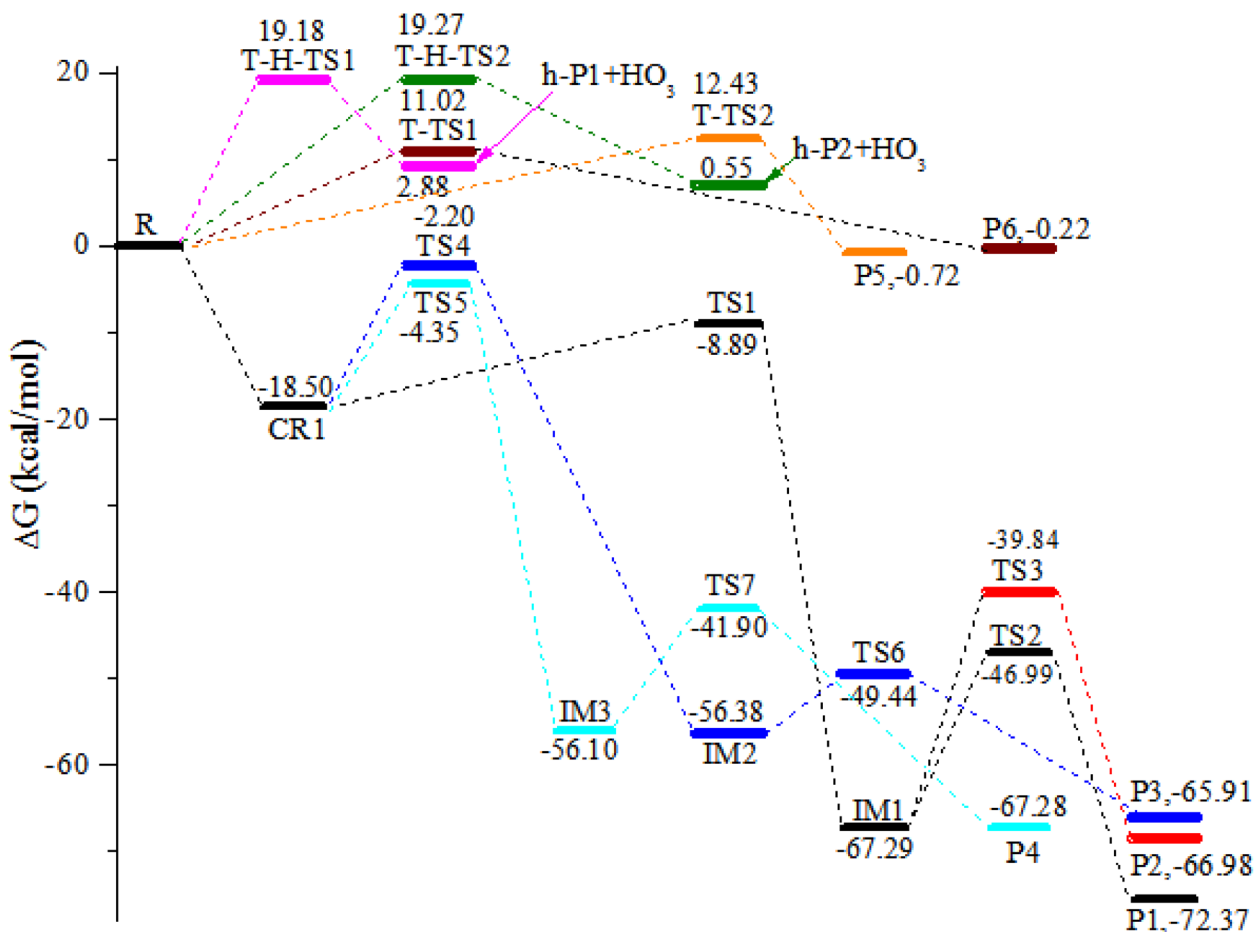


Fig. 2 Potential energy surface for the reaction of trifluoropropene (CF₃CH=CH₂) with ozone calculated at the CCSD(T)//cc-pVTZ//M06-2X/6-311++g(d,p) level of theory.



Table 1 Relative energies, reaction enthalpies and Gibbs free energy of all the species involved in the trifluoropropene with ozone reaction at 298 K (in kcal mol⁻¹)

Species	ΔE	ΔH	ΔG
CF ₃ CH=CH ₂ + O ₃	0.00	0.00	0.00
CR1	-28.47	-28.10	-18.50
IM1	-80.50	-81.84	-67.29
IM2	-67.81	-68.25	-56.38
IM3	-68.34	-68.91	-56.10
TS1	-21.35	-22.17	-8.89
TS2	-59.96	-61.07	-46.99
TS3	-52.75	-53.80	-39.84
TS4	-14.69	-15.58	-2.20
TS5	-16.64	-17.32	-4.35
TS6	-62.09	-63.02	-49.44
TS7	-53.09	-53.38	-41.90
T-TS1	0.75	0.61	11.02
T-TS2	1.83	1.67	12.43
T-H-TS1	9.24	9.32	19.18
T-H-TS2	9.42	9.56	19.27
P1	-75.46	-72.52	-72.37
P2	-68.37	-68.10	-66.98
P3	-65.81	-65.29	-65.91
P4	-68.08	-68.07	-67.28
P5	-2.41	-1.90	-0.72
P6	-1.28	-0.74	-0.22
H-P1 + HO ₃	9.30	4.30	2.88
H-P2 + HO ₃	7.05	2.12	0.55

than those of the reactants by 75.46 and 68.37 kcal mol⁻¹, respectively. At the same time, 72.52 and 68.10 kcal mol⁻¹ of heat are released to generate P1 and P2, respectively.

Starting from CR1, a terminal oxygen atom in the O₃ molecule is added to the two carbon atoms of the C=C double bond in CF₃CH=CH₂. Thereafter, the H atoms in the -CH₂ and -CH groups shift to the other terminal oxygen atom in the O₃ molecule *via* transition states TS4 and TS5, respectively. The free energy barriers of CR1 → TS4 → IM2 and CR1 → TS5 → IM3 are 16.30 and 14.15 kcal mol⁻¹, respectively. The energies of IM2 and IM3 are -67.81 and -68.34 kcal mol⁻¹, respectively. IM2 and IM3 can generate the final products (P3: CF₃CHCHO + HO₂ and P4: CF₃COCH₂ + HO₂) through TS6 and TS7, respectively, by breaking the O-O bond. The free energy barriers for IM2 → TS6 → P3 and IM2 → TS7 → P4 are 6.94 and 14.20 kcal mol⁻¹, respectively. However, because of the relatively high energy barriers for the addition process, the contribution of these two addition/elimination channels to the reaction may be relatively small, which will be proven in Section 3.5 (see Fig. 11).

3.2 Reaction mechanism of substitution

One of the end-group oxygen atoms in the O₃ molecule is also added to the carbon atoms of the C=C double bond in CF₃CH=CH₂, which is associated with the breaking of the O-O bond to generate P5 (CF₃CHOCH₂ + O₂(¹Δ)) and P6 (CF₃-CHCH₂O + O₂(¹Δ)) *via* triplet transition states T-TS1 and T-TS2, respectively. The corresponding free energy barriers for R → T-TS1 → P5 and R → T-TS2 → P6 are 11.02 and 12.43 kcal mol⁻¹,

respectively; hence, the importance of this channel for the reaction may be at higher temperature.

3.3 Reaction mechanism of hydrogen abstraction

It is worth mentioning that we did not find a transition state for hydrogen extraction on the singlet PES. While on the triplet PES, it was found that ozone can extract the hydrogen atoms on the -CH₂ and -CH groups in the CF₃CH=CH₂ molecule to generate products H-P1 + HO₃ and H-P2 + HO₃ *via* transition states T-H-TS1 and T-H-TS2, respectively. The two hydrogen abstraction reactions have free energy barriers of 19.18 and 19.27 kcal mol⁻¹, respectively. The lengths of the broken C-H bonds in T-H-TS1 and T-H-TS2 are 1.281 and 1.289 Å, respectively, and the lengths of the generated O-H bonds are 1.212 and 1.202 Å, respectively. The energies of H-P1 + HO₃ and H-P2 + HO₃ are 9.30 and 7.05 kcal mol⁻¹, respectively. Owing to the relatively high free energy barriers and unstable products, the contributions of the hydrogen extraction reaction channels on the triplet PES to the reaction are negligible.

3.4 Further reactions of the Criegee intermediates

The different Criegee intermediates resulting from the ozonation of trifluoropropene are named CI1 (CH₂OO) and CI2 (CF₃CHOO). CI1 is commonly found in the reaction of O₃ with olefins. The optimized structures of CI1 and CI2 are shown in Fig. 3. The calculated bond lengths of C-O and O-O in CI1 (CH₂OO) are consistent with the results observed in the previous investigation.⁴⁰ CI2 is a new class of CIs with aldehyde groups, and it may have different properties. Therefore, this section presents the reaction mechanisms of CI2 with NO, NO₂, SO₂, CH₂O, H₂O and O₂. In CI2, the carbon atom in the -CH group is the electrophilic reagent. Therefore, the nucleophilic atoms of NO, NO₂, SO₂, CH₂O, H₂O and O₂ tend to attack the C atom, and the corresponding reaction proceeds, and the PESs are presented in Fig. 4-9 and S2-S7, respectively. All the transition states involved in the reactions of CF₃CHOO with NO, NO₂, CH₂O, H₂O, SO₂ and O₂ at the M06-2X/6-311++g(d,p) level of theory are presented in Fig. S8. These results indicate that the final products from the CI reactions are common atmospheric substances, such as saturated trifluoroacetaldehyde, trifluoroacetic acid and formic acid, as the content of SOA. The present study enriches the literature on the types of CIs and plays a significant role in controlling atmospheric chemical pollution, which will be discussed in detail in the following sections.



Fig. 3 Optimized structure of the Criegee intermediates.



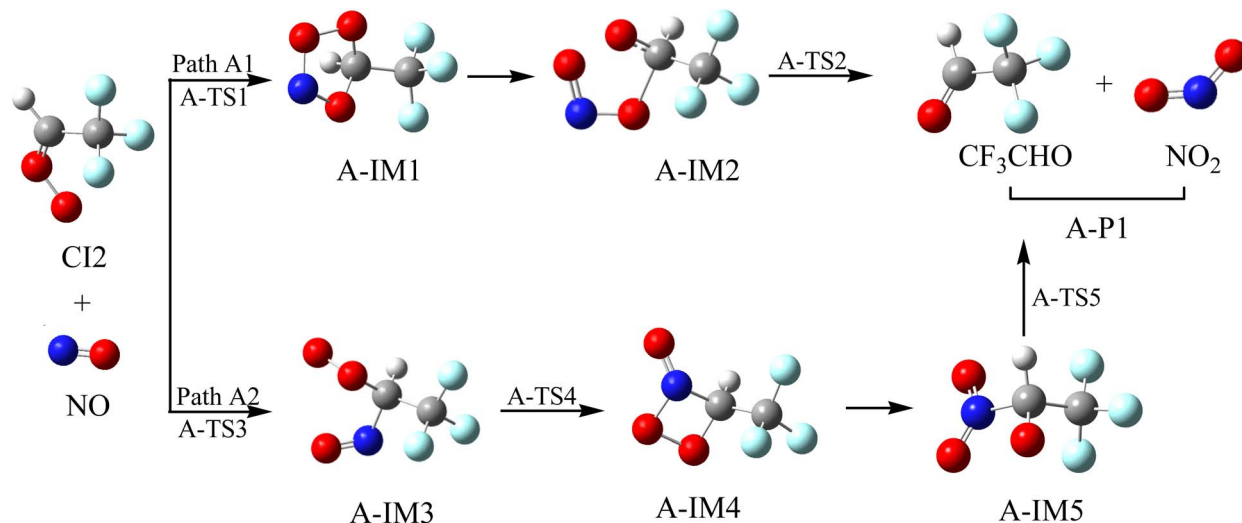


Fig. 4 Optimized geometrical configurations in the reaction of Cl₂ with NO.

3.4.1 Reaction mechanism of Cl₂ with NO. The reaction schematics, including the optimized geometries and the PES of the Criegee intermediate (CF₃CHOO(Cl₂)) with NO reaction, are presented in Fig. 4 and S2, respectively. There are two different addition/isomerization/elimination reaction channels (Path A1 and Path A2) for the reaction of Cl₂ with NO. For Path A1, the N and O atoms in NO can be simultaneously added to the terminal-O and C atoms of the -CH group in Cl₂ through A-TS1 to generate a five-membered ring intermediate, A-IM1. This process requires the crossing of a free energy barrier of 18.89 kcal mol⁻¹. A-IM1, with an internal energy of 18.30 kcal mol⁻¹, could directly break the O-O bond to generate A-IM2. It is worth noting that this decomposition process is a barrier-free process, and A-IM2 directly breaks the C-O bond to generate the final product (A-P1 (CF₃CHO + NO₂)) through A-TS2, surmounting a free energy barrier of 13.95 kcal mol⁻¹. For Path A2, the N atom in NO could also be added to the C atom in the -CH group of Cl₂, crossing a free energy barrier of 11.76 kcal mol⁻¹ via A-TS3 to generate A-IM3. Subsequently, A-IM3 passes through A-TS4 to generate a tetradentate cyclic intermediate (A-IM4) by interacting the N atom with the end-group O atom of -COO, overcoming a free energy barrier of 14.34 kcal mol⁻¹. A-IM4 can directly break both the O-O and C-N bonds to generate A-IM5. This direct decomposition process is also a barrier-free process. A-IM5 can eliminate an NO₂ to generate A-P1 (CF₃CHO + NO₂) through A-TS5 after overcoming a negative free energy barrier of 72.03 kcal mol⁻¹, indicating that NO₂ loss is easy.

3.4.2 Reaction mechanism of Cl₂ with NO₂. It was found that the Cl₂ + NO₂ reaction has two pathways, *i.e.*, the addition/isomerization/elimination pathway (Path B1) and the substitution pathway (Path B2). The reaction schematics, including the optimized geometries and the PES of this reaction, are presented in Fig. 5 and S3, respectively. As for Path B1, one of the O atoms in NO₂ could add to the C atom in the -CH group in Cl₂ to generate B-IM1 via B-TS1. This addition process requires

overcoming a free energy barrier of 17.19 kcal mol⁻¹. The length of the C-O bond in B-TS1 is 2.088 Å. The N atom in B-IM1 could interact with the terminal oxygen atom in -COO through B-TS2 to generate a five-membered ring intermediate (B-IM2), surmounting a free energy barrier of 29.82 kcal mol⁻¹. Subsequently, the five-membered ring intermediate (B-IM2) could be opened by breaking the O-O bond to generate B-IM3 through B-TS3, and then, it undergoes the synergistic reaction of 1,3-H migration and O-N bond breaking to generate B-P1 (CF₃COOH + NO₂) through B-TS4. The free energy barrier height of B-IM2 → B-TS3 → B-IM3 and B-IM3 → B-TS4 → B-P1 are 2.29 and 31.70 kcal mol⁻¹, respectively. The generation of B-P1 is exothermic, with an internal energy of 117.88 kcal mol⁻¹. For Path B2, the N atom in the NO₂ radical can attack the terminal-O atom in Cl₂, accompanied by breaking the O-O bond to generate B-P2 (CF₃CHO + NO₃) through B-TS5. The free energy barrier of Cl₂ + NO₂ → B-TS5 → B-P2 is 23.74 kcal mol⁻¹, which is 6.55 kcal mol⁻¹ higher than that of Cl₂ + NO₂ → B-TS1 → B-IM1. Thus, Path B1 is superior to Path B2. These reactions can supply some resources for NO₃ radicals and CF₃COOH radicals.

3.4.3 Reaction mechanism of Cl₂ with SO₂. Cl₂ is able to oxidize SO₂ to generate SO₃, which then generates a sulfuric acid aerosol.⁴¹⁻⁴⁵ The reaction schematics, including the optimized geometries and the PES of this reaction, are presented in Fig. 6 and S4, respectively. The cycloaddition/elimination (Path C1) and substitution (Path C2) reaction mechanisms have been found for the Cl₂ with SO₂ reaction. For Path C1, the S atom and one of the oxygen atoms in SO₂ could be simultaneously added to the terminal oxygen atom and the C atom in the -CH group in Cl₂ to generate a five-membered cycloaddition intermediate (C-IM1) through transition state C-TS1, surmounting a free energy barrier of 3.38 kcal mol⁻¹. The chemically activated adduct (C-IM1) (41.86 kcal mol⁻¹) could directly dissociate to the final product (C-P1: CF₃CHO + SO₃) through C-TS2, and it involves simultaneously breaking the C-O and O-O bonds. The free energy barrier for the process of C-IM1 → C-TS2 → C-P1 is



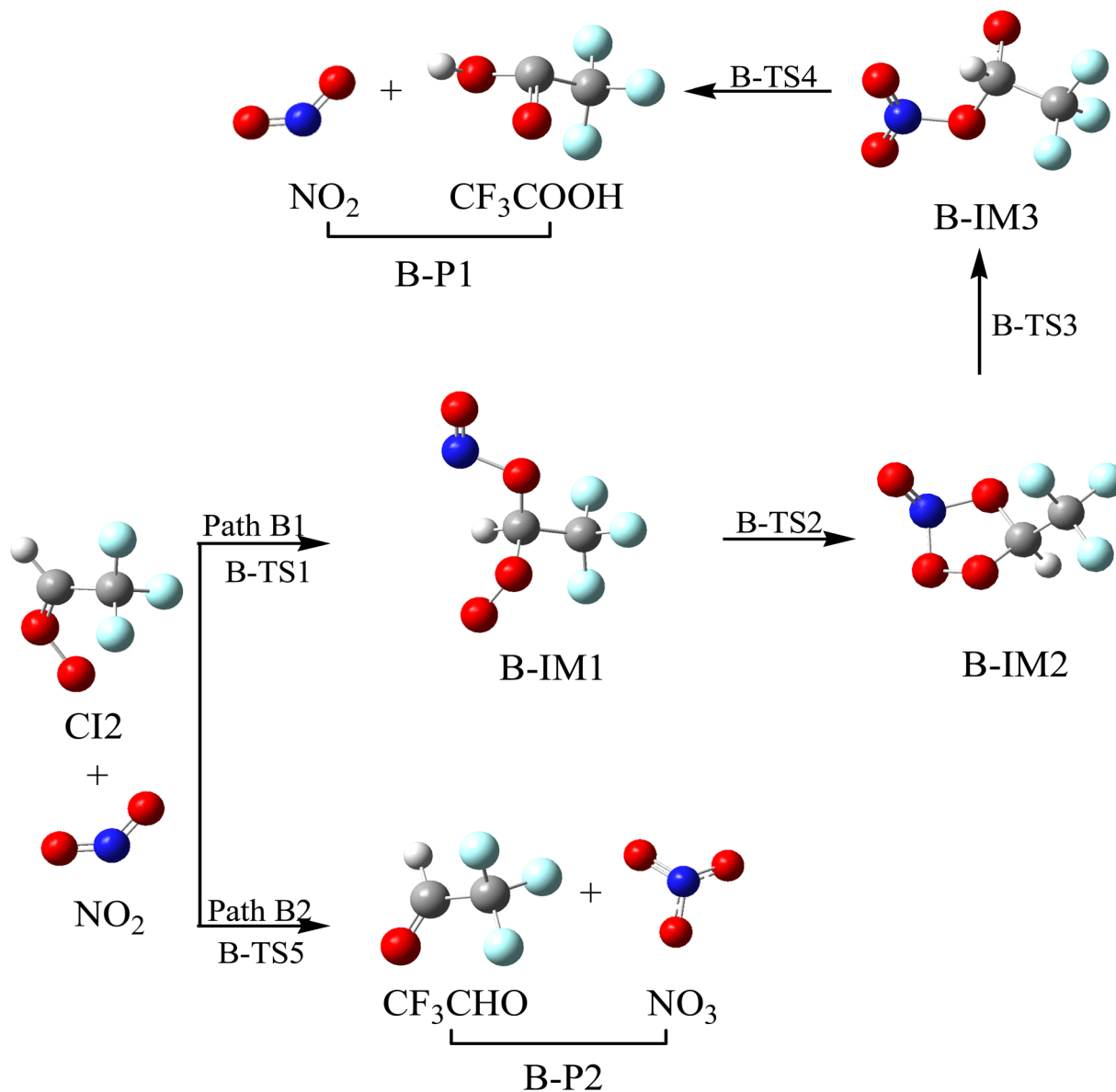


Fig. 5 Optimized geometrical configuration and the reaction schematic of the Cl₂ with NO₂ reaction.

16.24 kcal mol⁻¹. Similar to the reaction between Cl₂ and NO₂, the S atom in SO₂ attacks the terminal-O atom of Cl₂, kicking off the CF₃CHO to give out SO₃ through C-TS3. The free energy barrier of C-IM1 → C-TS3 → C-P1 is 20.76 kcal mol⁻¹, indicating that the generation of SO₃ through Path C1 is relatively easier than that through Path C2. Furthermore, these pathways will contribute to the generation of SOA.

3.4.4 Reaction mechanism of Cl₂ with H₂O. The investigation on the reaction between Cl₂ and H₂O primarily concentrates on the reaction between the simplest Criegee intermediate (CH₂OO) and water vapor, and the comprehensive theoretical investigation shows that the water dimer pathway dominates and water plays a catalytic role in the decay of CH₂OO.^{46,47} The reaction schematics, including the optimized geometries and the potential energy surface of Cl₂ with H₂O, are presented in Fig. 7 and S5, respectively.

The O atom in H₂O reacts with the C atom in the -CH group, and one of the H atoms in H₂O shifts to the terminal-O atom in Cl₂ at the same time to generate intermediate D-IM1 through transition state D-TS1 crossing a free energy barrier of 13.07 kcal mol⁻¹. The lengths of the new formations (C-O and O-H bonds) and the broken O-H bond are 1.960, 1.734 and 1.008 Å, respectively. D-IM1, with the internal energy of 50.00 kcal mol⁻¹, could decompose to D-P1 (CF₃COOH + H₂O) through transition state D-TS2. This involves the H atom in the OH group shifting to the middle-O atom in the -COOH group, accompanied by the breaking of the C-O bond through transition state D-TS2, surmounting a free energy barrier of 47.03 kcal mol⁻¹. In addition, D-IM1 can be reacted with monomolecular water *via* a six-membered ring transition state (D-TS3) to generate D-P1, and this is a two-hydrogen migration process. The free energy barrier of D-IM1 → D-TS3 → D-P1 is



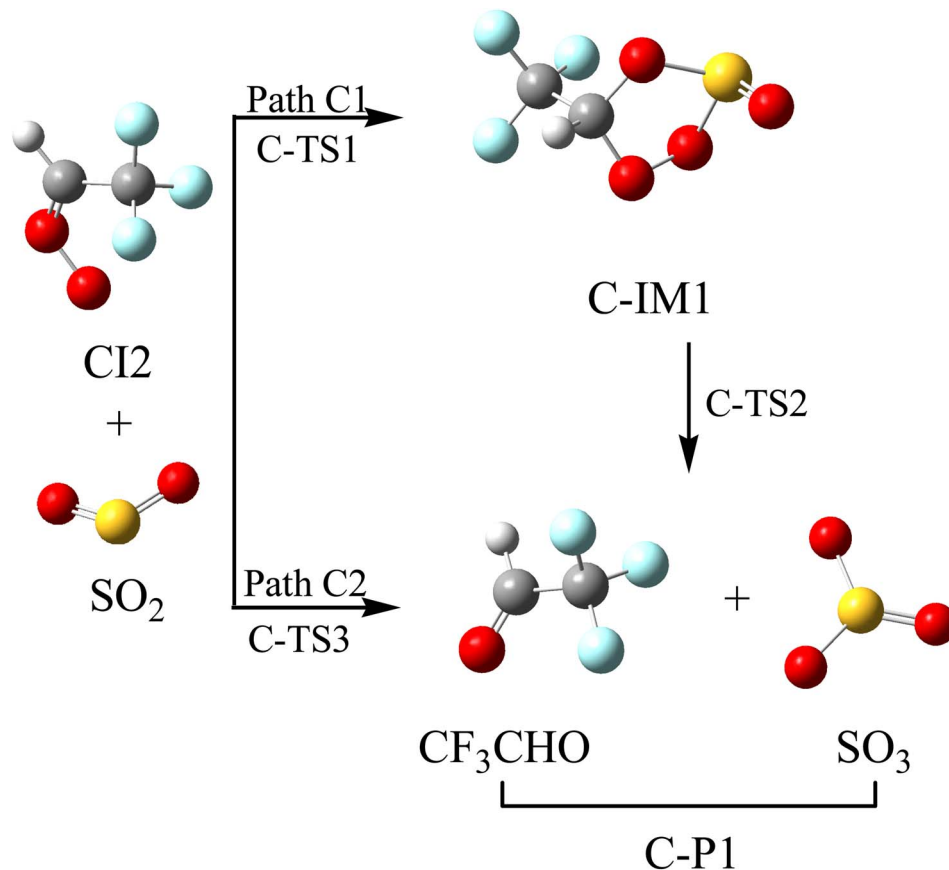


Fig. 6 Optimized geometrical configuration and the reaction schematic of the Cl₂ with SO₂ reaction.

31.93 kcal mol⁻¹, which is 15.10 kcal mol⁻¹ lower than that of D-IM1 → D-TS2 → D-P1, which indicates that the water molecule plays a catalytic role in this process. D-IM1 can also continue to react with the monomolecular water *via* a six-membered ring (D-TS4) to generate D-P2 (CF₃CHO + H₂O₂). The free energy of D-IM1 → D-TS4 → D-P2 (CF₃CHO + H₂O₂) is 46.58 kcal mol⁻¹, which is 0.45 kcal mol⁻¹ lower than that of D-IM1 → D-TS2 → D-P1 (CF₃COOH + H₂O). This is also a double hydrogen migration process, in which water plays a catalytic role. Alternatively, Cl₂ can directly react with the water dimer to form D-IM1 + H₂O *via* transition state D-TS5. In the reaction of Cl₂ with the water dimer, a water molecule acts as a reactant with Cl₂, and the other water molecule performs proton exchange. The free energy barrier of this process is 5.69 kcal mol⁻¹, which is 7.38 kcal mol⁻¹ lower than that of Cl₂ + H₂O → D-TS1 → D-IM1. Therefore, the reaction of Cl₂ with the water dimer is more feasible. Furthermore, it is shown that water autocatalysis will occur in Cl₂ with H₂O reactions and that the atmospheric resources of H₂O₂ are realized through these reactions.

3.4.5 Reaction mechanism of Cl₂ with CH₂O. Previous investigations^{48–50} have shown that CH₂OO with some aldehydes can prioritize generating a five-membered ring POZ, and then carry out further reactions. The reaction schematics, including the optimized geometries and the potential energy surface of Cl₂ with CH₂O, are presented in Fig. 8 and S6, respectively. Two

distinct reaction pathways (Path E1 and Path E2) have been discovered in the Cl₂ with CH₂O reaction. The C and O atoms in CH₂O can simultaneously be added to the terminal-O atom and C atoms in the –CH group in Cl₂ (Path E1) to generate intermediate E-IM1, respectively, or they can be added to the C atoms in the –CH group and terminal-O atoms in Cl₂ (Path E2) to generate intermediate IM1, respectively. The transition states corresponding to the above two processes are E-TS1 and TS3, respectively, with corresponding free energy barriers of 4.14 and 27.14 kcal mol⁻¹, respectively. Therefore, the reaction pathway of Path E1 is preferred over the reaction pathway of Path E2. E-IM1 can simultaneously break O–O and C–O to generate E-P1 (CF₃CHO + HCOOH) through E-TS2. The process of E-IM1 → E-TS2 → E-P1 needs to cross a free energy barrier of 49.11 kcal mol⁻¹, and therefore, the subsequent reaction of E-IM1 makes a small contribution to the reaction. The subsequent reaction of IM1 has been discussed in Section 3.2.

3.4.6 Reaction mechanism of Cl₂ with O₂. Cl₂ reacts with high concentrations of O₂, and the reaction schematics, including optimized geometries and PES, are presented in Fig. 9 and S7, respectively. As for Path F1, the cycloaddition intermediate (F-IM1) is directly generated with a barrier-free exothermic process, with a relative energy of 47.66 kcal mol⁻¹. F-IM1, with the relative energy of –46.48 kcal mol⁻¹, could simultaneously break the C–O and O–O bonds to generate F-P1 (CF₃CHO + O₃), easily surmounting a free energy barrier of 14.87 kcal mol⁻¹.



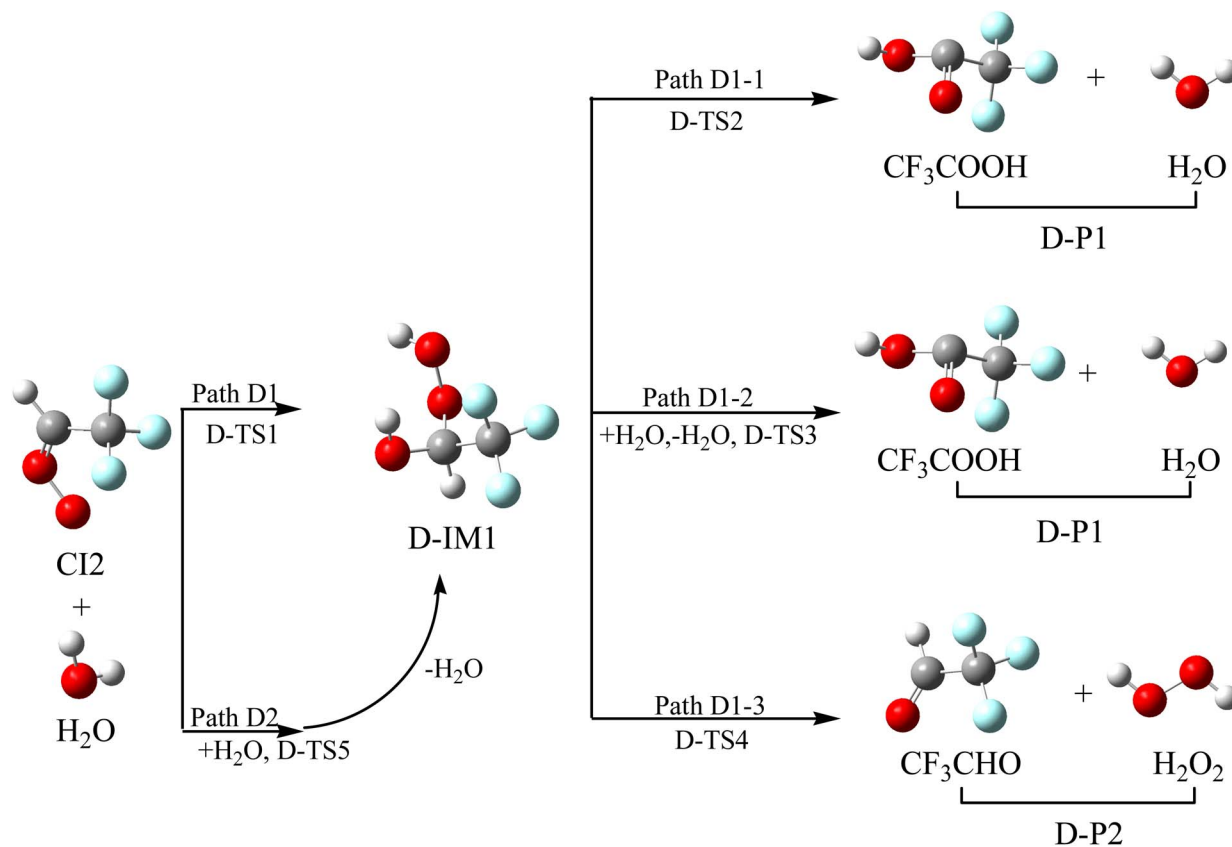


Fig. 7 Optimized geometrical configuration and the reaction schematic of the Cl₂ with H₂O reaction.

Path F2 involves the oxygen atoms in O₂ attacking the terminal O atoms in Cl₂, kicking off CF₃CHO to give out O₃ radical through transition state F-TS2. The Cl₂ → F-TS2 → F-P1 (CF₃CHO + O₃) process requires overcoming the free energy

barrier of 22.71 kcal mol⁻¹. The generation of O₃ results in the atmospheric cycling reaction of O₃ with CF₃CH=CH₂. The results of Path F1 and Path F2 supply a resource for the generation of O₃, which is crucial for understanding O₃

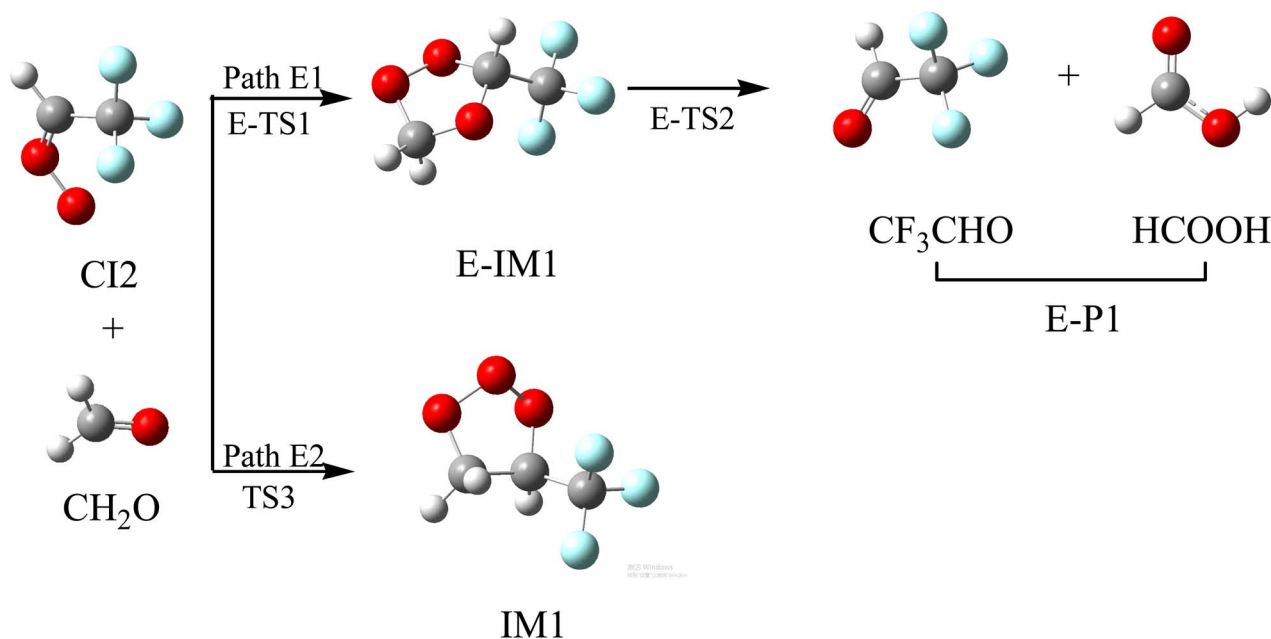


Fig. 8 Optimized geometrical configuration and the reaction schematic of the Cl₂ with CH₂O reaction.



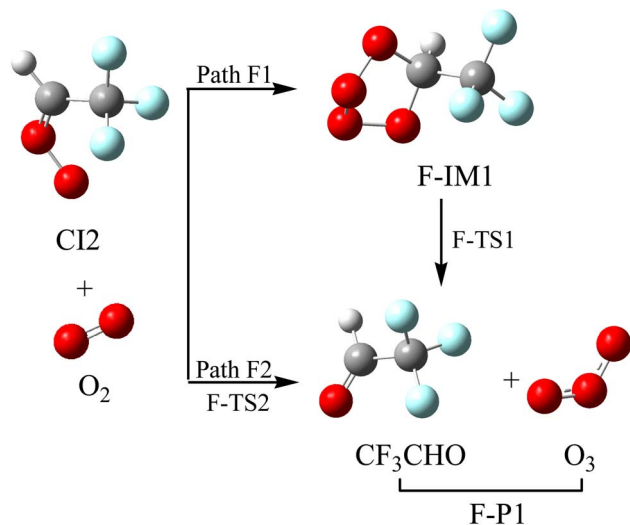


Fig. 9 Optimized geometric configurations and the reaction schematic of the Cl₂ with O₂ reaction.

pollution in specific regions. This result provides an important basis for formulating ozone pollution prevention and control measures and then taking corresponding emission reduction measures.

3.5 Kinetics

In order to understand reaction kinetics and compare the rate constants with experimental values, as well as guide the experimental investigation for the O₃ + CF₃CH=CH₂ reaction, the temperature dependence of the total and individual pathways is computed at 200–3000 K using the RRKM theory for the primary pathways (Schemes 1–3), which are considered in the following computations:

Where * represents the vibrational excitation of the intermediate (IM1). Steady-state approximation for the energized intermediate (IM1*) leads to the following expressions:

$$k_{\text{IM1}}(T, P) = \frac{\alpha_a}{h} \frac{Q_t^\ddagger Q_r^\ddagger}{Q_{\text{CF}_3\text{CH}=\text{CH}_2} Q_{\text{O}_3}} e^{-E_a/RT} \times \int_0^\infty \frac{\omega}{k_1(E) + k_2(E) + k_3(E) + \omega} N_a(E^\ddagger) e^{-E^\ddagger/RT} dE^\ddagger$$

$$k_{\text{P1}}(T, P) = \frac{\alpha_a}{h} \frac{Q_t^\ddagger Q_r^\ddagger}{Q_{\text{CF}_3\text{CH}=\text{CH}_2} Q_{\text{O}_3}} e^{-E_a/RT} \times \int_0^\infty \frac{k_2(E)}{k_1(E) + k_2(E) + k_3(E) + \omega} N_a(E^\ddagger) e^{-E^\ddagger/RT} dE^\ddagger \quad (2)$$

$$k_{\text{P2}}(T, P) = \frac{\alpha_a}{h} \frac{Q_t^\ddagger Q_r^\ddagger}{Q_{\text{CF}_3\text{CH}=\text{CH}_2} Q_{\text{O}_3}} e^{-E_a/RT} \times \int_0^\infty \frac{k_3(E)}{k_1(E) + k_2(E) + k_3(E) + \omega} N_a(E^\ddagger) e^{-E^\ddagger/RT} dE^\ddagger \quad (3)$$

For Scheme 2

$$k_{\text{IM2}}(T, P) = \frac{\alpha_a}{h} \frac{Q_t^\ddagger Q_r^\ddagger}{Q_{\text{CF}_3\text{CH}=\text{CH}_2} Q_{\text{O}_3}} e^{-E_a/RT} \times \int_0^\infty \frac{\omega}{k_1(E) + k_2(E) + \omega} N_a(E^\ddagger) e^{-E^\ddagger/RT} dE^\ddagger \quad (4)$$

$$k_{\text{P3}}(T, P) = \frac{\alpha_a}{h} \frac{Q_t^\ddagger Q_r^\ddagger}{Q_{\text{CF}_3\text{CH}=\text{CH}_2} Q_{\text{O}_3}} e^{-E_a/RT} \times \int_0^\infty \frac{k_2(E)}{k_1(E) + k_2(E) + \omega} N_a(E^\ddagger) e^{-E^\ddagger/RT} dE^\ddagger \quad (5)$$

For Scheme 3

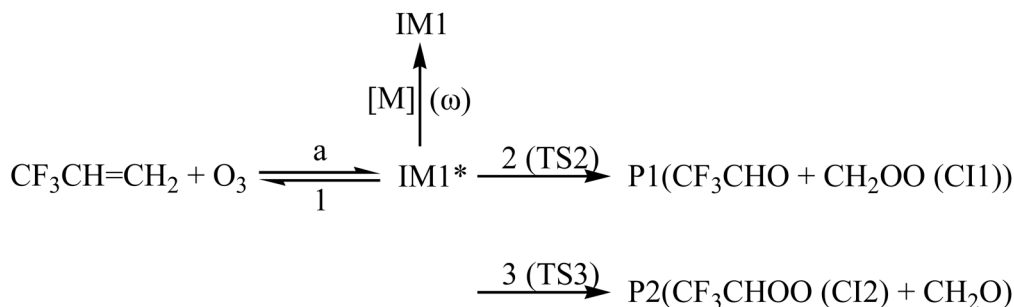
$$k_{\text{IM3}}(T, P) = \frac{\alpha_a}{h} \frac{Q_t^\ddagger Q_r^\ddagger}{Q_{\text{CF}_3\text{CH}=\text{CH}_2} Q_{\text{O}_3}} e^{-E_a/RT} \times \int_0^\infty \frac{\omega}{k_1(E) + k_2(E) + \omega} N_a(E^\ddagger) e^{-E^\ddagger/RT} dE^\ddagger \quad (6)$$

$$k_{\text{P4}}(T, P) = \frac{\alpha_a}{h} \frac{Q_t^\ddagger Q_r^\ddagger}{Q_{\text{CF}_3\text{CH}=\text{CH}_2} Q_{\text{O}_3}} e^{-E_a/RT} \times \int_0^\infty \frac{k_2(E)}{k_1(E) + k_2(E) + \omega} N_a(E^\ddagger) e^{-E^\ddagger/RT} dE^\ddagger \quad (7)$$

The microcanonical rate constant is calculated using the RRKM theory as follows:

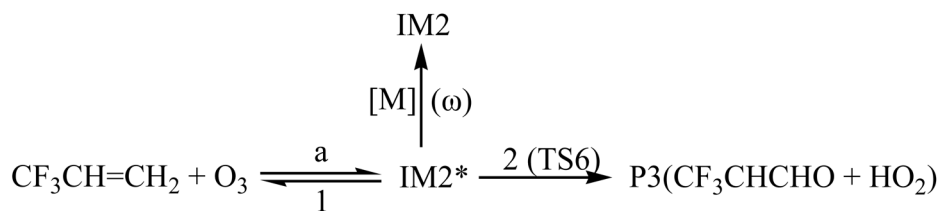
$$k_i(E) = \alpha_i C_i N_i(E_i^\ddagger) / h \rho_i(E_i) \quad (8)$$

- (1) In the above equations, α_a is the statistical factor for reaction Path a, and α_i is the statistical factor (degeneracy) for the i th

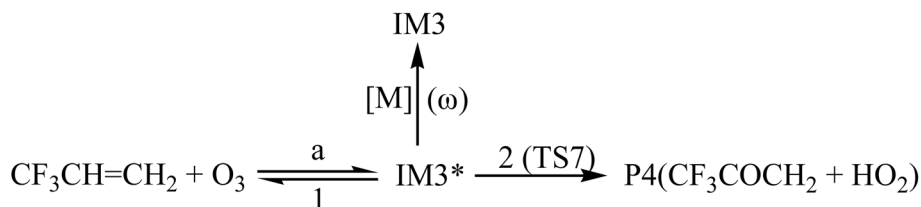


Scheme 1





Scheme 2



Scheme 3

reaction path; E_a is the energy barrier for reaction step a. Q_{O_3} and $Q_{\text{CF}_3\text{CH}=\text{CH}_2}$ are the total partition functions of O_3 and $\text{CF}_3\text{CH}=\text{CH}_2$, respectively; Q_t^\ddagger and Q_r^\ddagger are the translational and rotational partition functions of the entrance transition states. $N_a(E^\ddagger)$ is the number of states for the association transition state with excess energy (E^\ddagger) above the association barrier. $k_i(E)$ is the energy-specific rate constant for the i th channel, and C_i is the ratio of the overall rotational partition function of TS_i and IM_j ; $N_i(E_i^\ddagger)$ is the number of states at the energy above the barrier height for transition state i ; $\rho_j(E_j)$ is the density of states at energy E_j of the intermediate. The density of states and the number of states are calculated using the extended Beyer–Swinehart algorithm.

For the $\text{CF}_3\text{CH}=\text{CH}_2 + \text{O}_3$ reaction, the rate constants of the generation of P1, P2, P3, P4, IM1, IM2 and IM3 are denoted as

k_{P1} , k_{P2} , k_{P3} , k_{P4} , k_{IM1} , k_{IM2} and k_{IM3} , respectively, and the total rate constants are denoted as k_{tot} , $k_{\text{tot}} = k_{\text{P1}} + k_{\text{P2}} + k_{\text{P3}} + k_{\text{P4}} + k_{\text{IM1}} + k_{\text{IM2}} + k_{\text{IM3}}$, respectively. The temperature dependences of the total rate constants (k_{tot}) and individual rate constants (k_{P1} , k_{P2} , k_{P3} , k_{P4} , k_{IM1} , k_{IM2} and k_{IM3}) at 760 torr are presented in Fig. 10. The computed k_{tot} at 298 K and 760 torr is $1.50 \times 10^{-19} \text{ cm}^3$ per molecule per s, which is overestimated almost two times at 298 K relative to the data reported by Sulbaek Andersen *et al.*¹⁷ in 2005 ($k_{\text{tot}} = (3.50 \pm 0.30) \times 10^{-19} \text{ cm}^3$ per molecule per s). The difference in the above result may be due to the bath gas, experimental conditions and measurement technique. The total rate constants and the rate constants for the generation of products P1, P2, P3 and P4, as well as collisional stabilization channels, increase at first but decrease rapidly with increasing temperatures. The branching ratios for the primary products are also displayed in Fig. 11. The primary product is P1 ($\text{CF}_3\text{CHO} + \text{CH}_2\text{OO}$ (CI1)), and the pathway for generating P2 (CF_3CHOO (CI2) + CH_2O) contributes to the reaction to some extent over the entire temperature range. The contribution of the pathways for generating IM1, IM2, IM3, P3, and P4 to the reaction is negligible.

We also compute the rate constants for CI2 (CF_3CHOO) with a variety of atmospheric species (NO , NO_2 , CH_2O , H_2O , SO_2 and O_2) at 298 K and 1 atm using the RRKM theory. The detailed computation process is similar to the title reaction. The rate constants for CI2 with NO , NO_2 , CH_2O , H_2O , SO_2 and O_2 are $5.21 \times 10^{-16} \text{ cm}^3$ per molecule per s, $1.22 \times 10^{-19} \text{ cm}^3$ per molecule per s, $7.25 \times 10^{-12} \text{ cm}^3$ per molecule per s, $3.14 \times 10^{-18} \text{ cm}^3$ per molecule per s, $3.03 \times 10^{-11} \text{ cm}^3$ per molecule per s, $3.11 \times 10^{-9} \text{ cm}^3$ per molecule per s, respectively. Therefore, the CI2 with O_2 reaction is the fastest path, followed by those with SO_2 and CH_2O . Previous studies on the kinetics of the Criegee intermediate (CF_3CHOO , CH_2OO and $(\text{CH}_3)_2\text{COO}$) with a variety of atmospheric species (NO , NO_2 , CH_2O , H_2O , SO_2 and O_2)^{51,52} are provided in the SI (Table S2) and constitute valid evidence for assessing the transport and degradation of $\text{CF}_3\text{CH}=\text{CH}_2$. As

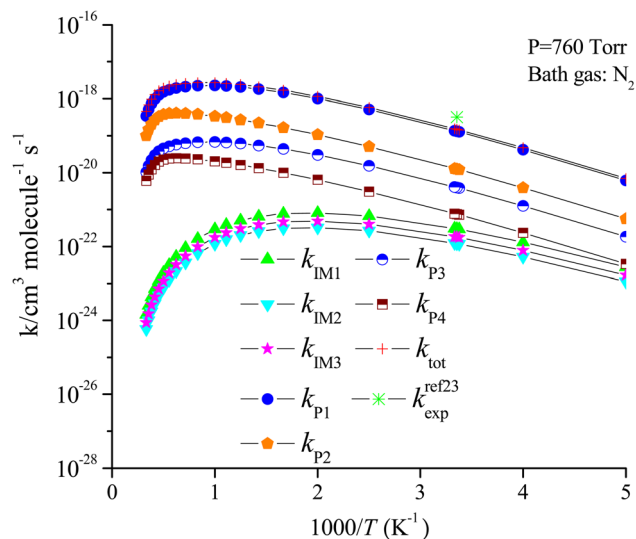


Fig. 10 Temperature dependence of the total and individual rate constants for the trifluoropropene with ozone reaction at 760 torr N_2 .



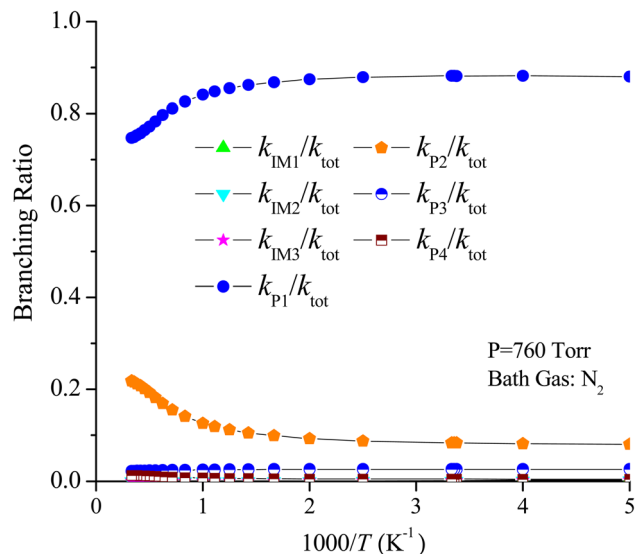


Fig. 11 Branching ratios of the important product channels for the trifluoropropene with ozone reaction in the temperature range of 200–3000 K at 760 torr pressure of N_2 .

shown in Table S2, because the CF_3 radical with relatively high electronegativity strongly attracts electrons located at the $C=C$ double bond, the electron density on the $C=C$ double bond is reduced. This leads to a decrease in the reactivity of the C atom of the $C=C$ double bond attack on the O atom of O_3 ; however, the $-(CH_3)_2$ group is the donor species, which increases the rate constants. Thus, theoretically, the trend of the reaction rate constant is $k((CH_3)_2COO) > k(CH_2OO) > k(CF_3CH=CH_2)$, which is quantitatively in line with the experimental results.

The atmospheric lifetime of $CF_3CH=CH_2$ induced by O_3 can be computed using the following formula: $\tau = (k_{tot}[O_3])^{-1}$, where k_{tot} is the total rate coefficient for $CF_3CH=CH_2$ with O_3 at 298 K (1.50×10^{-19} cm^3 per molecule per s), and $[O_3]$ is the atmospheric concentration of the ozone. The average concentration of O_3 is 1.00×10^{12} molecule per cm^3 .⁵³ At a normal temperature and pressure, the atmospheric lifetime of $CF_3CH=CH_2$ induced by O_3 is estimated to be 77.16 days, which is consistent with the experimental data (70 days). It is observed that $CF_3CH=CH_2$ can be degraded to relatively small molecules in the atmosphere.

4. Conclusion

In this study, the ozonation reaction mechanism of trifluoropropene was investigated using quantum chemistry methods. Addition/elimination, H-extraction and substitution mechanisms were discovered in the reaction of $CF_3CH=CH_2$ with O_3 , and the addition/elimination mechanism was dominant. The computed rate constants and atmospheric lifetime at a normal temperature and pressure are 1.50×10^{-19} cm^3 per molecule per s and 77.16 days, respectively, which are consistent with the experimental data ($(3.50 \pm 0.30) \times 10^{-19}$ cm^3 per molecule per s and 70 days).

We also studied the reaction mechanism between the Criegee intermediates and atmospheric substances (NO , NO_2 , CH_2O , H_2O , SO_2 and O_2) and summarized the reaction characteristics. The reactions between the Criegee intermediates and NO , NO_2 , and SO_2 are some of the sources of secondary organic aerosols in the atmosphere. Water has a self-catalytic effect in the reaction between H_2O and the Criegee intermediate; acid and H_2O were discovered in the product. Secondary ozone oxides (SOZ) can also be formed by reacting the Criegee intermediates with CH_2O . The addition reaction between O_2 and the Criegee intermediate could re-release ozone, achieving the atmospheric circulation reaction of ozone. The computed results manifested that the reaction of CI_2 with O_2 is the fastest path, followed by those with SO_2 and CH_2O .

The present investigation supplies many mechanical and kinetic data that could ascertain the degradation channels of $CF_3CH=CH_2$ by ozonolysis. Some significant conclusions could be obtained from the available data. $CF_3CH=CH_2$ is degraded through the reaction with O_3 in the troposphere to generate some products, which would result in the generation of secondary organic aerosols. These computations indicate the formation of Criegee intermediates, peroxy nitrates, and peroxy sulfates with environmental concerns.

Author contributions

The authors declared that all the co-authors are aware of and approve of the submission.

Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that support the findings of this study are available on request from the corresponding author.

Supplementary information (SI) is available. See DOI: <https://doi.org/10.1039/d5ra07265d>.

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