



An Efficient Method for the Catalytic Aerobic Oxidation of Cycloalkanes using 3,4,5,6-Tetrafluoro-*N*-Hydroxyphthalimide (*F*₄-NHPI)



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Abstract

N-Hydroxyphthalimide (NHPI) is known to be an effective catalyst for the oxidation of hydrocarbons. The catalytic activity of NHPI derivatives is generally increased by introducing an electron-withdrawing group on the benzene ring. In a previous report, two NHPI derivatives containing fluorinated alkyl chain were prepared and their catalytic activity was investigated in the oxidation of cycloalkanes. It was found that the fluorinated NHPI derivatives showed better yields for the oxidation reaction. As a continuation of our work with fluorinated NHPI derivatives, our next aim was to investigate the catalytic activity of the NHPI derivatives by introducing fluorine atoms in the benzene ring of NHPI. In the present research, 3,4,5,6-Tetrafluoro-*N*-Hydroxyphthalimide (*F*₄-NHPI) is prepared and its catalytic activity has been investigated in the oxidation of two different cycloalkanes for the first time. It has been found that *F*₄-NHPI showed higher catalytic efficiency compared with that of the parent NHPI catalyst in the present reactions. The presence of a fluorinated solvent and an additive was also found to accelerate the oxidation.

Keywords: Aerobic Oxidation; Fluorinated *N*-hydroxyphthalimide; Catalyst; Cycloalkane; Catalytic Activity

1. Introduction

Aerobic oxidations of cycloalkanes are very important industrial processes for the production of primary and specialty chemicals like alcohols, ketones and carboxylic acids [1-3]. These oxygenated products are very important raw materials for the production of plastics and synthetic fiber materials, polyesters, polycarbonates, etc. Among the cycloalkanes, cyclohexane (**1**) has a huge industrial applications. Nowadays, the aerobic oxidation of **1** leading to a mixture of cyclohexanol (**2**), cyclohexanone (**3**) and adipic acid (**4**) (Scheme 2). In order to obtain the mixture of **2** and **3**, which is generally referred to as K/A oil, the oxidation is usually carried out under the influence of a small amount of cobalt salts. In conventional autoxidation of **1** using cobalt catalysts, however, the reaction calls for the operation at around 150 °C [4, 5]. Under these conditions, the oxidation results in undesired products like glutaric acid and maleic acid. Therefore, the oxidation must be carried out in lower conversion (3-5%) of **1** to keep the selectivity to the K/A oil. If the oxidation of **1** is

capable to perform at lower temperature around 100 °C, it may be possible to carry out the reaction at higher conversion of **1**. Fortunately, a novel catalytic system consisting of *N*-hydroxyphthalimide (NHPI) and Co(II) for the aerobic oxidation of alkanes has been recently developed, which is generally referred to as Ishii oxidation system [6-9]. By the use of that catalytic system, cycloalkanes can be oxidized in acetic acid even at 100 °C to give oxygenated products like alcohols, ketones and dicarboxylic acids in higher conversion. However, the NHPI-catalyzed aerobic oxidation of cycloalkanes like cyclohexane (**1**) without solvent was difficult to perform in higher conversion because of slight solubility of polar NHPI having hydroxyimide group in non-polar cycloalkanes [10, 11]. Thus, some lipophilic NHPI derivatives having long alkyloxycarbonyl chains were prepared which are thought to easily dissolve in hydrocarbons [12]. After that, some other groups also paid their attention in preparing other lipophilic NHPI derivatives and observed their catalytic activities under various conditions [13-15]. The aerobic

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oxidation of cycloalkanes like **1** by lipophilic NHPI catalysts without any solvent afforded **2** and **3** in higher conversion along with a small amount of **4** [12]. However, the alkyl chain was found to be oxidized after the oxidation. In order to avoid the oxidation of the alkylated side chain, two NHPI derivatives containing fluorinated alkyl group were prepared and their catalytic activity was investigated in the oxidation of **1** [16] and cyclopentane (**5**) [17]. It was found that the fluorinated NHPI derivatives showed better yields for the oxidation reaction and could be recycled after the oxidation.

In the oxidation using NHPI, at first the phthalimide *N*-oxy (PINO) radical is formed from NHPI which represents the key intermediate of the catalytic cycle (Figure 1). The PINO radical thus generated abstract a hydrogen atom from the substrate to form alkyl radicals on which subsequent oxygenations with molecular oxygen give oxygenated products. If some electron-withdrawing group is present on the aromatic ring of NHPI, the NO–H bond dissociation energy (BDE) will be increased [18, 19] for NHPI derivative, make it less effective as a hydrogen donor. As a result, it will be much more difficult to generate PINO radical and finally to trap peroxy radicals. However, Lanzalunga et al. has shown that the rate of oxidation of 1-(4-methoxyphenyl)ethanol is possible to increase by introducing electron-withdrawing substituents in NHPI aryl ring, and therefore, the reactivity order parallels the increase of O–H BDE in the substituted NHPIs [19]. The effect of the electron-withdrawing substituents on the aromatic ring of NHPI and the stability of the transition state after hydrogen abstraction reaction by the PINO radical was also discussed by others [20–22]. After getting positive effects by using the fluorinated alkyl chain in NHPI, our next aim was to investigate the catalytic activity of another lipophilic NHPI derivative by introducing four electronegative fluorine atoms directly in the aryl ring of NHPI. Fluorine substituent on the aryl ring of NHPI, for example, 3-Fluoro-NHPI was reported to enhance the catalytic activity in the aerobic oxidation of benzyl alcohol [19], ethylbenzene [20] and hydrocarbon [23]; and 3,4,5,6-tetrafluoro-*N*-hydroxyphthalimide (*F*₄-NHPI) was reported to enhance the catalytic activity in the electrochemical oxidation of various alcohols [24] under both aerobic and anaerobic conditions. In contrary, Xu et al. reported that *F*₄-NHPI together with 1,4-diamino-2,3-dichloroanthraquinone (DADCAQ) exhibited an abnormal lower catalytic activity in the oxidation of ethylbenzene and other aromatic hydrocarbons [25]. According to the authors, the strongest four electron-withdrawing fluorine atoms attached to the aryl group of NHPI probably decreased the stability of the corresponding PINO radical, which resulted in a lower

efficiency. However, Kushch showed very recently that the instability of the PINO radical is not the main reason of its lower efficiency in the oxidation of ethylbenzene [26]. To the best of our knowledge, the catalytic activity of *F*₄-NHPI for the oxidation of cycloalkanes has not been studied so far. As a continuation of our work with fluorinated NHPI derivatives, in the present report, the catalytic performance of *F*₄-NHPI was investigated in the oxidation of cycloalkanes (Scheme 2 and 3) for the first time and found its high efficiency compared with that of the parent NHPI catalyst.

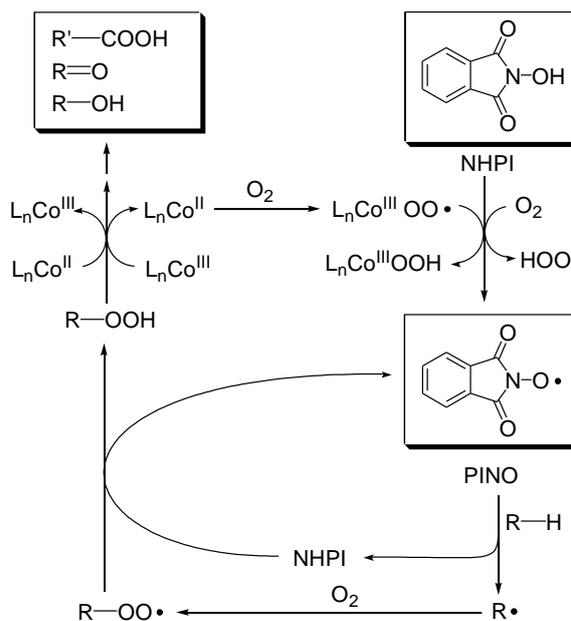


Figure 1. Mechanism of NHPI catalyzed oxidation reaction of hydrocarbon.

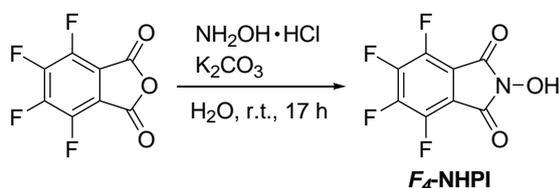
2. Experimental

2.1 Materials and Methods

Commercially available reagents (TCI, Aldrich) were used without further purification, unless otherwise noted. GC analysis was performed with a flame ionization detector using a 0.2 mm × 30 mm capillary column (OV-17). The ¹H and ¹³C NMR spectra were recorded on JEOL JNM-LA 300FT (300 MHz for ¹H and 67.8 MHz for ¹³C) NMR spectrometer. The chemical shifts of ¹H and ¹³C NMR are reported on the δ-scale relative to Si(CH₃)₄ (δ = 0.00 ppm) as internal standard. Infrared (IR) spectra were measured using KBr pellets on a JASCO FT/IR infrared spectrometer and MS spectra were obtained at ionization energy of 70 eV using a JEOL SX-102A mass spectrometer. GC analysis was performed with a flame ionization detector using a 0.2 mm × 30 mm capillary column (OV-17) and the yields of products were estimated from the peak areas on the basis of the internal standard technique by the use of GC.

2.2 Preparation of 3,4,5,6-Tetrafluoro-N-Hydroxyphthalimide (F_4 -NHPI)

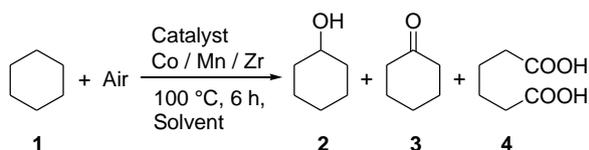
The 3,4,5,6-Tetrafluoro-N-Hydroxyphthalimide (F_4 -NHPI) derivative was prepared according to the modified literature procedure described in Scheme 1 [20]. To a solution of hydroxylamine hydrochloride (Aldrich, 416.94 mg, 6 mmol) and K_2CO_3 (TCI, 552.8 mg, 4 mmol) in H_2O were added 3,4,5,6-tetrafluorophthalic anhydride (Aldrich, 880.32 mg, 4 mmol) and the reaction mixture was stirred for 17 h at room temperature. After 17 h, EtOAc was added to the reaction mixture and the organic layer was separated and dried over Na_2SO_4 . After evaporating the solvent at reduced pressure, the crude product was purified by silica gel column chromatography (hexane/EtOAc = 2:1 - 1:1). The desired product (F_4 -NHPI) was obtained in 51% yield (479.4 mg) as pure form. 1H NMR (270 MHz, CD_3COCD_3): δ ppm 10.1 (1H, br, s); ^{13}C NMR (67.8 MHz, CD_3COCD_3): δ ppm 159.4, 147.6, 146.1, 143.1, 142.2, 112.5.



Scheme 1. Preparation of F_4 -NHPI

2.3 General Procedure for the Oxidation of Cycloalkanes Under Air

To a solution of cycloalkane (**1** or **5**, 37 mmol) in trifluorotoluene (4 mL) were added NHPI or F_4 -NHPI (0.0125 - 0.025 mmol), $Co(OAc)_2$ and $Mn(OAc)_2$ in a 50 mL teflon-coated autoclave and 10 atm of air was charged in it. After stirring for 6 h at 100 °C, it was cooled to room temperature and then diluted with ethanol. GC analysis was performed from that ethanolic solution to determine the amount of corresponding alcohol, ketone and the remaining cycloalkane. After evaporating under reduced pressure to remove the unreacted cycloalkane, ethanol (10 mL) and a small amount of a conc. sulfuric acid were added to the resulting mixture and stirred at 100 °C for overnight. The resulting reaction mixture was cooled to room temperature and GC analysis was performed to determine the yield of carboxylic acids.



Scheme 2. Oxidation of cyclohexane (**1**)

3. Results and Discussion

3.1 Aerobic Oxidation of Cyclohexane (**1**) Under Various Conditions

The F_4 -NHPI derivative was prepared according to the reaction shown in Scheme 1. After getting the catalyst in hand, at first, the catalytic activity was evaluated by examining the results obtained in the oxidation of **1** with that fluorinated NHPI derivative and compared with that of NHPI (Scheme 2 and Table 1). Initially, solvent free aerobic oxidation of **1** was investigated (entries 1, 2, 7 and 8). The oxidation of **1** with NHPI, Co and Mn at 100 °C for 6 h afforded **2**, **3** and **4** in a 40:59:1 ratio of with a TON of 25.9 (entry 1), and the oxidation by F_4 -NHPI gave **2**, **3** and **4** with a TON of 33.8 (entry 2). Even though F_4 -NHPI showed slightly better performance than NHPI, the yields of the products and the total TON were not quite satisfactory. By introducing a fluorinated solvent (trifluorotoluene) for that oxidation, the results were dramatically increased for F_4 -NHPI but slightly decreased for NHPI. For example, the oxidation of **1** with NHPI or F_4 -NHPI, Co/Mn in TFT for 6 h afforded mainly **2** and **3** with a trace amount of **4** in a TON of 17.4 (entry 3) and 82.2 (entry 4), respectively. The TON of the reaction for F_4 -NHPI was increased from 33.8 without solvent to 82.2 in TFT, whereas, for NHPI, it was decreased from 25.9 without solvent to 17.4 in TFT. This remarkable enhancement of catalytic activity of F_4 -NHPI is probably due to the increased solubility of F_4 -NHPI in TFT than in **1** and the slightly decrease for NHPI is probably due to its poor solubility in TFT than in **1**. In order to get some evidence for that assumption, next the oxidation was performed in acetic acid to examine the influence of the polarity of solvents. As expected, the solubility of NHPI is increased and the oxidation was occurred in higher yields as compared with the results obtained either in TFT or without solvent. The oxidation of **1** with NHPI or F_4 -NHPI, Co/Mn in AcOH for 6 h afforded **4** as the major product with a TON of 68 (entry 5) and 89 (entry 6), respectively.

The comparison of the oxidation results of **1** with NHPI and F_4 -NHPI under different solvent conditions is shown in Figure 2. In every cases, F_4 -NHPI showed better performance than NHPI, especially in TFT. It is very interesting to note that in the absence of solvent or in TFT, the major product obtained for both NHPI and F_4 -NHPI is cyclohexanone (**3**), whereas, in acetic acid the major product is adipic acid (**4**). The reaction is probably occurred in two stages and it is believed that both the catalysts dissolved easily in acetic acid and the oxidation of **1** proceeded smoothly to give **2** and **3** at the 1st stage. The resulting cyclohexanol and cyclohexanone are also dissolved in acetic acid and are more reactive than cyclohexane. As a result, the oxidation of **2** and **3** also occurred easily at the 2nd stage and produced **4** as the major product in AcOH. Since both the catalysts dissolved and react in similar way in

AcOH, therefore, no remarkable difference was observed for the catalytic performance of NHPI and F_4 -NHPI in the oxidation of **1**. As the solubility of **2** and **3** in TFT is low, the oxidation at the 2nd stage in TFT is probably negligible. Therefore, the oxidation of **1** by F_4 -NHPI in TFT is thought to lead to **2** and **3** in high selectivity with a little amount of **4** (Figure 3).

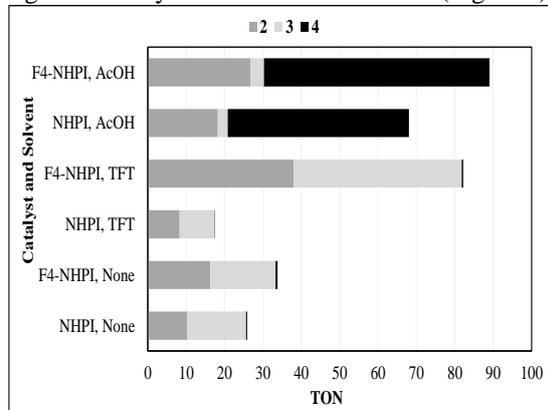


Figure 2. Aerobic oxidation of cyclohexane (**1**) with NHPI or F_4 -NHPI. Compound **1** (37 mmol) in solvent (4 mL) was allowed to react with NHPI or F_4 -NHPI (0.025 mmol), $\text{Co}(\text{OAc})_2$ (0.02 mmol) and $\text{Mn}(\text{OAc})_2$ (0.01 mmol) under air (10 atm) at 100 °C for 6 h.

3.2 Effect of Zr additive in the Oxidation of **1**

The above reaction was further studied in the presence of a Zr additive. The accelerating effect of Zr species in the oxidation of *p*-xylene to benzaldehyde was described in some previous studies [27-31]. For the present reaction, it was found that the catalytic activity of both NHPI and F_4 -NHPI is slightly increased in the presence of Zr additive. For example,

when the reaction was carried out without $\text{Zr}(\text{acac})_4$, the total TONs for F_4 -NHPI in the absence of solvent and in TFT were 33.8 and 82.2, respectively (entries 2 and 4, Table 1), whereas, in the presence of $\text{Zr}(\text{acac})_4$ the total TONs became 49.6 and 110.6 (entries 8 and 10, Table 1), respectively. The higher catalytic activity of F_4 -NHPI is clearly understood here as the TON 22.2 for NHPI (entry 9, Table 1) seems to be very poor compared with TON 110.6 for F_4 -NHPI (entry 10, Table 1), even though the major product remained the same, i.e. cyclohexanone in TFT and adipic acid in AcOH. These results clearly show that Zr plays an important role in the oxidation of cyclohexane. Probably, Zr forms a polynuclear Co/Mn/Zr coordination compound and the strong Lewis acidity of $\text{Zr}(\text{acac})_4$ promotes the decomposition of alkylhydroperoxide to alcohol and ketone. However, it needs more experiment to find out the actual effect of the Zr species in the present oxidation. No remarkable difference was observed for the catalysts when the reaction was carried out in AcOH (entries 11 and 12, Table 1).

Figure 4 shows the oxidation results of **1** with NHPI or F_4 -NHPI derivative in the presence of Co/Mn/Zr system. It is very attractive that F_4 -NHPI showed the highest TON in TFT.

Table 1. Oxidation of cyclohexane under various conditions^a

Entry	Catalyst	$\text{Zr}(\text{acac})_4$	Solvent	Product distribution/% ^b			TON ^c
				2	3	4	
1	NHPI	-	None	40	59	1	25.9
2	F_4 -NHPI	-	None	48	50	2	33.8
3	NHPI	-	TFT	48	52	trace	17.4
4	F_4 -NHPI	-	TFT	46	53	<1	82.2
5	NHPI	-	AcOH	27	4	69	68.0
6	F_4 -NHPI	-	AcOH	30	4	66	89.0
7	NHPI	0.01	None	47	52	1	38.1
8	F_4 -NHPI	0.01	None	50	48	2	49.6
9	NHPI	0.01	TFT	52	48	trace	22.2
10	F_4 -NHPI	0.01	TFT	36	60	4	110.6
11	NHPI	0.01	AcOH	27	8	65	77.0
12	F_4 -NHPI	0.01	AcOH	30	7	63	85.9

^aCompound **1** (37 mmol) in solvent (4 mL) was allowed to react with NHPI or F_4 -NHPI (0.025 mmol), $\text{Co}(\text{OAc})_2 \cdot 4\text{H}_2\text{O}$ (0.02 mmol), $\text{Mn}(\text{OAc})_2 \cdot 4\text{H}_2\text{O}$ (0.01 mmol) and $\text{Zr}(\text{acac})_4$ under air (10 atm) at 100 °C for 6 h.

^bGC yield.

^cTON (Turnover number) = $2+3+4$ (mmol) / NHPI or F_4 -NHPI (mmol).

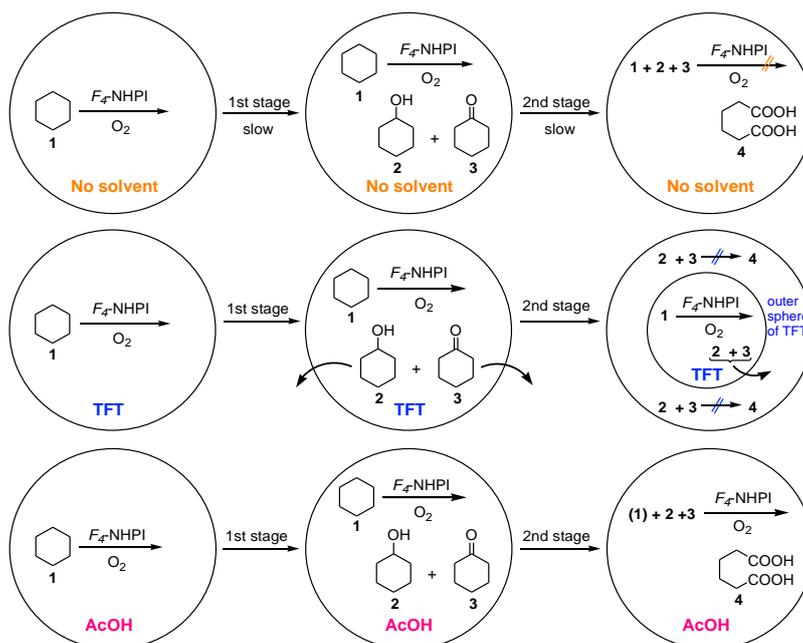


Figure 3. A plausible explanation for the selective formation of products depending on the solvents.

Table 2. Effect of the amount of catalyst in the oxidation of cyclohexane^a

Entry	Catalyst (mmol)	Solvent	Product distribution/% ^b			TON ^c
			2	3	4	
1 ^d	NHPI (0.025)	TFT	48	52	trace	17.4
2	NHPI (0.0125)	TFT	70	28	2	52.6
3 ^d	<i>F</i> ₄ -NHPI (0.025)	TFT	46	53	<1	82.2
4	<i>F</i> ₄ -NHPI (0.0125)	TFT	46	51	3	260.3
5 ^d	NHPI (0.025)	AcOH	27	8	65	77.0
6	NHPI (0.0125)	AcOH	32	5	63	142.5
7	<i>F</i> ₄ -NHPI (0.025)	AcOH	30	7	63	85.9
8 ^d	<i>F</i> ₄ -NHPI (0.0125)	AcOH	28	13	59	159.0

^a Compound **1** (37 mmol) in solvent (4 mL) was allowed to react with NHPI or *F*₄-NHPI, Co(OAc)₂·4H₂O (0.020 mmol) and Mn(OAc)₂·4H₂O (0.010 mmol) under air (10 atm) at 100 °C for 6 h.

^b GC yield.

^c TON (Turnover number) = 2+3+4 (mmol) / NHPI or *F*₄-NHPI (mmol).

^d Taken from Table 1 for comparison.

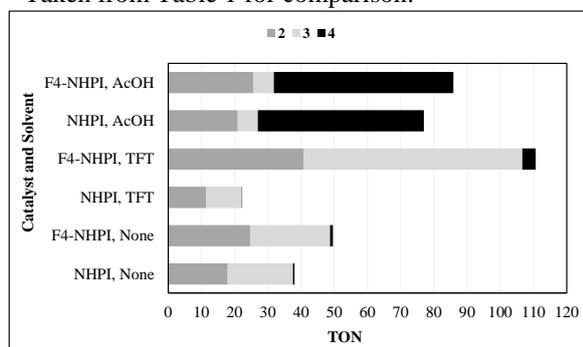


Figure 4. Aerobic oxidation of cyclohexane (**1**) with NHPI or *F*₄-NHPI. Compound **1** (37 mmol) in solvent (4 mL) was allowed to react with NHPI or *F*₄-NHPI (0.025 mmol), Co(OAc)₂ (0.02 mmol), Mn(OAc)₂ (0.01 mmol) and Zr(acac)₄ (0.01 mmol) under air (10 atm) at 100 °C for 6 h.

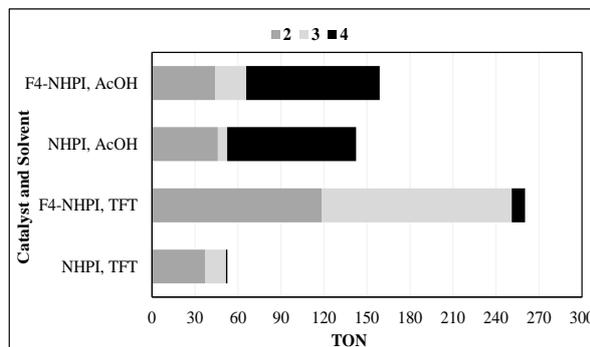
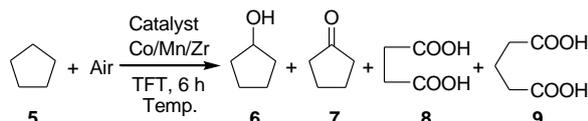


Figure 5. Aerobic oxidation of cyclohexane (**1**) with NHPI or *F*₄-NHPI. Compound **1** (37 mmol) in solvent (4 mL) was allowed to react with NHPI or *F*₄-NHPI (0.0125 mmol), Co(OAc)₂ (0.02 mmol), Mn(OAc)₂ (0.01 mmol) under air (10 atm) at 100 °C for 6 h.

3.3 Effect of the Amount of Catalyst in the oxidation of **1**

The amount and oxidized products as well as the TON could be increased by reducing the amount of catalyst. Results are summarized in Table 2 and Figure 5. The TON of F_4 -NHPI was increased from 82.2 (entry 3, Table 2) to 260.3 (entry 4) by decreasing the amount of catalyst from 0.025 to 0.0125 mmol forming **3** as the major product in both cases. The TON 260.3 is five times greater than the results obtained for the same amount of NHPI (entry 2) forming **2** as the major product. Therefore, it is clear from the above results that F_4 -NHPI showed excellent catalytic performance for the oxidation of **1** in TFT and could be considered a more active catalyst compared with NHPI. In comparison to TFT, **4** was obtained as the major product in AcOH for both NHPI and F_4 -NHPI with a TON of 142.5 and 159.0 (entries 6 and 8), respectively. The higher yields of the products and the TON clearly shows that very small amount of the catalysts also facilitate the present oxidation. The present reaction condition in TFT could be a very effective method for the selective production of K/A oil in good yields.



Scheme 3. Oxidation of cyclopentane (**5**)

3.4 Higher Catalytic Efficiency of F_4 -NHPI than NHPI

It is clear from the above results that in every cases F_4 -NHPI showed better performance than NHPI,

especially in TFT. The higher activity of F_4 -NHPI can be explained by two factors: i) the improved solubility of F_4 -NHPI in TFT as well as in **1** is due to the lipophilic character of the fluorinated aryl group and ii) the presence of strongest electron-withdrawing fluorine atoms in the NHPI aryl ring. The results obtained in entries 1-4 and 7-10 of Table 1 support the first assumption, whereas, the results obtained from entries 5, 6, 11 and 12 support the second assumption as the solubility of NHPI and F_4 -NHPI is almost the same in AcOH. The slightly higher catalytic activity of F_4 -NHPI in AcOH, as expected, must be due to the strong electron-withdrawing fluorine atoms in the F_4 -NHPI aryl ring. The observed higher efficiency of F_4 -NHPI is therefore overcoming the limitation described in a previous report where it was thought that the four electron-withdrawing fluorine atoms attached to the aryl ring of NHPI probably decreased the stability of the corresponding PINO radical, which resulted in a lower efficiency [25, 32]. As already described above, the lower efficiency of F_4 -NHPI derivative in the oxidation of ethylbenzene is not due to the instability of the corresponding PINO radical [26], it is probably due to the solvent used for the reaction. The authors used CH_3CN as the solvent for their oxidation reaction and it is reported that CH_3CN is a good hydrogen-bond acceptor and forms complex with NHPI, resulting in the decreased catalytic activity [33, 34]. Furthermore, the self-decomposition of PINO influenced by hydrogen-bond formation at the radical center might be also considered [35].

Table 3. Oxidation of cyclopentane under various conditions^a

Entry	Catalyst	Zr(acac) ₄	Temp (°C)	Product distribution/% ^b				TON ^c
				6	7	8	9	
1	NHPI	0.01	100	29	18	40	13	86.3
2	F_4 -NHPI	0.01	100	20	33	35	12	116.8
3	NHPI	-	100	32	21	36	11	84.7
4	F_4 -NHPI	-	100	21	31	35	13	110.3
5	NHPI	0.01	90	78	18	2	2	53.4
6	F_4 -NHPI	0.01	90	52	43	3	2	63.0
7	NHPI	-	90	69	23	5	3	52.2
8	F_4 -NHPI	-	90	52	39	6	3	63.7

^aCompound **5** (37 mmol) in TFT (4 mL) was allowed to react with NHPI or F_4 -NHPI (0.0125 mmol), $\text{Co}(\text{OAc})_2 \cdot 4\text{H}_2\text{O}$ (0.020 mmol), $\text{Mn}(\text{OAc})_2 \cdot 4\text{H}_2\text{O}$ (0.010 mmol) and $\text{Zr}(\text{acac})_4$ under air (10 atm) for 6 h.

^bGC yield.

^cTON (Turnover number) = **6**+**7**+**8**+**9** (mmol) / NHPI or F_4 -NHPI (mmol).

3.5 Aerobic Oxidation of Cyclopentane (5)

Next the oxidation of cyclopentane (**5**) was performed by the same catalysts in TFT at 100 °C for 6 h (Scheme 3 and Table 3). The resulting oxidized products are cyclopentanol (**6**), cyclopentanone (**7**), succinic acid (**8**) and glutaric acid (**9**). In this case also, *F*₄-NHPI showed better performance than NHPI and Zr was found to play a little positive role in the oxidation.

Surprisingly, when the oxidation of **5** was carried out in TFT at 100 °C, the major product obtained for both NHPI and *F*₄-NHPI is succinic acid (**8**) (entries 1-4, Table 3), not the alcohol (**6**) or ketone (**7**). These results differ remarkably with the results obtained in the oxidation of cyclohexane (**1**), where alcohol **2** (for NHPI) or ketone **3** (for *F*₄-NHPI) were obtained as the major products under exactly the same conditions (Table 2, entries 2 and 4, respectively). These results are probably due to the more solubility of **6** and/or **7** in TFT than that of **2** or **3**. The stability of cyclohexane and cyclopentane may also play a role here. As cyclohexane is more stable than cyclopentane, the cleavage of the C–C bond after the initial oxidation of cyclopentane might be easier at 100 °C than that of cyclohexane. As a result, the carboxylic acid derivative **8** was obtained as the major product for cyclopentane, whereas the alcohol or ketone was the major product from cyclohexane.

Finally, the effect of temperature on the oxidation of **5** was investigated. It is very interesting to note that the product composition as well as the TON differ when the reaction was carried out at different temperatures. At 100 °C the TON for *F*₄-NHPI is higher than that of 90 °C (entry 2 vs. 6). This is probably due to the fact that as the O–H bond is strengthened by the presence of electronegative groups, the formation of active intermediate PINO radical becomes difficult at lower temperature. Again, the formation of major product is changed from succinic acid (**8**) to cyclopentanol (**6**) when the temperature is changed from 100 °C to 90 °C. So, temperature plays a vital role in the oxidation of **5**. It seems that the rate of the reaction is lower at 90 °C as compared to 100 °C. As a result, after formation of cyclopentanol, the further oxidation could not take place at low temperature. It should be also noted that at 90 °C, both of the catalysts showed almost the similar results for the oxidation of **5** (entries 5-8). Thus, by controlling the reaction temperature, the selectivity of the products can be altered according to the choice.

4. Conclusions

In conclusion, we have developed a very simple and highly efficient method for the catalytic aerobic oxidation of cycloalkanes by 3,4,5,6-tetrafluoro-*N*-hydroxyphthalimide (*F*₄-NHPI). That fluorinated NHPI

derivative was also found to act as an effective catalyst for the reaction without any solvent. In all cases, it has been found that the *F*₄-NHPI has a higher catalytic activity than NHPI in the oxidation of both cyclohexane and cyclopentane. Even though that fluorinated compound had been reported for its abnormal lower catalytic activity [25], but by this report the efficiency of *F*₄-NHPI as a catalyst will be newly established. It will now, therefore, can be considered as an effective catalyst for the oxidation reaction. Related works are in progress and will be published in due time.

5. References

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