The Removal of Indoor Formaldehyde by Various Air Cleaners

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ABSTRACT

The formaldehyde (HCHO) in indoor air is mainly emitted from interior decoration materials, adhesives and paints. Due to the excessive interior decoration and the lack of appropriate regulation and control strategy, sometimes the cancer risk caused by formaldehyde is 100 to 1,000 times greater than the acceptable level in many office buildings. This research studied the removal efficiency and the removal mechanism of indoor formaldehyde by various types of air cleaners.

Four types of air cleaners were studied, including photo-catalytic, activated carbon, negative ion, and ozone air cleaners, at various relative humidity, temperatures, and formaldehyde concentrations. Batch experiments were conducted in an air-tight test chamber revised from standard method AHAM AC-1. The formaldehyde removal efficiencies were determined from three experiments: (1) the natural decay of formaldehyde, (2) formaldehyde with cleaner turn-off, and (3) formaldehyde with cleaner turn-on. Formaldehyde concentrations were sampled and recorded every 10 to 30 minutes to study the removal efficiency.

The results indicated that formaldehyde removal efficiency was affected by formaldehyde concentration, temperature, and relative humidity. Low removal efficiencies of formaldehyde were observed by the activated-carbon air cleaner (3.3~28.6%) and the negative-ion air cleaner (18.5~30.8%). The removal efficiencies of formaldehyde by photo-catalytic air cleaner were ranged 18.7~56.0%. The removal efficiencies by ozone air cleaner were ranged 18.2~44.2%. Results suggested that air cleaners were inadequate to remove formaldehyde to meet WHO guidelines (0.08 ppm). Source reduction and ventilation improvement should be conducted to eliminate indoor formaldehyde concentration.

INTRODUCTION

The formaldehyde in indoor air is mainly emitted from interior decoration materials, adhesives and paints. Due to the hot and humid climate, excessive interior decoration and the lack of appropriate regulation and control strategy in Taiwan, sometimes the cancer risk caused by formaldehyde is 100 to 1,000 times greater than the acceptable level (10^{-6}) in many office buildings.[1]

Many air cleaners with various functions are sold in the market. However, most of the air cleaners address on the particle, odor, and VOCs removal. Few studies were done for the performance and mechanism of indoor formaldehyde removal. This research studied the removal efficiency and the removal mechanism of indoor formaldehyde by various types of air cleaners. The removal mechanism and energy efficiency will be discussed as well.

Literature Review

Symptoms of formaldehyde exposure include burning sensation, coughing, wheezing, laryngitis, shortness of breath, headache, nausea, and vomiting. Formaldehyde is a probable human carcinogen. Most national IAQ standards set the acceptable limit at 0.08~0.1 ppm. In Taiwan, the formaldehyde concentration in the indoor air of office buildings ranged from 0.13~0.89 ppm, which are much greater than WHO guideline 0.08 ppm for 30 min exposure.

Some studies evaluated the VOCs removal by activated carbon and ozone air cleaners. Activated carbon air cleaners could reduce 30.0 ppm formaldehyde to 20.0 ppm.[5] Ozone air cleaners could remove 1.8~34.4% of 1.0 ppm formaldehyde.[6] However, most of the researches are nor comparable due to the different experiment conditions. None of the researches is focus on the formaldehyde removal performance in the full range of air cleaners.

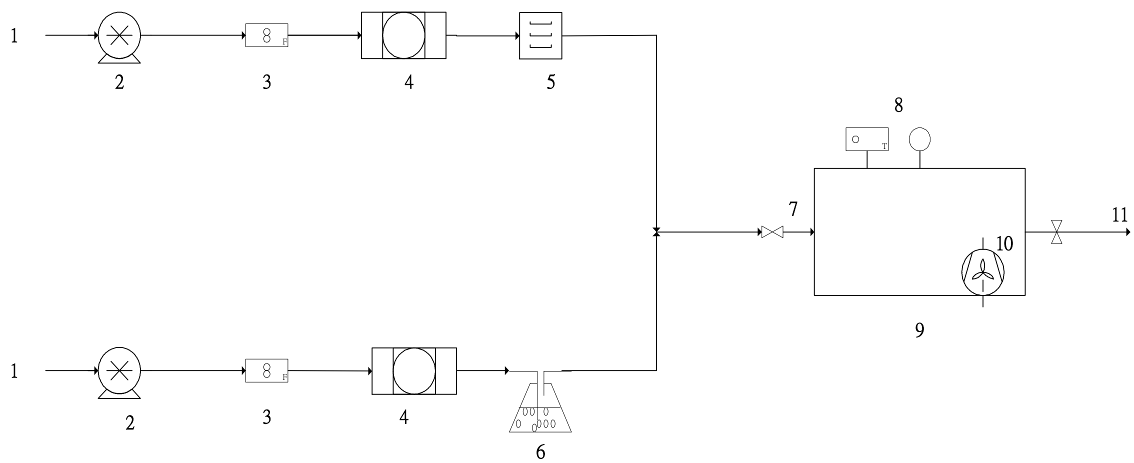
Some standard methods are available to exam the particles removal performance of air cleaners, such as AHAM AC-1, JEM 1467, CNS 7620, JIS C 9615. Few methods (CNS 7620, JIS C 9615) exam the gaseous pollutants removal, but do not consider the adsorption of air cleaner itself. AHAM AC-1 is developed by U.S. Association of Home Appliance Manufacturers to exam the particles removal performance of air cleaners. Niu et al. (1998) modified AHAM AC-1 method to exam the performance of gaseous pollutants removal.[7]

Experiment Setup

Four types of best-selling air cleaners (photo-catalytic, activated-carbon, negative ion, and ozone air cleaners, as shown at Tab 1) were studied for formaldehyde removal efficiencies at various relative humidity (50%, 80%), temperatures (20^{o}C, 30^{o}C), and formaldehyde concentrations (0.50, 1.00, 4.00 ppm). These conditions represent the typical conditions of normal indoor air environment in Taiwan. According to the modified AHAM AC-1 method,[7] batch experiments were conducted in an air-tight stainless steel chamber (0.7m×0.7m×0.7 m) as shown in Fig 1.

Ambient air was pumped in and filtered by particle filter and desiccant column. One way served as dilution gas and the other as formaldehyde carrier gas. Formaldehyde concentrations were controlled by the mixing ratios of these two gases. Gaseous formaldehyde was generated from paraformaldehyde (98%, Merck) by aeration. The relative humidity and temperatures of test chamber were controlled as well. Air cleaner was placed in the chamber in advance. When the target humidity, temperature, and concentration were reached, the inlet and outlet valves were closed. The experiment did not begin until formaldehyde concentration was stable for 10~20 minutes to ensure no leak in the chamber. Each test lasted 4 hours, and formaldehyde concentration was sampled and recorded by formaldehyde monitor (PPM Formaldemeter 400, resolution 0.01 ppm) every 10~30 minutes. The final removal efficiencies reported in this paper is the formaldehyde removal efficiency at the end of the fourth hours, in most cases, the formaldehyde concentration reached a stable value. The removal efficiency was calculated from the concentrations as described in the following section.

Fig 1 Experiment Setup



1: Ambient Air 2: Pump 3: Mass flow controller 4: Particle Filter 5: Desiccant Column 6: HCHO Generator 7: Chamber Inlet 8: Hygrometer and Thermometer 9: Testing Chamber (0.7m×0.7m×0.7 m) 10: Mixing Fan 11: Chamber Outlet

The reducing of formaldehyde concentration may due to the adsorption of chamber wall, the adsorption of air cleaner, and the function of air cleaner. For each experiment condition, therefore, the following three tests were conducted:

Test 1: The natural decay of formaldehyde (without the air cleaner in the chamber)

The purpose of this test is to evaluate the amount of chamber wall adsorption and the natural decay (oxidation) of formaldehyde. The natural decay of formaldehyde in 4 hours was approximately 5% of the initial concentration in all tests.

$$\text{Natural decay (\%)} = \left(\frac{\text{Initial HCHO conc. - HCHO Conc. at } 4^{\text{th}} \text{ hr.}}{\text{Initial HCHO conc.}} \right)_{\text{without cleaner}} \qquad \text{Eq. 1}$$

Test 2: Formaldehyde removal with cleaner/turn-off

The purpose of this test is to evaluate the amount of natural decay (Test 1) plus the amount of adsorption by the air cleaner surface.

$$\text{With cleaner turn-off (\%)} = \left(\frac{\text{Initial HCHO conc. - HCHO Conc. at } 4^{\text{th}} \text{ hr.}}{\text{Initial HCHO conc.}} \right)_{\text{with cleaner/off}} \qquad \text{Eq. 2}$$

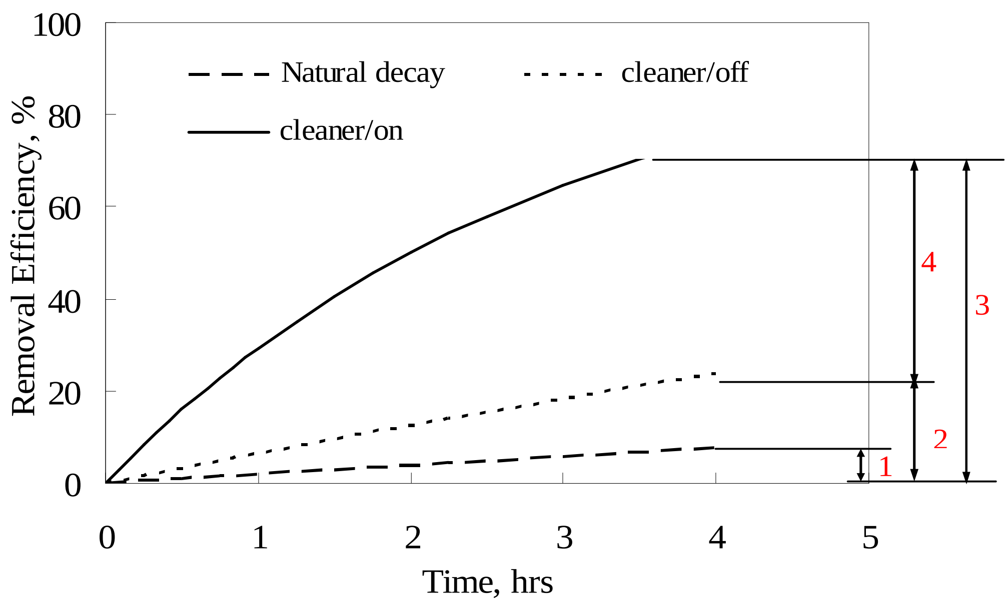
Test 3: Formaldehyde removal with cleaner/turn-on

The real formaldehyde removal due to function of air cleaner is the concentration difference between cleaner on (eq. 3) and cleaner off (eq. 2), as shown in Fig 2.

$$\text{With cleaner turn-on (\%)} = \left(\frac{\text{Initial HCHO conc. - HCHO Conc. at } 4^{th} \text{ hr.}}{\text{Initial HCHO conc.}} \right)_{\text{with cleaner/on}} \quad \text{Eq. 3}$$

Formaldehyde removal efficiency (%) = cleaner turn-off (%) - cleaner turn-on (%)   Eq. 4

Fig 2 Formaldehyde Removal Efficiency



1. Natural decay, 2. with cleaner/turn-off
3. with cleaner/turn-on, 4. HCHO removal of the cleaner

Tab 1 The Specification of Air Cleaners

Type	Cleaner Size	flowrate	power consumption	Target Room size	Price	Filter	Other
	cm	m^3/min	W	m^2	US$		
Activated-Carbon	ϕ35*39	5.00	79.2	13~20	$147	Activated-Carbon filter 2400 cm^2	HEPA Core
Negative Ion	41*20*46	3.20	39.1	26~33	$206	HEPA filter 1090 cm^2	Negative ion discharger
Ozone	25*9*8	0.15	3.3	13	$53	filter 45 cm^2	Ozone Generator
Photo-catalytic A	41*20*46	3.20	44.5	26~33	$206	HEPA filter 1090 cm^2	Photocatalyst 630 cm^2, 1 UV Tube.
Photo-catalytic B	40*20*48	4.50	39.1	26~40	$721	HEPA filter 1050 cm^2	Photocatalyst 1680 cm^2, 2 UV Tubes.

Results Discussion

1. Activated Carbon Air Cleaner

The formaldehyde removal efficiency ranged 3.3~28.6% as shown in Tab 2. In general, activated carbon air cleaners have the worst performance of formaldehyde removal. The formaldehyde molecules are small and light so the Van der Waals force between the formaldehyde and activated carbon is very week. Formaldehyde is difficult to be adsorbed, especially within the short contact time in the cleaner, but easy to be desorbed.

High formaldehyde concentration (4 ppm) resulted in high removal efficiency (15.8~28.6%), comparing with low concentration (0.5 ppm), 3.3~19.6%. According to the Langmuir isotherm, increasing the partial pressure of the absorbate causes more of it to be absorbed at a given temperature. However, high formaldehyde concentrations shorten the breakthrough time of activated-carbon filter.

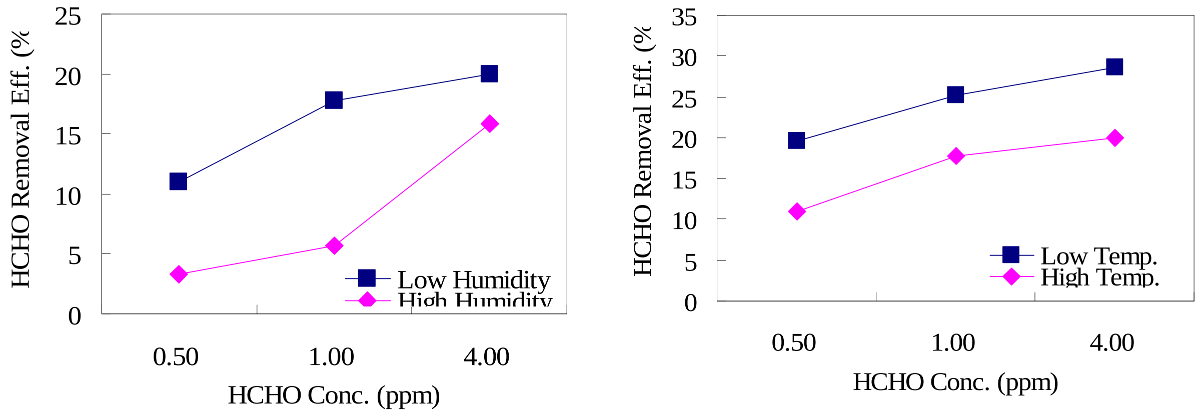
Temperature and humidity effects are shown at Fig 3. As would be expected, an increase in the temperature for a given condition decreased the amount of adsorbed gas.[9] Removal efficiencies were higher at low temperature (19.6~28.6%) than at high temperature (11~20%).

Formaldehyde removal efficiencies were higher at low humidity (11~20%) than at high humidity (3.3~15.8%). This is because the water molecules may occupy the functional group of activated carbon for adsorption when the air is humid.[8] The absorbed formaldehyde on the surface of activated carbon may re-emit under high humidity or temperature conditions. The competition between adsorption and desorption decreased the removal efficiency.[5,7] Activated carbon air cleaners should not be used in a humid and warm indoor environment. Activated carbon filter should be replaced regularly to prevent secondary pollution.

Tab 2 The Removal Efficiency of Activated Carbon Air Cleaner

Temperature	R.Humidity	HCHO Conc.	Cleaner turn-off	Cleaner turn-on	Removal Eff.	CADR
°C	%	ppm	%	%	%	L/hr
30	50	0.50	14.0	25.0	11.0	8.20
		1.00	29.3	47.1	17.8	18.10
		4.00	28.5	48.5	20.0	13.82
30	80	0.50	12.3	15.6	3.3	1.47
		1.00	15.9	21.6	5.7	4.01
		4.00	16.9	32.7	15.8	5.73
20	50	0.50	23.7	43.3	19.6	23.36
		1.00	23.9	49.1	25.2	30.66
		4.00	29.6	58.2	28.6	34.27

Fig 3 The Temperature and Humidity Effects of Activated-Carbon Air Cleaner



Temp: 30°C, RH: 50% and 80%   Temp: 20°C and 30°C, RH: 50%

2. Negative Ion Air Cleaner

The formaldehyde removal efficiency ranged 18.5~30.8% as shown in Tab 3. In general, formaldehyde can not be effectively removed by the negative ion air cleaners. The major ions from the indoor negative ion air cleaners are O^-, O_2^-, O_3^-. Among them, O_2^- ions are the most in quantity but the least in oxidation ability.[10] These negative oxygen ions are with less oxidation ability than ozone and hydroxyl radical. The ionization energy of formaldehyde (10.88 eV) is close to the ionization energy of oxygen (12.07 eV). Because ionization energy and bond dissociation energy are of comparable magnitudes (around 10 eV), chemical compounds with ionization energy greater than 10 eV are not amenable to treatment by air ionization.[10]

High formaldehyde concentration resulted in high removal efficiency (24.9~30.8%), comparing with low concentration, 18.5~23.5%. During the short life time of negative ions, high formaldehyde concentration results in more encounter opportunity between formaldehyde molecules and negative ions.

Temperature and humidity effects are shown at Fig 4. Removal efficiencies were slightly higher at low temperature (23.5~30.8%) than at high temperature (18.5~26.1%). There are no obvious difference of formaldehyde removal efficiencies between low humidity (18.5~26.1%) and high humidity (21.2~26.3%). It may be the result of the following two competing mechanisms.

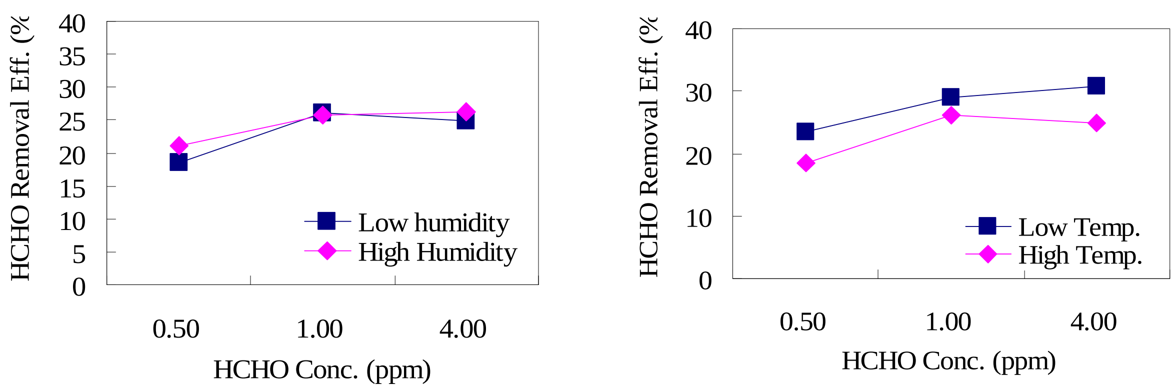
1. Under high humidity condition, more hydroxyl radicals may be formed from the ionizer and from the reaction between the water molecules and negative ions. These highly-oxidizing hydroxyl radicals increase the formaldehyde removal.[10]

2. However, the life time of negative ion decreases under high humidity condition, which decreases the formaldehyde removal.[11]

Tab 3 The Removal Efficiency of Negative Ion Air Cleaner

Experimental Condition			Removal Efficiency			
Temperature	R.Humidity	HCHO Conc.	Cleaner turn-off	Cleaner turn-on	Removal Eff.	CADR
^oC	%	ppm	%	%	%	L/hr
30	50	0.50	19.6	38.1	18.5	10.26
		1.00	21.6	47.7	26.1	17.18
		4.00	28.3	53.2	24.9	24.28
30	80	0.50	20.3	41.5	21.2	12.83
		1.00	22.2	47.9	25.7	22.30
		4.00	23.3	49.6	26.3	13.86
20	50	0.50	24.1	47.6	23.5	11.97
		1.00	25.9	54.9	29.0	28.06
		4.00	28.1	58.9	30.8	13.89

Fig 4 The Temperature and Humidity Effects of Negative Ion Air Cleaner



Temp: 30°C, RH: 50% and 80%

Temp: 20°C and 30°C, RH: 50%

3. Photo-Catalytic Air Cleaners

The formaldehyde removal efficiency ranged 18.7~38.0% (cleaner A) and 29.4~56.0% (cleaner B) as shown in Tab 4. In general, photo-catalytic air cleaners have the best performance of formaldehyde removal, because the major removal mechanism is the oxidation reaction between hydroxyl radical and formaldehyde.

High formaldehyde concentration resulted in high removal efficiency (27.9~56.0%), comparing with low concentration, 18.7~39.5%. Obee et al. have reported that the oxidation rate of formaldehyde increases as the formaldehyde concentration increases when the formaldehyde concentrations are between 0.1~10.0 ppm.[12]

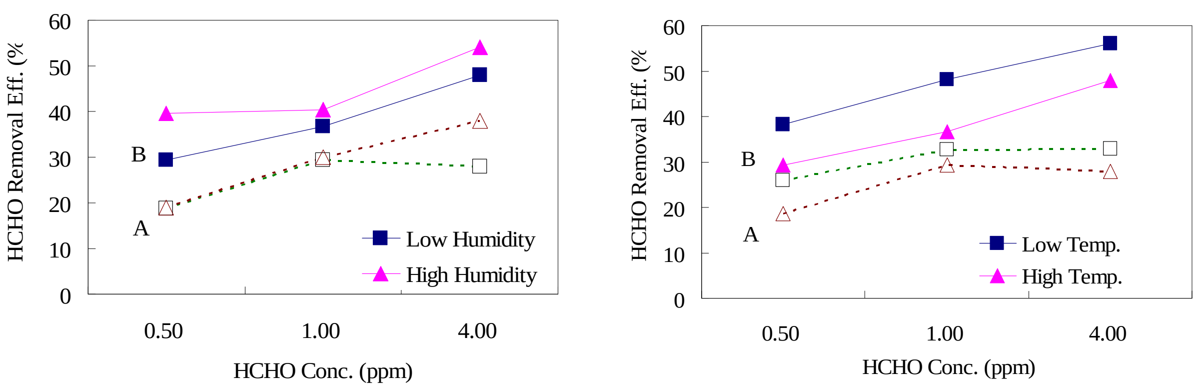
Temperature and humidity effects are shown at Fig 5. Formaldehyde removal efficiencies were higher at high humidity than at low humidity, because more hydroxyl radicals were formed on the surface of photo-catalyst under high humidity condition. These highly-oxidizing hydroxyl radicals increase the formaldehyde removal. And since the photo-catalytic reaction occurs on the surface of photo-catalyst inside the cleaner, there is no such negative effect as the decreasing life time of negative ion under high humidity condition.

Removal efficiencies were higher at low temperature than at high temperature. This is because the oxidation rate of formaldehyde increases as the formaldehyde concentration decreases when the temperatures are between 15~50^{o}C.[12]

Tab 4 The Removal Efficiency of Photo-Catalytic Air Cleaners

	Experimental Condition			Removal Efficiency			
	Temperature	R.Humidity	HCHO Conc.	Cleaner turn-off	Cleaner turn-on	Removal Eff.	CADR
	^{o}C	%	ppm	%	%	%	L/hr
Cleaner A	30	50	0.50	19.6	38.3	18.7	7.99
			1.00	21.6	50.9	29.3	12.79
			4.00	28.3	56.2	27.9	10.94
	30	80	0.50	20.3	39.2	18.9	19.83
			1.00	22.2	52.3	30.1	31.42
			4.00	23.3	61.3	38.0	31.11
	20	50	0.50	24.1	50.0	25.9	10.98
			1.00	25.9	58.5	32.6	20.92
			4.00	28.1	60.9	32.8	16.70
Cleaner B	30	50	0.50	25.0	54.4	29.4	26.41
			1.00	27.7	64.4	36.7	17.80
			4.00	32.9	80.9	48.0	31.66
	30	80	0.50	23.8	63.3	39.5	13.51
			1.00	25.0	65.5	40.5	17.66
			4.00	25.4	79.4	54.0	34.99
	20	50	0.50	29.0	67.2	38.2	27.44
			1.00	25.5	73.6	48.1	59.92
			4.00	27.8	83.8	56.0	44.62

Fig 5 The Temperature and Humidity Effects of Photo-Catalytic Air Cleaners



Temp: 30^{o}C, RH: 50% and 80%

Temp: 20^{o}C and 30^{o}C, RH: 50%

4. Ozone Air Cleaner

The formaldehyde removal efficiency ranged 18.2~44.2% as shown in Tab 5. In general, formaldehyde can be effectively removed by the ozone air cleaner due to the high oxidation ability of ozone. However, excess indoor ozone may harm the human health. In an air-tight indoor environment, ozone concentration will be easily raised up and excess the WHO guidelines (0.08 ppm). But Esswein et al. reported that oxidation of formaldehyde by ozone is not obvious unless the ozone is accumulated more than 0.5 ppm.[13]

High formaldehyde concentration (4 ppm) resulted in low removal efficiency (18.2~20.2%), comparing with low concentration (0.5 ppm), 28.8~38.8%. For other types of cleaners, the formaldehyde concentration reached a stable value at the end of the fourth hours. But for ozone air cleaner, formaldehyde concentration kept decreasing as long as the ozone was generated. In terms of the formaldehyde removal amount at the end of the fourth hours, more formaldehyde was removed (i.e. faster removal rate) at high formaldehyde concentration.

Temperature and humidity effects are shown at Fig 6. Formaldehyde removal efficiencies were higher at low humidity (20.2~44.2%) than at high humidity (20.0~31.1%). This is because the water molecules may consumed the ozone as well, which decreased the formaldehyde oxidation. Removal efficiencies were higher at high temperature (20.2~44.2%) than at low temperature (18.2~30.4%).

Tab 5 The Removal Efficiency of Ozone Air Cleaners

Experimental Condition			Removal Efficiency			
Temperature	R.Humidity	HCHO Conc.	Cleaner turn-off	Cleaner turn-on	Removal Eff.	CADR
^oC	%	ppm	%	%	%	L/hr
30	50	0.50	14.3	53.1	38.8	56.60
		1.00	13.2	57.4	44.2	66.30
		4.00	15.6	35.8	20.2	21.85
30	80	0.50	15.5	44.3	28.8	34.30
		1.00	20.4	51.5	31.1	43.53
		4.00	20.6	40.6	20.0	27.06
20	50	0.50	16.4	46.8	30.4	39.99
		1.00	15.2	45.1	29.9	38.45
		4.00	17.1	35.3	18.2	23.74

Fig 6 The Temperature and Humidity Effects of Ozone Air Cleaners

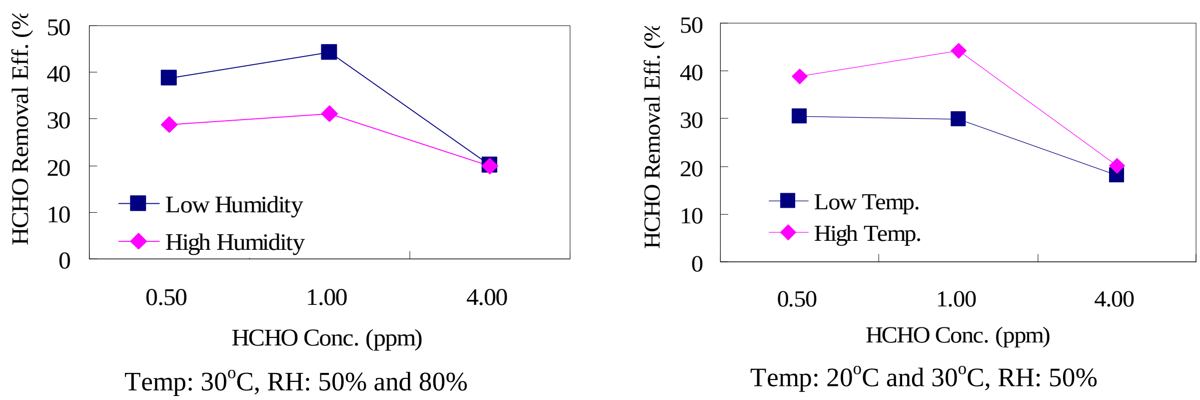
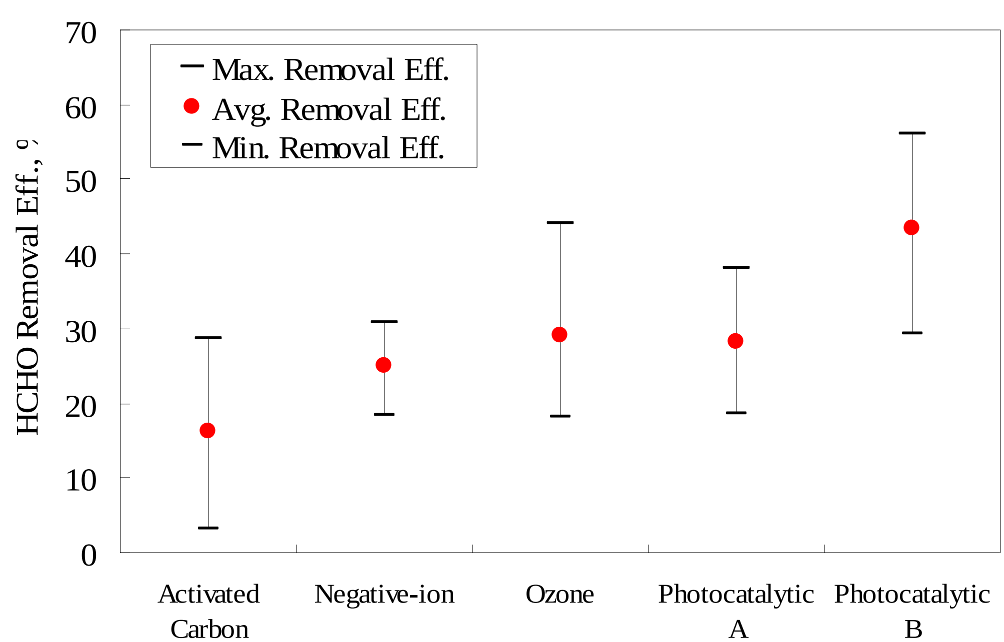


Fig 7 shows the summary of the formaldehyde removal efficiency for four types of air cleaners. Photo-catalytic air cleaner ranks the best while activated carbon air cleaner is the worst. However, all the air cleaners were inadequate to remove formaldehyde to meet WHO guidelines (0.08 ppm).

Fig 7 Summary of the Formaldehyde Removal Efficiency for Four Types of Air Cleaners



5. Energy efficiency of Formaldehyde Removal

As shown in Tab 6, ozone air cleaner has the highest energy efficiency (4.53~25.4 mg/kWh), followed by photo-catalytic cleaner (0.39~6.115 mg/kWh). Activated carbon air cleaner has the lowest energy efficiency (0.022~1.542 mg/kWh). The energy efficiency is not necessary proportional to the formaldehyde removal efficiency. The energy efficiency is related not only to the removal mechanism, but also the design of air cleaner (pump, filter, etc.).

The ozone air cleaner has the highest energy efficiency is because:

(1) Due to the adverse health effects, the energy for ozone generation is limited.

(2) The purpose of the fan/pump is to deliver ozone, not to drive the room air through the air cleaner. Comparing with other types of cleaners, only very small power is required by ozone air cleaner.

(3) The purpose of the filter is to protect the discharge electrodes for ozone generation, not to filter the room air for particle removal. Therefore, only very small power is required by ozone air cleaner.

Tab 6 The Energy Efficiency of Formaldehyde Removal (mg-HCHO/kWh)

HCHO Conc.	Temp	R.H.	Activated Carbon	Negative-ion	Ozone	Photo-catalytic A	Photo-catalytic B
0.50 ppm	30	50%	0.072	0.245	6.10	0.218	0.390
	30	80%	0.022	0.281	4.53	0.220	0.524
	20	50%	0.132	0.321	4.92	0.311	0.521
1.00 ppm	30	50%	0.233	0.692	13.89	0.683	0.974
	30	80%	0.075	0.682	9.78	0.702	1.074
	20	50%	0.340	0.792	9.67	0.782	1.313
4.00 ppm	30	50%	1.048	2.642	25.40	2.601	5.094
	30	80%	0.828	2.791	25.15	3.543	5.730
	20	50%	1.542	3.363	23.55	3.147	6.115
Rank			5	3	1	3	2

CONCLUSION

1. Formaldehyde removal efficiency was affected by formaldehyde concentration, temperature, and relative humidity.

2. In general, photo-catalytic air cleaner achieved the best performance of formaldehyde removal (18.7~56.0%), followed by ozone air cleaner (18.2~44.2%), and negative-ion air cleaner (18.5~30.8%). Activated carbon air cleaner is the worst (3.3~28.6%).

3. Excess indoor ozone may harm the human health. The absorbed formaldehyde on the surface of activated carbon may re-emit under high humidity or temperature conditions. The secondary pollution of some air cleaners should be aware of.

4. The ozone air cleaner has the highest energy efficiency of formaldehyde removal (4.53~25.4 mg/kWh), followed by photo-catalytic air cleaner (0.39~6.115 mg /kWh). Activated carbon air cleaner is the worst (0.022~1.542 mg /kWh)。

5. For high formaldehyde concentration, photo-catalytic, ozone, negative-ion air cleaner is recommended.

6. For high humidity, photo-catalytic air cleaner is recommended. For low humidity, ozone or activated carbon air cleaner is recommended.

7. For high temperature, ozone air cleaner is recommended. For low temperature, photo-catalytic, ozone, negative-ion air cleaner is recommended.

8. All the air cleaners were inadequate to remove formaldehyde to meet WHO guidelines (0.08 ppm). Source reduction and ventilation improvement should be conducted to eliminate indoor formaldehyde concentration.

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Keywords:

Indoor Air cleaner, Formaldehyde (HCHO), Volatile Organic Compounds (VOCs), Indoor Air Quality (IAQ)