



A Review on VOCs Control Technology Using Electron Beam

Youn-Suk Son¹⁾, Ki-Joon Kim²⁾ and Jo-Chun Kim^{1),3),*}

¹⁾Department of Advanced Technology Fusion, Konkuk University, 1 Hwayang-dong, Gwangjin-gu, Seoul 143-701, Korea

²⁾Emission Source Research Division, National Institute of Environmental Research, Incheon 404-708, Korea

³⁾Department of Environmental Engineering, Konkuk University, 1 Hwayang-dong, Gwangjin-gu, Seoul 143-701, Korea

*Corresponding author. Tel: +82-2-455-2994, E-mail: jckim@konkuk.ac.kr

ABSTRACT

The removal characteristics for aromatic and aliphatic VOCs by electron beam (EB) were discussed in terms of several removal variables such as initial VOC concentration, absorbed dose, background gas, moisture content, reactor material and inlet temperature. It was reviewed that only reactor material was an independent variable among the potential control factors concerned. It was also suggested that main mechanism by EB should be radical reaction for the VOC removal rather than that by primary electrons. It was discussed that the removal efficiency of benzene was lower than that of hexane due to a closed benzene ring. In the case of aromatic VOCs, it was observed that the decomposition of the VOCs with more functional groups attached on the benzene ring was much easier than those with less ones. As for aliphatic VOCs, it was also implied that the longer carbon chain was, the higher the removal efficiency became. An EB-catalyst hybrid system was discussed as an alternative way to remove VOCs more effectively than EB-only system due to much less by-products. This hybrid included supporting materials such as cordierite, Y-zeolite, and γ -alumina.

Key words: Electron beam, Aromatic VOC, Catalytic oxidation, By-product, Toluene

1. INTRODUCTION

Volatile organic compounds (VOCs) are emitted into the atmosphere from a variety of industrial processes. They have adverse effects on the environment and public health through the formation of ozone, carcinogenic and toxic substance. Therefore, many countries have paid more attention to efficient control methods for these VOCs (Jeon *et al.*, 2008; Kim *et al.*, 2004; Kim, 2002).

There are many different traditional techniques to control VOCs emissions such as carbon adsorption, absorption, catalytic oxidation, thermal incineration, and biotreatment. These techniques share both advantages and limitations (Kim *et al.*, 2005; Kim *et al.*, 2004; Faisal and Aloke, 2000). Table 1 shows a brief review for VOCs removal methods (Khan and Ghoshal, 2000; Rafson, 1998). Recently, there have been many researches on the decomposition of VOCs using electron beam (EB), plasma, and photocatalytic oxidation/UV and hybrid system treatment in order to resolve their problems (Boulamanti *et al.*, 2008; Chmielewski *et al.*, 2007; Chmielewski, 2007; Chaichanawong *et al.*, 2005; Kim *et al.*, 2005; Chmielewski and Hajj-Saeid, 2004; Tanthapanichakoon *et al.*, 2004; Han *et al.*, 2003; Licki *et al.*, 2003). However, most plasma and corona methods needed energy over 100 J/L for efficient VOC treatment (Lu *et al.*, 2006; Kim *et al.*, 2005). On the other hand, in terms of its energy effectiveness, it was reported that efficiency of VOC removal by EB was 50 times higher than that by plasma or corona (Penetrante *et al.*, 1997; Penetrante *et al.*, 1995). Furthermore, it is well known that the economic range of absorbed dose in EB technology is below 10 kGy (~10 J/L).

The method of VOC removal by EB irradiation has been considered one of the most upgraded and novel technologies (Kim *et al.*, 2004; Licki *et al.*, 2003; Hirota *et al.*, 2002; Kim, 2002; Ogata *et al.*, 1999; Hirota *et al.*, 1995a; Paur *et al.*, 1991). EB method can be applied to high emission rate and/or low concentration of source facilities at ambient air temperature and requires relatively low dose. However, one of disadvantages associated with this technique is the formation of by-products (Kim *et al.*, 2010; Sun *et al.*, 2009; Jeon *et al.*, 2008; Kim *et al.*, 2005). In order to solve that problem, a few research groups have investigated the decomposition of VOCs using a hybrid technology such as combination of EB or plasma with catalyst (Kim *et al.*, 2010, 2005, 2004; Jeon *et al.*, 2008; Ogata *et al.*,

Table 1. Comparison of various VOC control techniques.

Techniques	Annual operating cost (\$/cfm)	Removal efficiency (%)	Positive and negative remarks
Absorption	25-120	90-98	-Product recovery can offset annual operating costs -Requires rigorous maintenance -Requires pretreatment of the VOCs
Adsorption (Activated carbon)	10-35	80-90	-Recovery of compounds, which may offset annual operating costs -Susceptible to moisture, and some compounds (ketones, aldehydes, and esters) can clog the pores
Biofiltration	15-75	60-95	-Requires less initial investment, less non-harmful secondary waste, and non-hazardous -Slow, and selective microbes decomposes selective organics, thus requires a mixed culture of microbes
Condensation	20-120	70-85	-Product recovery can offset annual operating costs -Requires rigorous maintenance
Catalytic oxidation	15-90	90-98	-Energy recovery is possible (maximum up to 70%) -Efficiency is sensitive to operating conditions
Thermal oxidation	15-90 (Recuperative) 20-150 (Regenerative)	95-99	-Energy recovery is possible (maximum up to 85%) -Halogenated and other compounds may require additional control equipment
Zeolite	15-40	90-96	-Effective in more than 90% RH, Recovery of compounds offsets annual operating costs -High cost of zeolite, restricted availability
Membrane separation	15-30	90-99	-No further treatment, recovery of solvent may offset the operating costs -Membranes are rare and costly

(Source : Khan and Ghoshal, 2000)

1999; Kohno *et al.*, 1998). Therefore, the objective of this research is to review all the subjects covering EB for the decomposition of aromatic and aliphatic VOCs.

2. REVIEW ON VOC REMOVAL TECHNIQUE USING EB

2.1 What is the Principle of Electron Beam Process to Decompose VOCs?

The EB operation time is quite short because the electrons are generated during 10^{-18} - 10^{-12} seconds and interact with the gas molecules. Besides, this reaction produces free radicals and ions during 10^{-8} - 10^{-1} seconds (Kim *et al.*, 2006b; Kim *et al.*, 2005; Kim, 2002). When air is irradiated by an electron beam with the energy of electrons of 1 MeV, the maximum penetration range is about 2.8-3 m (Vazquez *et al.*, 2002).

More specifically, when the energy of the fast electrons is absorbed in the air, it causes ionization and excitation processes of the nitrogen and oxygen molecules in the air stream. At first, Primary species and secondary electrons are formed, and the latter are

thermalized within 1 ns in air at 1 bar pressure. These primary species and the thermalized secondary electrons react with VOCs by a series of reactions to cause their decomposition (Chmielewski *et al.*, 2007). After irradiation, primary electrons interact with gas creating various ions and free radicals, the primary species formed include e^- , N_2^+ , N^+ , O_2^+ , O^+ , H_2O^+ , OH^+ , H^+ , CO_2^+ , CO^+ , N_2^* , O_2^* , N , O , H , OH , and CO . In addition, in the case of high water vapor concentration, the oxidizing radicals OH and $HO_2\cdot$, and exited ions as $O(^3P)$ are the most important product (Chmielewski, 2007; Licki *et al.*, 2003). These species take part in a variety of ion-molecule reactions, neutralization reactions, and dimerization (Person and Ham, 1988).

2.2 Absorbed Dose and Initial Concentration

The decomposition characteristics of representative VOCs such as toluene, benzene, and styrene were investigated as a function of initial concentration and absorbed dose (Kim *et al.*, 2005; Kim, 2002). They found that the removal efficiencies of these target compounds increased as their concentrations decreased or the absorbed doses increased. Sun *et al.* (2009) also suggested that the decomposition efficiency of toluene

Table 2. A comparison of removal efficiencies for aromatic and aliphatic VOCs among different studies.

VOC compounds	Absorbed dose (kGy)	Concentration (ppmC)	Removal efficiency (%)	Reference
o-xylene	10	744	65	Hakoda <i>et al.</i> , 1998 Hashimoto <i>et al.</i> , 2000 Hirota <i>et al.</i> , 2002 Hirota <i>et al.</i> , 1995b
		784	54	
		176	87	
		184	85	
Toluene	10	1050	43	Hakoda <i>et al.</i> , 1998 Hashimoto <i>et al.</i> , 2000 Han <i>et al.</i> , 2003 Kim <i>et al.</i> , 2004
		945	60	
		900	50	
		630	66	
	8.9	1500	60	Kim <i>et al.</i> , 2005
	6	60	90	Kim, 2002
	14.5	224	50	Sun <i>et al.</i> , 2009
		443.8	37	
		546	34.5	
Butylacetate	10	240	60	Mätzing <i>et al.</i> , 1994 Hirota <i>et al.</i> , 1995b Hirota <i>et al.</i> , 1995a
Ethylbenzene	10	960	60	Han <i>et al.</i> , 2003 Hirota <i>et al.</i> , 1995a
Styrene	6	640	95	Kim <i>et al.</i> , 2004
	8.9	1500	80	Kim <i>et al.</i> , 2005
Hexane	10	600	50	Kim <i>et al.</i> , 2006b
		300	88	
		140	96	
Methane	5	10600	3.8	Kim <i>et al.</i> , 2006a
		800	18.3	
		270	20.7	
		100	54.8	
	20	10600	6.4	
		800	20.8	
		270	26.3	
		100	58.7	

increased with absorbed dose but decreased with initial concentrations. The decomposition of aromatic VOCs (toluene, ethylbenzene, xylene and chlorobenzene) has been carried out using the similar systems as above. Han *et al.* (2003) observed that decomposition efficiencies were 55-65% for “non-chlorinated” aromatic VOCs (initial concentration from 50 to 2,000 ppm) and 85% for chlorobenzene (initial concentration from 150 to 300 ppm). This trend was also observed similarly for aliphatic VOCs such as methane and hexane (Kim *et al.*, 2006a, b). Besides, Hirota *et al.* (1995a) revealed that the removal efficiency of xylene was higher than that for butylacetate in the dose range 0-10 kGy. A compilation of the VOCs removal efficiencies obtained from various electron beam studies is presented in Table 2. It was found that different research groups used different initial VOC concentrations and

dose ranges.

2. 3 Effect of Different Background Gases on Aromatic and Aliphatic VOCs Decomposition

Toluene (140 ppmC) removal at different matrix gases in a batch system was studied by Kim (2002). The decomposition efficiency under He atmosphere was significantly lower than other gaseous conditions. Kim *et al.* (2006b) conducted hexane removal at the same matrix of gaseous conditions and found that the removal trend was very similar to the previous study of Kim (2002). However, decomposition efficiencies of toluene in different background gases were slightly higher than those of hexane. Likewise, Chmielewski *et al.* (2007) evaluated 1,4-dichlorobenzene (DCB) decomposition in different base gas mixtures at the initial concentration

50 ppm. It was found that the decomposition efficiency of 1,4-DCB in nitrogen was higher than that in air. It indicates that electrons generated by electron beam radiolysis did not lead to considerable decomposition of those compounds. Sun *et al.* (2006) also reported that the order of background gases to affect the decomposition of 1,4-DCB was as follows: $N_2 > Air > 1.027\% NO/N_2$. On the other hand, Kim (2002) suggested that order of the background gases ($N_2 > air > O_2 > He$) should be different from those ($O_2 > air > H_2 > He$) for TCE decomposition (Won *et al.*, 2002). It was also found that the decomposition efficiency of TCE under helium atmosphere was significantly low because of the stability of background gases.

2.4 Effect of Moisture on Aromatic and Aliphatic VOCs Degradation

The effect of water vapor on the decomposition of aromatic VOCs in batch and flow system using EB was studied by Kim (2002). In this work, the addition of water vapor into the reactors of batch and flow systems resulted in 5-10% and 15-20% increase of target VOC decomposition efficiencies, respectively, compared to the work without water vapor injection. It was presented that OH radical played a pivotal role in the VOC removal reaction (Sun *et al.*, 2009, 2008; Chmielewski *et al.*, 2007; Penetrante *et al.*, 1998). Won *et al.* (2002) also found that the decomposition efficiency for different initial trichloroethylene concentrations with the addition of water vapor was slightly larger than that in dry air at 10-20 kGy. Besides, it was observed that water vapor addition enhanced the removal efficiency of chlorinated organic compounds (Chmielewski *et al.*, 2007). For chlorinated aliphatic hydrocarbons' decomposition, Sun *et al.* (2006) also found that OH radical reaction with VOCs play major role for VOCs removal.

2.5 Comparison of Aromatic and Aliphatic VOCs Degradation

As for aliphatic VOC, the removal efficiency of n-decane ($C_{10}H_{22}$) by EB was the highest. Then, those of n-hexane (C_6H_{14}), n-butane (C_4H_{10}), and methane (CH_4) were followed (personal communication). On the other hand, when the decomposition efficiency for aromatic VOCs was considered, that for benzene (C_6H_6) was the lowest. In contrast, those of toluene (C_7H_8), ethylbenzene (C_8H_{10}), and p-xylene (C_8H_{10}) were similar. When n-hexane was compared with benzene, it was revealed that the latter was more difficult to decompose than the former. Besides, Chmielewski *et al.* (2007) found that the removal efficiency for chlorinated compounds with higher numbers of chlorine groups was higher than their lower numbered

counterparts.

2.6 The Characteristics of Decomposition by Different Reactor Materials

In order to observe removal efficiencies by different container materials, a flow system was used in this study. All experimental approaches are well depicted elsewhere (Kim, 2002). Transition metals (Fe, Cu, Zn and Al) and stainless steel were employed as reactor materials to compare toluene (160 ppmC) removal characteristics at the same conditions. As for different reactor materials regarding SS, Fe, Cu, Zn, Al, the degradation efficiency was 57.9-61.8, 59.9-61.65, 62.3-62.9, 59.2-62.4 and 58.4-60.0%, respectively. This work clearly showed similar removal efficiencies regardless of reactor materials. This result suggested that decomposition efficiency not be affected by reactor materials.

2.7 The Characteristics of VOC Decomposition by Inlet Gas Temperature

The characteristics of VOC removal efficiency by inlet temperature were investigated by Kim (2002). The decomposition efficiency of toluene was approximately constant from 30°C to 130°C. However, it was decreased substantially when the temperature rose up to 170°C. It was found that the energy-rich OH aromatic adduct was removed back to toluene at the high temperature of 170°C. A more detailed explanation of reaction and back reaction mechanism can be found in a previous paper (Kim, 2002).

2.8 By-products Generated from VOCs by EB Process

In general, it is known that ozone, CO, CO₂, aerosol and other trace compounds such as benzene, benzaldehyde, etc. are by-products found in the course of radiolysis destruction of various VOCs (Kim *et al.*, 2010, 2006a, 2005, 2004; Sun *et al.*, 2009; Han *et al.*, 2003; Kim, 2002; Won *et al.*, 2002; Hirota *et al.*, 1995a, b; Pür and Mätzing, 1993; Pür *et al.*, 1991).

2.8.1 Formation of Ozone, CO, and CO₂

In general, ozone concentration generated from irradiation systems for VOC treatment increased as absorbed dose increased (Kim *et al.*, 2004; Hiroto *et al.*, 1995). CO and CO₂ concentration also increased with dose rise (Won *et al.*, 2002), and these two compounds occupied 56% among the total by-products at 18 kGy. Kim *et al.* (2004) also found that ozone and CO₂ levels by irradiation of toluene were 164 ppm and 14.4% at 10 kGy, respectively, and were proportional to temperature. Besides, the CO₂ yield for the by-product analysis by EB was about 17% (Kim *et al.*, 2005). On the

other hand, the CO and CO₂ yields were almost negligible up to 18 kGy while toluene was destructed (Han *et al.*, 2003). Although the yield was different with respect to various compounds, the amount of CO and CO₂ produced was from 10 to 56% among decomposed VOCs (Won *et al.*, 2002; Hirota *et al.*, 1995a, b; Mätzing *et al.*, 1994; Pär and Mätzing, 1993; Pär *et al.*, 1991). However, the amount of ozone produced by electron beam can be mitigated using catalysts according to researches by Kim *et al.* (2004) and Jeon *et al.* (2008).

2.8.2 Other Trace Compounds

By-products generated from VOCs decomposition process were studied by Kim *et al.* (2010, 2005). In these results, benzene, benzaldehyde, and other trace materials were found as by-products out of toluene removal using EB. Benzaldehyde was also reported as a by-product in previous works (Sun *et al.*, 2009; Han *et al.*, 2003). This benzaldehyde formation strongly suggested the involvement of the Russell's and Bennett's mechanisms associated with the peroxy radicals (Kim *et al.*, 2010). Other oxidation reactions might also occur as reported by Shepson *et al.* (1984) and Atkinson (1985). Besides, Han *et al.* (2003) reported that the main by-products in the radiolytic oxidizing of toluene were dipropyl 1,2-benzenedicarboxylic acid and other trace compounds such as acetone, hexane, benzene.

In the study on butylacetate removal conducted by Mätzing *et al.* (1994), main by-products after EB irradiation were acetate, and minor ones were formate, propion, and butyrate. The artifacts by o-xylene and butylacetate decomposition were confirmed by Hirota *et al.* (1995a, b). It was reported that formic acid, acetic acid, propionic acid and butyric acid were identified as by-products in their work at 2-10 kGy.

Han *et al.* (2003) identified methyl chloride, dipropyl 1,2-benzenedicarboxylic acid, toluene, nitromethane as by-products generated from the EB irradiation of ethylbenzene and chlorobenzene. Also, those generated from trichloroethylene by EB irradiation were investigated by Won *et al.* (2002). It was found that the main by-products were HCl, dichloroacetic acid (DCAA), dichloroacetyl chloride (DCAC) and dichloroethyl ester acetic acid (DCEA). Among these compounds, DCAA, DCAC, DCEA were recognized as intermediate products, which were decomposed to produce CO and CO₂.

By-products from hexane decomposition using EB were identified by Kim *et al.* (2006a). In this case, they were acetone, benzene, 2-hexanone, 3-hexanone, etc. Especially, acetone and benzene generated from this process continuously increased as adsorbed dose increased. On the other hand, the production of 2-hexa-

none and 3-hexanone significantly increased when the adsorbed dose increased up to 2.5 kGy. However, the production rate of those compounds relatively decreased as adsorbed dose increased from 2.5 to 10 kGy.

3. ADVANTAGE OF EB-CATALYST COUPLING SYSTEM

One of disadvantages associated with EB technique is the formation of by-products (Kim *et al.*, 2010; Sun *et al.*, 2009; Jeon *et al.*, 2008; Kim *et al.*, 2005). In order to solve the problem, some research groups have carried out works on decomposition of VOCs using hybrid technology such as combined EB or plasma with catalyst (Kim *et al.*, 2010, 2005, 2004; Jeon *et al.*, 2008; Moon, 2003; Ogata *et al.*, 1999; Kohno *et al.*, 1998). In this study, the EB-catalyst coupling system has been introduced as an advanced oxidizing technology as follows.

3.1 Comparison of Removal Efficiency by Hybrid Reactor Type

Recently, a research group has demonstrated the effectiveness of the EB-catalyst hybrid system for the decomposition of VOCs (Kim *et al.*, 2010, 2008, 2005, 2004). In order to compare the combined types of hybrid system such as only electron beam (EB-only), EB-ceramic, EB-catalyst and EB-catalyst-support material, a hybrid study was carried out by Kim *et al.* (2004). It was found that removal efficiencies for toluene (initial concentration: 82 ppmC, flow gas rate: 670 m³/h) were 26.5-66, 39.1-76.1, 40.6-89.3 and 63.9-95.5%, respectively, while the adsorbed dose was increased from 2 to 10 kGy. The trend of styrene decomposition was similar to that for toluene at the same conditions.

Moon (2003) found that the removal efficiency of toluene using plasma combined with Pt/Al₂O₃ was 15% higher than that using only plasma at the same conditions. Besides, it was reported that DBD (dielectric barrier discharge)-Mn catalyst hybrid system enhanced toluene removal more efficiently than sole DBD (Magureanu *et al.*, 2005). In the study on SDR (silent discharge reactors) with and without coupling MnO₂ for benzene removal, the decomposition efficiency for SDR-MnO₂ coupling was higher than that of only SDR (Futamura and Gurusamy, 2005; Furamura *et al.*, 2004).

Kim *et al.* (2005) conducted an experiment for toluene removal to compare the removal efficiency for the EB-ceramic with that for EB-catalyst hybrid. It was concluded that decomposition efficiency of EB-catalyst hybrid system was higher than that of EB-

ceramic hybrid. Also, in the comparison study on the independent effect of EB-catalyst and catalyst itself, the decomposition efficiency with EB-catalyst revealed a 10% improvement in toluene treatment and an increase of 20% in styrene treatment. The by-products identified in their studies were aerosol, CO, CO₂ and traces of benzene, benzaldehyde, and other compounds. Kim's group who applied the hybrid technique showed that there was a considerable increase in CO₂, while the amount of aerosol decreased to half compared to EB-only (Jeon *et al.*, 2008; Kim *et al.*, 2005, 2004).

3.2 The Decomposition Characteristics by Various Catalysts

In order to evaluate the toluene removal efficiencies by various catalysts in EB-catalyst hybrid system, noble (Pt, Pd) and transition metal (Mn, Cu) were deposited to ceramic honeycomb, when initial concentration of toluene was 1,500 ppmC (Jeon *et al.*, 2008). First, the decomposition efficiency of EB, EB-ceramic, and EB-ceramic (Pt 1 wt.%) were compared in order to estimate the effect of ceramic itself. It was confirmed that there was no momentous effect of ceramic on the removal efficiencies of the aromatic VOCs.

In the presence of Pt, Pd, Mn and Cu catalysts with EB system, the decomposition efficiencies were increased approximately by 33, 37, 22 and 6% when compared to the EB-only. Especially, the CO₂ selectivity of EB-Pt hybrid was considerably higher than the hybrid with catalysts such as Pd, Mn, and Cu at a relatively low irradiation dose. More detailed illustration was reported in a previous literature (Jeon *et al.*, 2008)

3.3 The Removal Efficiencies of Toluene with EB-catalyst Hybrid by Loading Rate of Catalysts

Jeon *et al.* (2008) have conducted a study about comparison of decomposition efficiencies of toluene by catalyst (Pt, Pd, and Mn) loading rates in a hybrid system. The removal efficiencies did not differ eminently with respect to different loading rates.

3.4 The Comparison of Removal Efficiency by Support Materials

The decomposition efficiency of toluene by combined support material such as cordierite, Y-zeolite, and γ -alumina with EB processes was investigated by Kim *et al.* (2010). This result indicated that the removal efficiency of platinum catalyst was higher than that of palladium. It was also found that Y-zeolite showed the highest efficiency among support materials concerned. Besides, it was found that roughly 100% decomposition of toluene was observed at 8.9 kGy when catalyst with 12 wt% of Pt and Pd was used.

4. INDUSTRIAL APPLICATIONS OF ELECTRON BEAM

Research on the EB process for decomposition of gases pollutants has been continued in many countries such as Japan, U.S.A, Germany and Poland, after Ebara Co. demonstrated the removal of SO₂ using linear accelerator in 1970 (Frnak, 1995; Machi, 1983). Two pilot plants for the removal of SO₂ and NO_x were installed by Japanese Ebara company in Karlsruhe, Germany and Indianapolis, USA. The former (0.3 Mev and 180 kW) had a capacity of 16,000-32,000 m³/h and the latter (0.8 Mev and 160 kW) 10,000-20,000 m³/h. The Ebara company built, first, a full-scale plant in China, its capacity was 320 kW for the treatment of 270,000 N m³/h of flue gas. Its removal efficiency was 80% for SO_x and 20% for NO_x (Chmielewski, 2007; Doi *et al.*, 2000). The more detailed contents on the pilot and industrial plants can be found in previous papers (Chmielewski, 2007; Chmielewski and Haji-Saeid, 2004).

The studies of EB process for VOCs decomposition in flue gas began in advanced countries in the early 1990s. In the case of Poland, a research on simultaneous removal of SO_x, NO_x, and VOCs was conducted in Kaweczun electric power stations. Fundamental studies were carried out by many scientists after that (Machi, 2004; Licki *et al.*, 2003; Chmielewski *et al.*, 2002; Hashimoto *et al.*, 2000; Ostapczuk *et al.*, 1999; Hakoda *et al.*, 1998; Wu *et al.*, 1997; Hirota *et al.*, 1995a; Mätzing *et al.*, 1994; Pür and Mätzing, 1993). Furthermore, recent papers documented that EB process was technically and economically practicable (Chmielewski and Haji-Saeid, 2004; Hirota *et al.*, 2003). On the other hand, no VOC control plant has been installed since the VOC technique is still under development.

5. SUMMARY

In this work, VOC removal techniques by electron beam (EB) irradiation were reviewed. VOC removal variables such as initial VOC concentration, absorbed dose, background gas, moisture content, reactor material and inlet temperature were compared and discussed for aliphatic and aromatic VOCs. However, it was found that only reactor material was an independent variable among them. It was also concluded that radical reaction was a major mechanism for VOC decomposition rather than that by primary electrons.

Benzene (C₆H₆) and hexane (C₆H₁₄) were compared in terms of their removal efficiencies, and it was found

the decomposition efficiency of hexane was higher than that of benzene. In the case of aromatic VOCs, it was also revealed that as more functional groups were attached on the benzene ring, the decomposition of the VOCs was much easier than less ones. As for aliphatic VOCs, it was concluded that the longer carbon chain was, the higher the removal efficiency was.

Besides, main by-products generated from VOC decomposition using EB were all listed with respect to VOCs concerned. Since by-products obtained from EB irradiation bring about a secondary problem, EB hybrid techniques have been reviewed to find out a way to work it out. In the end, an EB-catalyst hybrid was evaluated as an alternative technique to remove VOCs more effectively than EB-only system since much less by-products were generated. This hybrid included support materials such as cordierite, Y-zeolite, and γ -alumina.

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