

Chemosphere 42 (2001) 615-623

Removal of dioxins and related aromatic hydrocarbons from flue gas streams by adsorption and catalytic destruction

Per Liljelind ^{a,*}, John Unsworth ^b, Onno Maaskant ^c, Stellan Marklund ^a

^a Environmental Chemistry, Chemistry Department, Umeå University, SE-902 87 Umeå, Sweden

^b Fuels Business Group, Shell Global Solutions, Shell Research and Technology Centre, Thornton, P.O. Box 1, Chester CH1 3SH, UK ^c CRI Technology Services BV, Koninginnegracht 23, 2514AB The Hague, Netherlands

Abstract

The dioxin removing capacity of the shell dedioxin system (SDDS – a Ti/V oxidative type catalyst) has been tested using the Umeå lab-scale incinerator over the temperature range 100–230°C and at space velocities of 8000 and 40,000 h^{-1} . Other analogous organic compounds, such as PCBs, PAHs, chlorobenzenes and chlorophenols have also been investigated. Results show a high degree of dioxin removal already at 100°C (82%), which occurs mainly by adsorption. When the temperature is raised a transition towards destruction is seen and at 150°C, gas hour space velocity (GHSV) 8000 and at 230°C, GHSV 40,000 virtually all removal is by destruction. High PCDD/F destruction efficiencies are reported (> 99.9%, based on I-TEQ); the other dioxin-related species and PAHs are also removed and destroyed to a significant extent. The SDDS has proved to be an effective means of destroying organic compounds in the gas phase, particularly dioxins, at temperatures as low as 150°C. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: Catalyst; Chlorobenzenes; Chlorophenols; Combustion; Conversion; End-of-pipe; Incineration; Low temperature; PCB; PCDD; PCDF; PAH

1. Introduction

The technology of low temperature catalytic removal and destruction of dioxins and related compounds from incineration processes is a promising strategy for end-ofpipe use. Fitting low temperature catalytic converters after the scrubber and bag house in an incinerator can avoid costly reheating of flue gases, yet effect conversion, thus minimising investment needed for remediating measures.

Several technologies for polychlorinated dibenzo-*p*dioxin (PCDD) and dibenzofuran (PCDF) removal have been developed in response to legislation limiting the dioxin concentration in flue gas from waste incineration (Buekens and Huang, 1998). The principal technology introduced has been adsorption onto active carbon, often combined with lime injection to remove acids, and installed before a bag filter. This process yields solid residue containing carbon contaminated with dioxins, heavy metals etc., which needs handling as hazardous waste, and which presents a continuous disposal problem. In addition to yielding contaminated waste, fixed carbon beds can pose fire hazards (Siret and Gilman, 1996).

Not only is the average dioxin removal efficiency important but also the final form of the dioxin hazard, which in adsorptive solutions, is simply transferred from the gas phase to a solid stream. Measures to limit the likelihood of intermittent high dioxin excursions also need to be considered. Thus, focus should be on solutions which are both fail-safe, and which actually destroy dioxins rather than merely removing them for recycling elsewhere in the biosphere. Some preventive

^{*}Corresponding author. Tel.: +46-90-786-9321; fax: +46-90-128-133.

E-mail address: per.liljelind@chem.umu.se (P. Liljelind).

measures have proved efficient, such as hot gas quenching to avoid the low temperature dioxin forming temperature window (250–450°C). This is an option but the heat recovery efficiency is reduced and it is often still necessary to clean flue gases further (Fängmark et al., 1994).

From the available catalysts with varying properties, the oxidative type consisting of metal oxides with different composition has proved to be effective for PCDD/ F removal (Hiraoka et al., 1989; Boos et al., 1992; Morsbach et al., 1996). Catalytic reactors of the monolithic and honeycomb type are widely used. In this study, however, a grain-shaped, highly porous extrudate is employed, which provides a bed that gases are passed through. This ensures good contact between gas components and catalytic surfaces, and hence gives high conversion rates. Beds can cause fairly high pressuredrops unless container design measures are taken to minimise them. The equivalent construction for use in full-scale plants is the lateral flow reactor where vertically placed sub-units with a bed thickness of not more than 3-5 cm are used with good results (Andersson et al., 1998).

A test programme was undertaken to study the operational boundary limits of the titanium/vanadium (Ti/ V) catalyst (the shell dioxin destruction system, SDDS) supplied by CRI Catalysts UK, specifically developed for low temperature utilisation as an end-of-pipe solution. The combustion unit for simulating full-scale waste combustion at the Chemistry Department, Environmental Chemistry, Umeå University, Sweden, is well suited for doing this. The tests performed were designed to confirm removal of dioxins, which had been observed earlier (Andersson et al., 1998), and to determine whether removal occurred via adsorption or destruction. Experiments were carried out at low temperatures and for medium to high space velocity conditions. The effectiveness of the system for the destruction of PCDDs and PCDFs were determined, together with that for additional analogous compounds: polychlorinated biphenyls (PCBs), polycyclic aromatic hydrocarbons (PAHs) and dioxin precursors, e.g., polychlorobenzenes (PCBz) and polychlorophenols (PCP).

2. Experimental

2.1. The Umeå reactor

The 5 kW lab-scale incinerator unit (Fig. 1) is equipped with a fluidised bed through which primary air is fed. There are also two radial inlets of secondary air above the sand bed. The fuel is fed onto the bed as pellets (6 mm outer diameter) via a motorised screw. The fuel used was an artificial municipal solid waste (MSW) designed to reflect the contents of real waste, primarily in Sweden (Wikström and Marklund, 1998). The temperature of the bed and freeboard was around 800°C. The convector part (boiler) consists of five 3 m long steel tubes with temperatures from 600°C down to 200°C in the last section. After this a cyclone is placed, followed by a coarse metal filter for particle removal, and a lime filter to reduce SO₂ and HCl flue gas concentrations to levels more typical of post-air pollution control conditions. A summary of operating conditions is shown in Table 1, and for a more elaborate description of the reactor and its operation see Wikström et al. (1998). The main gas stream went through a wet scrubber and finally through a carbon chemical filter (activated carbon, KMnO₄, Al₂O₃), before entering the atmosphere by way of a fan.

The combustion gases CO_2 and O_2 were continuously measured with IR and zirkonium sensors while SO_2 , HCl and particle contents were determined off-line.



Fig. 1. Schematic view of the Umeå laboratory scale fluidised bed reactor and location of coupling point to the SDDS.

Table 1
Typical Umeå lab-scale incinerator operating conditions during
the different experiments with the SDDS

Combustion efficiency	>99.5%
Bed and freeboard temperature	$780 \pm 30^{\circ}\mathrm{C}$
O ₂ -level	$10.5 \pm 3.5\%$
Particle content ^a	$\sim 170 \text{ mg/Nm}^3$
HCl concentration ^a	$\sim 240 \text{ mg/Nm}^3$
SO ₂ ^a	$\sim 30 \text{ mg/Nm}^3$

^a Sampled after coupling point to SDDS as seen in Fig. 1.

2.2. The SDDS reactor

After the lime filter (Fig. 1, coupling point) a side stream was led first through an additional less coarse metal filter, then via heated tubing to the heated catalytic reactor (SDDS, Fig. 2). This cylindrical container made of stainless steel has an internal diameter of 23 mm and is 250 mm long and was mounted vertically. A metal net in each end acts as a catalyst support. The catalyst temperature was monitored directly under the net in the low end. After passing the SDDS gases were cooled and sampled.

2.3. The catalyst

The catalyst, originally developed for the Shell Denox System for use together with ammonia (NH_3) by CRI Catalysts UK, is a titanium dioxide/vanadium pentoxide type extrudate of 3–6 mm length and 1.0–1.6 mm diameter. This allows ready diffusion of target molecules to the high internal surface area giving very high intrinsic activity and removal efficiency at operating temperatures up to 350°C. The amount of catalyst used in the experiments was either 12 or 60 g yielding a gas hour space velocity (GHSV) of 8000 or 40,000 with a constant flow of 8 l/min.

2.4. Experimental plan

The removal and destruction efficiencies of PCDD/F have been determined in six independent experiments by analysing the flue gas before the reactor (RAW), after the reactor (CLEAN) and on the catalyst (CAT), see Table 2. They were performed on separate days and numbered chronologically. Experiments 1, 2 and 6 were conducted iso-thermally with catalyst temperatures



Fig. 2. Experimental set-up of the SDDS and location of coupling point to the Umeå reactor.

Table 2	
Levels of PCDD/F expressed as toxic equivalents [I-TEQ] after (CLEAN), before (RAW) and in the catalyst (CAT)	

Name	Catalyst temperature (°C)	GHSV (ml catalyst/ ml ^a h)	CLEAN (after catalyst) (ng/Nm ³)	RAW (before catalyst) (ng/Nm ³)	CAT (catalyst) (ng/Nm ³)	Measured catalyst temperature (°C)
Exp 1	230	8000	0.03	286 ^a	_	233
Exp 2	150	8000	0.13	55	0.05	152
Exp 3	100	40,000	10	61	89	96
Exp 4	150	40,000	1.5	115	9.3	148
Exp 5	230	40,000	0.93	78	0.05	228
Exp 6	100	8000	0.36	172	2.5	101

^a Exp 1B was sampled before the last filter, possibly yielding a high value in this case due to the particle bound PCDD/F included here.

Table 3 Efficiency of the different organic compounds analysed^a

Name	Catalyst	GHSV	PCDD/F	PCB	PCB DIN	PAH	PCBz	PCPh	
	temp.		(%)	(%)	(%)	(%)	(%)	(%)	
Removal efficiency									
Exp 3	100	40,000	82.1	31.6	64.7	75.0	NR^{b}	NR	
Exp 4	150	40,000	98.6	84.8	93.2	88.2	23.1	76.6	
Exp 5	230	40,000	98.8	93.9	92.1	95.2	32.5	98.0	
Exp 6	100	8000	99.7	96.9	98.8	95.3	86.3	99.6	
Adsorption efficiency									
Exp 3	100	40,000	100	100	100	19	_	_	
Exp 4	150	40,000	6.1	39	100	0.6	0.9	0.1	
Exp 5	230	40,000	0.1	18	100	0.1	0.3	0.2	
Exp 6	100	8000	1.1	-	_	-	_	_	
Destruction efficiency									
Exp 3	100	40,000	ND^{c}	ND	ND	56	ND	ND	
Exp 4	150	40,000	92.5	46	ND	87.6	22.3	76.5	
Exp 5	230	40,000	98.7	76	ND	95.1	32.2	97.8	
Exp 6	100	8000	98.6%	_	_	_	_	_	

^a Polychlorinated dibenzo-*p*-dioxins and dibenzofurans (PCDD/F), polychlorobiphenyls (PCB) and the specific DIN-congeners (IU-PAC # 28, 52, 101, 138, 153, 180), polychlorophenols (PCP), polychlorobenzenes (PCBz), and polycyclic aromatic hydrocarbons (PAH).

^c ND – No destruction.

230°C, 150°C and 100°C, respectively, at the lower space velocity (8000 h⁻¹), whereas experiments 5, 4 and 3 represent the same temperature sequence but at 40,000 h⁻¹. In addition various related compounds, i.e., PCP, PCBz, polychlorobiphenyls (PCBs) and PAHs, have also been determined in the experiments 3–6, thus making some efficiency calculations impossible (denoted "–" in Tables 2 and 3).

Samples taken after the catalyst (CLEAN) correspond to emissions to the atmosphere. Samples of filtered raw gas (RAW) were taken in parallel to the above (CLEAN) before the catalyst reactor, except in experiment 2 when it was taken at the exact same location but before in time with an empty SDDS. In experiment 1, the raw gas sample was taken before the last filter and NH₃-inlet. In experiments 1 and 2, NH₃ was added to the gas stream. The ammonia is added to enable simultaneous removal of NO_x. Its effect on dioxin removal is not likely to be significant. The catalyst itself was replaced between experiments and these samples were denoted as "CAT".

The incinerator was run under normal operating conditions with high combustion efficiency, see Table 1. The gases entering the SDDS reactor are not particle free, the residual fine dust escaping up-stream filters has not been separated from the catalyst material (and would be expected to have contributed to levels found in the catalyst samples, leading to an overestimation of the adsorption to an unknown extent).

2.5. Sampling

The side stream ended going through the dioxin samplers, each sample has been collected for approximately 2 h (\sim 1 Nm³ of gas). The cooled probe technique was used, where the gases are first quenched to < 20°C; this is followed by a two-stage condensation impinger system with water and ethylene glycol, respectively, in the flasks. Finally, there is a polyurethane foam adsorbent (PUF) and an aerosol filter and a second PUF as a precaution (Fängmark et al., 1990; Marklund et al., 1992). The sampler is approved by the CEN (the standardising committee of the European Union) for dioxin analysis. It also works well for the related compounds analysed: PCBs, PAHs, PCBz and PCP.

2.6. Analysis

The flue gas samples were worked-up using standard validated (Fängmark et al., 1990; Marklund et al., 1992). First, the water/ethylene glycol solution was filtered by C-18 solid phase extraction (SPE), followed by soxhlet-Dean–Stark (SDS)-extraction of filter, SPE-disc and PUF's. Thereafter, open column liquid chromatography (LC) was used in three steps with silica, alumina and activated carbon. The catalyst has also been analysed – the whole amount was extracted with soxhlet, and further cleaned-up using the same LC columns (Marklund, 1990; van Bavel et al., 1992). The analysis of PCDD/F was performed on a high resolution gas chromatograph

^bNR – No removal.

(HRGC) coupled to a high resolution mass spectrometer, the other organic compound groups were analysed on a HRGC/low resolution mass spectrometer. The compounds analysed were: tetra- to octaCDD/F, tri- to decaCB, di- to pentaCPh, di- to hexaCBz and 3 to 5ringed PAHs. The 2, 3, 7, 8-substituted PCDD/Fs and PCB DIN-congeners (IUPAC # 28, 52, 101, 138, 153, 180) were isomer specifically determined. The homologue sums for PCDD/F and PCB were determined using the response of the 2, 3, 7, 8-substituted PCDD/Fs and PCB DIN-congeners. The PAHs determined were: phenanthrene (Ph), anthracene (A), fluoranthene (Fl), pyrene (Py), benzo(a)anthracene (BA), chrysene (C), benzo(b)fluoranthene + benzo(k)fluoranthene (BF1), benzo(a)pyrene (BPy), indeno(1,2,3-cd)pyrene (IPy), benzo(g,h,i)perylene (BPe), dibenso(a,h)anthracene (DBA). In experiments 1 and 2, no sums or other compounds than PCDD/F (I-TEQ) were determined.

The content of organic compounds in the flue gas can vary over time during an experiment due to fluctuations in combustion conditions and parallel sampling was used in order to obtain good efficiency estimates. Apart from the sampling and analytical error ($\sim 20\%$), cost constraints dictated that only one sample of each type could be taken during each experiment. Clearly, more statistically robust efficiency estimates would require additional experiments and samples.

2.7. Calculation

The efficiency estimates expressed as percentages have been calculated as follows:

Removal, R = (1-[CLEAN]/[RAW])*100Adsorption, A = ([CAT]/[RAW])*100Destruction, D = (1-([CLEAN]+[CAT])/[RAW])*100

3. Results

Dioxin levels in experiment 1, sample A had a TEQvalue less than 0.1 ng/Nm³ and experiment 2, CLEAN, was a similar level, 0.13 ng/Nm³, indicating very satisfactory dioxin removal with respect to the statutory limit value, despite the high raw gas concentration of PCDD/ F, see Table 2. In experiment 1, RAW, the dioxin level was especially high, probably because sampling before the last filter included more particles in this sample.

Space velocity effects: The average residence time of the combustion gases in the catalyst bed was much longer (450 ms) at GHSV 8000 ml/[ml cat and h] (experiments 1, 2 and 6) compared to that at GHSV 40,000 (90 ms – experiments 3, 4 and 5). Except for PCDD/F, relatively few experiments allow comparison of space velocity differences at constant temperatures. Results for PCDFs at 100°C and 150°C are shown in Figs. 3(a) and



Fig. 3. PCDF homologue removal (R) by destruction (D) and adsorption (A) in per cent – comparison of space velocity differences at constant temperatures. The lines represent levels in ng/Nm^3 (log scale), raw gas (RAW) – normal line, after cat (CLEAN) – stretched line, and catalyst (CAT) – dotted line. (a) 100°C; (b) 150°C.

(b), respectively. At the lower temperature, the effect of increasing space velocity from 8000 to 40,000 h⁻¹ is a switch from removal mainly by destruction to one by adsorption only. Increasing the temperature to 150° C increases the destruction mode such that removal at both space velocities is now predominantly via destruction. The results for PCDDs are very similar, see overall efficiences in Tables 2 and 3.

Temperature effects: Results for the higher space velocity showing the effect of temperature increase from 100°C to 150°C to 230°C are given in Figs. 4(a)–(f) for PCDFs, PCDDs, PCBs, PCBz and PCPh homologues, and for individual PAH compounds, respectively. Thus:

- For PCDFs and PCDDs, removal efficiency increases from approximately 80% to > 98% as temperature increases from 100°C to 150°C, with only a marginal further increase from 150°C to 230°C. At 100°C removal is by adsorption, at 150°C it is mainly by destruction, and by 230°C it is entirely via destruction. Fig. 5 shows a contour plot of the dependence of PCDD/F (as I-TEQ) removal efficiency on temperature and flow rates.
- For PCBs removal efficiency increases progressively from 32% to 94% as the temperature increases. At 100°C removal is by adsorption only, at 150°C it is by both adsorption and destruction, and by 230°C



Fig. 4. Temperature effects on overall removal (R) by destruction (D) and adsorption (A) in per cent of (a) PCDFs, (b) PCDDs, (c) PCBs, (d) PCBz and (e) PCPh homologues, and for (f) individual PAH compounds (space velocity 40,000 h^{-1}). The lines represent levels in ng/Nm³, log scale, raw gas (RAW) – normal line, after cat (CLEAN) – stretched line, and catalyst (CAT) – dotted line.

it is mainly via destruction. Destruction appears to be more effective for more highly chlorinated homologues.

- For PCBz removal efficiency is low, increasing progressively from nil to 33% as the temperature increases. Whatever removal is detected is mainly by destruction, which seems to be less effective for more highly chlorinated benzenes – little or no adsorption is observed.
- For PCPh removal efficiency increases progressively from nil to 98% as temperature increases. Although no removal is detected at 100°C, removal efficiency rises rapidly, but only as destruction again little or no adsorption is observed. No clear homologue selectivity was observed.
- For PAHs removal efficiency increases progressively from 75% to 98% as temperature increases. At 100°C removal is already at a high level but by both adsorption and destruction, at 150°C it is mainly by destruction, and by 230°C it is almost entirely via destruction. No clear compound selectivity was observed.

Thus, the chloro-homologue profiles for almost all compound classes remained virtually unaffected when levels decreased significantly after the catalyst, the exception being the PCBs where there was a clear difference in behaviour between overall sums and the DINcongeners. Some of the DIN-congeners seem to accumulate or even form over the catalyst under certain conditions. The total PCB amounts illustrate how well



Fig. 4. (continued).



Fig. 5. Contour plot of PCDD/F [I-TEQ] removal efficiency percentage (%) estimated from the six experiments performed, see Fig. 3.



Fig. 6. Mode of removal, adsorption or destruction for polychlorobiphenyls (PCB) depending on temperature (Temp) at a GHSV of 40,000.

the behaviour gradually shifted from adsorption to destruction when the temperature was raised (Fig. 6) whereas dioxins predominantly were destructed as soon as the temperature was higher than 100°C.

4. Discussion

These results confirm the dioxin removing capacity of the catalyst system and have distinguished between dioxin removal by adsorption and by catalytic destruction. The fact that dioxins and other organic compounds could be extracted from the catalyst showed that the initial adsorption is reversible. There might be a risk that the adsorption characteristics change with increasing temperature giving irreversible binding rather than destruction. This needs to be ruled out and provisional results of ¹⁴C labelled dioxin experiments have detected the formation of ¹⁴CO₂ in support of complete destruction.

Destruction efficiency trends with temperature and gas space velocity obtained for dioxins were similar whether expressed as TEQs or when considering the sum of the PCDD/F homologues. The chloro-homologue profiles from tetra to octa were also similar before and after the catalyst passage, no relative enrichment of any homologue group can be seen. Weber et al. (1999) saw that on a TiO₂-based V₂O₅-WO₃ catalyst more highly chlorinated PCDD/Fs were destroyed to a lesser extent due to their electron withdrawal effect, this is something we cannot see. Whether the mechanism of destruction means C-C bond breakage directly or is via loss of substituents needs more study even though we do not see dechlorination of PCDD/Fs here. Weber et al. (1999) also saw little destruction at 150°C, 59-75% adsorption, while we at 8000 SV virtually only have destruction (99.7%). These differences are probably due to the different type of catalyst material and experimental procedures used.

In the transition from adsorption to destruction of PCB's, seen in Fig. 6, what might be a rearrangement of chlorine atoms or a dechlorination of the biphenyl backbone occurs prior to ring cleavage. This is supported by the increased amount of specific congeners adsorbed in the CAT samples compared to RAW case. More data, however, are needed in order to formulate a mechanism for destruction.

The temperature dependence for effective removal is more pronounced for chlorophenols than for dioxins and PAH. This could be caused by the molecular size where the larger PAHs and dioxins have a lower volatility and are more easily adsorbed onto catalytic surfaces, and the higher activation energy for conversion for smaller molecules like PCPhs. The total PCB removal is intermediately dependent on temperature where the DIN-congeners resemble PCDD/Fs more in behaviour, but only being adsorbed not destructed.

Using as high space velocity as 40,000 in the experiments was warranted by finding the limits of effective catalysis rather than by regular dedioxin situations for standard operation and long-term use and the results showed that it is indeed possible to operate this high and still have a large degree of removal at 150°C and above.

Possibilities to perform periodic heating exist; the catalyst system can be operated under adsorption conditions and then heated to a temperature sufficient to ensure destruction at time intervals depending on concentration and adsorption capacity.

Further studies are planned to investigate removal in more detail, also how efficiency depends on other factors, such as flue gas dioxin concentration, SO_x and HCl concentration, NH₃-injection, particle loading etc. With a better practical as well as theoretical understanding a reaction mechanism can be proposed. Sustained long-term actitivity will also be studied and has been demonstrated by the experience of the Watco waste incineration plant in Roosendaal, Netherlands, where the dioxin removing capacity of an SDS-DeNOx reactor unit has been monitored for the last 3 yr (Unsworth, 1997). Supporting evidence for dioxin destruction has been obtained from the absence of any accumulation of dioxins on the SDS catalyst after 3 yr operation of the Watco incinerator (Andersson et al., 1998).

5. Summary

The shell dedioxin system (SDDS) has been shown to be a highly efficient way of removing gas phase PCDD/F, even at temperatures as low as 100°C and under relatively severe flue gas composition conditions.

By measuring dioxin levels in the catalyst, as well as flue gas composition pre- and post-catalyst, it has been possible to distinguish between dioxin removal by adsorption and by catalytic destruction for a range of temperatures and space velocities.

Dioxin destruction by SDDS could proceed via formation of other aromatic structures like chlorinated phenols or benzenes, however, these species are not accumulated but instead converted themselves almost as effectively.

The ratio of gas flow rate to amount of catalyst (GHSV) is more important for the removal efficiency than temperature over the range tested. Destruction efficiencies higher than 98% were obtained for the PCDD/ F at the lower gas space velocity at all three temperatures from 100° C to 230° C, however, for the higher

GHSV destruction efficiencies were temperature dependent.

To ensure destruction and avoid adsorption and in order to achieve less than 0.1 ng I-TEQ per Nm³ in the off-gas a temperature of approximately 150°C is preferred. The precise temperature needed is dependent both on the amount of catalyst and on the level of dioxin in the flue gas.

Acknowledgements

The authors thank Gunilla Löfvenius and Maria Hjelt for the invaluable help in the chemical analysis. The project MINIDIP – Minimization of Dioxins in Thermal Industrial Procedures, funded by the European Union, is acknowledged for financial support.

References

- Andersson, P., Rappe, C., Maaskant, O., Unsworth, J.F., Marklund, S., 1998. Low temperature catalytic destruction of PCDD/F in flue gas from waste combustion. Organohalogen Compound 36, 109–112.
- van Bavel, B., Fängmark, I., Marklund, S., Söderström, G., Ljung, K., Rappe, C., 1992. Quantitative analysis of organic compounds by isotope dilution: formation of non-ortho PCBs 77, 126, 169 during incineration. Organohalogen Compound 8, 225–228.
- Boos, R., Budin, R., Hartl, M., Stock, M., Wurst, F., 1992. PCDD- and PCDF-destruction by a SCR-unit in a municipal waste incinerator. Chemosphere 25, 375–382.
- Buekens, A., Huang, H., 1998. Comparative evaluation of techniques for controlling the formation and emission of chlorinated dioxins/furans in municipal waste incineration. J. Hazard. Mater. 62, 1–33.

- Fängmark, I., Wikström, L.-E., Marklund, S., Rappe, C., 1990. Studies on sampling methods for PCDD and PCDFs in stack emission. Chemosphere 20, 1333–1340.
- Fängmark, I., Strömberg, B., Berge, N., Rappe, C., 1994. The influence of post combustion temperature profiles on the formation of PCDDs, PCDFs, PCBzs and PCBs in a pilot reactor. Environ. Sci. Technol. 28, 624–629.
- Hiraoka, M., Takeda, N., Okajima, S., 1989. Catalytic destruction of PCDDs in flue gas. Chemosphere 19, 361– 366.
- Marklund, S., Söderström, G., Ljung, K., Rappe, C., Kraft, M., Hagenmaier, H.-P., 1992. Parallel sampling using various sampling techniques at a Swedish MSW incinerator. Waste Management Res. 10, 21–36.
- Marklund, S., 1990. Dioxin emissions and environmental imissions. Ph.D. Thesis, Umeå University, Sweden ISBN 91-7174-496-7.
- Morsbach, B., Odermatt, P., Spahl, R., 1996. BASF catalysts for the removal of NO_x and dioxin in various applications. In: Proceedings of the VTT Symposium 163, pp. 77–94.
- Siret, B., Gilman, K., 1996. A survey of post-combustion PCDD/PCDF control technologies. In: Proceedings of the International Conference Incineration and Thermal Treatment Technology, pp. 583–586.
- Unsworth, J.F., 1997. Dioxin removal by CRI's shell denox system. Heeren Waste Incineration trials, Roosendaal, The Netherlands. Report, CRI Catalyst Co. UK Ltd., Woking, GU21 5BH, UK.
- Weber, R., Sakurai, T., Hagenmaier, H., 1999. Low temperature decomposition of PCDD/PCDF, chlorobenzenes and PAHs by TiO₂-based V₂O₅–WO₃ catalysts. Appl. Catal. B 20, 249–256.
- Wikström, E., Marklund, S., 1998. Combustion of an artificial municipal solid waste in a laboratory fludised bed reactor. Waste Management Res. 16, 342–350.
- Wikström, E., Andersson, P., Marklund, S., 1998. Design of a laboratory scale fluidized bed reactor. Rev. Sci. Instr. 69, 1850–1859.