

Supplementary Information

Particulate matter generated from electrolysis processes: a review of pollution, formation, and control technologies

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Table S1 Acid mist concentrations in electrolysis facilities

Electrolysis system	Scale	Acid mist concentration (mg/m ³)			References
		Inhalable (PM ₁₀₀)	Thoracic (PM ₁₀)	Respirable (PM ₄)	
Zinc electrolysis	Field testing	1.91-5.49	0.41-0.98	0.02-0.04	(Magne et al., 2004)
Zinc electrolysis	Field testing	0.096	--	0.001	(Rondia and Closset, 1985)
Zinc electrolysis	Field testing	0.13-2	0.11-0.72	0.005-0.068	(Ma et al., 2020a)
Zinc electrolysis	Laboratory testing	0.61-3.49	--	--	(Dhak et al., 2011)
Zinc electrolysis	Laboratory testing	10-20	--	--	(Papachristodoulou A et al., 1985)
Copper electrolysis	Field testing	0.13-0.71	--	--	(Tian, 2013)
Copper electrolysis	Field testing	0.02-0.22	0.004-0.029	--	(Breuer et al., 2012)
Copper electrolysis	Laboratory testing	7.0-47.6	--	--	(Al Shakarji et al., 2011)
Chrome Electroplating	Laboratory testing	408-926	--	--	(Mason et al., 2001)
Chrome Electroplating	Pilot testing	6.445	--	--	(Mason et al., 2001)
Lead-acid battery charging	Field testing	0.071-1.02	0.03-0.37	--	(Breuer et al., 2012)
Aluminum electrolysis	Field testing	0.025-0.021	0.016-0.0073	--	(Breuer et al., 2012)

Table S2 Relationships between particle characteristics and bubble characteristics

Particle type	Formula	Empirical coefficient	Bubble size range (mm)	References
Film droplets		$N_{\text{film}}=1.96 \cdot R_{\text{bubble}}^2$ (S1)	0.71–3.14	(Blanchard and Syzdek, 1988)
		$N_{\text{film}}=1.65 \cdot R_{\text{bubble}}^2$ (S2)	0.71–3.14	
	$N_{\text{film}}=A \cdot R_{\text{bubble}}^B$	$N_{\text{film}}=2.16 \cdot R_{\text{bubble}}^2$ (S3)	0.52–5.0	(Resch and Afeti, 1991)
		$N_{\text{film}}=2.85 \cdot R_{\text{bubble}}^2$ (S4)	1.47–6.29	(Spiel, 1997)
		$N_{\text{film}} = {}^{5/3}D_{\text{bubble}}^{5/3}$ (S5)	1.04–10.0	(Resch and Afeti, 1992)
Jet droplets		$N_{\text{jet}}=7.5 \cdot \exp(-D_{\text{bubble}}/3)$ (S6)	0.35–1.48	(Blanchard, 1989)
		$N_{\text{jet}}=7 \cdot \exp(-2R_{\text{bubble}}/3)-1.3R_{\text{bubble}}$ (S7)	0–1.72	(Wu, 1994)
		$R_{\text{drop } 1}=0.0345 \cdot R_{\text{bubble}}^{1.206}$ (S8)	0.35–1.48	
	$R_{\text{jet}}=C \cdot R_{\text{bubble}}^D$	$R_{\text{drop } 2}=0.0172 \cdot R_{\text{bubble}}^{1.316}$ (S9)	0.35–1.48	(Spiel, 1994)
		$R_{\text{drop } 3}=0.000679 \cdot R_{\text{bubble}}^{1.796}$ (S10)	0.35–1.48	

Note: N_{film} is the number of film droplets formed by a single bubble bursting, R_{bubble} is the bubble radius, A and B are the empirical coefficients for the relationship between the number of film droplets and the bubble radius, N_{jet} is the number of jet droplets formed by a single bubble bursting, C and D are the empirical coefficients for the relationship between the radius of the jet droplets and the bubble radius, $R_{\text{drop } i}$ is the radius of the first three jet droplets produced by a single bubble bursting.

Table S3 Properties of solutions involving bubble bursting or electrolysis reactions

Type	Major components	Typical operation temperature, °C	Viscosity, Pa·s (10^{-3})	Surface tension, mN/m	References
Pure water	H ₂ O	/	0.936-1.79	12	(Xu et al., 2009; Ni et al., 2019; Khorolskyi and Malomuzh, 2023)
Sea water	H ₂ O=964 g/L; Na ⁺ =10.8 g/L; Cl ⁻ =19.4 g/L; Mg ²⁺ =1.28 g/L; SO ₄ ²⁻ =2.71 g/L; Ca ²⁺ =0.41 g/L; K ⁺ =0.39 g/L	/	1.02-1.34	61.1-80.2	(Othmer., 1969; Sanda-Carmen Georgescu et al., 2002; Millero et al., 2008; Nayar et al., 2014)
Zinc electrolysis	Zn ²⁺ =45.0-50.0 g/L; H ₂ SO ₄ =150-160 g/L; Mn ²⁺ =1.00-10.0 g/L	40-45	/	83	(Zhang et al., 2018; Qi et al., 2023)
Copper electrolysis	Cu ²⁺ =35.0-45.0 g/L; H ₂ SO ₄ =149-180 g/L; (Fe ²⁺ , Fe ³⁺)=0.15-6.00 g/L; Co ²⁺ =0.10-0.15 g/L; Cl ⁻ =0.02-0.03 g/L	40-55	1.21-1.80	30.0-70.0	(Das, 1989; McGinnity and Nicol, 2014)
Lead electrolysis	PbSiF ₆ =115-125 g/L; H ₂ SiF ₆ =95.0-105 g/L; glue=2.00 g/L; lignin sulphonate =2.00 g/L	39-43	/	/	(Dobrev T and S., 1996)
Chrome electroplating	CrO ₃ =150-300 g/L; H ₂ SO ₄ =2.50 g/L	40-45	1.30	72.5	(Mason et al., 2001)
Manganese electrolysis	Mn ²⁺ =18.8-37.5 g/L; (NH ₄) ₂ SO ₄ =100 g/L; Mg ²⁺ =10.0-30.0 g/L	35-40	1.56 -1.99	74.9-79.7	(Qin J. et al., 2019)
Nickel electrolysis	Ni ²⁺ =50.0-80.0 g/L; Na ₂ SO ₄ =80.0 g/L; H ₃ BO ₃ =0-12.0 g/L; Al ³⁺ =0.005-5.00 g/L	59-61	1.01 -1.26	71.5-76.9	(Imamura and Toguri, 1994; Schoeman et al., 2020)

Table S4 Performance of source controlling methods on the EPM reduction efficiency and the changes of the production indicators (the electrolysis energy consumption (EC), the current efficiency of metal deposition (CE), and the impurity content in the deposited metal (IC)).

Classification	Methods	Electrolysis System	Materials and Treatment	RE, %	CE, %	EC, %	IC, %	References
Floaters	Floating barriers	Zinc	Polystyrene microspheres (with thickness of~15 mm)	~100	/	/	/	(Qu et al., 2023)
			Porous polymethyl methacrylate board & Microsphere matrix	97.2	/	/	/	(Qu et al., 2023)
		Copper	Floating balls	60.0	/	/	/	(Al Shakarji et al., 2013)
Polypropylene barriers	56.0		/	/	/	(Al Shakarji et al., 2013)		
Polyethylene barriers	59.4		/	/	/	(Al Shakarji et al., 2013)		
Surfactants	Foaming surfactants	Zinc	Quillaja (3.8 ppm)	99.0	- 0.32	/	Negative	(Cheng et al., 2004)
			Licorice (21.6 ppm)	94.0	- 0.21	/	Negative	(Cheng et al., 2004)
			Tennafroth 250 & Saponins	87.0	- 4.18	+ 8.83	/	(Dhak et al., 2011)
			Dowfroth 250 & Saponins	86.5	- 6.59	/	/	(Dhak et al., 2011)
			Saponin	28.0	- 4.40	/	/	(Dhak et al., 2010)
			Dowfroth 250	78.0	- 4.40	/	/	(Dhak et al., 2010)
			Tennafroth 250	74.0	- 4.95	/	/	(Dhak et al., 2010)
			FS-101(15 mg/L)	79.6	- 3.44	- 7.21	/	(Qi et al., 2023)
			FS-301(15 mg/L)	60.7	+ 2.90	- 2.28	/	(Qi et al., 2023)
			FS-401(5 mg/L)	43.0	+ 1.93	- 10.4	None	(Qi et al., 2023)
Copper	BASF Pluronic F67 (0.5-2.0 g/L)	>90	/	/	/	(Sigley et al., 2003)		
Non-foaming surfactant	Copper	FC-1000 (30 ppm)	84.5	/	/	/	(Otero et al., 2003)	
		FC-1000 (50-100 ppm)	90	/	/	/	(Al Shakarji et al., 2013)	
		Mistop (1.8 mg/L)	99.7	- 1.51	/	None	(Alfantazi et al., 2004)	
Chromium	HEEF (volume fraction 2%)	99.8	/	/	/	(Mason et al., 2001)		

Adjusting operating parameters	Current density	Copper	Current density (400 →200 Am ⁻²)	25.6	/	/	/	(Al Shakarji et al., 2011)
	Electrolyte temperature		Electrolyte temperature (60→30°C)	85.3	/	/	/	(Al Shakarji et al., 2011)
	Acidity		Acidity (100 →250 g/L)	23.6	/	/	/	(Al Shakarji et al., 2011)
	Electrolyte temperature	Zinc	Electrolyte temperature (40→25°C)	89.0	- 5.44	-10.2	-34.8	(Ma et al., 2024)
	H ₂ SO ₄ concentration		H ₂ SO ₄ concentration (160 →110 g/L)	12.6	+1.31	+ 1.00	-18.7	(Ma et al., 2024)
	Current density		Current density (500 →300 Am ⁻²)	19.1	+ 0.62	- 4.67	-4.34	(Ma et al., 2024)
Ultrasonication	Bath sonication	Zinc	Ultrasonication (120 kW, 48 kHz)	59.9	+ 57.40	- 39.61	+ 62 (Pb)	(Ma et al., 2020b)
			Ultrasonication (200 W)	44.4	+ 3.06	- 1.75	+ 102	(Zhang et al., 2021)
	Airborne ultrasonication		Airborne ultrasonication (20-100 kHz)	92.4	/	/	/	(Mason et al., 2001)
	Airborne and Bath ultrasonication	Chromium	Airborne and bath ultrasonication	94.4	/	/	/	(Mason et al., 2001)
	Bath ultrasonication		Bath ultrasonication (40 kHz)	77.3	+3.00	/	/	(Mason et al., 2001)
Combination methods	Surfactant & Barriers	Copper	FC-1100 & spheres barriers	95.0	/	/	/	(Al Shakarji et al., 2013)
	Surfactant & Temperature		FC-1100 (30 ppm) & Temperature	99.8	/	/	/	(Al Shakarji et al., 2011)
	Surfactant & Current density		FC-1100 (30 ppm) & Current density (400 →200 Am ⁻²)	90.0	/	/	/	(Al Shakarji et al., 2011)
	Acidity & Current density		Acidity (100 →250 g/L) & Current density (400 →200 Am ⁻²)	40.8	/	/	/	(Al Shakarji et al., 2011)
	Acidity & Temperature		Acidity (100 →250 g/L) & Temperature (60→30°C)	90.5	/	/	/	(Al Shakarji et al., 2011)
	Surfactant & Ultrasonication	Chromium	Surfactant (HEEF) & Ultrasonication	63.0~83.8	/	/	/	(Mason et al., 2001)
Other methods	/	Zinc	Decreasing the distance between the adjacent electrode by 90%	94.0	/	/	/	(McGinnity and Nicol, 2014)

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