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Photoacoustic hygrometer for icing wind tunnel water content measurement: design, analysis, and intercomparison

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Table S1: Non-exhaustive list of literature reported minimum detectable concentrations (MDCs) for photoacoustic water vapor detection, together with the method and conditions used for the MDC estimation. All MDC values are (re-)evaluated for three standard deviations of the noise ($3\sigma_\mathrm{n}$) based on the information available in the respective publication. Lines highlighted in gray indicate instruments where negligible underestimation of the true MDC is expected for water vapor detection in air according to Lang et al. (2020).

Reference	MDC[a] ($3\sigma_\mathrm{n}$, ppm)	Linear extrap.[b]	Buffer gas	MDC calculation[c]		PAS type[d]	Source mod.[e]	Source type[f]	Integration time[g] (s)
				Concentration (ppm)	Pressure (hPa)				
Besson et al. (2006)	0.024	yes	N_2	1-50	-	PAS	WM	DFB	10
Bijnen et al. (1996)	0.10	no	air	-	-	PAS	IM	IC CO	-
Szakáll et al. (2006)	0.18	yes	N_2	0.1-100	1000	PAS	WM	DFB	1.5
Szakáll et al. (2007)	0.19	yes	N_2	1-100	1000	PAS	WM	DFB	1.5
Szakáll et al. (2004)	0.20	yes	N_2	0.1-250	500	PAS	WM	DFB	4
Kosterev et al. (2006)	0.24	yes	N_2	44.2	80	QEPAS	WM	DFB	1
Szakáll et al. (2009)	0.29	yes	N_2	2-103	-	PAS	IM	DFB	4
Yi et al. (2012b)	0.50	yes	air	18160	ambient	QEPAS	WM	DFB	1
Wang et al. (2019)	0.50	yes	-	1100	1000	QEPAS	WM	DFB	0.2
Liu et al. (2009a)	0.71	yes	air	4420	ambient	QEPAS	WM	DFB	1
Liu et al. (2015)	0.75	yes	air	8000	ambient	QEPAS	WM	DFB	1
Liu et al. (2010)	0.78	yes	air	14600	ambient	QEPAS	WM	DFB	1
Tátrai et al. (2015)	1.4	no	air	10	200	PAS	WM	DFB	-
Mikkonen et al. (2018)	1.4	yes	air	7000	1000	CEPAS	-	BBSCS	50
Szakáll et al. (2001)	2.4	yes	air	5-230	975	PAS	IM	DFB	10
Zhang et al. (2019)	2.7	yes	-	500-1480	ambient	PAS	WM	DFB	-
Shi et al. (2012)	3	yes	air	7300	-	PAS	IM	DFB	1
Wang et al. (2020a)	3.3	yes	-	1500	ambient	QEPAS	WM	DFB	-
Liu et al. (2017)	3.8	yes	N_2	1430	ambient	PAS	WM	DFB	0.01
Ma et al. (2018)	4	yes	air	2960	-	QEPAS	WM	DFB	1
Bozóki et al. (1996)	10	yes	air	10000	-	PAS	IM	EC DL	-
Dang et al. (2018)	17	yes	air	13000	ambient	QEPAS	WM	DFB	-
This work	23	no	air	-	800	PAS	IM	DFB	1
Liu et al. (2009b)	28	yes	air	6400	ambient	QEPAS	WM	DFB	1
Bozóki et al. (1999)	39	yes	air	4-150	ambient	PAS	IM	EC DL	0.48
Kachanov et al. (2013)	46	yes	air	11000	1010	PAS	WM	EC QCL	0.3
Elefante et al. (2019)	60	yes	air	16000	270	QEPAS	WM	DFB	0.1
Ma et al. (2015)	70	yes	air	2100	ambient	QEPAS	WM	DFB	1
Mao et al. (2016)	72	yes	N_2	1500	ambient	PAS	WM	TEDFL	-
Bozóki et al. (2010)	81	yes	air	2800	ambient	PAS	WM	DFB	0.1
Wu et al. (2019)	96	yes	N_2	4000	270	QEPAS	WM	DFB	1
Liu et al. (2018)	120	yes	air	11700	ambient	PAS	WM	DFB	0.03
Elefante et al. (2020)	126	yes	air	16000	270	QEPAS	WM	ICL	0.2
Hippler et al. (2010)	218	yes	air	22500	200	PAS	WM	EC DL	16
Yi et al. (2012a)	450	yes	air	27200	ambient	QEPAS	WM	DFB	1
Weidmann et al. (2004)	580	yes	-	-	-	QEPAS	WM	SGDBRL	1
Rey and Sigrist (2008)	750	yes	air	4400	-	PAS	IM	LED	30
Wang et al. (2020b)	834	yes	air	11460	ambient	QEPAS	WM	DFB	-

[a] $\mathrm{MDC} = 3x_\mathrm{w}/\mathrm{SNR} = 3x_\mathrm{w}/(S/\sigma_\mathrm{n}) = 3\sigma_\mathrm{n}/s$, with signal amplitude S and sensitivity s

[b] Linear extrapolation used in the estimation of the MDC

[c] MDC estimation performed with PA signals determined at given measurement concentration (range) and pressure

[d] Type of PA cell: Conventional resonator (PAS), quartz-enhanced (QEPAS), cantilever-enhanced (CEPAS)

[e] Radiation source modulation: Intensity modulation (IM), wavelength modulation (WM)

[f] Distributed feedback laser diode (DFB), intracavity CO-laser (IC CO), broadband supercontinuum source (BBSCS), external cavity diode laser (EC DL), external cavity quantum cascade laser (EC QCL), tunable erbium-doped fiber laser (TEDFL), interband cascade laser (ICL), sampled grating distributed Bragg reflector laser (SGDBRL), light emitting diode (LED)

[g] For wavelength modulation, single line scan times may be considerably longer than the stated integration time

References

Besson, J.-P., Schilt, S., and Thévenaz, L.: Sub-ppm multi-gas photoacoustic sensor, Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy, 63, 899–904, https://doi.org/10.1016/j.saa.2005.10.034, 2006.

Bijnen, F. G. C., Harren, F. J. M., Hackstein, J. H. P., and Reuss, J.: Intracavity CO laser photoacoustic trace gas detection: cyclic CH_4, H_2O and CO_2 emission by cockroaches and scarab beetles, Applied Optics, 35, 5357, https://doi.org/10.1364/AO.35.005357, 1996.

Bozóki, Z., Sneider, J., Szabó, G., Miklós, A., Serényi, M., Nagy, G., and Fehér, M.: Intracavity photoacoustic gas detection with an external cavity diode laser, Applied Physics B Laser and Optics, 63, 399–401, https://doi.org/10.1007/BF01828745, 1996.

Bozóki, Z., Sneider, J., Gingl, Z., Mohácsi, Á., Szakáll, M., Bor, Z., and Szabó, G.: A high-sensitivity, near-infrared tunable-diode-laser-based photoacoustic water-vapour-detection system for automated operation, Measurement Science and Technology, 10, 999–1003, https://doi.org/10.1088/0957-0233/10/11/304, 1999.

Bozóki, Z., Szabó, A., Mohácsi, Á., and Szabó, G.: A fully opened photoacoustic resonator based system for fast response gas concentration measurements, Sensors and Actuators, B: Chemical, 147, 206–212, https://doi.org/10.1016/j.snb.2010.02.060, 2010.

Dang, H., Ma, Y., Li, Y., and Wan, S.: High-Sensitivity Detection of Water Vapor Concentration: Optimization and Performance, Journal of Russian Laser Research, 39, 95–97, https://doi.org/10.1007/s10946-018-9694-4, 2018.

Elefante, A., Giglio, M., Sampaolo, A., Menduni, G., Patimisco, P., Passaro, V. M., Wu, H., Rossmadl, H., MacKowiak, V., Cable, A., Tittel, F. K., Dong, L., and Spagnolo, V.: Dual-Gas Quartz-Enhanced Photoacoustic Sensor for Simultaneous Detection of Methane/Nitrous Oxide and Water Vapor, Analytical Chemistry, 91, 12 866–12 873, https://doi.org/10.1021/acs.analchem.9b02709, 2019.

Elefante, A., Menduni, G., Rossmadl, H., Mackowiak, V., Giglio, M., Sampaolo, A., Patimisco, P., Passaro, V. M., and Spagnolo, V.: Environmental monitoring of methane with quartz-enhanced photoacoustic spectroscopy exploiting an electronic hygrometer to compensate the h2o influence on the sensor signal, Sensors (Switzerland), 20, 2935, https://doi.org/10.3390/s20102935, 2020.

Hippler, M., Mohr, C., Keen, K. A., and McNaghten, E. D.: Cavity-enhanced resonant photoacoustic spectroscopy with optical feedback cw diode lasers: A novel technique for ultratrace gas analysis and high-resolution spectroscopy, Journal of Chemical Physics, 133, 44 308, https://doi.org/10.1063/1.3461061, 2010.

Kachanov, A., Koulikov, S., and Tittel, F. K.: Cavity-enhanced optical feedback-assisted photo-acoustic spectroscopy with a 10.4 μm external cavity quantum cascade laser, Applied Physics B: Lasers and Optics, 110, 47–56, https://doi.org/10.1007/s00340-012-5250-z, 2013.

Kosterev, A. A., Tittel, F. K., Knittel, T. S., Cowie, A., and Tate, J. D.: Trace Humidity Sensor based on Quartz-Enhanced Photoacoustic Spectroscopy, Lacsea, pp. Paper TuA2 1–3, 2006.

Lang, B., Breitegger, P., Brunnhofer, G., Prats Valero, J., Schweighart, S., Klug, A., Hassler, W., and Bergmann, A.: Molecular relaxation effects on vibrational water vapor photoacoustic spectroscopy in air, Applied Physics B: Lasers and Optics, 126, 1–18, https://doi.org/10.1007/s00340-020-7409-3, 2020.

Liu, K., Guo, X., Yi, H., Chen, W., Zhang, W., and Gao, X.: Off-beam quartz-enhanced photoacoustic spectroscopy, Optics Letters, 34, 1594, https://doi.org/10.1364/OL.34.001594, 2009a.

Liu, K., Li, J., Wang, L., Tan, T., Zhang, W., Gao, X., Chen, W., and Tittel, F. K.: Trace gas sensor based on quartz tuning fork enhanced laser photoacoustic spectroscopy, Applied Physics B: Lasers and Optics, 94, 527–533, https://doi.org/10.1007/s00340-008-3233-x, 2009b.

Liu, K., Yi, H., Kosterev, A. A., Chen, W., Dong, L., Wang, L., Tan, T., Zhang, W., Tittel, F. K., and Gao, X.: Trace gas detection based on off-beam quartz enhanced photoacoustic spectroscopy: Optimization and performance evaluation, Review of Scientific Instruments, 81, 103 103, https://doi.org/10.1063/1.3480553, 2010.

Liu, K., Wang, L., Tan, T., Zhang, W., Chen, W., and Gao, X.: Trace-Gas Detection with Off-Beam Quartz Enhanced Photoacoustic Spectroscopy, International Journal of Thermophysics, 36, 1066–1073, https://doi.org/10.1007/s10765-014-1691-4, 2015.

Liu, K., Mei, J., Zhang, W., Chen, W., and Gao, X.: Multi-resonator photoacoustic spectroscopy, Sensors and Actuators, B: Chemical, 251, 632–636, https://doi.org/10.1016/j.snb.2017.05.114, 2017.

Liu, K., Cao, Y., Wang, G., Zhang, W., Chen, W., and Gao, X.: A novel photoacoustic spectroscopy gas sensor using a low cost polyvinylidene fluoride film, Sensors and Actuators, B: Chemical, 277, 571–575, https://doi.org/10.1016/j.snb.2018.09.037, 2018.

Ma, Y., Yu, X., Yu, G., Li, X., Zhang, J., Chen, D., Sun, R., and Tittel, F. K.: Multi-quartz-enhanced photoacoustic spectroscopy, Applied Physics Letters, 107, 021 106, https://doi.org/10.1063/1.4927057, 2015.

Ma, Y. F., Tong, Y., He, Y., Long, J. H., and Yu, X.: Quartz-enhanced photoacoustic spectroscopy sensor with a small-gap quartz tuning fork, Sensors (Switzerland), 18, 2047, https://doi.org/10.3390/s18072047, 2018.

Mao, X., Zhou, X., Gong, Z., and Yu, Q.: An all-optical photoacoustic spectrometer for multi-gas analysis, Sensors and Actuators B: Chemical, 232, 251–256, https://doi.org/10.1016/j.snb.2016.03.114, 2016.

Mikkonen, T., Amiot, C., Aalto, A., Patokoski, K., Genty, G., and Toivonen, J.: Broadband cantilever-enhanced photoacoustic spectroscopy in the mid-IR using supercontinuum, https://doi.org/10.1364/ol.43.005094, 2018.

Rey, J. M. and Sigrist, M. W.: New differential mode excitation photoacoustic scheme for near-infrared water vapour sensing, Sensors and Actuators, B: Chemical, 135, 161–165, https://doi.org/10.1016/j.snb.2008.08.002, 2008.

Shi, W., Li, G., and Prasad, C.: Compact laser photoacoustic spectroscopy sensor for atmospheric components measurements, vol. 8366, p. 83660N, https://doi.org/10.1117/12.919297, 2012.

Szakáll, M., Bozóki, Z., Kraemer, M., Spelten, N., Moehler, O., and Schurath, U.: Evaluation of a Photoacoustic Detector for Water Vapor Measurements under Simulated Tropospheric/Lower Stratospheric Conditions, Environmental Science & Technology, 35, 4881–4885, https://doi.org/10.1021/es015564x, 2001.

Szakáll, M., Bozóki, Z., Mohácsi, Á., Varga, A., and Szabó, G.: Diode laser based photoacoustic water vapor detection system for atmospheric research, Applied Spectroscopy, 58, 792–798, https://doi.org/10.1366/0003702041389373, 2004.

Szakáll, M., Huszár, H., Bozóki, Z., and Szabó, G.: On the pressure dependent sensitivity of a photoacoustic water vapor detector using active laser modulation control, Infrared Physics & Technology, 48, 192–201, https://doi.org/10.1016/j.infrared.2006.01.002, 2006.

Szakáll, M., Csikós, J., Bozóki, Z., and Szabó, G.: On the temperature dependent characteristics of a photoacoustic water vapor detector for airborne application, Infrared Physics and Technology, 51, 113–121, https://doi.org/10.1016/j.infrared.2007.04.001, 2007.

Szakáll, M., Varga, A., Pogány, A., Bozóki, Z., and Szabó, G.: Novel resonance profiling and tracking method for photoacoustic measurements, Applied Physics B, 94, 691–698, https://doi.org/10.1007/s00340-009-3391-5, 2009.

Tátrai, D., Bozóki, Z., Smit, H., Rolf, C., Spelten, N., Krämer, M., Filges, A., Gerbig, C., Gulyás, G., and Szabó, G.: Dual-channel photoacoustic hygrometer for airborne measurements: background, calibration, laboratory and in-flight intercomparison tests, Atmospheric Measurement Techniques, 8, 33–42, https://doi.org/10.5194/amt-8-33-2015, 2015.

Wang, C., Wang, Z., and Pang, X.: Quartz-Enhanced Photoacoustic Spectroscopy for Four-Component Gas Detection Based on Two Off-Beam Acoustic Microresonators, Frontiers in Physics, 8, 543, https://doi.org/10.3389/fphy.2020.594326, 2020a.

Wang, Z., Chang, J., Wang, C., Feng, Y., Tian, C., Li, H., Feng, Z., Yu, H., Zhang, H., Zhang, X., Tang, L., and Zhang, Q.: Three acoustic microresonator quartz-enhanced photoacoustic spectroscopy for trace gas sensing, Optics Communications, 452, 286–291, https://doi.org/10.1016/j.optcom.2019.07.061, 2019.

Wang, Z., Zhang, Q., Chang, J., Tian, C., Tang, L., Feng, Y., Zhang, H., and Zhang, X.: Quartz-Enhanced Photoacoustic Spectroscopy Based on the Four-Off-Beam Acoustic Micro-Resonator, Journal of Lightwave Technology, 38, 5212–5218, https://doi.org/10.1109/JLT.2020.2998848, 2020b.

Weidmann, D., Kosterev, A. A., Tittel, F. K., Ryan, N., and McDonald, D.: Application of a widely electrically tunable diode laser to chemical gas sensing with quartz-enhanced photoacoustic spectroscopy, Optics Letters, 29, 1837, https://doi.org/10.1364/OL.29.001837, 2004.

Wu, H., Dong, L., Yin, X., Sampaolo, A., Patimisco, P., Ma, W., Zhang, L., Yin, W., Xiao, L., Spagnolo, V., and Jia, S.: Atmospheric CH4 measurement near a landfill using an ICL-based QEPAS sensor with V-T relaxation self-calibration, Sensors and Actuators B: Chemical, 297, 126 753, https://doi.org/10.1016/j.snb.2019.126753, 2019.

Yi, H., Chen, W., Guo, X., Sun, S., Liu, K., Tan, T., Zhang, W., and Gao, X.: An acoustic model for microresonator in on-beam quartz-enhanced photoacoustic spectroscopy, Applied Physics B, 108, 361–367, https://doi.org/10.1007/s00340-012-4988-7, 2012a.

Yi, H., Chen, W., Sun, S., Liu, K., Tan, T., and Gao, X.: T-shape microresonator-based high sensitivity quartz-enhanced photoacoustic spectroscopy sensor, Optics Express, 20, 9187, https://doi.org/10.1364/oe.20.009187, 2012b.

Zhang, H., Tian, C., Wang, Z., and Zhang, X.: Trace double-component gas sensor in photoacoustic spectroscopy based on frequency division multiplexing, Optical and Quantum Electronics, 51, 268, https://doi.org/10.1007/s11082-019-1981-y, 2019.