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A fast-response quartz-enhanced photoacoustic spectroscopy SF_6 sensor for measuring contaminant transport

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SUMMARY
To explore the rapid changes in tracer-gas measurements in enclosed environments, we first developed a fast-response SF_6 sensor based on quartz enhanced photoacoustic spectroscopy (QEPAS). Transient tracer-gas measurements were then carried out in an environmental chamber with both the developed sensor and B&K 1302. Compared with the existing commercial monitor, the QEPAS sensor can capture more rapid changes in SF_6 concentration. The developed QEPAS sensor has potential in exploring the transient contaminant transport in enclosed environments.

KEYWORDS
Quartz-enhanced photoacoustic spectroscopy, Sulfur hexafluoride, Response time, Transient contaminant transport

1 INTRODUCTION
The human cough is a significant vector for transmitting respiratory diseases in enclosed environments (Wei and Li, 2017). When individuals infected with respiratory disease, such as tuberculosis, smallpox, pneumonic plague, cough, sneeze, or speak, pathogen-containing particles of saliva and mucus are emitted, accordingly may cause airborne transmission of infection (Morawska, 2006; Nicas et al., 2005). Though within a very short period, droplets containing virus or bacteria can be emitted by an infected person in large quantities (Chao and Wan, 2006; Lai and Wong, 2010).

Motivated by this, transient contaminant transport in enclosed environments has been receiving much research attention. Lai and Wong (2010) experimentally investigated spatial and temporal aerosol distributions in a tempered glass/stainless steel chamber after a release of 0.1 s. The results confirm the ventilation effectiveness of displacement ventilation system is always higher than that of ceiling-type ventilation. Seepana and Lai (2012) studied the spatial droplet concentration generated by human sneezing and its potential effect on the adjacent person under two ventilation scenarios. The results show multiple peaks of droplets concentrations over time for the susceptible manikin standing near wall under both ventilation schemes.

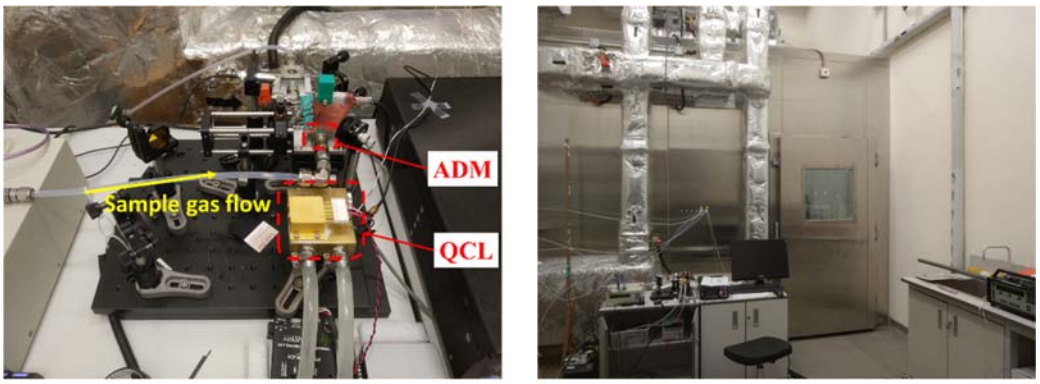
Literature review indicated limited attempts that have been made to conduct transient gaseous contaminants measurement. This is because the contaminant concentration could vary significantly within the response time of the existing SF_6 commercial measuring monitors, such as INNOVA 1314 and Brüel & Kjær (B&K) 1302, which can be up to 45 s (Brüel & Kjær, 1990; You et al., 2018)

To explore the rapid changes in contaminant concentration in indoor environments, we first developed a fast-response SF_6 sensor based on quartz enhanced photoacoustic spectroscopy (QEPAS). Transient tracer-gas measurements were then carried out in an environmental chamber with both the developed sensor and B&K 1302

2 METHODS

QEPAS sensor

QEPAS is an alternative method of photoacoustic detection of tracer gas that works by combining PAS and a quartz tuning fork (QTF) (Patimisco et al., 2014; Wang et al., 2016). The sharply resonant QTF instead of a traditional microphone is utilized as a resonant acoustic transducer using the piezoelectric effect to convert the sound wave generated by gas absorption of the modulated light intensity into an electrical signal (Wang et al., 2016; Wei et al., 2019). The QEPAS SF_6 sensor in this study is shown in Figure 1(a). A 10.5 μm continuous-wave (cw) distributed-feedback quantum cascade laser (DFB-QCL) (Alpes Lasers) was used as the light source. The custom-designed acoustic detection module (ADM), with a compact size of 3 cm × 3 cm × 1.6 cm, was equipped with two wedged ZnSe windows, a QTF and two micro-resonator (mR) tubes installed adjacent to the QTF (Wang et al., 2020). More details about the sensor setup can be found in our recent study (Wang et al., 2020).



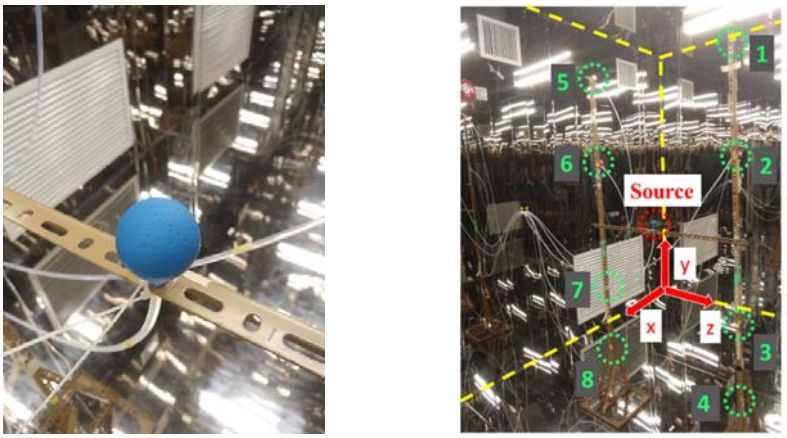
(a) (b)

Figure 1. (a) Experiment layout and (b) QEPAS sensor.

Experimental setup

As shown in Fig. 1(b), a stainless steel environmental chamber with a dimension of 4 m (length), 2.7 m (width) and 2.9 m (height) was used in this study. Fresh air was supplied from the upper two grills and exhausted from the lower grill (as shown in Fig. 2b). This study used SF_6 as tracer-gas, controlled by a mass flow controller (Sevenstar) at a flow rate of 1.8 ± 0.018 L/min.

A porous rubber bulb (see figure 2a) was used as the source with zero momentum. The exact location of the source and the sampling points are shown as in Figure 2(b). The source release time was 10 s, and the measurement time at each location was 750 s. Measurements with both the QEPAS sensor and B&K 1302 were carried out. Each case was repeated 3 times.

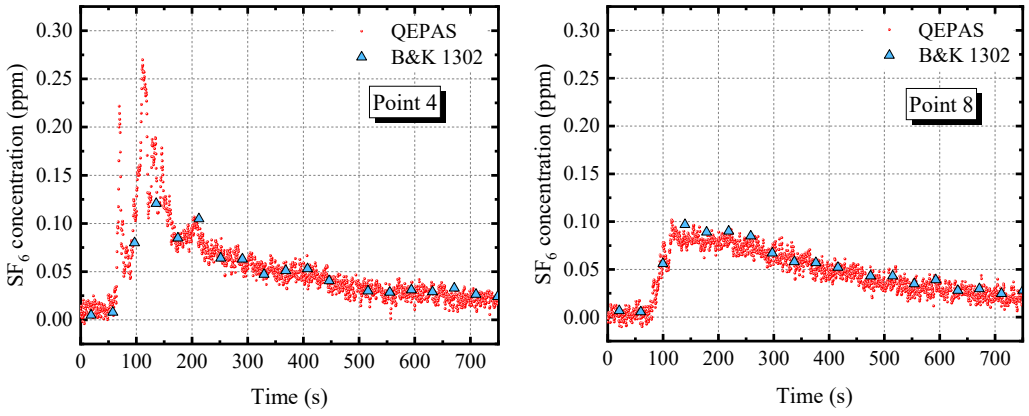


(a) **(b)**

Figure 2. (a) Contaminant source and (b) sampling points locations.

3. RESULTS AND DISCUSSION

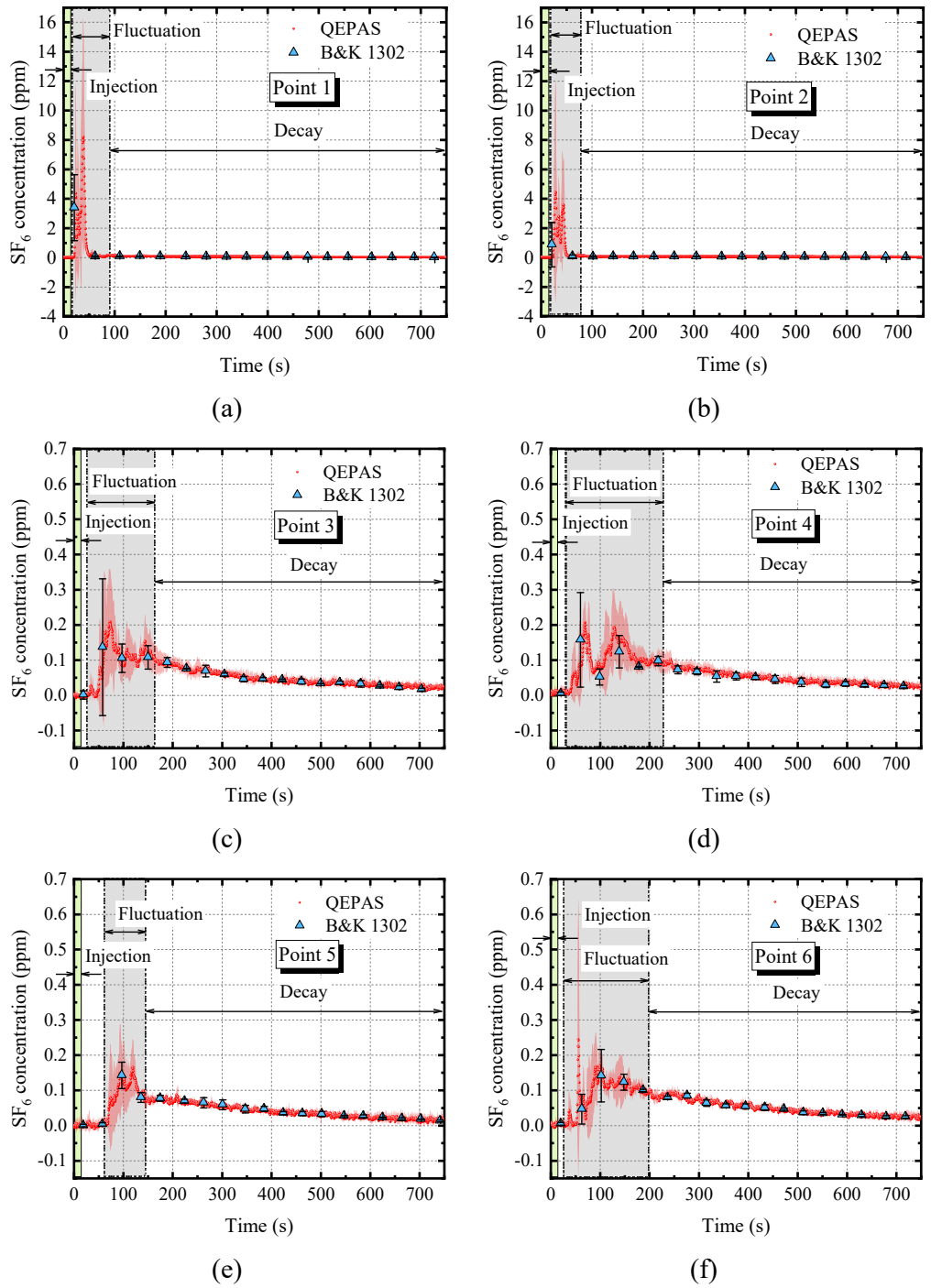
Figure 3 compares the measured SF_6 concentrations at sampling points 4 and 8 as obtained by the two instruments. A reasonable agreement can be found between the two measurements. This shows that the QEPAS sensor was validated by the traditional commercial instrument B&K 1302. In addition, in figure 3(a), the peak concentration measured by the QEPAS sensor was 0.27 ppm at 112 s, while that by B&K 1302 was 0.12 ppm at 136 s. This shows that the QEPAS sensor, with a much lower response time, can capture the peak concentration more accurately.

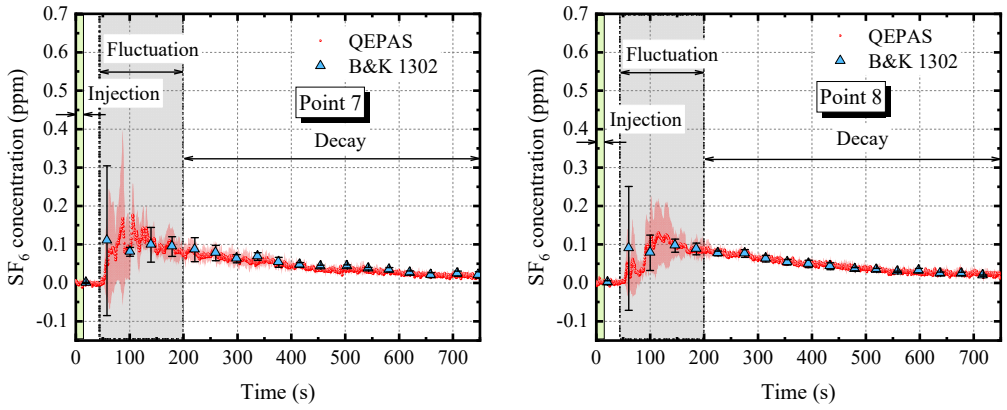


(a) (b)

Figure 3. Comparison of measurements of transient SF_6 concentrations at sampling points 30 and 39 using the developed QEPAS sensor and B&K 1302.

Figure 4 compares the transient SF_6 concentrations at different sampling points as measured by the two instruments. Each solid point in the figure represents the average value of three repeat tests, with red shaded areas and error bars showing the standard deviations.





(g) (h)

Figure 4. Comparison of measurements of transient SF_6 concentrations at different sampling points using the developed QEPAS sensor and B&K 1302.

As seen in figure 4 (a) and (b), the QEPAS results show that the SF_6 concentration peaks could be over 8 and 4 ppm at points 1 and 2, respectively. However, at these two points, the peaks captured by the B&K 1302 were 3.4 and 0.9 ppm, respectively. Furthermore, at point 6 (figure 4 (f)), just after 100 s the QEPAS sensor captured a peak near 0.25 ppm. However, the B&K 1302 did not capture this peak. Similarly, at points 7 and 8 (figure 4 (g) and (h)), the QEPAS sensor captured several peaks between 50 and 150 s. While, again, those peaks were ignored by the B&K 1302. At points 3-5 (figure 4 (c)-(e)), the two instruments obtained similar general changing trends of SF_6 concentration, but the B&K 1302 slightly underestimated the peaks.

Compared with the existing commercial monitor, the newly developed QEPAS sensor featured with a 0.4 s time resolution can capture more rapid changes in SF_6 concentration in the high-frequency fluctuation segment. This provides us with a valuable means of exploring the rapid changes in contaminant concentration in the study of the transient contaminant transport in indoor environments.

4. CONCLUSION

This study first developed a fast-response SF_6 sensor based on quartz enhanced photoacoustic spectroscopy (QEPAS). Transient tracer-gas measurements were then carried out in an environmental chamber with both the developed sensor and B&K 1302. Based on the results, conclusions can be made:

(1) Compared with the existing commercial monitor, the newly developed QEPAS sensor featured with a 0.4 s time resolution can capture more rapid changes in SF_6 concentration.

(2) The developed QEPAS sensor has potential in exploring the transient contaminant transport in enclosed environments.

5. ACKNOWLEDGEMENT

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