Photoacoustic Research Development in Industrial Era 4.0

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Abstract. Photoacoustic (PA) is the phenomenon of changing optical power into acoustics (sound). Photoacoustic research continues to grow and have broader field of application, especially after the development of laser technology and the development of laser diodes. In the industrial era 4.0, PA research is increasingly developing, especially in the PA tomography topics or PA imaging which is widely applied in medicine, as well as in single molecular imaging research and the 3D imaging of body tissue system.

1. Introduction

The photoacoustic effect was first discovered by Bell (1881) when he passed sunlight with modulated intensity into a solid material, producing an acoustic wave [1]. This effect become more interested to the researchers and more progress were achieved when laser was found as a source of radiation in 1968. Kerr and Atwood (1968) used a Ruby laser to detect water vapor and CO$_2$ in N$_2$ and a minimum absorption coefficient of $3 \times 10^{-7}$ cm$^{-1}$ and $1.2 \times 10^{-7}$ cm$^{-1}$ was obtained [2]. In 1971, Kreuzer used a He-Ne laser as a radiation source to detect methane (CH$_4$) in N$_2$, and a detection limit of 0.01 ppmv was obtained [3]. Chan (1986) used a CO$_2$ laser to detect C$_2$H$_4$ and NH$_3$ in N$_2$, and obtained a minimum detectable concentration of 50 ppbv [4]. Woltering et al. (1990) used a photoacoustic spectrometer (PAS) with a CO$_2$ laser and a longitudinal resonance photoacoustic cell model to detect C$_2$H$_4$ from Cymbidium flowers, and reached a minimum detection limit of 0.03 nl/l was obtained [5].

To increase the PAS sensitivity, Harren (1988) placed photoacoustic cells in a CO$_2$ laser cavity (intra-cavity configuration) and obtain a minimum detection limit of 6 pptv (1: 10$^{12}$) [6], whereas Nägele and Sigrist (2000) used multi-pass photoacoustic resonant cell model (extra-cavity configuration) and a detection limit of 70 pptv is obtained [7]. In recent years, PAS has been applied in many fields of research. Meyer and Sigrist (1990) used PAS detectors to monitor air pollution [8]. Schramm et al. (2002) successfully detected NO$_2$, N$_2$O, and SO$_2$ gases from diesel engine output gases using PAS [9]. Schilt et al. (2003) utilize PAS to monitor ammonia gas levels in the semiconductor industry area [10]. Keller et al. (2004) use PAS as a smoke detector to detect the presence of fire [11].

In the fields of biology and medicine, Harren et al. (1999 and 2000) and Berkelmans et al. (2003) have used PAS to detect ethylene emitted from the skin and in respiratory breathing as an indicator of skin damage due to ultraviolet irradiation and free radicals in lipid peroxidation [12,13,14]. Mitrayana (2004) has utilized PAS to determine the trachea volume and respiratory pattern of insects by detecting the emitted SF$_6$ gas [15]. Wang et al. (2004) have been able to create mouse brain images in a non-invasive
way with photoacoustic tomography methods for early detection of brain cancer [16]. Costa et al. (2019) have successfully utilized photoacoustic imagery to study tumors in vivo [17].

In this paper, we will review the development of photoacoustic research in various fields in the time span from 1998 (modern era) to 2019 (industrial era 4.0). We classify photoacoustic research base on the phase of the sample materials, i.e. gas, liquid and solid sample materials. Based on the data in www.sciencedirect.com up until July 18th, 2019 the total number of papers in the journals specifically for the photoacoustic field is 11,185 papers [18], with the distribution of the number of papers annually can be seen in Figure 1.

![Figure 1. Distribution of the annual number of photoacoustic research papers from 1998 to 2019 [18]](image)

2. Photoacoustic with Gas Sample

From the data [18], the total number of papers related to photoacoustic research with gas type samples up to 2019 was 5,943 papers in various field of applications. The distribution of the number of papers per year from 1998 to 2019 can be seen in Figure 2.

![Figure 2. Distribution of the number of papers per year from 1998 to 2019, specifically for Photoacoustic with a gas type sample [18]](image)
Some research setups can be seen from the following papers. Mitrayana et al (2017) was able to identify acetone gas as bio-markers from diabetic patients and healthy volunteers when exercising. The research setup is shown in Figure 3 [19].

Liu et al (2018), have succeeded in designing a PAS system with a polyvinylidene fluoride (PVDF) film sensor and applying it to detect water vapor (H$_2$O) [20]. The experimental setup can be seen in Figure 4. Zheng et al (2018) have succeeded in designing the set-up of quartz enhanced photoacoustic spectroscopy (QPAS) experiments with quartz tuning fork s detectors (QTFs) used for trace gas detectors [21]. The experimental setup can be seen in Figure 5. Chen et al. (2019) have succeeded in designing the PAS experimental set-up using a multi-cell system enabled him to increase the sensitivity up to 6.4 times compared to single cell setup [22]. Schematic of the experimental setup conducted by Chen et al. can be seen in Figure 6.
Figure 5. Schematic of the experimental setup of QPAS experiments with QTFs detectors, built by Zheng et al [21]

Figure 6. Schematic of the experimental setup of PAS multi-pass cell experiments designed by Chen et al [22]

3. Photoacoustic with Liquid Sample
From the data [18], the total number of papers related to photoacoustic research with liquid sample up to 2019 is 4,686 papers, with various fields of application. The distribution of the number of the papers per year from 1998 to 2019 can be seen in Figure 7.
Figure 7. Distribution of annual paper numbers from 1998 to 2019, specifically for photoacoustic with liquid type sample [18]

Some research setups can be seen from the following papers. Kurniawan et al (2017) have succeeded in designing and building PAS systems using diode laser sources and condenser microphone detectors [23]. The system setup scheme that has been designed and built can be seen in Figure 8.

Figure 8. Schematic of a series of photoacoustic systems for blood concentration test designed by Kurniawan et al. [23]

Liu et al (2018) succeeded in designing and developing photoacoustic tomography systems to detect and image murky media sample [24]. The system scheme can be seen in Figure 9.
Zhang et al. (2019) have successfully combined photoacoustic and ultrasonic imaging capabilities for real time tumor imaging of experimental animals [25]. The experimental setup scheme can be seen in Figure 10.

4. Photoacoustic with Solid Samples
From the data [18], the total number of papers related to photoacoustic research with solid type samples up to 2019 is 6,431 papers, in various applied fields. The distribution of the number of papers per year from 1998 to 2019 can be seen in Figure 11.
Some research setups can be seen from the following papers. Setiawan et al (2018) have succeeded in designing the PAS system using diode laser sources and condenser microphone detectors [26]. The experimental setup that was designed and built can be seen in Figure 12.

Widyaningrum et al (2018) have succeeded in designing a photoacoustic tomography system using a diode laser as the light source and applied it to detect tongue cancer in test mice [27]. The experimental setup that was designed and built can be seen in Figure 13.

Figure 11. Distribution of annual paper numbers from 1998 to 2019, specifically for photoacoustic with solid type samples [18]

Figure 12. Schematic of a photoacoustic imaging system with solid samples built by Setiawan et al. [26]
Dubyk et al (2019) have successfully designed a PAS system with a piezoelectric detector for measuring thermal conductivity of silicon nano materials [28]. The experimental setup that was built can be seen in Figure 14.

![Figure 13](image1.png)

**Figure 13.** Schematic of photoacoustic tomography tool designed by Wiyaningrum et al [27]

![Figure 14](image2.png)

**Figure 14.** PAS setup scheme with LED sources, built by Dubyk et al [28]

5. Conclusions

The development of PA research have been reviewed through the number of papers published on the the Sciencedirect website up until 2019. The trend of the PA research development in the industrial era 4.0 is in the use of diode and LED laser sources with compact, portable and economical system geometries.

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