Frequency Dependence of Resonant Photoacoustic Cells: The Extended Helmholtz Resonator

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Abstract. Photoacoustic cells consisting of two chambers connected by a long narrow tube were studied at room temperature. Amplitude and phase angle of the PA signal were measured as a function of chopping frequency, tube length and buffer gas. Multiple-resonance spectra were observed which can be interpreted quantitatively by a modified model of the acoustic Helmholtz resonator. The theoretical description is based on the analogy to the electrical transmission line theory.

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Photoacoustic spectroscopy (PAS) has become a very efficient and convenient method for optical and calorimetric investigations of inorganic and biological materials [1]. Although a great number of applications are restricted to room temperature conditions, there is a growing interest of temperature dependent photoacoustic (PA) experiments, especially in the calorimetry. A possible way to realize a PA cell for measurements at variable temperatures is to separate the sample chamber and the microphone chamber. In order to retain large acoustic amplification of the whole arrangement, small gas volumes and resonance-type acoustic cells are required. In this work we have investigated experimentally and theoretically PA cells in which the sample chamber was separated from the microphone by a long narrow cylindrical tube. Similar constructions have already been used for low and high temperature PAS [2–4]. The acoustic behaviour of the cells had not been studied specifically although in some cases more than one acoustic resonance peak had been observed [3–5]. The results of the present work may also be helpful for PA cell designs which make use of a short duct in order to protect the microphone from direct illumination [1, 6–8]. Investigations of the resonance enhancement of these cells have been reported by several authors [9, 10]. Good agreement between experiment and theory could be achieved with the help of the Helmholtz resonator model, but the quantitative data often suffered from discrepancies not negligible mainly at higher acoustic frequencies. The present approach of resonant PA cells proceeds from the analogy to electrical transmission lines in order to take care of the retardation effects of the acoustic waves in spatially extended systems. As both components, that of the simple Helmholtz resonator and that of acoustic conduits, are incorporated into our model we shall use the notation “extended Helmholtz resonator” (EHR). This model is capable of explaining the multiple acoustic resonances which are characteristic for spatially extended PA cells. It also yields an improved quantitative description of the acoustic dispersion of the amplitude and of the phase angle of the PA signals.

1. Experimental

The photoacoustic cell design used in the experiments is shown in Fig. 1. It consists of two cylindrical PA cells ($V_1$, $V_2$) which are connected by a narrow cylindrical tube of length $l$. The gas volumes are nearly identical ($V_1 = 716$ mm$^3$, $V_2 = 721$ mm$^3$), but the cells are machined from different materials, lucite and alu-
minium, respectively. The connecting tube is of stainless steel, with an inner diameter of 1.5 mm. It is sealed into the input hole of the cell with plasticine and grease to avoid leaks. Later the cells were also supplied with an additional valve for exchanging the gas in the whole arrangement. Each cell contains a miniature microphone (Knowles, Type BT-1759), so that the PA signal could be measured at either side of the interconnecting tube. In the present experiments the photoacoustic signal was always generated in the cell $V_1$. The sample consisted of graphite powder, which had been pressed after it was filled into the cell $V_1$. All measurements were performed using a nondispersive optical arrangement with a 100 W tungsten lamp as a light source and a frequency variable light chopper (Sinar, Model 7503). The PA signal of each cell ($V_1$, $V_2$) was detected by a lock-in analyzer (Ithaco, Model 393). The amplitude and the phase angle were recorded simultaneously as a function of the chopping frequency in the range 36–800 Hz. Runs were performed at room temperature with three different lengths $l$ of the interconnecting tube ($l=200, 400, 600 \text{ mm}$) and with three different gases (air, argon, helium).

2. The Helmholtz Resonator (HR)

The response of an acoustic resonator to an external perturbation which is periodic in time can be described by differential equations very similar to those used for electrical resonance systems. For this reason electric-circuit analogies have become a very efficient and manageable method to treat acoustic resonators. The acoustic analogy to the electrical RCL-circuit is the Helmholtz resonator (HR). The properties of the system are represented by discrete circuit elements such as resistance, inductance and capacitance. This concept remains an adequate description as long as the wavelength of the sound waves is large compared to the spatial dimension of the acoustic system. The same restriction also applies to the electrical problem. As the sound velocities in gases are six orders of magnitude smaller than those of electromagnetic waves, retardation effects become important at quite different frequencies in electrical and acoustic circuits.

For completeness and also for comparison with the extended model (EHR) developed in this work we briefly discuss the Helmholtz resonator approximation for the double cell configuration shown in Fig. 1. The cell is represented schematically in Fig. 2a together with its analogous electrical circuit (Fig. 2b). The discrete elements of the analogous circuit are the acoustic resistance $R$, the inductance $L$ and the acoustic capacitance $C$. They are defined as follows [11]:

$$R = \frac{8\pi \eta l}{A^2}, \quad L = \rho l / A, \quad C = V_s^2 / (c^2 \cdot g).$$

(1)

The properties of the gas are taken into account by the mass density $\rho$, the viscosity $\eta$ and the free-space sound velocity $v_s$. Numerical values for three gases are listed in Table 1. The dependence on the cell geometry is introduced by the length $l$ and the cross-sectional area