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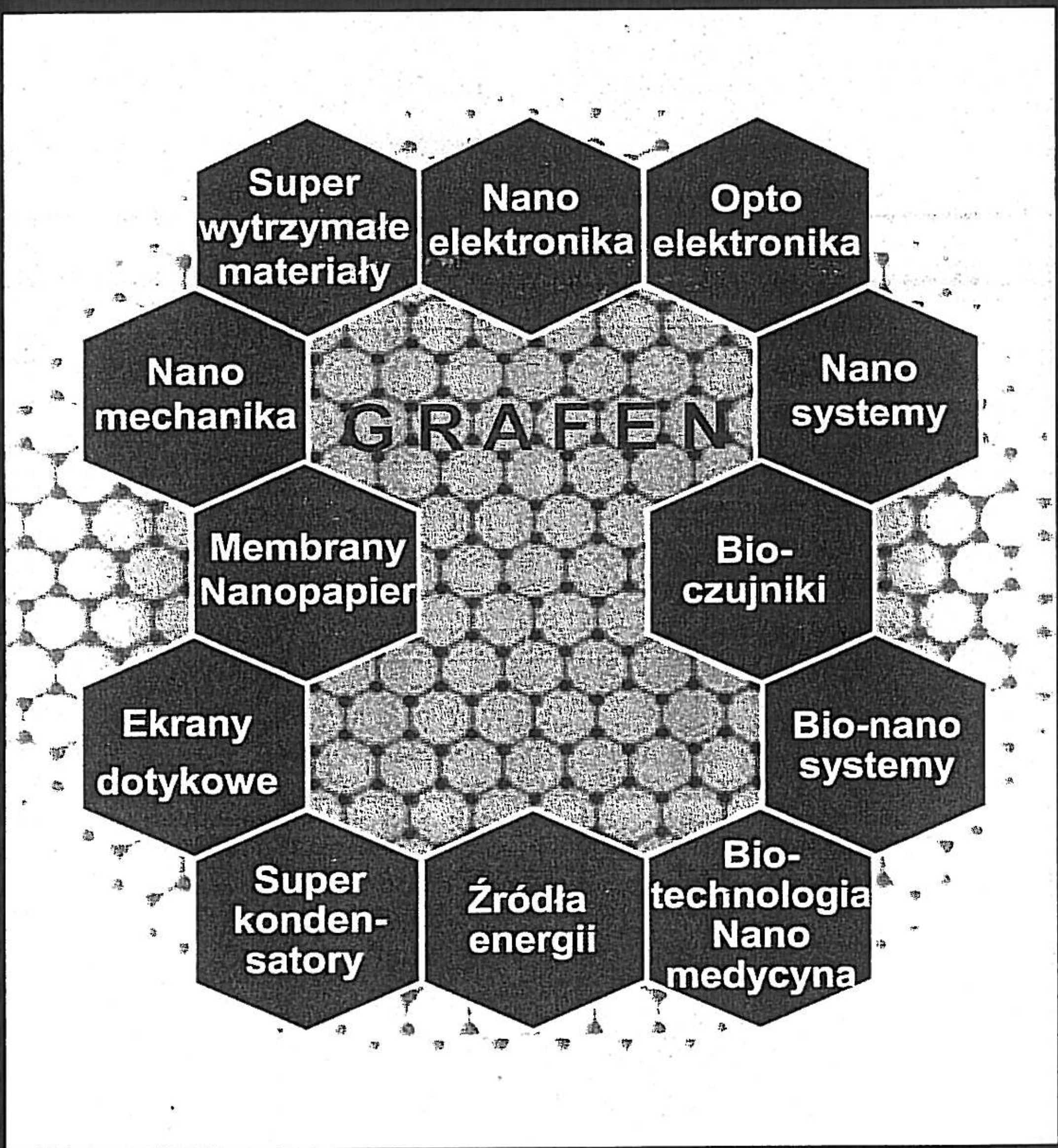

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Application of optical wave microphone to gliding arc discharge

Abstract. In this paper, principle and application of a novel method of an optical wave microphone to gliding arc discharge were introduced. The optical wave microphone is based on Fraunhofer diffraction, which can identify slight refractive index change of atmosphere after each discharges. Simultaneous measurement of applied voltage, discharge current and optical wave microphone for an arc discharge was carried out.

Streszczenie. Przedstawiono podstawy nowej metody wykorzystującej mikrofon optyczny w zastosowaniu do ślizgającego się wyładowania łukowego. Metoda bazuje na dyfrakcji Fraunhofera i pozwala wyznaczyć zmiany współczynnika załamania światła w powietrzu po wyładowaniu elektrycznym. Zmierzono napięcie, prąd i falę optyczną wyładowania łukowego (**Zastosowanie mikrofonu optycznego do ślizgającego się wyładowania łukowego**).

Keywords: gliding arc discharge, light-sound interaction, Fraunhofer diffraction, optical wave microphone.
Słowa kluczowe: ślizgające się wyładowanie łukowe, interakcje światło-dźwięk, dyfrakcja Fraunhofera, mikrofon optyczny

Introduction

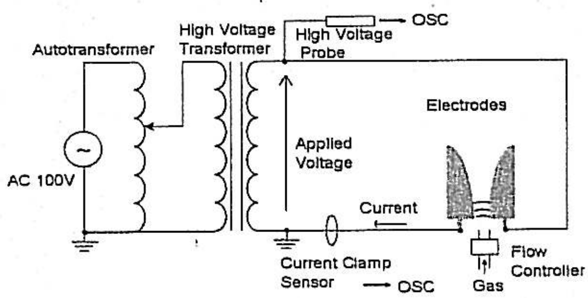
Application of gliding arc discharge to gas treatment has been progressed [1-5]. We have investigated multi-phase gliding arc discharge systems for industrial application. In addition, basic characteristics such as voltage-current property, energy efficiency, optical emission and movement of arc have been studied using single phase gliding arc discharge system. We have also focused on evaluation of sound or shock wave emitted after an pulsed discharge for surface and gliding arc discharges from practical and energetic point of view [6-11]. In this field, conventional condenser microphones have been used to detect sound or ultrasonic wave after discharge, however they have limitation for detectable frequency and geometry, which made it impossible to reveal relationship between a discharge and sound caused by the discharge.

In this work, we introduce a new optical method of an optical wave microphone, which is expected to substitute for conventional condenser microphones or other optical methods. The optical wave microphone is a unique technique which can detect compressional wave or slight change of density in gas medium or even in liquid medium with a probe laser, a Fourier lens and a detector. The initial stage of the development of the optical wave microphone started for detection of plasma wave. However, because this technique is based on Fraunhofer diffraction between compressional wave and a probe laser, it is very useful to detect not only audible sound but also ultrasonic wave or shock wave without disturbing propagation of compressional wave and electric field in case of electric discharge. We employed this technique to gliding arc discharge.

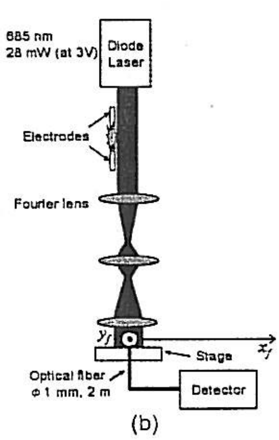
Experimental setup

Schematic diagrams of gliding arc discharge circuit and optical wave microphone setup are shown in Figure 1 (a) and (b), respectively. In Figure 1 (a), two knife edge-shaped electrodes are made of iron and their shortest gap was 2 mm. Outlet (ϕ=5 mm) of a gas supply was placed at 2 cm below the shortest gap. The gas flow rate was controlled by a digital flow instrument. During optical wave microphone measurement, gas flow was stopped to exclude influence of the density change of atmosphere. High voltage (sine wave, 60 Hz) was applied between the two electrodes with a high voltage transformer (VIC international, 120:1). The amplitude was adjusted with a voltage slide autotransformer (TAMABISHI, S-130-39). Applied voltage waveform during discharge was observed with a high voltage probe (IWATSU, HV-P60). Discharge current was measured by clamping a current sensor (HIOKI, 9018-50).

In Figure 1 (b), the optical wave microphone system consists of a diode laser, a Fourier lens, a beam expander, an optical fibber and an detector. The discharge electrodes should be placed between the diode laser and the Fourier lens. The probe laser beam (w_0=2 mm, 28 mW) was set at 3 mm apart from the electrodes and at the same height as that of the shortest gap along parallel direction to discharge. The two lenses after the Fourier lens, which are not necessary, play a role of the beam expander. The diffraction signal which was caused by interaction between the laser beam and the discharge sound wave was detected with the detector through the optical fiber. The use of the optical fiber was available to reduce discharge noise.



(a)



(b)

Fig.1. Schematic diagrams of (a) gliding arc discharge circuit and (b) optical wave microphone setup.

Principle of optical wave microphone

Theoretical explanation of the optical wave microphone is as follows. When a probe laser beam crosses refractive index change such as sound wave at (x_0,y_0), diffracted waves are generated and propagate with and in the penetrating beam through a Fourier optical lens and reach the observing detector which is set at Fraunhofer diffraction region or at the back focal plane (x_f,y_f) of the Fourier lens. The optical wave distribution $u_w(x_f,y_f)$ at the detector position (x_f,y_f) is shown in the next equation.

(1) $$u_w(x_f,y_f)=\left\{\frac{i\exp(-2k_i f)}{\lambda_i f}\right\}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}u_w(x_0,y_0)T(x_0,y_0)\exp\left\{\frac{ik_i(x_0x_f+y_0y_f)}{f}\right\}dx_0dy_0$$

where:

$u_w(x_0,y_0)$ - complex amplitude of laser at (x_0,y_0)

$T(x_0,y_0)$ - phase modulation component by refractive index change

k_i - wave number of laser

λ_i - wave length of laser

f - focal length of Fourier lens

When the amplitude of the laser beam and the phase modulation component are assumed to be the following equations,

(2) $$u_w(x_0,y_0)=\sqrt{\frac{2P_0}{\pi w_0^2}}\exp\left\{-\frac{x_0^2+y_0^2}{w_0^2}\right\}$$

(3) $$T(x_0,y_0)=\exp\{i(\phi_0+\Delta\phi_0\cos(k_p x_0-\omega_p t))\}$$

the time dependent component of the intensity I_{ac} is expressed by the next equation.

(4) $$I_{ac}=\left(\frac{2P_0}{\pi w_0^2}\right)\Delta\phi_0\left[\exp\left\{-\left(u^2+(u-\theta)^2\right)\right\}-\exp\left\{-\left(u^2+(u+\theta)^2\right)\right\}\right]\sin\omega_p t$$

where:

P_0 - laser power

w_0 - beam waist of laser

k_p - wave number of refractive index change

ω_p - angular frequency of refractive index change

ϕ_0 - phase of refractive index change

u - normalized x-coordinate (x_f/w_f)

w_f - beam waist in the focal plane

θ - normalized wave number $(k_p w_0/2)$

Therefore, it can be interpreted that the diffracted optical waves are heterodyne-detected by using the penetrating optical wave as a local oscillating power. Spatial Fourier transform is finished at the detecting plane. In this paper, compressional wave of air generated just after one pulsed arc discharge was detected by this method.

Results and discussion

Figure 2 shows laser beam intensity profile at the detecting position measured by changing the fibber position along x_f axis (y_f=0). The beam waist at the detecting plane w_f, which is half width where the intensity of the profile is 1/e^2, was approximately 2.0 mm. In the figure, the normalized detector position u, which is defined as x_f/w_f, is shown along the upper axis.

In the current setup, detecting position should be adjusted along x_f axis at y_f keeping 0 mm because refractive index change by an arc discharge crosses laser beam mainly along x_0 direction. It is possible to decide the optimum detector position using the equation (4) theoretically.

Figure 3 shows theoretical curves for the normalized wave number θ dependence of the relationship between amplitude of I_{ac} and normalized detector position u. The most sensitive setup can be obtained at θ=0.7. This means that selection of diameter of laser beam is important. The position u_m where the amplitude of I_{ac} becomes maximum also depends on θ.

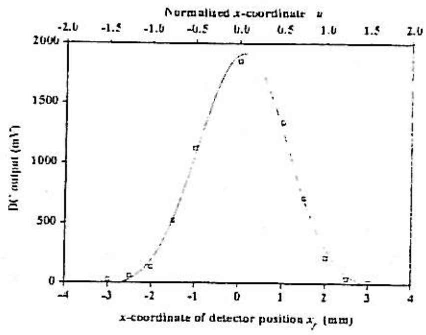


Fig.2. Laser beam intensity profile at detecting plane along direction (y_f=0).

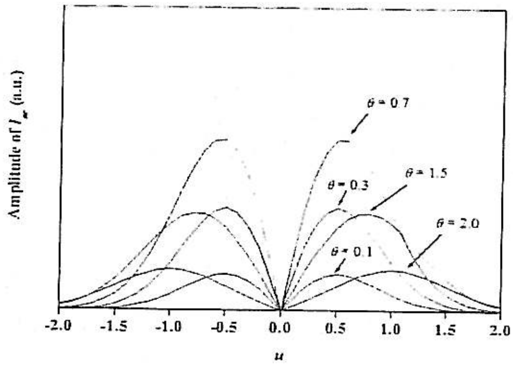


Fig.3. θ dependence of the relationship between amplitude of I_{ac} and normalized x-coordinate u.

Figure 4 shows relationship between the u_m, the maximum I_{ac} and θ. As can be noticed from this figure, the optical wave microphone has sensitivity around θ=0.7 but shows relatively superior sensitivity to refractive index change with lower frequency (θ<0.7) compared to that with higher frequency if diameter of laser beam assumed to be constant. In addition, the u_m increases with the increase of the θ which is attributed to the spatial Fourier transform. However, it is clear that the u_m exists from 0.5 to 1.5 which means that the optical wave microphone signal appears within laser beam (see Fig.2.) that is quite different point from other optical method. In this experiment, the detector position was fixed at x_f =1 mm (u=0.5) because frequency component of a compression wave after an arc discharge was unknown.

High voltage of 8 kV was applied between the electrodes without gas flow to carry out measurement of optical wave microphone. Because the optical wave microphone is very sensitive to density change of atmosphere, no gas flow is desired. The position of the optical fiber was fixed at (x_f,y_f) = (1 mm, 0 mm). The most sensitive frequency of this setup which is decided by the laser beam waist is approximately 40 kHz.

Figure 5 shows an typical optical wave microphone waveform captured simultaneously with applied voltage and current waveforms. The generation of one arc discharge started at 0 us when the pulsed current flowed and applied voltage decreased drastically due to higher conductivity of the arc between the electrodes. It is impossible to observe in the current waveform due to the lack of the dynamic range of the oscilloscope but slight current flow, which may concern with ionic component, exists after the large pulsed current until the recovery of the applied voltage. It was obvious from the optical wave microphone waveform that a compressional wave emitted by the generation of the arc discharge was detected successfully by this method.

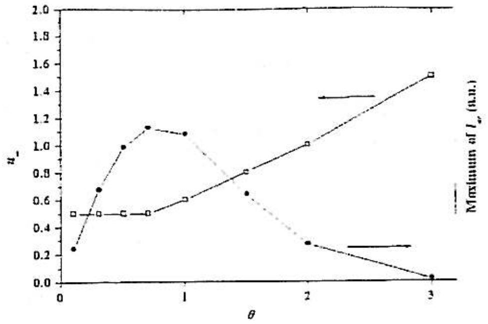


Fig.4. Relationship between u_m, maximum I_{ut} and θ.

The obtained waveform means frequency resolved waveform of the compressional wave. The wave arrived at the probe laser approximately 8 us delayed after the generation of the pulsed discharge, which exhibits the speed of the wave propagation almost corresponds to that of sound in air. More precise measurement is required however it is suggested that the wave should be observed as a shock wave near the discharge after that it degenerates to sound wave at detecting position as far as 3 mm. If we can detect shock wave, it is possible to estimate the energy of the shock wave which is another approach to evaluate energy of each discharges.

Figure 6 shows Fast Fourier Transform (FFT) analysis of the optical wave microphone waveform in Figure 5. The main frequency component of this optical wave microphone signal analyzed by FFT was about 100 kHz. This setup is the most sensitive to 40 kHz wave, nevertheless component around 100 kHz was remarkable. Measurement using smaller laser beam is needed to investigate higher frequency component but such high frequency component can not be detected with mechanical devices like conventional condenser microphones.

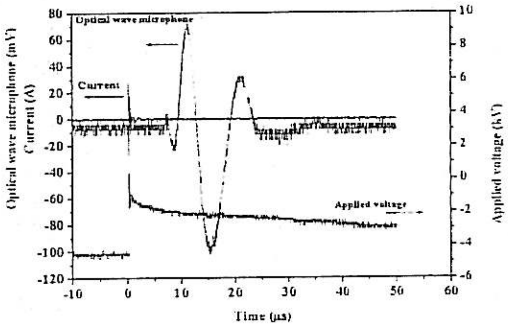


Fig.5. Waveforms of optical wave microphone, applied voltage and discharge current for an arc discharge.

Moreover, it is impossible to characterize relationship between generation of discharge and sound wave via condenser microphones because it cannot be set at very close position to high electric field and cannot follow a sound wave during high frequent discharges.

Therefore, from above mentioned results, we propose the optical wave microphone as one of the potential techniques to evaluate discharge energy as well as sound of arc.

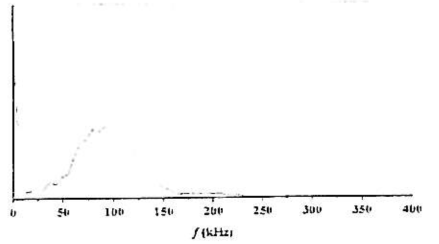


Fig.6 FFT analysis of the optical wave microphone waveform.

Conclusion

The principle of the optical wave microphone was introduced with the theoretical calculation and its application to single phase gliding arc discharge was carried out.

The compressional wave after an pulsed arc discharge was detected successfully near the electrodes by the optical wave microphone method. The FFT analysis showed that the main frequency component of the obtained signal was approximately 100 kHz which can not be detected via conventional condenser microphones. Therefore, it was revealed that this technique has potential to measure and interpret compressional wave after discharge correctly, moreover, to estimate energy of an discharge from that of shock wave.

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