Glow Discharge Enhancement by Shock Waves

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The effect of shock waves on the glow discharge is investigated experimentally. A fast electric discharge is generated across a shock wave for this purpose. The lower pressure around the cathode in front of the shock wave enables electrons to strongly diffuse radially, and therefore the glow is maintained with little constriction even at high average pressures. Moreover, the glow diameter, discharge fluorescence and current are enhanced by the shock wave.

1. Introduction

Since the invention of the CO_2 laser, there has been a renewed interest in electrical discharges. In order to produce high-power lasers one should try not only to introduce large electrical power into the discharge but also to raise the pressure and volume of the laser medium, which readily leads to a filamentary arc. Arc discharge is unsuitable for most gas lasers because the electron temperature is too low.

In order to avoid an arc, in this experiment a shock wave is applied between the electrodes. The pressure around the cathode is in this way kept low. Electrons can be emitted from the cathode as easily as in the low-pressure glow discharge. Because of the increased number density of the molecules behind the shock wave, a large number of them can be excited.

The influence of supersonic flow and shock waves on the characteristics of the static glow discharge has been studied by Wasserstrom et al. [1]. However, the present work is different from theirs because a fast impulse discharge ($\sim$ 400 nsec duration) is dealt with here. The gas flow can be neglected under these conditions.

It will be shown in this study that the interaction of a shock wave with the electrical discharge contributes not only to the suppression of the arc but also increases the discharge fluorescence and its current and volume under certain conditions. Consequently the glow discharge can be enhanced by shock waves.

2. Experiments

The experiments were performed in a stainless steel shock tube shown in Figure 1. The high-pressure section is 5 cm in inner diameter and 1 m long. The low-pressure section is about 3 m long and connected to the discharge section, where the discharge is fired. A Mylar film is used to separate the high and low-pressure sections. It is broken by a needle in order to produce the shock waves. The nitrogen used in the low-pressure section, including the discharge section, is dry and 99.999% pure, and that in the high-pressure section is 99.996% pure.

The construction of the discharge section is as follows: The tube consists of a steel cylinder of 20 cm length which supports a plastic liner (PMMA) of the same inner diameter as the low pressure section. The electrodes of tungsten wire are 1 mm in diameter and hemispherically ended. Both the electrodes are located in the center of the shock tube and electrically insulated from it. Electric discharges are generated between these electrodes along the shock tube axis. The gap length d can be varied but is kept constant to 20 mm in this paper.

The speed of the shock wave is in the normal experiment less than 1 mm/µs ($M_1 < 3$) and the discharge time is less than 1 µs. As in this time the shock wave travels accordingly less than 1 mm in the gap, the shock wave motion can be ignored.

The quartz windows make the phenomena of discharge visible from both sides and are used for fluorescence studies.

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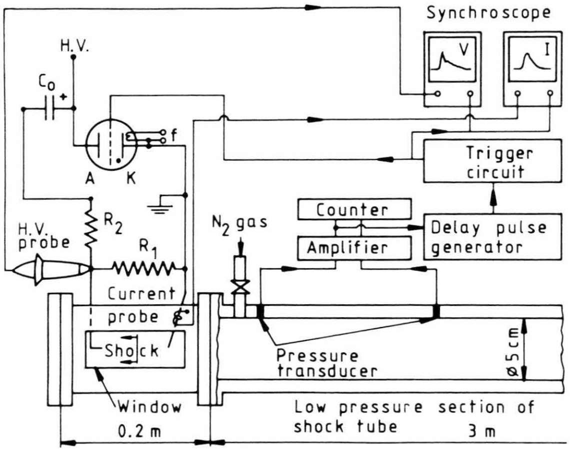

Fig. 1. Scheme of the experimental apparatus.

The discharge circuit is also shown in Figure 1. Capacitor C_0, resistor R_1 and R_2 amount to 1500 pF, 1 MΩ and 60 Ω, respectively. When a shock wave enters the region between the two electrodes, the thyratron (TOSHIBA, 2G22P) is fired and the discharge occurs.

The fluorescence intensity is measured using a biplanar phototube (HTV, R1193-U2). Breakdown voltages and discharge currents are also measured with both Tektronix high voltage (P6015) and current probe (CT2).

Shock waves can be visualized by taking photographs of the discharge channel owing to the abrupt constriction of the discharge channel as well as the radiation intensity difference [2].

3. Results and Discussions

Figure 2 shows the scheme of the electrode configuration and the position of shock wave. The

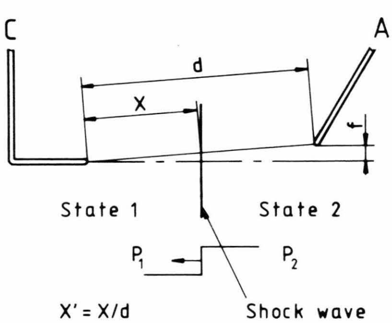

Fig. 2. Scheme of the electrode configuration and the position of the shock wave.

shock wave moves to the left (cathode). X means the distance between cathode and shock front. Shock position X' is here defined as X/d. The anode tip is shifted 2.5 mm ($=f$) from the extension of the cathode so that the possible wake of the anode can not much affect the discharge.

The gas pressure P_2 and temperature T_2 were determined as follows: The time for the shock wave to pass between two upstream stations 0.5 m away from each other (i.e., the shock velocity) was recorded on a counter and read out immediately following each experiment (Figure 1). From the shock Mach number M_1, the gas pressure P_2 and the temperature T_2 are readily determined from the well-verified Rankine-Hugoniot equations in terms of the initial pressure P_1 and temperature T_1 of the low-pressure section of the shock tube.

In the experiments, the gas pressure P_1, the normalized gas pressure $P_2' = P_2 T_1/T_2$, the gas temperature T_2, the shock position X and the applied voltage V_0 (voltage on capacitor C_0) are important and influencing parameters.

3.1. Arc suppression and discharge channel expansion by shock waves

In Fig. 3 four photographs of the discharge channel are given. Figure 3(a) shows a discharge across a shock wave under $P_1 = 5.3$ kPa (40 Torr), $P_2' = 15.3$ kPa (115 Torr), $T_2 = 530$ K, $X' = 0.08$ and $V_0 = 7.6$ kV.

Figure 3(b) shows the discharge channel under the same conditions but the shock front lying on the cathode rod, the channel being completely in the shocked region. Figure 3(c) presents a discharge without shock wave under $P = 15.3$ kPa (115 Torr) and $V_0 = 7.6$ kV. It shows an arc discharge due to the high pressure while photograph (a) shows a much expanded glow discharge in spite of the high pressure. The main reason is that the pressure around the cathode is small enough to allow electrons to diffuse radially and then rush into the high pressure gas with little constriction. This effect is briefly mentioned in [2].

Photograph (b) also shows a glow discharge in spite of the high pressure. Here an additional temperature effect suppresses the arc discharge [3]. When a gas is heated by a shock wave, the thermal conductivity of the gas grows and the thermal dissipation from the discharge channel to the wall

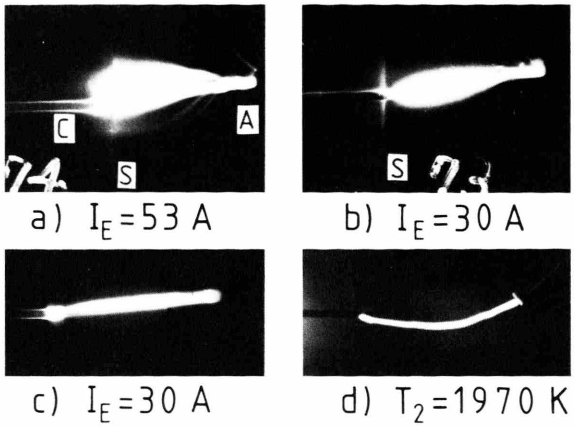

Fig. 3. Photographs of the discharge channel. – (a) Discharge across shock wave, $P_1 = 5.3$ kPa, $P_2' = 15.3$ kPa, $T_2 = 530$ K, $X' = 0.08$ and $V_0 = 7.6$ kV. – (b) Discharge in shock wave, the same condition as (a). – (c) Discharge without shock wave, $P = 15.3$ kPa, $V_0 = 7.6$ kV. – (d) Discharge at high temperature in shock wave, $P_2' = 6.3$ kPa, $T_2 = 1970$ K, $V_0 = 9.5$ kV.

increases. This prevents the discharge channel from thermalization. As a result, the glow discharge is maintained without transition to an arc. On the other hand, when the gas temperature is too high, the temperature difference between discharge channel and surrounding gas becomes smaller and the thermal dissipation decreases. As a result, a transition from glow to arc occurs. Figure 3(d) presents this fact. The photograph was taken under the conditions $P_2' = 6.3$ kPa (47 Torr), $T_2 = 1970$ K and $V_0 = 9.5$ kV.

3.2. *Enhancement of discharge fluorescence*

In this experiment, the fluorescence arising from C → B transition in the second positive band of the nitrogen molecule was measured.

Figure 4 shows the relationship between phototube output and shock position under the conditions $P_1 = 2.7$ kPa, $P_2' = 8.5$ kPa and $T_2 = 570$ K with the applied voltage V_0 as parameter. In the range $0 < X' < 1$, the values show the output in the shock wave experiment. But the values at $X' = 0$ and 1 mean the output under static pressures of $P_2' = 8.5$ kPa and $P_1 = 2.7$ kPa at normal temperature without shock wave. For the broken lines see below.

Figure 5 shows the relationship between phototube output and gas pressure at normal temperature with V_0 as parameter. As the discharge conditions were best around 3.2 kPa (24 Torr), the fluorescence was found to be maximum there. In Fig. 4, the fluorescence grows with increasing X', namely with decreasing the shocked region, because the mean pressure becomes lower and approaches the pressure of the maximum fluorescence.

The broken lines in Fig. 4 present the output values for weighted average pressure P_m of front and rear states of the shock wave expressed by $P_m = X' P_1 + (1 - X') P_2'$ for the cold gas, which are obtained from Figure 5. From these, the enhancement of the fluorescence can be seen between $X' = 0$

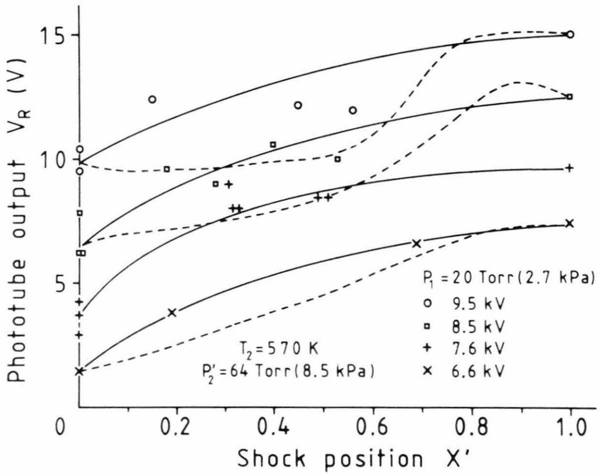

Fig. 4. Phototube output vs. shock position, $P_1 = 2.7$ kPa, $P_2' = 8.5$ kPa, $T_2 = 570$ K.

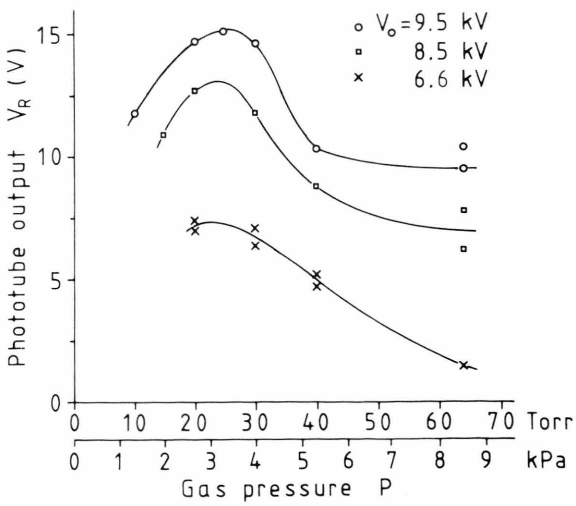

Fig. 5. Phototube output vs. gas pressure at normal temperature.

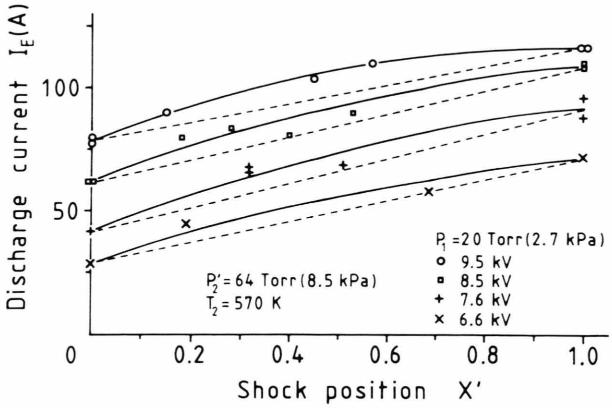

Fig. 6. Discharge current vs. shock position, $P_1 = 2.7$ kPa, $P_2' = 8.5$ kPa, $T_2 = 570$ K.

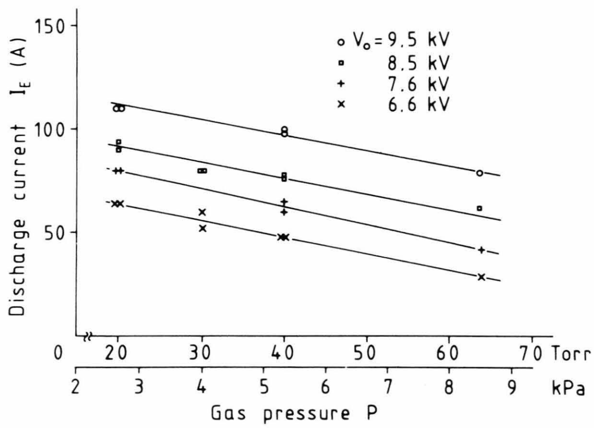

Fig. 7. Discharge current vs. gas pressure at normal temperature.

and $X' = 0.8$. The fluorescence at $V_0 = 8.5$ kV and $X' = 0.5$ is increased by about 30% in comparison with that of the weighted average pressure. With increasing applied voltage the enhancement becomes stronger.

3.3. *Enhancement of discharge current*

In Figure 6 the relationship between the discharge current and the shock position is shown. The dependence of the discharge current on the gas pressure at normal temperature is presented in Figure 7. The current values in Fig. 7 (which were obtained at a later time than those of Fig. 6) are at most 10% smaller than the corresponding values of Fig. 6, probably because of the electrode contamination. Therefore one cannot this time use the values of Fig. 7 to get the broken lines. But as the discharge current decreases linearly with gas pressure in the range of the experiments, one can easily obtain the broken lines as shown in Figure 6. From these, one can also find the enhancement of the discharge current by shock waves. With increasing the applied voltage the enhancement becomes stronger.

The reason for the better enhancement of the discharge fluorescence and current at a higher applied voltage is as follows: In general, the electrons in the outer region of the discharge channel in front of the shock wave, which have less energy than those in the inner region, lose their kinetic energy through the collision processes in the high pressure region behind the shock wave, and recombine under certain circumstances. But in the case of high E/P, the electrons are quite energetic and can reach the anode, exciting further molecules.

4. Conclusions

This paper has shown experimentally that by the use of shock waves, the glow discharge can be maintained even at high pressures, where usually an arc discharge occurs. Glow diameter, discharge fluorescence and current can be enhanced, too.

This type of a shocked discharge possesses the possibility of increasing laser outputs when used in combination with gas lasers.

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