Laser Deflection Diagnostics Of Shock Wave Interacting With Ar And N_2 DC Discharge

G. Cicala[1], A. Russo[2], M. Capitelli[2], O. De Pascale[1], S.Longo[2], D. Bruno[1], P. Minelli[1], A. Boggia[3], A. C. Rainò[3], and V. Nassisi[4]

[1]IMIP-CNR Bari, Via G. Amendola 122/D, 70126 Bari, Italy
[2]Dipartimento di Chimica, University of Bari, Via E. Orabona 4, 70126 Bari, Italy
[3] Dipartimento di Fisica/INFN Sezione di Bari, University of Bari, Via E. Orabona 4, 70126 Bari, Italy
4Dipartimento di Fisica, University of Lecce, Via Arnesano C.P.193, 73100 Lecce, Italy

Abstract. Shock waves generated *in-situ* by a spark gap are propagated either in atomic argon or molecular nitrogen at dc discharge *off* and *on*. Specifically, it is stressed how the Ar and N_2 glow discharges affect the shock wave properties. In both gases the shock wave structure does not change in the pre-plasma region, strongly changes in plasma region and is perfectly recovered in the after-glow region, as detected by Schlieren signals. The arrival times of shock waves in ionized gas (discharge *on*) are shorter than those in neutral gas (discharge *off*). Additionally, the propagation velocity of shock wave in molecular N_2 is higher than that in atomic Ar. At discharge *off* the reason for this is the fact that N_2 is lighter than Ar, whereas at discharge *on* the causes are both the different weight and plasma energetics.

Keywords: Ar and N_2 gases, non equilibrium dc discharges, shock wave.
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INTRODUCTION

Recent investigations on the shock wave (SW) propagation in non equilibrium dc discharge are receiving a growing interest in aerospace field [1], especially as for the reentry flows.

This paper deals with shock waves generated *in-situ* by a spark gap and propagated either in atomic argon or molecular nitrogen at dc discharge *off* and *on*. Up to now, it is not well-known what is the difference of the shock wave propagation in the inert Ar or the molecular N_2 gas (the major ingredient of our atmosphere). In this contribution we present and discuss results obtained by optical diagnostics on the one hand and electrical plasma characterization on the other. The influence of discharge current on the shock wave structure and propagation velocity in Ar and N_2 gas was studied by varying the discharge current from 0 to 90 mA and holding constant the pressure at 3 Torr and the gas flow at 200 sccm.

In particular, the shock wave interaction was detected by laser deflection technique [2], based on the density gradient created by the passage of shock wave, which permits to evaluate the propagation velocity of shock wave at discharge *off* and *on*. Besides, in ionized gas, the acceleration of the shock wave propagation and the decrease of density gradient was observed and was found to increase by enhancing the ionization degree i.e. the discharge current.

The two gases exhibit different behaviours due to the fact that not only the Ar ionization process is easier than that of N_2 and the Ar (atomic weight, A.W.=40) is heavier than N_2 (molecular weight, M.W. = 28), but also that the electrical characteristics such as discharge voltage (V_{disch}) and plasma resistance (R_{pl}) for Ar dc discharge are found much lower than those for N_2 plasma. Therefore, the comparison between argon and nitrogen permits to point up these differences and at the same time enables us to state if the distinct shock wave broadening and acceleration in the two kinds of gas is simply due to the different energetics of plasma or to the fact that the Ar is atomic and the N_2 is molecular or to the different weigth of Ar and N_2 or to the simultaneous action of the previous factors.

EXPERIMENTAL

The experimental apparatus, shown in Fig.1, comprises a pyrex tube and a spark gap. In the pyrex tube (80 cm long and 4.3 cm inner diameter) a non equilibrium dc discharge is ignited by a dc supplier (Alintel SHV 1000, 200mA/5000Volt) between a pair of stainless steel annular electrodes (4 and 3.3 cm external and inner diameter, respectively, and 1 cm length). The third and the fourth electrodes are 38.5 and 58.5 cm, respectively, far from the spark gap. In the discharge circuit a ballast resistance (R_B of 20 kΩ) connected in series with plasma resistance (R_{pl}) was used to: 1) protect the dc supplier from discharge transient and 2) meet conditions for discharge stability at investigated current range (8-110 mA). The spark gap, located at one end of the pyrex tube, consists of two stainless steel cylindrical electrodes (14 mm diameter and 15 mm high) with a gap distance of 7 mm. Acoustic shock waves were produced by the spark gap driven by a high voltage capacitor (0.5 μF, 12.5 kV), a triggered home-made spark switch and a dc supplier (50 kV). A typical voltage of 10 kV is applied to the spark gap electrodes that discharge an energy pulse of about 25 J. The experiments were done in two types of gas Ar and N_2 that were fed by independent MKS gas flowmeters. Each gas flow was fixed at 200 sccm by flowing in the opposite direction in comparison with shock wave propagation (see Fig.1), and the pressure was maintained constant at 3 Torr. The effect of discharge current on the electrical characteristics (such as discharge voltage and plasma resistance) and on the shock wave structure and propagation velocity was investigated by varying the current from 0 to 90 mA.

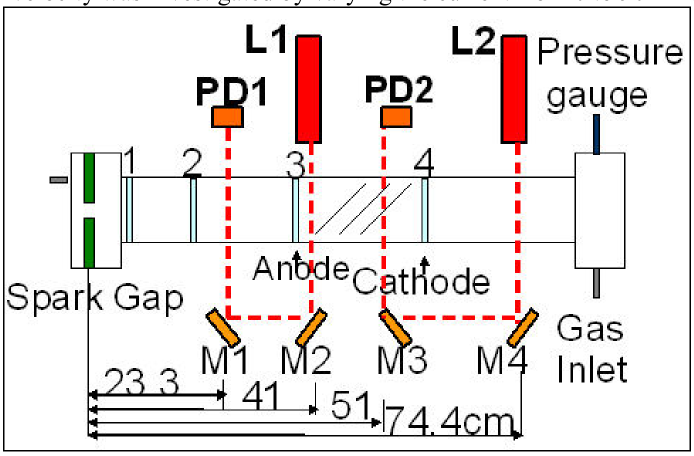

FIGURE 1. Schematic of the experimental apparatus.

The laser deflection measurements were carried out by an optical deflectometer based on the Schlieren principle i.e. on the density gradient induced by the passage of a shock wave transverse to a beam laser path. In the present study the Schlieren optical system consists of two He-Ne lasers (Melles Griot Mod.25-LHR-991: 632.8 nm, 10 mW, divergence beam 1.2 mrad and a diameter beam of 0.68 mm with a Gaussian profile) L1 and L2, two amplified Silicon detectors (Thorlabs PDA155-EC: 50MHz BW, 200-1100nm response time of 20 ns, active detection area of 0.8 mm^2) PD1 and PD2, an oscilloscope (Tektronix Mod.TDS2014: four channels) and a computer. Four front-surfaced mirrors M1, M2, M3 and M4 were used in order to double the two laser beams through the tube normal to its axis and the shock front. The first (23.3 cm) and the fourth (74.4 cm) beams probe regions outside the plasma, precisely pre- and after-glow, whereas the second (41 cm) and the third (51 cm) ones explore zones inside the dc discharge.

RESULTS AND DISCUSSION

In the present section results on the electrical plasma characterization and laser deflection diagnostics are presented, compared and discussed for the Ar and N_2 dc discharges.

Electrical Plasma Characterization

The dc supply voltage, the discharge voltage, and the voltage drop on the ballast resistance as a function of the discharge current exhibit the trends shown in Fig. 2a for Ar and N_2. In the same range of discharge current the voltage drop is almost the same in both Ar and N_2 discharges, being used the identical ballast resistance, whereas the values of dc supply voltage and the discharge voltage are in Ar much lower than those in N_2. Additionally, the power of Ar discharge is lower than that of N_2 discharge (see the discharge power, W_{disch}, values listed in Table 1 and calculated by the following equation):

$$W_{disch} = I_{disch} \cdot V_{disch} \tag{1}$$

where I_{disch} and V_{disch} are the current and voltage of the discharge, respectively.

TABLE 1. Discharge power (W_{disch}), width of Schlieren peaks and arrival time of shock wave (t_{SW}) at 41 cm in N_2 and Ar dc discharges at various values of discharge current (I_{disch}).

I_{disch}	(mA)	0	20	30	40	50	60	70	80	90
$W_{disch\ N2}$	(Watt)	0	18.8	25.5	32.0	38.5	45.0	53.2	61.6	70.2
$W_{disch\ Ar}$	(Watt)	0	6.8	10.2	13.2	16.5	19.8	23.8	27.2	30.6
$W_{disch\ N2}/W_{dischAr}$			2.76	2.50	2.42	2.33	2.27	2.24	2.26	2.29
$W_{disch\ N2}-W_{dischAr}$		0	12.0	15.3	18.8	22.0	25.2	29.4	34.4	39.6
Schlieren Width in N_2	(μs)	1.0		1.8		3.3		6.0		8.2
Schlieren Width in Ar	(μs)	1.0		1.2		2.1		2.9		5.6
t_{SWinN2}	(μs)	796.2		764.5		754.4		747.2		726.9
t_{SWinAr}	(μs)	874.0		859.5		854.6		852.0		840.2
$t_{SWinAr} - t_{SWinN2}$	(μs)	77.8		95.0		100.2		104.8		113.3

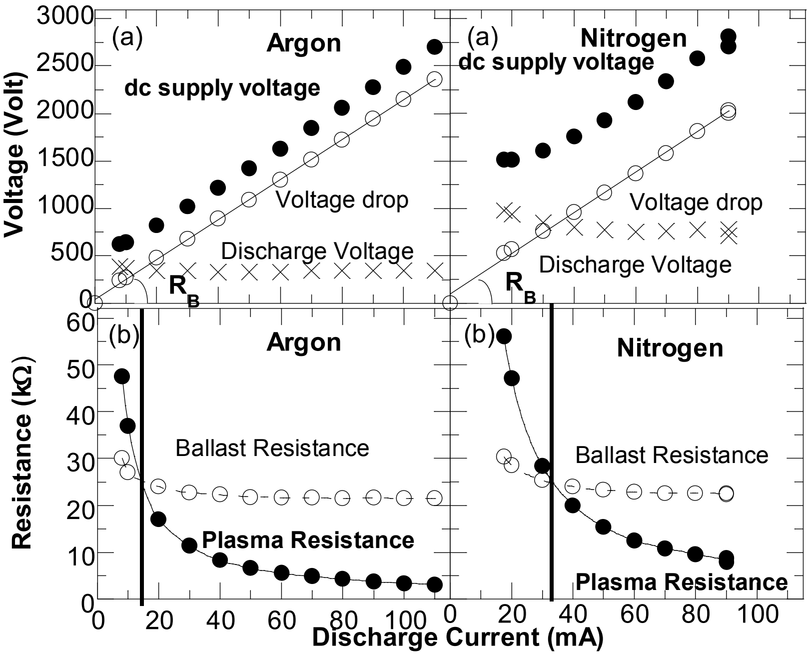

FIGURE 2. (a) Current-Voltage characteristics, (b) ballast and plasma resistance for Ar (Φ=200sccm) and N_2 (Φ=200sccm) plasmas vs discharge current at constant pressure of 3 Torr.

Figure 2b shows the plasma resistance profile for Ar and N_2 as a function of discharge current; in the same figure the ballast resistance as calculated by voltage drop is reported for comparison. In both gases the calculated R_B values correspond to its nominal known value, except at low discharge current. The R_{pl} trend for the Ar and N_2 decreases with increasing the discharge current, but in the explored current range the resistance of Ar plasma is always lower than that of N_2 plasma. The crossing between the plasma and ballast resistance curves is set at 14 and 34 mA for Ar and N_2, respectively. The crossing between the plasma and ballast resistance curves permits to distinguish two regimes: low and high current. The high current regime (>14 mA for Ar and > 34 mA for N_2) satisfies the requirement that the ballast resistance of the supply circuit must be much higher than the plasma resistance [3, 4] and in this regime the plasma is stable and uniform; whereas the low current regime (≤ 14 mA for Ar and ≤ 34 mA for N_2) violates the previous condition. In fact, the resistance of Ar and N_2 plasmas increases abruptly and exceeds the value of ballast resistance and the dc discharges become unstable; 8 and 17.5 mA are the minimum values of plasma ignition for Ar and N_2, respectively.

The discharge voltage, as expected [4], denotes a slight negative impedance of dc discharge for both Ar and N_2 and is much lower (380-340Volt for Ar; 980-710 Volt for N_2) than the dc supply voltage (620-2700 Volt for Ar, 1510-2710 Volt for N_2) and the voltage drop (240-2360 Volt for Ar, 530-2030 Volt for N_2) when the current increases from 8 to 110mA for Ar and from 17.5 to 90 mA for N_2. Thus, finally, the Ar dicharge is less energetic and resistive than N_2 one.

Laser Deflection Diagnostics

As an example, Fig. 3 shows the Schlieren signals detected by the second laser beam (41 cm) inside the plasma, precisely 2.5 cm far from the anode (3° electrode) in both N_2 and Ar plasmas by changing the discharge current from 0 to 90 mA. The effect of the discharge current on the Schlieren signals for N_2 and Ar gas is very similar and causes an increasing attenuation, broadening, dispersion and shift of the peak towards shorter (earlier) time by increasing the discharge current. Nevertheless, a careful inspection of this plot evidences three marked differences at discharge *off* and *on*:

1) the arrival times of signals for N_2 (t_{SWinN2}) are shorter than those for Ar (t_{SWinAr});
2) the temporal shift extent for N_2 (defined as the difference between two consecutive values of SW arrival times) is higher than that for Ar;
3) the broadening of Schlieren peaks for N_2 is higher than that for Ar.

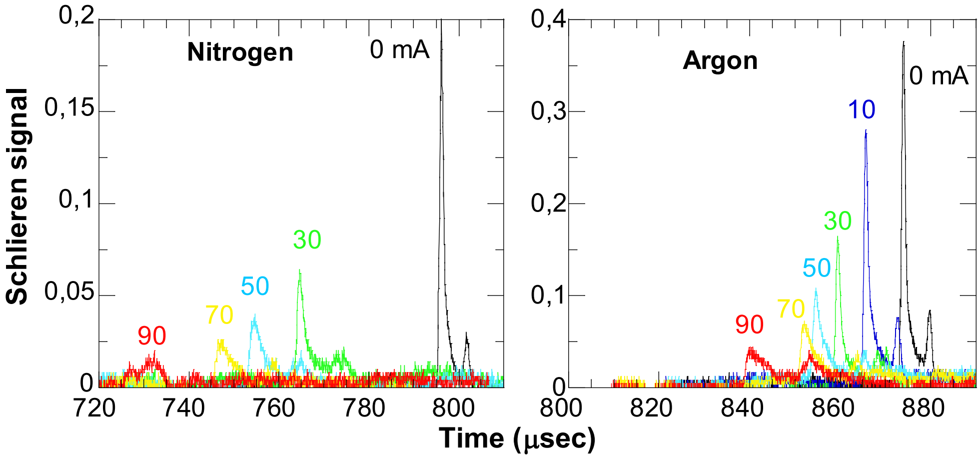

FIGURE 3. Schlieren signal by laser deflection technique at different discharge current for N_2 and Ar plasmas.

At discharge *off* the SW arrival time in N_2 (as measured by the Schlieren signal) is shorter than that in Ar for the fact that N_2 (M.W=28) is lighter than Ar (A.W.=40). Indeed, the shock wave propagation velocity in N_2 (v_{SWinN2}) is higher than that in Ar (v_{SWinAr}) of a factor of 1.10 as calculated by the following ratio:

$$\frac{v_{SWinN_2}}{v_{SWinAr}} \propto \frac{t_{SWinAr}}{t_{SWinN_2}} = 1.10 \qquad (2)$$

This value is well comparable to that calculated by the following expression:

$$\frac{v_{SWinN_2}}{v_{SWinAr}} \propto \frac{v_{soundN_2}}{v_{soundAr}} \propto \frac{\sqrt{A.W._{Ar}}}{\sqrt{M.W._{N_2}}} = \frac{\sqrt{40}}{\sqrt{28}} = 1.19 \qquad (3)$$

therefore, the increase of SW propagation velocity is due to the higher sound speed in N_2 medium [5] with respect to Ar.

At discharge *on* the different extent of temporal shift in Ar and N_2 plasmas seems to be strongly correlated to the different discharge power useful to sustain the Ar and N_2 discharges at the same values of current. In fact, the temporal shift of the Schlieren signals in N_2 discharge between two successive values of current is almost doubled with respect to that in Ar discharge (see Fig. 3), like to the variation of N_2 discharge power with respect to the Ar one (see Table 1). The differences (t_{SWinAr} - t_{SWinN_2}) and (W_{N_2} - W_{Ar}) increase by increasing the discharge current as shown in Table 1 and once again evidence that the SW velocity in ionized N_2 gas is higher than that in ionized Ar because the N_2 plasmas are more energetic than those of Ar plasmas, besides the fact that N_2 is lighter than Ar.

The Schlieren peak width in both gases is the same at discharge *off* (0 mA); whereas its broadening in N_2 gas is always larger than that in Ar at discharge *on* (20-90mA) and becomes wider with increasing the discharge current, as shown in Table1. The higher efficiency of N_2 discharge in shock wave broadening and dispersion with respect to Ar is due to the higher discharge power in N_2 gas.

A similar effect of discharge current has been found for Schlieren signals detected by the third beam because it is inside the plasma like the second beam. The discharge current does not affect the Schlieren peaks gathered by the first, outside and pre-plasma beam, whereas influences those detected by the fourth, outside and after-glow beam by shifting them at shorter time. Nevertheless, as already found by other researchers [6-7], at 15.9 cm far from the fourth electrode the Schlieren peaks in after-glow is fully recovered for each value of discharge current.

Figure 4 shows the shock wave velocity, derived by the Schlieren measurements collected in pre-, in- and after-glow corresponding to the four beams localized at 23.3, 41, 51 and 74.4 cm axial positions, as a function of discharge current. The SW velocities are calculated dividing the distances of the four axial positions from the spark gap by the corresponding arrival times of SW, whereas the local velocity is estimated dividing the distance between the second and the third beam inside the plasma by the difference of the SW arrival times measured by the corresponding Schlieren signals.

As for Ar gas, at the 23.3 cm position in pre-plasma region, the shock wave velocity values are about 540 m/s and, as expected, are not affected either the plasma is *off* and *on* or the current is increased. Instead for the 41 and 51 cm positions inside the plasma and 74.4 cm outside and after-glow, the velocity of shock wave increases by increasing the current of dc discharge, as already observed by many authors [6-8].

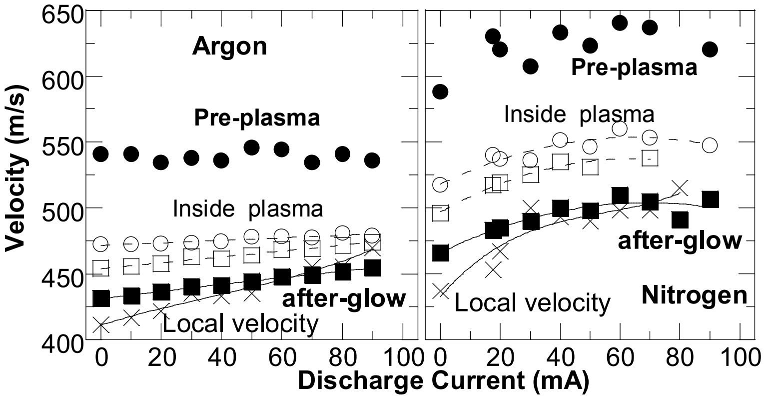

FIGURE 4. The propagation velocity of shock wave at the four axial positions 23.3 cm (●), 41 cm (○), 51 cm (□), 74.4 cm (■) vs discharge current in Ar and N_2 plasmas.

As for N_2 gas, the SW velocities corresponding to the four axial positions are always higher than those of Ar as observed in Fig. 4. In both gases, the comparison of velocity values estimated at the four positions evidences a shock wave that becomes less energetic as it goes away from the spark gap. It is important to underline that in Ar the enhancement of velocity gradients (Δv=8, 20, 23 m/s corresponding to 41, 51, 74.4 cm positions) seems to depend on the interaction length of Ar plasma (L_{pl}=2.5, 12.5 and 20cm), whereas in N_2 the velocity gradients (Δv=43, 42, 44 m/s corresponding to 41, 51, 74.4 cm positions) are constant and do not depend on the interaction length of N_2 plasma. However, the gradient of local velocity is 58 and 78m/s for Ar and N_2, respectively, that are much higher than the corresponding velocity gradient.

Gas temperatures have been calculated from the eq. (1) of ref. [9] by utilizing the local SW velocity of N_2 and Ar and have been listed in Table 2. It shows that the gas temperatures increase by increasing the discharge current and in N_2 the gas temperature reaches values higher than that in Ar.

At discharge *on* the further increases of 1) SW velocity (see Fig.4), 2) gas temperature (see Table 2), 3) temporal shift extent and 4) broadening of Schlieren peaks (see Table 1), by increasing the current, are mainly due to the power of N_2 plasma that is higher than that of Ar.

The discharge power increases by increasing the current, however the power of N_2 discharge reaches values

TABLE 2. Local propagation velocity of shock wave and gas temperature in N_2 (T_{N2}) and Ar (T_{Ar}) gas at various values of discharge current.

I_{disch} (mA)	0	20	30	40	50	60	70	80	90
$v_{SWin\,N2}$ (m/s) 41-51cm	437	467	500	493	490	498	498	515	---
T_{N2} (K)	300	349	408	395	389	403	403	436	
$v_{SWin\,Ar}$ (m/s) 41-51cm	412	422	435	433	435	448	455	456	470
T_{Ar} (K)	300	320	335	337	335	364	378	378	405

higher than Ar ones (see Table1) because the enthalpy of molecular nitrogen (H_{N2}) is higher than that of atomic Ar (H_{Ar}) according to the following thermodynamic equations:

$$H_{N_2} = \frac{9}{2} RT_{N_2} + \frac{2\alpha_{N_2}}{1+\alpha_{N_2}} \cdot \frac{D_{N_2}}{2} \tag{4a}$$

$$H_{Ar} = \frac{5}{2} RT_{Ar} \tag{4b}$$

where R (1.9859×10^{-3} kcal $K^{-1} mol^{-1}$) is the molar gas constant, α_{N2} and D_{N2} (224.92 kcal mol^{-1}) are the dissociation degree and dissociation energy of N_2, respectively.
The matching between the values of power ratio ($W_{disch\ N2}/W_{dischAr}$, see Table 1) and the values of enthalpy ratio (H_{N2}/H_{Ar}) is found only if in the eq. (4a) some energy of the N_2 discharge is utilized for its low dissociation.

CONCLUSIONS

On the basis of the present results, the authors state that at discharge *off* an arrival time of SW in N_2 shorter than that in Ar is explained exclusively by the fact that the molecular weight of N_2 (M.W.=28) is lower than atomic weight of Ar (A.W.=40), whereas at discharge *on* the further shortening of arrival time of SW in N_2 is attributed to the simultaneous action of weight and plasma energetics (the N_2 plasma has been found to be more energetic than that of Ar). It seems that it is caused by the molecular nature of the nitrogen which strongly affects the plasma parameters such as: discharge voltage, plasma resistance and discharge power (see Table 1. and Fig. 2a-b). In fact, in N_2 the energy surplus is either distributed in vibrational freedom degree or utilized for the dissociation. These effects occur obviously only in molecular N_2 and not in inert atomic Ar.

Furthermore, from the calculated gas temperatures data (shown in Table 2) it comes out that the N_2 more energetic dc discharges heat more efficiently the gas and therefore the enhancement of *thermal effects* are responsible at discharge *on* for the higher propagation velocity of shock wave in molecular nitrogen with respect to atomic argon.

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