Analysis of polarization degree of monochromatic line in H_2-Ne gas mixture

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The purpose of this paper is to analyse the variance of the Polarization Degree (PD) for the mixture of gases H_2-Ne, using the intensity of the monochromatic line (λ=585,23nm) measuring at different values of the discharge current for different values of the pressure. Such a research can be integrated in the statistical model 'Analysis of Variance (ANOVA)', which offers the possibility to follow the evolution of a phenomenon under different conditions. Said in another way, we expect that the means obtained for the four values of the pressure to differ enough in order to decide that their variance is connected with the cumulative effect of the polarization degree, induced by the different values of the concentration of the mixture.

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Keywords: Polarization Degree (PD), Monochromatization–effect (M-effect), Analysis Of Variance (ANOVA) method

1. Introduction

In the last 20 years, studies performed in electronegative-electropositive gas mixtures plasma, at a total pressure varying in the range of ten to hundred mbar, reported the appearance of a quasi-mochromatization effect of the emitted radiation. Due to the fact that the modified spectrum is reduced to this dominant line, the phenomenon was called the "Monochromatisation-effect" (M-effect).

For instance, in Ne+H_2 gas mixtures plasma in a dielectric barrier discharge (DBD), the M-effect consists in the reduction of the discharge emission spectrum practice at one strong spectral line λ = 585.3 nm [1÷4]. Figures 1 show the emission spectrum of a dielectric barrier discharge in Ne+H_2 gas mixtures.

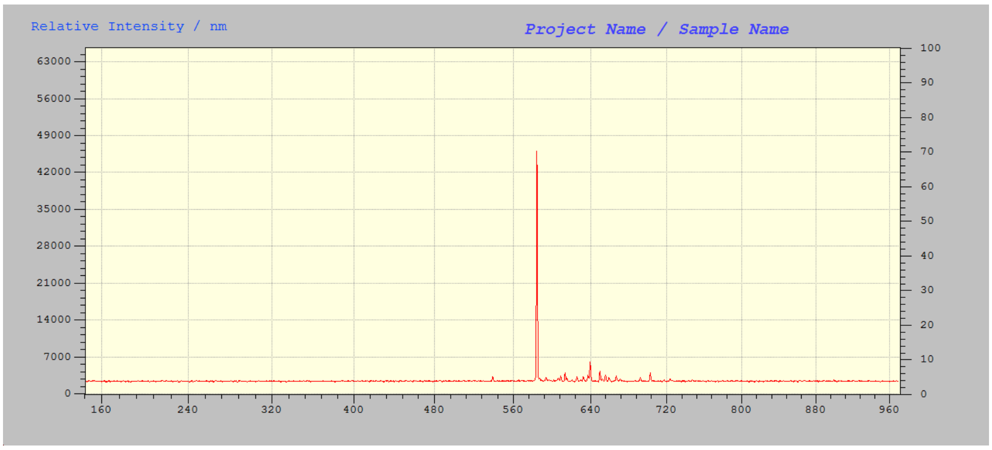

Fig. 1. Emission spectrum of DBD in Ne+H_2 gas mixtures.

The M-effect has proven to have a general character because its appearance was observed not only in A.C. but also in D.C. discharges, the main condition being that the gas mixture has to be formed from electronegative/electropositive gases, at moderate to high total pressures [5, 6].

The main reaction mechanism of the M-effect is represented by the resonant three-body polar reaction of ionized, excited and ground state atoms, with the important contribution of the electronegative gas metastable [7÷10].

The general form of the reaction, in case of the M-effect, is:

$$P^{+} + N^{-} + N^{met} \rightarrow P^{*} + N^{graundstate} + \left(N^{met}\right)^{*} + \\ + \Delta E\left(\Delta E \approx 0\right) \quad (1)$$

where

P, N - the symbols of the atoms of electropositive and respectively, electronegative gases in the mixture,

P^+ - the symbol for the positive ion,

N^- - the symbol of the negative ion,

N^{met} – the symbol for the metastable negative atom,
$(N^{met})^*$ - is the symbol of the excited electronegative atom standing in an upper state energy that the metastable level,
P* - the electropositive atom in an excited state,
ΔE - the reaction energy defect.

This reaction is based on the existence of a third particle, in a convenient energetic state, namely the metastable atoms of the electronegative gas. Only if this condition is accomplished, the reaction becomes resonant:

$$Ne^+ + H^- + H^*(n=2) \rightarrow \left(Ne^+H^-\right) + H^*(n=2) \rightarrow Ne^*(2p1) + H^*(n=3) + H(n=1) \pm \Delta E \quad (2)$$

For the gas mixtures in which the electronegative gas has a strong electronic affinity, like the chlorine atoms, the generation reaction for the M-effect could be binary in the classical sense of the Landau-Zenner theory [11-14], [17-20].

2. Experimental

In order to allow the passage of the UV radiation, the RF discharge was produced in a quartz tube with 16 mm inside diameter and 20 mm outside diameter respectively, between two identical wolfram-thorium cylinders electrodes of 12 mm diameter, spaced at 6 mm distance.

The experimental discharge device can be pumped down up to a vacuum value of 10^{-4}torr and then filled with various gas mixtures of spectral purity. The electrical power supply used in the experiment had the following characteristics: maximum output electrical tension of 2kV corresponding to a maximum electrical current intensity of 150mA, one optional frequency of 25 kHz. The optical emission spectra of the plasma discharges were registered using an Optical Analyzer Multichannel, spectral range 220÷900nm, integration time of 15ms and a resolution of 1.5nm. A photo - view of the experimental set - up is presented in Fig. 2. The measurements of the polarization degree were performed in hydrogen-neon gas mixtures (ν_{H2}/ν_{Ne}=19/56 and ν_{H2}/ν_{Ne}=1) for the dominant spectral line with λ=585.3nm, at four values of total pressures namely 19torr, 30torr, 45torr and 63torr. Each set of measurements was done for one frequency, at 25 kHz. The discharge electrical current intensity was varying with a rate of 2.5mA within the range of 6÷24mA.

Fig. 2. View of the experimental device.

The experimental data are presented in Fig. 3 and Fig. 4.

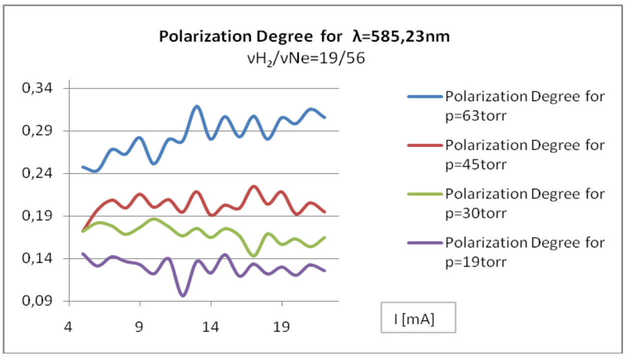

Fig. 3. Polarization Degree for ν_{H2}/ν_{Ne}=19/56.

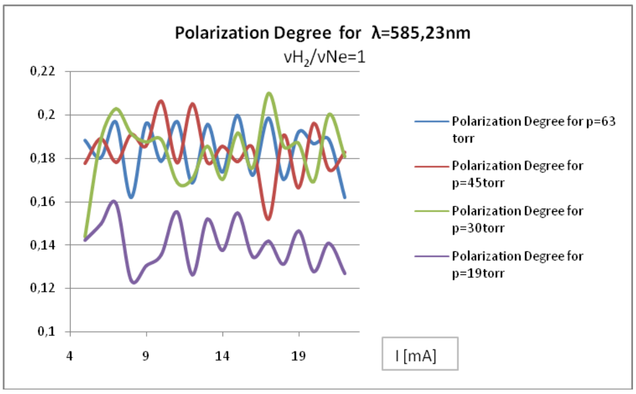

Fig. 4. Polarization Degree for ν_{H2}/ν_{Ne}=1.

3. Results and discussion

For the statistical analyses in this paper we used the IBM-SPSS Trial program, version 22.0.0 [15].

The research model supposes the variance analysis of a variable measured repeatedly in different conditions. Such a research can be integrated in the statistical model 'Analysis of Variance (ANOVA)' [16], which offers the possibility to follow the evolution of a phenomenon under different conditions. In such an analysis, the total variance (SS_T- the variance of the individual values of all the researched samples, independent of the group they belong, multiplied with n-1 degrees of freedom) of the values in the table below is fully provided by the variance within-subject (SS_W-the within-subjects variance), which, in its turn, is composed of the variance provided by the levels of the independent variables (SS_M – the variance of the means of each group – condition of measurement – compared with the total mean considering all values together) and the variance of the error, which is not explained by the independent variables (SS_E – the sum of the variances for each condition of measurement). The F ratio describes the model in the statistical test,

$$F = \frac{SS_M}{SS_E}$$

The higher the variance induced by conditions of measurement (SS_M) compared to the variance of the unexplained error (SS_E), the higher the F value, being able in this way to reach the threshold of statistical significance.

Table 1. The PD Values for four values of the pressure

Current	PD_19torr	PD_30torr	PD_45torr	PD_63torr	average
5	0,1452529	0,1720359	0,171696	0,247684	0,184167
6	0,1313081	0,1819724	0,197573	0,243683	0,188634
7	0,1424355	0,1781508	0,208662	0,268158	0,199352
8	0,1364826	0,1686948	0,199517	0,262731	0,191856
9	0,1333516	0,1767493	0,21528	0,28227	0,201913
10	0,1221737	0,1867289	0,20045	0,251496	0,190212
11	0,1400368	0,1771772	0,209034	0,279885	0,201533
12	0,096526	0,1668905	0,194839	0,278316	0,184143
13	0,1370501	0,175391	0,218618	0,318635	0,212423
14	0,1231812	0,1644513	0,19084	0,279879	0,189588
15	0,1443839	0,175212	0,202756	0,306675	0,207257
16	0,1191825	0,1665651	0,198894	0,283145	0,191947
17	0,1337276	0,1430132	0,224452	0,30717	0,202091
18	0,1221166	0,1690128	0,203663	0,280084	0,193719
19	0,1304734	0,1568098	0,218	0,305458	0,202685
20	0,1206695	0,1632515	0,192693	0,298318	0,193733
21	0,1325371	0,1541711	0,205579	0,315454	0,201935
22	0,1254084	0,1645372	0,194551	0,305637	0,197533
average	0,1297943	0,1689342	0,202617	0,284149	0,196373

ANOVA *one-way*

In this study it has been analyzed the variance of the Polarization Degree (PD), $(I_{max}+I_{min})/(I_{max}-I_{min})$, for the mixture of gases H_2-Ne, (ν_{H2}/ν_{Ne}=19/56), using the intensities of the monochromatic line (λ=585,23nm), I_{max} and I_{min}, measuring at different values of the discharge current, I [mA] at the frequency of 25 kHz for different values of the pressure (63torr, 45torr, 30torr and 19torr).

Table 2: Within-Subjects Factors

Measure: PolarisationDegree	
Pressure	Dependent Variable
1	PD_19torr
2	PD_30torr
3	PD_45torr
4	PD_63torr

The Table 3 contains the means and the standard deviations for the PD and the four values of the gas mixture.

Table 3. Descriptive Statistics

	Mean	Std. Deviation	N
PD_19torr	,12979430	,011719654	18
PD_30torr	,16893415	,010598993	18
PD_45torr	,20261650	,012342662	18
PD_63torr	,28414882	,023215864	18

The data in the Table 4 indicates a statistically significant variance (p<0.001) of the PD depending on the pressure, with a very high level of the effect size (0,980) and an observed maximum power (1,000).

Table 4: Multivariate Tests[a]

Effect		Value	F	Hypothesis df	Error df	Sig.	Partial Eta Squared	Noncent. Parameter	Observed Power
Pressure	Pillai's Trace	0,98	243,949[b]	3,00	15,0	,00	,980	731,85	1,000
	Wilks' Lambda	0,02	243,949[b]	3,00	15,0	,00	,980	731,85	1,000
	Hotelling's Trace	48,79	243,949[b]	3,00	15,0	,00	,980	731,85	1,000
	Roy's Largest Root	48,79	243,949[b]	3,00	15,0	,00	,980	731,85	1,000
a. Design: Intercept Within Subjects Design: Pressure									
b. Exact statistic									
c. Computed using alpha = ,05									

The same result we obtained using the 'Tests of Within-Subjects Effects' - see the table below. Analyzing the results on the line of the 'Sphericity Assumed' it can be observed that the F test ist statistically significant (p<0.0005), which confirms the research hypothesis, according to which the value of the PD varies with the pressure. The dimension of the effect very high (0,952), and the observed power is maximum (1,000).

Table 5: Tests of Within-Subjects Effects

Measure: Polarisation Degree									
Source		Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared	Noncent. Parameter	Observed Power[a]
Pressure	**Sphericity Assumed**	**,233**	**3**	**,078**	**334,6**	**,00**	**,952**	**1004**	**1,000**
	Greenhouse-Geisser	,233	1,681	,138	334,6	,00	,952	562,5	1,000
	Huynh-Feldt	,233	1,844	,126	334,6	,00	,952	617,2	1,000
	Lower-bound	,233	1,000	,233	334,6	,00	,952	334,6	1,000
Error Pressure	Sphericity Assumed	,012	51	,000					
	Greenhouse-Geisser	,012	28,6	,000					
	Huynh-Feldt	,012	31,4	,000					
	Lower-bound	,012	17,0	,001					
a. Computed using alpha = ,05									

The Table of "Pairwise Comparisons' presents the significance of the differences between all the four mean pairs of the PD for the values of the pressure. Statistically significant differences can be observed for all the values of the pressure.

Table 6. Tests of Within-Subjects Effects

Pairwise Comparisons						
Measure: PolarisationDegree						
(I) Pressure	(J) Pressure	Mean Difference (I-J)	Std. Error	Sig.[b]	95% Confidence Interval for Difference[b]	
					Lower Bound	Upper Bound
1	2	-,039*	,003	,000	-,049	-,029
	3	-,073*	,004	,000	-,084	-,062
	4	-,154*	,006	,000	-,173	-,136
2	1	,039*	,003	,000	,029	,049
	3	-,034*	,004	,000	-,046	-,021
	4	-,115*	,007	,000	-,137	-,094
3	1	,073*	,004	,000	,062	,084
	2	,034*	,004	,000	,021	,046
	4	-,082*	,005	,000	-,095	-,068
4	1	,154*	,006	,000	,136	,173
	2	,115*	,007	,000	,094	,137
	3	,082*	,005	,000	,068	,095
Based on estimated marginal means						
*. The mean difference is significant at the ,05 level.						
b. Adjustment for multiple comparisons: Bonferroni.						

The graphic below shows the PD mean variance for the four values of the pressure.

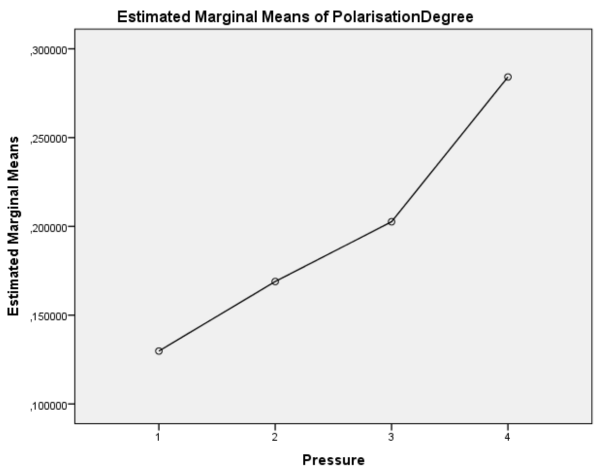

Fig. 5. The variance of PD depending on pressure.

As it can be observed the data sustain the hypothesis and the image illustrates the existence of a statistically significant global variation, and also significant differences from one pressure to another, with the highest increase of pressure from pressure 3, of 45torr, to pressure 4, of 63torr.

ANOVA *two-way*

For analyzing the variance with repeated measurements of type ANOVA two-way, the goal of the research is the evaluation of the polarization degree, considering the four different pressures for two values of the concentrations of the gas mixture. Said in another way, we expect that the means obtained for the four values of the pressure to differ enough in order to decide that their variance is connected with the cumulative effect of the polarization degree, induced by the different values of the concentration of the mixture.

Such a research can be considered a longitudinal, within-subjects research model, which offers the possibility to analyze the evolution of the Polarization Degree (PD) for different values of the concentration of the mixture.

Table 7. Within-Subjects Factors

Measure: PolarisationDegree		
Pressure	Mix	Dependent Variable
1	1	PD_mix1_19torr
	2	PD_mix2_19torr
2	1	PD_mix1_30torr
	2	PD_mix2_30torr
3	1	PD_mix1_45torr
	2	PD_mix2_45torr
4	1	PD_mix1_63torr
	2	PD_mix2_63torr

The Table Descriptive Statistics shows the means and the standard deviations of the PD, for the four values of the pressure and the two concentration values of the gas mixture.

Table 8. Descriptive Statistics

	Mean	Std. Deviation	N
PD_mix1_19torr	,12979430	,011719654	18
PD_mix2_19torr	,13974417	,011118903	18
PD_mix1_30torr	,16893415	,010598993	18
PD_mix2_30torr	,18317847	,015286590	18
PD_mix1_45torr	,20261650	,012342662	18
PD_mix2_45torr	,18335876	,012830105	18
PD_mix1_63torr	,28414882	,023215864	18
PD_mix2_63torr	,18371767	,012953928	18

The Table Multivariate Tests shows a statistically significant variation of the PD ($p<0.01$), regarding the two factors (pressure and concentration of the mixture), with a high level of the size of the effect (0,936 - 0,982) and a maximum observed power (1,000).

Table 9. Multivariate Tests[a]

Effect		Value	F	Hypothesis df	Error df	Sig.	Partial Eta Squared	Noncent. Parameter	Observed Power[c]
Pressure	Pillai's Trace	,982	278,505[b]	3,00	15,0	,00	,982	835,514	1,000
	Wilks' Lambda	,018	278,505[b]	3,00	15,0	,00	,982	835,514	1,000
	Hotelling's Trace	55,7	278,505[b]	3,00	15,0	,00	,982	835,514	1,000
	Roy's Largest Root	55,7	278,505[b]	3,00	15,0	,00	,982	835,514	1,000
Mix	Pillai's Trace	,936	247,002[b]	1,00	17,0	,00	,936	247,002	1,000
	Wilks' Lambda	,064	247,002[b]	1,00	17,0	,00	,936	247,002	1,000
	Hotelling's Trace	14,5	247,002[b]	1,00	17,0	,00	,936	247,002	1,000
	Roy's Largest Root	14,5	247,002[b]	1,00	17,0	,00	,936	247,002	1,000
Pressure * Mix	Pillai's Trace	,955	106,990[b]	3,00	15,0	,00	,955	320,971	1,000
	Wilks' Lambda	,045	106,990[b]	3,00	15,0	,00	,955	320,971	1,000
	Hotelling's Trace	21,4	106,990[b]	3,00	15,0	,00	,955	320,971	1,000
	Roy's Largest Root	21,4	106,990[b]	3,00	15,0	,00	,955	320,971	1,000

a. Design: Intercept
Within Subjects Design: Pressure + Mix + Pressure * Mix

b. Exact statistic

c. Computed using alpha = ,05

If we use the univariate tests, we have to analyze first the Mauchly Test for the sphericity, which is significant not only for the pressure and for the mixture, but also for the interaction pressure*mixture.

Table 10. Mauchly's Test of Sphericity[a]

Measure: PolarisationDegree							
Within Subjects Effect	Mauchly's W	Approx. Chi-Square	df	Sig.	Epsilon[b]		
					Greenhouse-Geisser	Huynh-Feldt	Lower-bound
Pressure	,286	19,659	5	,001	,672	,763	,333
Mix	1,000	,000	0	.	1,000	1,000	1,000
Pressure * Mix	,375	15,408	5	,009	,671	,762	,333
Tests the null hypothesis that the error covariance matrix of the orthonormalized transformed dependent variables is proportional to an identity matrix.							
a. Design: Intercept Within Subjects Design: Pressure + Mix + Pressure * Mix							
b. May be used to adjust the degrees of freedom for the averaged tests of significance. Corrected tests are displayed in the Tests of Within-Subjects Effects table.							

As the Mauchly test is significant for the three categories we use the Greenhouse-Geisser correction. As it is shown in the table below, both the main effects of the two factors and their interaction is statistically significant. This means that the values of the PD vary by the pressure, by the concentration of the gas mixture and also by the effect of the interaction of the two factors.

Table 11. Tests of Within-Subjects Effects

Measure: PolarisationDegree									
Source		Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared	Noncent. Parameter	Observed Power[a]
Pressure	Sphericity Assumed	,182	3	,061	321,85	,0	,950	965,5	1,00
	Greenhouse-Geisser	**,182**	**2,02**	**,090**	**321,86**	**,0**	**,950**	**648,7**	**1,00**
	Huynh-Feldt	,182	2,29	,080	321,86	,0	,950	736,2	1,00
	Lower-bound	,182	1,00	,182	321,86	,0	,950	321,8	1,00
Error Pressure	Sphericity Assumed	,010	51	,000					
	Greenhouse-Geisser	,010	34,3	,000					
	Huynh-Feldt	,010	38,9	,000					
	Lower-bound	,010	17,0	,001					
Mix	Sphericity Assumed	,021	1	,021	247,00	,0	,936	247,0	1,00
	Greenhouse-Geisser	**,021**	**1,00**	**,021**	**247,02**	**,0**	**,936**	**247,0**	**1,00**
	Huynh-Feldt	,021	1,00	,021	247,02	,0	,936	247,0	1,00
	Lower-bound	,021	1,00	,021	247,02	,0	,936	247,0	1,00
Error(Mix)	Sphericity Assumed	,001	17	8,307E-005					
	Greenhouse-Geisser	,001	17,0	8,307E-005					
	Huynh-Feldt	,001	17,0	8,307E-005					
	Lower-bound	,001	17,0	8,307E-005					
Pressure * Mix	Sphericity Assumed	,076	3	,025	113,69	,0	,870	340,8	1,00
	Greenhouse-Geisser	**,076**	**2,01**	**,038**	**113,69**	**,0**	**,870**	**228,8**	**1,00**
	Huynh-Feldt	,076	2,29	,033	113,69	,0	,870	259,6	1,00
	Lower-bound	,076	1,00	,076	113,69	,0	,870	113,6	1,00
Error(Pressure*Mix)	Sphericity Assumed	,011	51	,000					
	Greenhouse-Geisser	,011	34,2	,000					
	Huynh-Feldt	,011	38,8	,000					
	Lower-bound	,011	17,0	,001					
a. Computed using alpha = ,05									

The post-hoc test of the multiple comparisons for the two factors shows the existence of a statistically significant difference between all the values of the pressure.

Table 12. Pairwise Comparisons

Measure: PolarisationDegree						
(I) Pressure	(J) Pressure	Mean Difference (I-J)	Std. Error	Sig.[b]	95% Confidence Interval for Difference[b]	
					Lower Bound	Upper Bound
1	2	-,041*	,003	,000	-,049	-,034
	3	-,058*	,003	,000	-,068	-,048
	4	-,099*	,003	,000	-,110	-,089
2	1	,041*	,003	,000	,034	,049
	3	-,017*	,002	,000	-,022	-,012
	4	-,058*	,004	,000	-,070	-,046
3	1	,058*	,003	,000	,048	,068
	2	,017*	,002	,000	,012	,022
	4	-,041*	,004	,000	-,052	-,029
4	1	,099*	,003	,000	,089	,110
	2	,058*	,004	,000	,046	,070
	3	,041*	,004	,000	,029	,052
Based on estimated marginal means						
*. The mean difference is significant at the ,05 level.						
b. Adjustment for multiple comparisons: Bonferroni.						

The picture below illustrates the variation of the Marginal Means of PD for the two factors, at the four values of the pressure.

For the first concentration of the gas mixture, the Marginals Means of PD increases progressively from one pressure to another. For the second concentration of the gas mixture (ν_{H2}/ν_{Ne} =1) it can be observed that starting with pressure 2 (30 torr) the Marginal Means of PD become stationary.

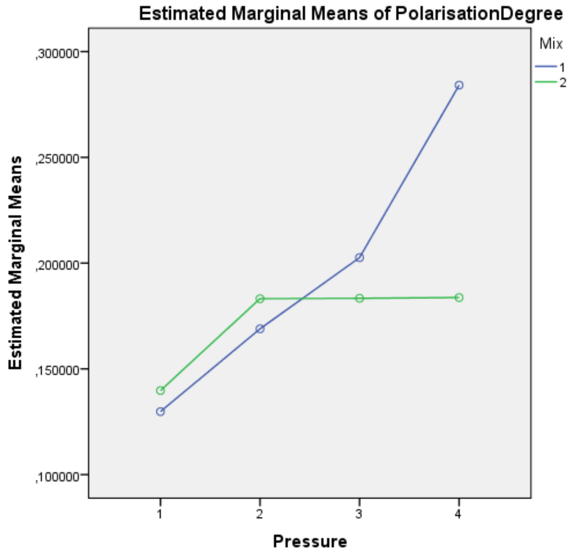

Fig. 6. The variance of PD depending on pressure for tow concentration of gas mixture.

4. Conclusion

The goal of this paper was the statistical analysis of Polarization Degree of Monochromatic Line in H_2-Ne Gas Mixture. First it has been analyzed the variance of the Polarization Degree for the mixture of gases H_2-Ne, ν_{H2}/ν_{Ne} =19/56, for different values of the pressure (63torr, 45torr, 30torr and 19torr) using ANOVA method. We obtained a statistically significant global variation for PD, and also significant differences from one pressure to another, with the highest increase of pressure from pressure of 45 torr, to pressure of 63 torr. Then we analyzed the evaluation of the polarization degree, considering the four different pressures for two values of the concentrations of the gas mixture. For the first concentration, ν_{H2}/ν_{Ne} =19/56, of the gas mixture, the global variation of PD increases progressively from one pressure to another. For the second concentration of the gas mixture (ν_{H2}/ν_{Ne} =1), starting with pressure of 30 torr the global variation of PD become stationary. As we expected, the means obtained for the four values of the pressure differ enough in order to decide that their variance is connected with the cumulative effect of the polarization degree, induced by the different values of the concentration of the mixture.

References

[1] L.C. Ciobotaru, Optoelectron. Adv. Mater. Rapid Commun., **6**(5-6), 668 (2012).
[2] L.C. Ciobotaru, Optoelectron. Adv. Mater. Rapid Commun. **5**(3), 327 (2011).
[3] L.C. Ciobotaru, Romanian Reports in Physics, **62**(1), 134 (2010).
[4] G. Musa, L.C. Ciobotaru, Optoelectron. Adv. Mater. Rapid Commun, **1**(3), 137 (2007).
[5] L.C. Ciobotaru, Romanian Reports in Physics, **61**(1), 53 (2009).
[6] L.C. Ciobotaru, Proceedings of The 8-th International Symposium on Applied Plasma Science (ISAPS), p.78, 31 August- 4 Sept., Hakone, Japan, 2011.
[7] C. Gavrila, C. P. Lungu, I. Gruia, Proceedings of SPIE, **8001**, Nr. 80013D, (2011).

[8] L.C. Ciobotaru, G. Musa, Turkish Journal of Physics, **36**(1), 77 (2012).
[9] G. Musa, L.C. Ciobotaru, J. Optoelectron. Adv. Mater., **6**(4), 1339 (2004)
[10] L. Landau, Phys., Z. Sowjet, **46**, 221 (1932).
[11] C. Zener, Proceedings of Royal Society A, **137**, 696 (1932).
[12] A. K. Shuaibov, I. V. Shevera, Optics and Spectroscopy, **104**(4), 534 (2008).
[13] R. Vladoiu, M. Contulov, A. Mandes, G. Musa, European Physical Journal D, **54**(2), 287 (2009).
[14] R. Vladoiu, M. Contulov, V. Ciupina, G. Musa, Contributions to Plasma Physics, **50**(2), 177 (2010).
[15] www14.software.ibm.com/download/data/web/en_US/trialprograms/W110742E06714B29.html.
[16] M. Dumitrescu, A. Batatorescu, Applaied Statistics, Ed. Univ. Bucharest, 2006.
[17] C. C. Surdu-Bob, P. M. Racolta, M. Badulescu, C. Chiojdeanu, N. Arsene, C. Logofatu, C. Ionescu, D. Sporea, I. Gruia, Optoelectron. Adv. Mater. Rapid Commun., **5**(12), 1336 (2011).
[18] M. Badulescu, I. Gruia, C. Surdu-Bob, C. Iacob, Optoelectron. Adv. Mater. Rapid Commun., **3**(12), 1269 (2009).
[19] M. Badulescu, I. Gruia, C. Surdu-Bob, C. Iacob, Optoelectron. Adv. Mater. Rapid Commun., **3(**11), 1231 (2009)
[20] M. Badulescu, I. Gruia, V. Micheli, L. Calliari, C. Surdu-Bob, Optoelectron. Adv. Mater. Rapid Commun., **3** (11), 1207 (2009).

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