SELECTING SPECTROMETER CONFIGURATION FOR USING IN ARC WELDING

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Abstract. *Optical Emission Spectroscopy (OES) has been used in different studies of arc welding, such as temperature measurement, arc light sensoring for arc height control, radiation measurement for safety purposes and joint tracking, among others. It has proved itself as a very powerful tool for understanding the phenomena behind the electric arc. However, due to the versatility of the equipment (the spectrometer), it is not always straightforward to set it up for its best performance. Different issues, such as excess of light, radiation that not reach the correct region of its CCD (charge coupled device) and misalignment, could take place and must be sorted out before the actual measurements. Therefore, it is presented here the very first actions to be taken into account to achieve a robust performance of an existent spectrometer set-up. A Robust (Taguchi) Design was employed to assess the influence of the various parameters that are necessary to adjust the whole rig. It is concluded for the suitability of the methodology and the most robust set of parameters are presented.*

Keywords*: Optical Emission Spectroscopy, Taguchi, Welding.*

1. INTRODUCTION

Optical Emission Spectroscopy (OES) has been extensively applied on the study of different arc-welding process and also technologically applied for monitoring and control. Examples can be found for temperature measurement, arc light sensoring for arc height control (AVC – automatic voltage control), radiation measurement for safety purposes and joint tracking, among others. It has proved itself as a very powerful tool for understanding the phenomena behind the electric arc. However, due to the versatility of the equipment (the spectrometer), it is not always straightforward to set it up for its best performance. Different issues, such as excess of light, radiation that not reach the correct region of its CCD (charge coupled device) and misalignment could take place and must be sorted out before the actual measurements. Therefore, it is presented here the very first actions to be taken into account to achieve a robust performance of an existent spectrometer set-up. A Robust (Taguchi) Design was employed to assess the influence of the various parameters that are necessary to adjust the whole rig. It is concluded for the suitability of the methodology and the most robust set of parameters are presented.

1.1. Sources of error

In order to quantify thoroughly the experimental errors involved in the temperature calculation, the following critical points as error sources are proposed.

The main sources of error while performing a spectroscopic measurement are the system misalignment (Fig. 1), that consists of four possibilities: two angular deviations and two shifting deviations; the arc striking method, which could shift the torch/plate or electrode contamination (in case of TIG welding); time of arc running, which could change the heat flow or deterioration of the electrode tip could occur; the sensitivity of the CCD employed by the manufacturer of the spectrometer must be known and compensated according to the measured wavelength (for instance, Fig. 2).

1.2. Data acquisition and treatment

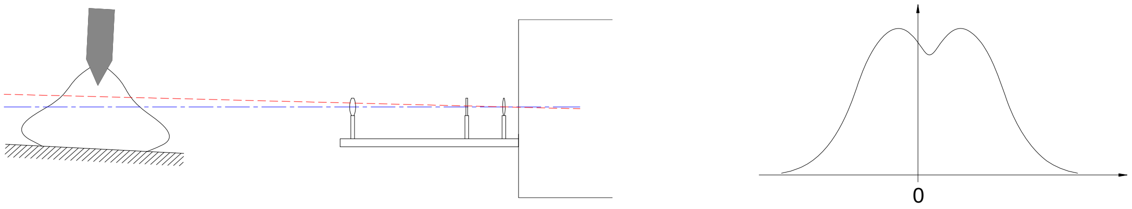
The spectrometer acquires the spectrum in a determined resolution, for instance, 0.02 nm. In order to quantify further error due to the spectral intensity measurements, one should estimate a distribution for the error. In this particular case, one can expect that a Poisson error can represent the measurement (photons reaching the CCD area). In this sense, an error of $\Delta I_{mr} = \sqrt{I_{mr}}$ should be expected.

If Abel inversion and the Fowler-Milne method are employed to calculate the temperature profiles, the experimental error in temperature can be carried out using Eq. 1 proposed by Eddy (1976). This formula will be used as first attempt, because it brings the dependency of the experimental errors with the atomic transition probability (A_{mr}), which is doubtful, since the method does not depend directly of it. Also the dependence of the ratio between the particle density and the partition function is not computed; although Murphy (1994) states that temperature results have only a small uncertainty upon this ratio.

The final step is the construction of the temperature maps. Normally, commercial softwares are employed with different curve-fitting options: linear, quadratic, least square, weight function and spline. This can lead to different temperature maps and must be used carefully.

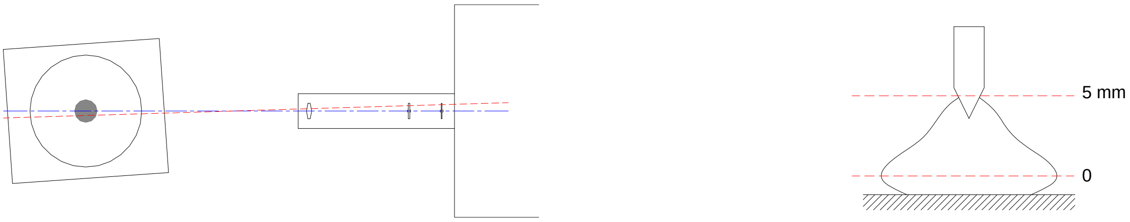
$$\frac{\Delta T}{T} = \frac{k_B T}{E_m} \sqrt{\left(\frac{\Delta I_{mr}}{I_{mr}}\right)^2 + \left(\frac{\Delta A_{mr}}{A_{mr}}\right)^2} \qquad (1)$$

where, T is the calculated temperature; k_B is the Boltzman constant; E_m is the energy level m; I_{mr} is the measured intensity and A_{mr} is the transition probability



(a) Horizontal shifting deviation

(b) Vertical angular deviation.



(c) Horizontal angular deviation

(d) Vertical shifting deviation.

Figure 1. Possible system misalignments.

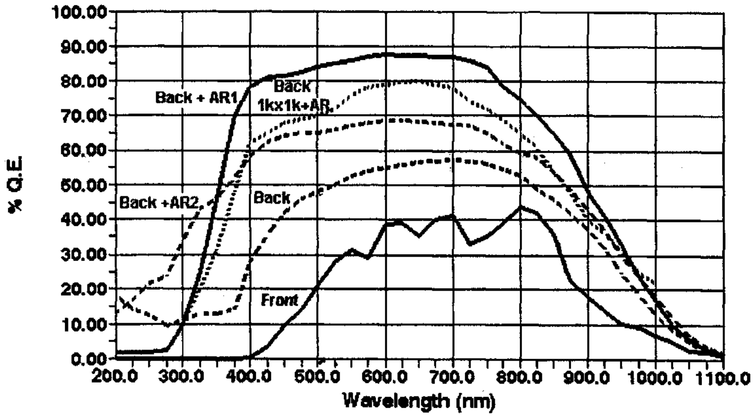


Figure 2. Example of CCD efficiency curve (Isa Instruments, 1996).

1.3. Robust Design (Taguchi) principles

There are literally hundreds of choices of experimental design available for experimenters. Unfortunately, in order to choose a specific design one must have a wide knowledge of the statistical methods available in order to ensure that an efficient design will be chosen, what, definitely, is not an easy task. First reference books and papers (for instance, Hahn, 1977; Box et al., 1978 and Montgomery, 2001) bring good introduction about this subject. Despite the different experimental designs (full factorial, 2^k factorial, one factor at a time, etc) and different ways of analyse the results (Myers et al., 1989), this work will handle with the Robust Design, also known as Taguchi Design (Phadke, 1989). This choice relies on the reduction of the experimental array (number of experiments) and in the facility of analysing the results, since there are commercial programs available. Examples of Taguchi Methodology applied to welding can be found in Howse (1997) and Correia (1999).

2. EXPERIMENTAL DESIGN FOR S/N RATE EVALUATION

All the experiments were carried out capturing the arc radiation from a TIG arc at 100 A over a cooled-cooper anode, 5 mm of arc length, pure Ar at 12 l/min, the electrode is AWS EWTh-2 with 3.2 mm of diameter ground to a 60º include angle and truncated to a 0.2-mm flat tip. The power source is a transistor series regulated one (model GEC AWP H350sr), which provides a highly uniform output (current ripples less than ± 0.1 A).

The arc radiation is imaged at a 1:1 ratio on to a 50-microns diameter pinhole. Light from the pinhole is collected by a second lens and imaged to the monochromator. The monochromator (Spex model 1704) has a 1m focal length and a reciprocal linear dispersion of 0.8nm/mm for first order images.

All of spectrums refer to a position of 3 mm above the anode, focused by the optical system. The 696.54-nm ArI line was chosen to be evaluated, since the major literature refers about it.

To evaluate the signal-to-noise rate (S/N), where signal means line intensity and noise its background, a set of runs is proposed. This set intends to assess the influence of light collecting area of CCD, the dark offset utilisation or not, the entrance slit value and the integration time.

The Area factor has nine levels, Slit and Time have three levels and Dark Offset has two levels, as showed in Table 1. The experimental design was done using Taguchi Robust Design in a L9 array. One condition of this experimental design is to have a maximum of three levels in each factor. Thus, the Area factor was split into three different array designs as show in Fig. 3.

Table 1. Factors with respect levels to analyse S/N rate.

Factors	Levels
CCD Area	9 split into 3 different L9 arrays (Fig. 3)
Entrance Slit	20; 50 and 80 μm
Integration Time	0.1; 0.5 and 1 s
Dark Offset	On and Off

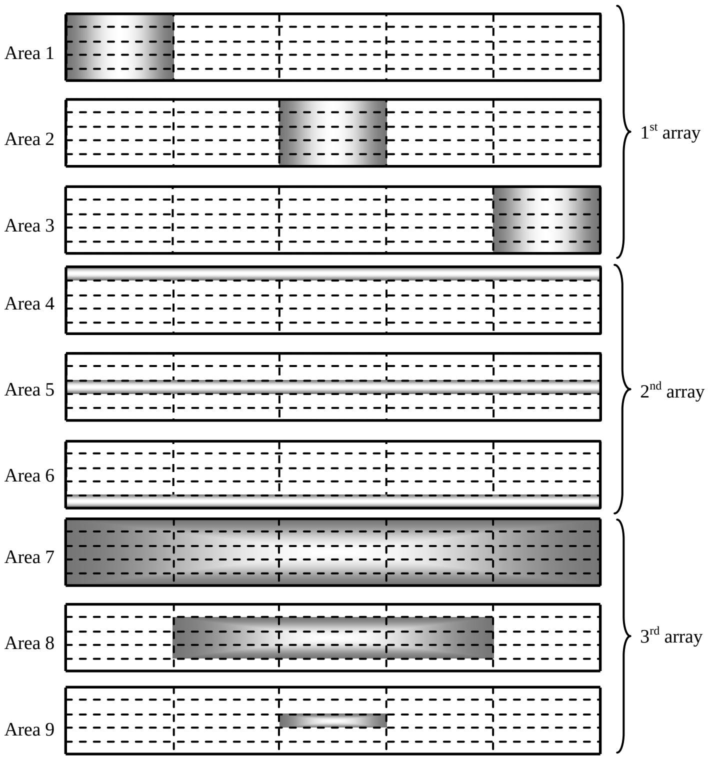


Figure 3. Nine different CCD areas to be covered by Taguchi Robust Design.

The experimental array generated in the Robust Design is a L9 design with 4 factors. It is important to point out that the fourth factor has only two levels in this case (Dark Offset). In previous experiments were noticed that very likely future experiments won't utilised the Dark Offset (therefore, it is Off), since the spectrometer takes a long time to process the arc spectrum (7 hours to scan 2500 points, as each scan is composed by two shots). Thus, it is reasonable to want to know more about the effects of the Dark-Offset-Off condition. This is done using the 3rd possibility for the Factor D, as it would be the 2nd. Finally, after applying this new modified array to the present situation, the Tabs. 2, 3 and 4 are created and shown the final experimental design to be conducted.

Table 2. First experimental Taguchi array.

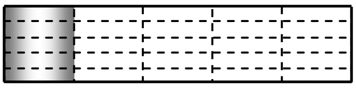
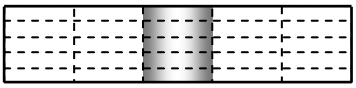
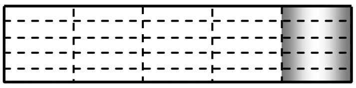
Run	CCD Area	Entrance Slit [μm]	Integration Time [s]	Dark Offset
A1		20	0.1	On
A2		50	0.5	Off
A3		80	1.0	Off
A4		20	0.5	Off
A5		50	1.0	On
A6		80	0.1	Off
A7		20	1.0	Off
A8		50	0.1	Off
A9		80	0.5	On

Table 3. Second experimental Taguchi array.

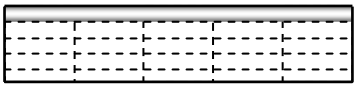
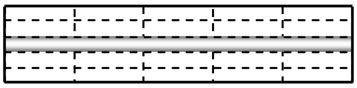
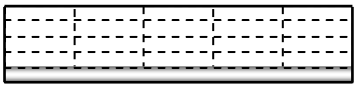
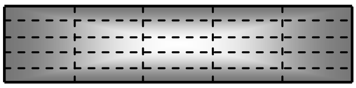
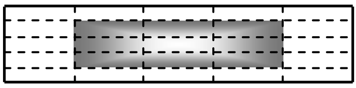
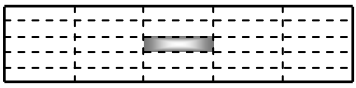
Run	CCD Area	Entrance Slit [μm]	Integration Time [s]	Dark Offset
B1		20	0.1	On
B2		50	0.5	Off
B3		80	1.0	Off
B4		20	0.5	Off
B5		50	1.0	On
B6		80	0.1	Off
B7		20	1.0	Off
B8		50	0.1	Off
B9		80	0.5	On

Table 4. Third experimental Taguchi array.

Run	CCD Area	Entrance Slit [μm]	Integration Time [s]	Dark Offset
C1		20	0.1	On
C2		50	0.5	Off
C3		80	1.0	Off
C4		20	0.5	Off
C5		50	1.0	On
C6		80	0.1	Off
C7		20	1.0	Off
C8		50	0.1	Off
C9		80	0.5	On

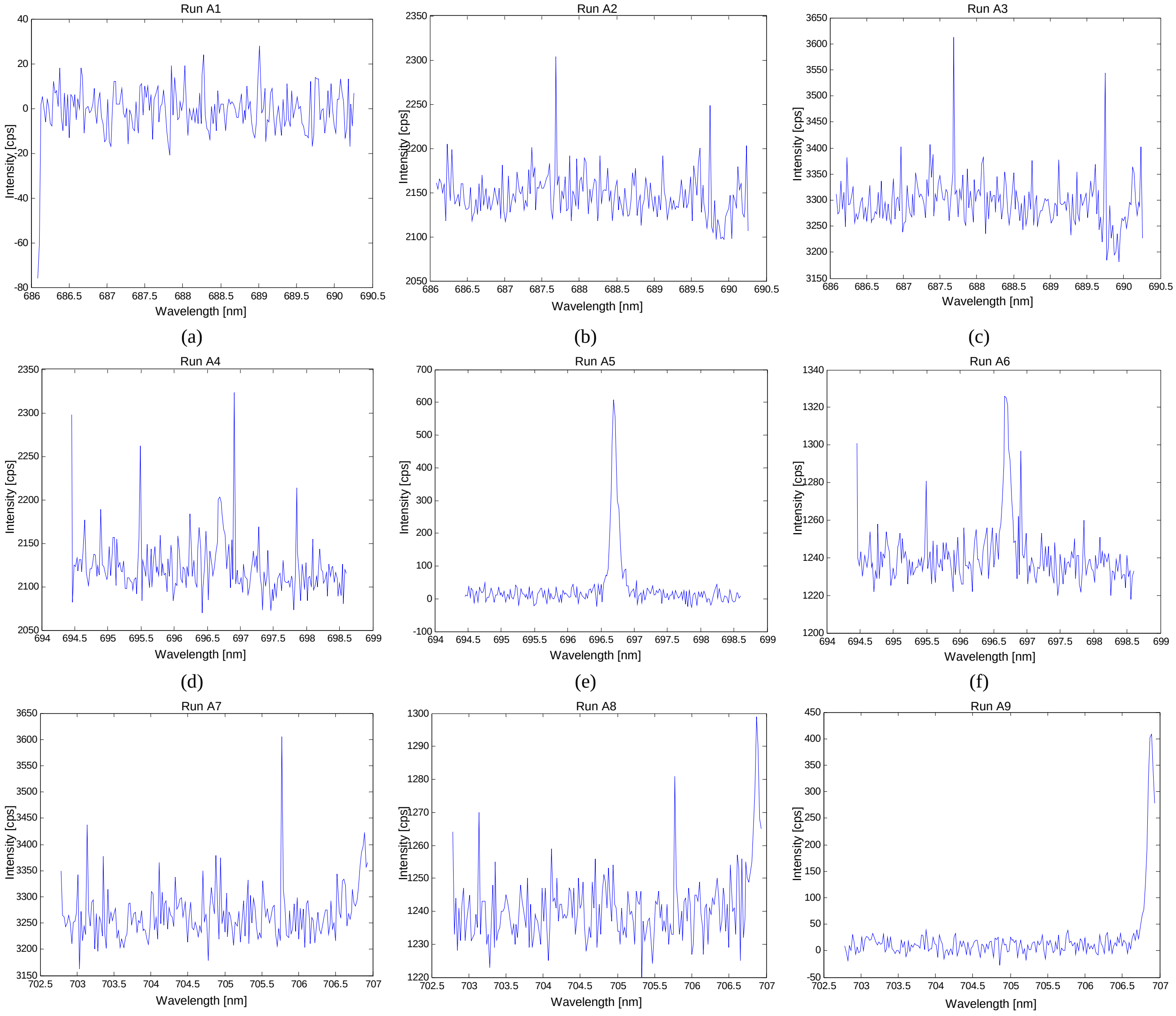
3. **RESULTS AND DISCUSSION**

The spectrum for each run (A1 to C9) is shown in the Figs. 3, 4 and 5 for each experimental matrix presented in Tabs. 2, 3 and 4, respectively. All pictures come from a program ("TreatData.m") written in Matlab®, which reads an ASCII file that contains two columns: wavelength and spectral intensity. There is no interpolation between points (Vilarinho, 2002).

Table 5 presents the values for the spectral intensity calculated by "TreatData.m". It is shown the value for the background intensity in both sides (left and right) of the line (696.54 nm), the peak intensity and the difference between the peak intensity and the average of both backgrounds.

Before proceeding the Taguchi Methodology it is possible to point out an important result. The influence of the horizontal shifting the CCD area can be traced from spectrums of runs A1 to A9. The different vertical areas, selected for the runs A1 to A9, shift the sampling window of the spectrometer. As the 696.54-nm line is the interested one here and it does not appear for the runs A1, A2, A3, A7, A8 and A9, due to the window shifting, the "TreatData.m" calculated zero for the difference between the peak intensity and the background. Thus, in order to acquire a desired line, one must keep in mind to centre the CCD area, otherwise it will be shifted.

After this brief analysis of the spectrums, Taguchi Methodology was employed to analyse data using a statistic commercial software package (Statistica®). The response graphics are shown in Figs. 6, 7 and 8. The S/N ratio values are values generated during data analysis.



(a) (b) (c)

(d) (e) (f)

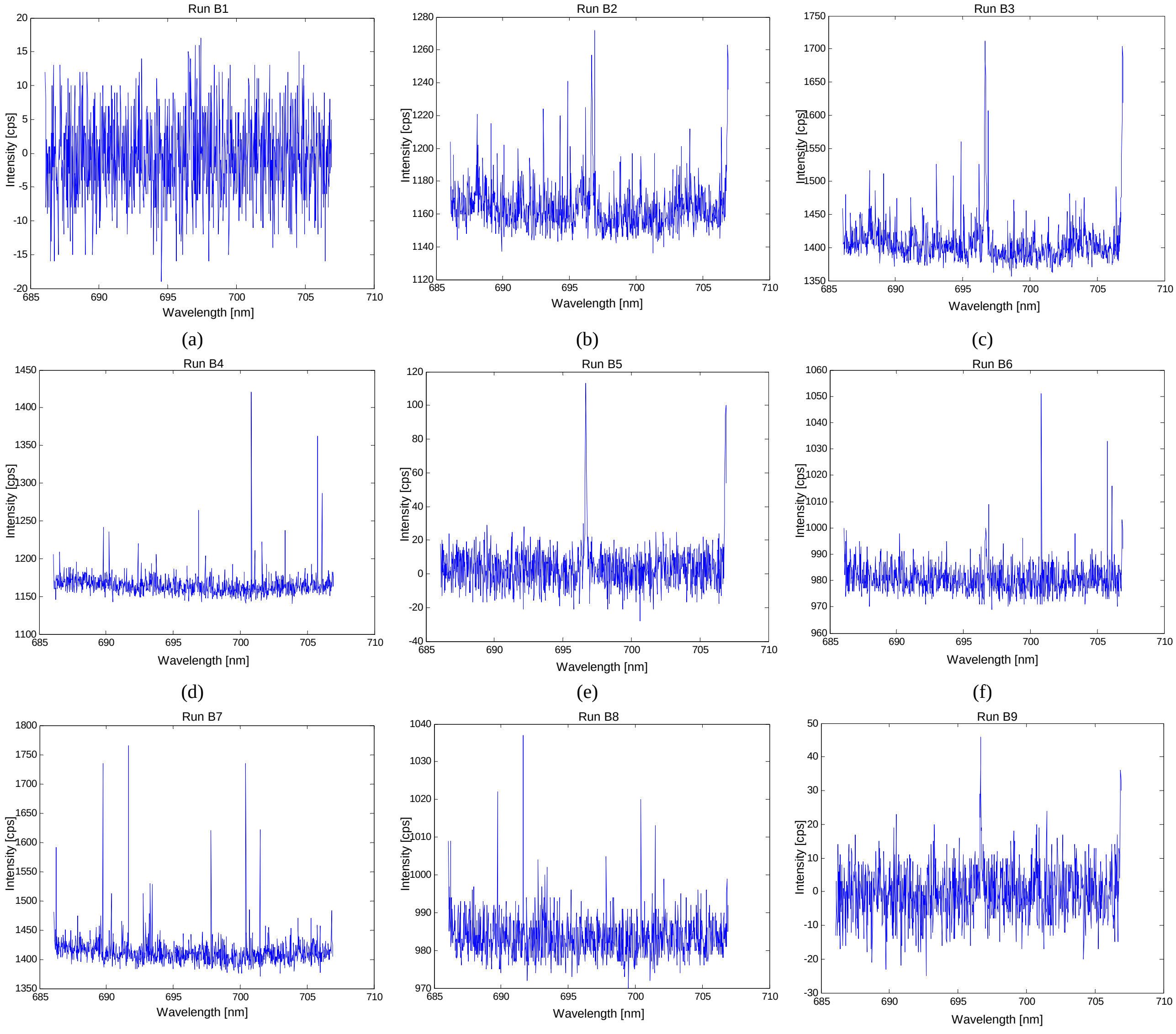
(g) (h) (i)

Figure 3. Spectrums for the first experimental Taguchi array (A1 to A9).

From Fig. 6 (runs A1 to A9) is possible to assert the condition 2nd Area, 50 µm, 1.0 s and Dark Offset On provides the most robust design, i.e., this condition gives the best signal-to-noise rate. For this combination Taguchi Methodology predicts a S/N ratio value of 599. In this case, this combination has already been done (Run A5) and the same value was found. It is important to point out that the most suitable combination matching a previous one is just a coincidence. As stated before, this series of runs just confirms the role of the CCD Area horizontal position.

Now, from Fig. 7 (runs B1 to B9), the most favourable combination would be 1st Area, 80 µm, 1.0 s and Dark Offset Off, which coincides with Run B3. In this case a value of 277 was predict, whereas the Run B3 has an intensity of 313. This shows that there are correlated variables and a further experimental design will be necessary to distinguish them.

For runs C1 to C9 (Fig. 8), the most suitable combination would be 1st Area, 80 µm, 1.0 s and Dark Offset Off. Again, by change, Run C3 is this combination. Taguchi Methodology predicts an intensity of 871, in contrast it was found 936, showing correlated-variable problems. This series of runs presented an interesting characteristic. The dashed lines in Figure 10 represent a 2% standard deviation, which means the spectral intensity does not vary sufficiently to be analysed by Taguchi. This can be explained due to the major role played by the CCD area. Since in all runs from C1 to C9, the active area is always on the centre of the CCD, the response (spectral intensity) does not sense it in a strong way.



(a) (b) (c)

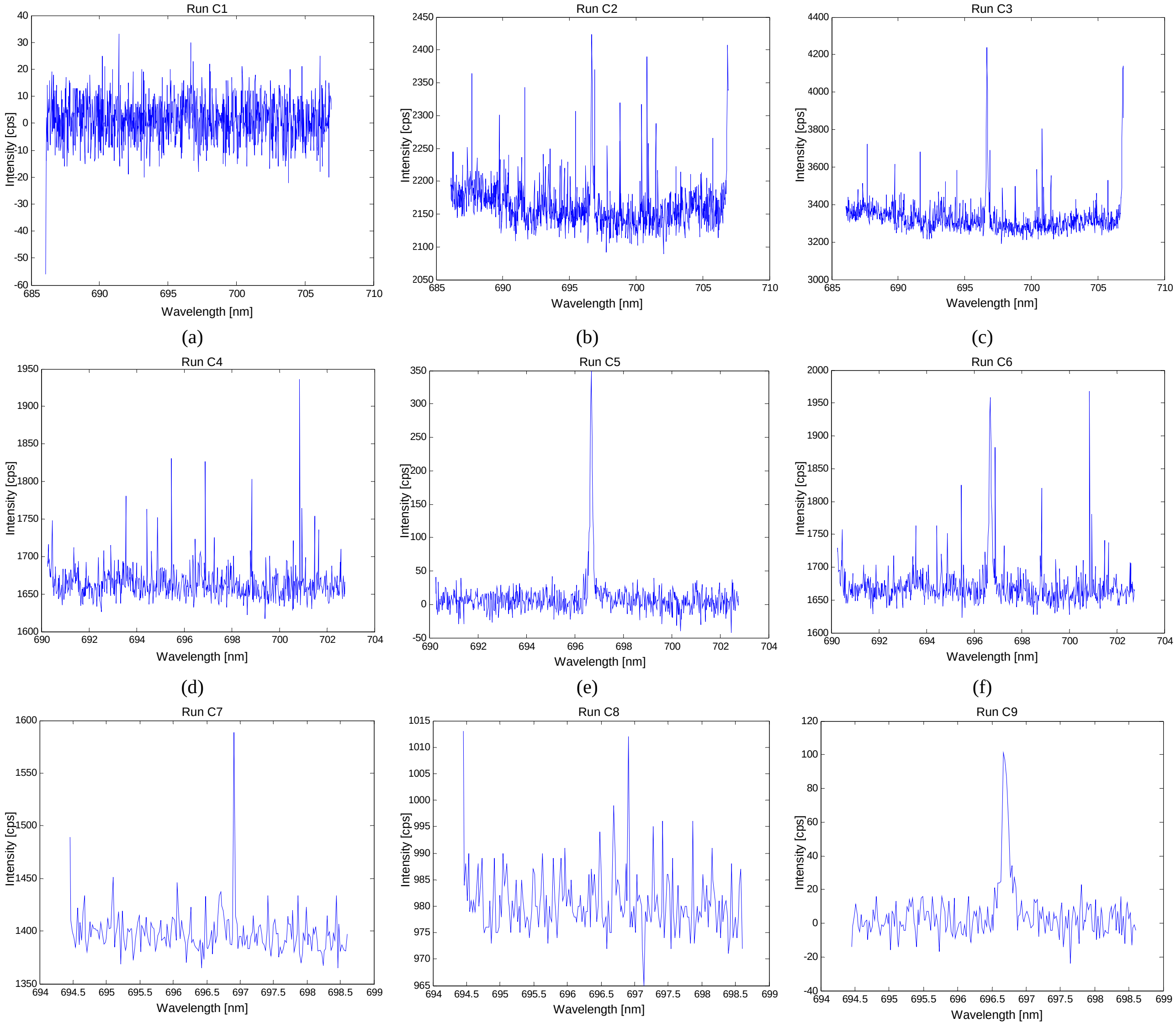
(d) (e) (f)

(g) (h) (i)

Figure 4. Spectrums for the second experimental Taguchi array (B1 to B9).

Analysing all three sets of runs, it is possible to state the peak intensity is proportional to the Integration Time, which is reasonable physically. Increasing the exposure time of the CCD, more photons will reach it. Practically, the limit of this is the time to conduct the experiment. In this case 0.5 s with Dark Offset Off leads to 2 ¼ hours to scan 2500 points in the arc.

Even though runs A1 to A9 indicate a maximum of spectral intensity using an entrance slit of 50 µm, this result is a little bit questionable. Runs from B1 to B9 and C1 to C9 indicate a maximum at 80-µm entrance slit, which is more reasonable, because opening more the entrance slit, more the probability that a photon can reach the CCD. To explain the contradictory result of runs A1 to A9, one can suppose that shifting the CCD area, not all the photons would reach the settled area.



(a) (b) (c)

(d) (e) (f)

(g) (h) (i)

Figure 5. Spectrums for the third experimental Taguchi array (C1 to C9).

Since the experimental design suffered from correlated variable problem, the following strategy was to implement a One Factor at a Time design. This method entails keeping one factor at a constant level and measuring the effect of varying the level of the remaining factor (Howse, 1997). As the effect of the Integration Time factor was already state, it will be kept constant at 1.0 s to maximise the peak intensity (maximising the S/N ratio), even though, as it was said, a value of 0.5 s will be employed in the experiments due to time restriction. The importance of a central CCD area was already emphasised too and in all runs it will be aimed to analyse effects of the central region. The CCD Areas chosen are shown in Table 7, which also brings all conditions. Thirteen runs are proposed in order to study the effects of CCD Area, Entrance Slit and Dark Offset. Since there is still a doubt between 50 and 80 μm as Entrance Slit, the value of 20 μm was discarded.

Runs in Tab. 6 try to cover the doubts pointed out in the previous paragraphs. Comments are stated in Tab. 6, in order to establish a connection with Taguchi runs.

Table 5. Results for spectral intensity from the “TreatData.m” program. All values in [cps].

Run	Left Background	Intensity	Right Background	Intensity – Background
A1	0	0	0	0
A2	2141	2144	2147	0
A3	3305	3300	3295	0
A4	2122	2203	2110	87
A5	9	607	8	599
A6	1238	1326	1236	89
A7	3273	3262	3251	0
A8	1242	1244	1246	0
A9	5	7	9	0
B1	0	15	0	15
B2	1160	1257	1159	98
B3	1405	1712	1394	313
B4	1163	1180	1165	16
B5	3	113	2	111
B6	980	1000	980	20
B7	1409	1410	1402	5
B8	983	988	982	6
B9	0	46	0	46
C1	2	30	2	28
C2	2159	2424	2143	273
C3	3311	4237	3291	936
C4	1665	1706	1660	44
C5	7	350	5	344
C6	1669	1958	1663	292
C7	1395	1437	1395	42
C8	981	999	980	19
C9	2	101	2	99

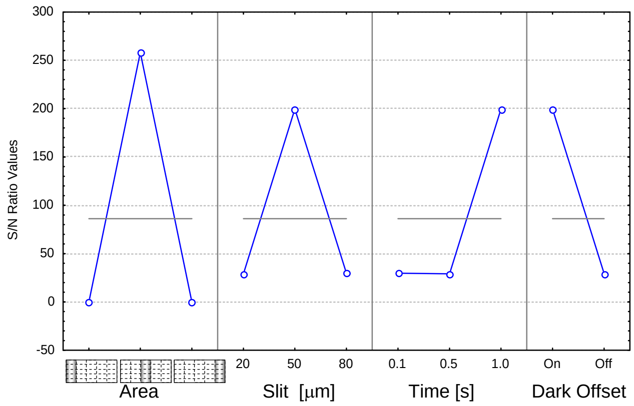


Figure 6. Responses obtained by Taguchi Methodology; runs A1 to A9.

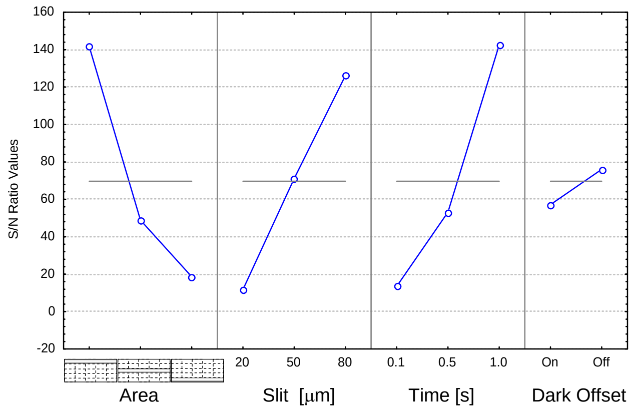


Figure 7. Responses obtained by Taguchi Methodology; runs B1 to B9.

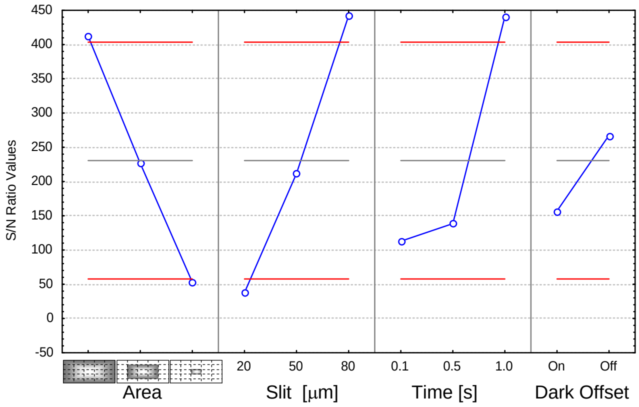
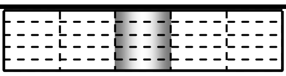
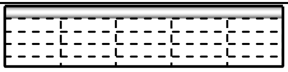
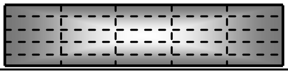
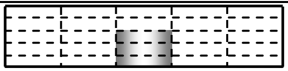
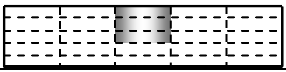
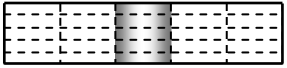
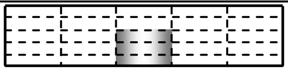
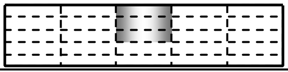
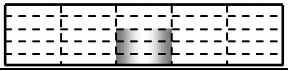
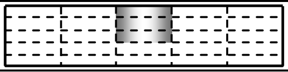
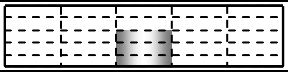
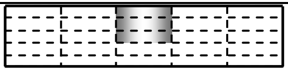
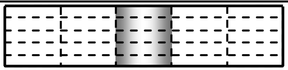


Figure 8. Responses obtained by Taguchi Methodology; runs C1 to C9.

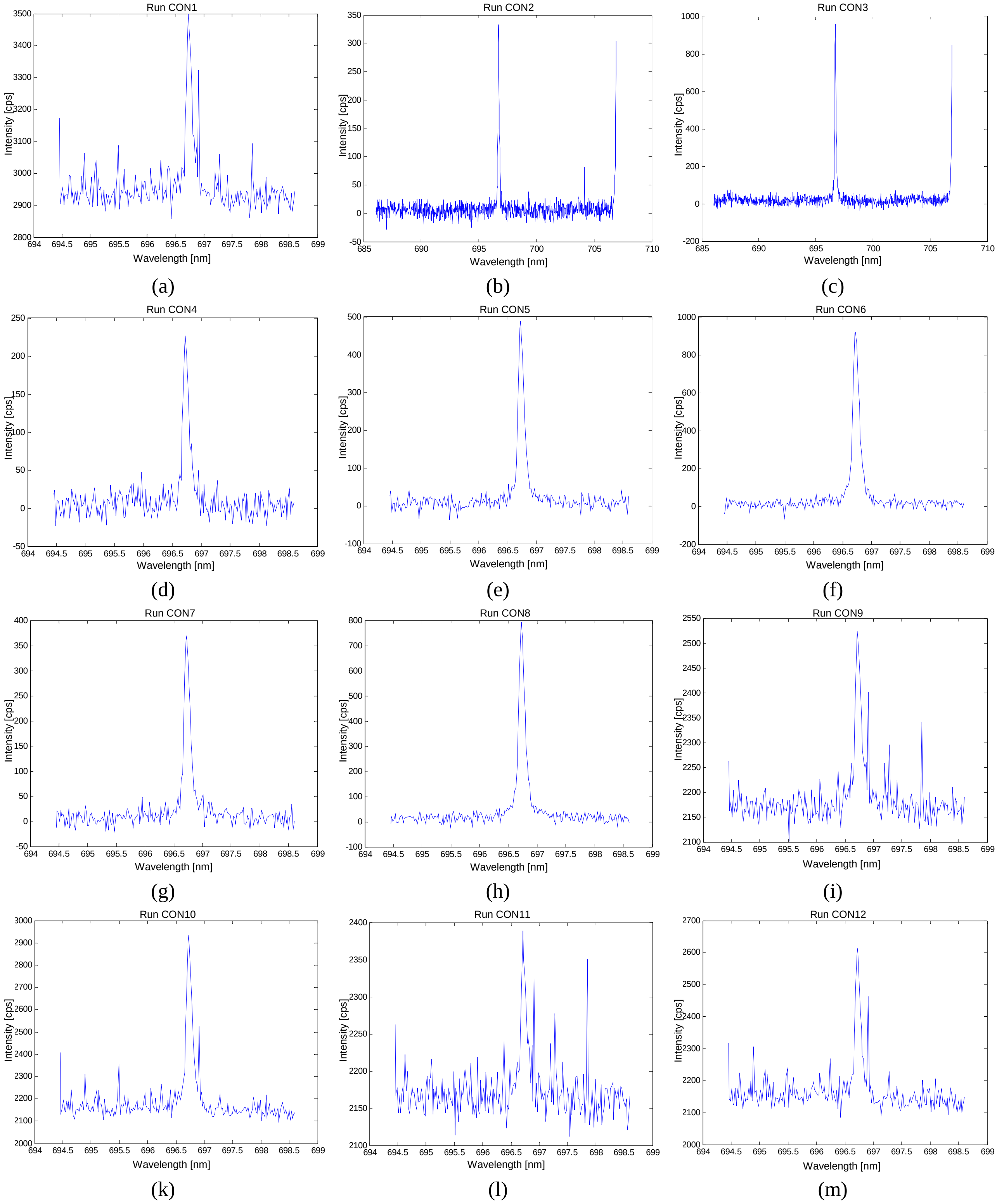
Table 6. Proposed One Factor at a Time design (Integration Time constant at 1.0 s).

Run	CCD Area	Entrance Slit [µm]	Dark Offset	Comments
CON1		50	Off	Run A5 with Dark Offset Off
CON2		80	On	Run A5 with Dark Offset On
CON3		80	On	Run C3 with Dark Offset On
CON4		50	On	Run A5 with new Area 1
CON5		50	On	Run A5 with new Area 2
CON6		80	On	Run A5 with 80 µm
CON7		80	On	Run A5 with new Area 1 and 80 µm
CON8		80	On	Run A5 with new Area 2 and 80 µm
CON9		80	Off	Run A5 with new Area 1; 80 µm and Dark Offset Off
CON10		80	Off	Run A5 with new Area 2; 80 µm and Dark Offset Off
CON11		50	Off	Run A5 with new Area 1 and Dark Offset Off
CON12		50	Off	Run A5 with new Area 2 and Dark Offset Off
CON13		80	Off	Run A5 with 80 µm and Dark Offset Off

The runs presented in Tab. 6 were carried out and their spectrums are shown in Fig. 9. All the procedures and parameters were kept constant (current, electrode, power supply, arc striking, etc).

Once more, all of the spectrums were analysed using the “TreatData.m” program and the results are shown in Tab. 7. Analysing this table, it is possible to state the Run CON3 has the best result (biggest peak intensity regarded to its background). Thus, in principle, one can just use the factors utilised in this run. However, as it was said before, using a Dark Offset (On), it leads to a time-prohibited experiment. If someone looks carefully to runs CON6 and CON13, will see that the Dark Offset factor does not play an important role, since CON6 has an spectral intensity of 905 and CON13 has 906, both regarded to their respectively backgrounds.

Until now, one should choose an Entrance Slit of 80 µm in the Run CON3, which confirms the trend presented so far. Nevertheless, a final analysis must be carried out. There is an intrinsic diffraction problem. Moreover, increasing the Entrance Slit promotes line broadening, because of spurious wavelengths have now more space to come into the monochromator. Although a substantial final gain is obtained by increasing the Entrance Slit from 50 µm (599 cps – Run A5) to 80 µm (905 cps – Run CON6), i.e., around 51 %, it must be pointed out that the not-controlled phenomena of diffraction and broadening could interfere in the final results. Thus, the 50-µm value for the Entrance Slit is preferred to be used.



(a) (b) (c)

(d) (e) (f)

(g) (h) (i)

(k) (l) (m)

Figure 9. Spectrums for the One Factor at a Time design.

Table 7. Results for spectral intensity from the “TreatData.m” program.

Run	Left Background [cps]	Intensity [cps]	Right Background[cps]	Intensity – Background [cps]
CON1	2945	3499	2927	563
CON2	4	333	4	329
CON3	14	961	16	946
CON4	6	227	0	224
CON5	8	488	7	481
CON6	12	919	16	905
CON7	6	368	8	361
CON8	13	793	18	778
CON9	2170	2524	2170	354
CON10	2168	2933	2150	774
CON11	2165	2389	2171	221
CON12	2160	2613	2143	462
CON13	2977	3877	2966	906

4. CONCLUSION

Considering the studied experimental range, it is possible to summarise the results in the following:

- The employed Robust Design (Taguchi Methodology) gave some directions to understand the effects of the main factors, although it was not adequate to predict the most robust combination of them due to correlated variables;
- The CCD Area defines the spectrum-sampling window. In order to achieve a maximum spectral intensity, it should be settled as a full area;
- Until 80 μm, increasing the Entrance Slit increases the spectral intensity. Above 80 μm, it leaves to have great importance;
- Spectral intensity is proportional to the Integration Time inside the studied range (0.1 s to 1.0 s);
- The Dark Offset does not play an important role for achieving the maximum spectral intensity;
- The final condition to be utilised is full CCD Area, 50 μm, 0.5 s and Dark Offset Off.

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7. RESPONSIBILITY NOTICE

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