EFFECTS OF WATER FLOW RATE AND EXIT DUCT LENGTH ON THE PERFORMANCE OF A CYCLONE SCRUBBER

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Abstract. *A cyclone scrubber system was developed in order to be used as air conditioner when outdoor conditions are suitable. Surrounding air was introduced into the system by aspiration provided by a fan located at the cyclone gas outlet. Liquid water was injected in the air flow through a pressure swirl atomizer to simultaneously provide air cooling and humidification. This kind of equipment has been developed to become a viable alternative for air conditioning using evaporative cooling principles. This paper presents experimental results for a factorial design 2^2, with five replications for each operational condition, with the aim of identifying the influence of water flow rate (0 and 1.0 L/s) and exit duct length (425 and 625 mm) on the cyclone scrubber pressure drop and air humidity ratio increment inside the equipment. Concerning studied operational conditions, results showed that an increment on water flow rate increases the variation on the air humidity ratio inside the cyclone scrubber. Also, pressure drop trough the system increased with the increment on the exit duct length mainly for the tests using two nozzels. An empirical model was proposed to estimate performance parameters as a function of the studied variables concerning a fixed outdoor condition.*

Keywords*: Cyclone scrubber, factorial experimental design, evaporative cooling*

1. INTRODUCTION

Industrial plants, warehouses, laboratories and commercial buildings are designed for proper environmentally conditions that include temperature, humidity, air motion and air quality in order to provide thermal comfort and high productivity. Air must be conditioned and contaminants must be collected by the air conditioner system to assure the necessary indoor quality (ASHRAE, 1999). For worker efficiency, the environment should be comfortable and not harmful to human health. Evaporative cooling systems are viable alternatives for air conditioning and they have been used for long time to provide comfort when outdoor conditions are suitable (Brown, 2000). Evaporative cooling is envinronmentaly friendly, because electricity usage is just limited to the required water pumping and air circulation. In addition, this kind of climatization process is free from harmful fluids to the ozone layer such CFC or HCFC. Another benefit is the total air renovation that avoids spreading bacterias and reduce stactic eletricity, dust and solvents concentration.

Cyclones are widely used for removing particles from fluids because of their simplicity and low costs in terms of construction, operation and energy consumption (Yang and Yoshida, 2004). A cyclone scrubber consists of a cyclone and a device to disperse the scrubbing liquid. The cyclone serves as a contact room in which the interaction of dust particles and scrubbing liquid droplets takes place. Very good separation efficiencies have been possible by using atomizing nozzles in the cyclone to inject liquid water inside the gas stream (Krames, Buttner and Ebert, 1993).

Fassani and Goldstein Jr. (2000) studied the effect of solids loading at the entrance of the cyclone on its pressure drop and collection efficiency. They found that the collection efficiency increases with the solids loading in the cyclone inlet.

Xiang, Park, and Lee (2001) results showed that the size of the cyclone conical section presents a significant influence on the cyclone performance as others cyclone geometric dimensions.

Chen and Shi (2007) developed a universal model to predict the cyclone pressure drop. Their method is suitable for the prediction of the pressure drop in cyclones operating with pure or dust-laden gases at normal or high temperatures. A detailed comparison between the experimental results and calculations showed that this method has a high accuracy and, in general, is better than other ones, and can meet the design requirement of most commonly used, reverse flow cyclones.

Keshavarz *et al.* (2008) studied experimentally and simulated the liquid film formation and the influence of nozzles real locations on the performance of the spray scrubber in gaseous and particulate scrubbing processes. They concluded that the nozzles real locations and liquid film formation can affect the spray scrubber performance significantly for gas scrubbing, while the major factor influencing particle scrubbing is the inlet jet velocity.

This work presents an experimental study in a cyclone scrubber in order to identify the influence of water flow rate (0 and $1.0.10^{-3}$ m^3/s) and exit duct length (0.425 and 0.625 m) on the cyclone scrubber pressure drop and air humidity ratio increment on the equipment performance.

2. MATERIALS AND METHODS

2.1. Factorial design

A factorial design in two levels was applied to identify the influence of factor A (water flow rate, Q_w) and factor B (exit duct length, H), both in two levels, on the responses: cyclone scrubber pressure drop (ΔP) and air humidity ratio increment ($\Delta\omega$) inside the equipment. Experimented levels and the experimental design are presented in Tab.1 and Tab.2. Each tested condition was replicated five times.

Table 1. Factors and their design levels for the experiments

Levels	Water flow rate, Q_w (m^3/s)	Exit duct length, H (m)
(-)	0	0.425
(+)	1.10^{-3}	0.625

Table 2. Experimental design

Operational conditions	Q_w(m^3/s)	H (m)
1	-	-
2	+	-
3	-	+
4	+	+

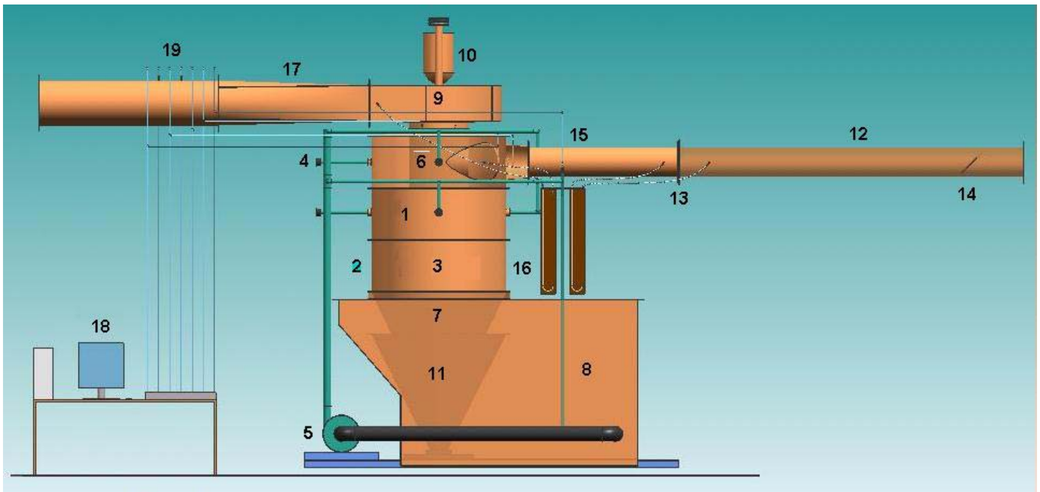
A two-factor factorial experiment can be written in a regression model represented by Eq. (1):

$$y = \beta_0 + \beta_1.x_1 + \beta_2.x_2 + \beta_{12}.x_1.x_2 + \varepsilon \tag{1}$$

where y is the response (ΔP or $\Delta\omega$), the β´s are parameters whose values are determined from experimental data, x_1 is a variable that represents factor A (Q_w), x_2 is a variable that represents factor B (H), and ε is a random error term.

2.2. Cyclone scrubber configuration and design

A schematic diagram of the experimental apparatus is shown in Fig. 1. It has been configured on the basis of the geometric ratios of American Cyclone which relative dimensions are illustrated by Fig. 2.



1. Cylindrical body; 2. Adapted Ring (modules); 3. First cone; 4. Spray Nozzles and Bourdon manometers; 5. Electric motor and Pump; 6. Exit duct (cyclone); 7. Second cone; 8. Water box; 9. Exhaustion; 10. Electric motor; 11. Decantation cone; 12. Inlet duct; 13. Orifice plate; 14. Butterfly valve; 15. Thermocouples; 16. Manometer; 17. Exit duct; 18. Computer; 19.Wet and dry bulb thermocouples.

Figure 1. Schematic illustration of the cyclone scrubber

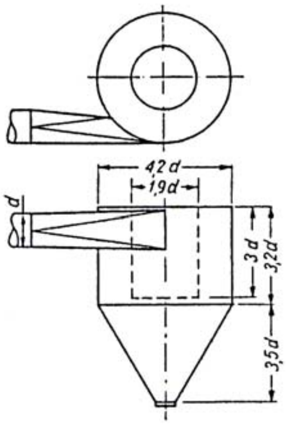


Figure 2. Geometric ratios of American Cyclone (Majewski, 2002)

Unlike the cyclones reported in the literature, this cyclone scrubber showed in Fig. 1 was designed in a modular fashion. The cylindrical body [1] of this cyclone scrubber has a 0.900 m diameter made of three ring-shaped modules, each with a height of 0.345 m. The modules are connected to each other by typical flanges, which are sealed using rubber gaskets. The lower ring, module [2], is a support for the first [3] and second cones [7]. The first and second modules accommodate nozzles atomizers [4] arranged orthogonally relative to the gas flow. These nozzles are equipped with Bourdon manometers and are connected to the water supply and pressurized by a centrifugal pump [5] drove by a 220 V and 4.6 kW motor. The internal gas exit duct [6] is 0.725 m in height and 0.400 m in internal diameter. The bottom of the cone is immersed in the water contained in the collecting and purification box [8]. Therefore, the system provides a hydraulic seal that separates the pressurized portion from the other parts under atmospheric pressure. It employs a centrifugal blower [9] drove by a 220 V and 3.7 kW electric motor located in the upper portion of the cyclone scrubber, which works under depressurization and provides the suction of gas and dust in order to flow into the cyclone scrubber.

The cyclone scrubber is assembled above the collection and purification box [8] which presents 1.90 length, 0.91 m width and 1.05 height. Pumping system [5] and feeding nozzles [4] provides the atomizing water through the cylindrical body of the cyclone. After that, the water is conduced to the storage tank, where particle separation occurs by decantation or gravitational forces. In order to accelerate the separation of the pollutants, the storage tank also allows the introduction of flocculants, and thus, purifying the water by chemical means allowing water reuse. The contention box comprises three basic elements. The first is the box that supports the cyclone. The second element is a decantation cone [11] for controlling the water flow rate and collecting the solid particles. A hatch provides access for cleaning and maintenance of the box. The third element is the discharge valve through which the water/particles are discharged into the sewer when it is open. The box has a capacity of 1.8 m^3. A float valve maintains the water level inside the tank. The gas is captured through a 0.22 m diameter circular PVC duct [12] equipped with orifice plate built as ISO-5167 (ISO, 1989) [13] and a U manometer to gas flow rate measurement. A butterfly valve [14] at the duct inlet allows the gas flow rate to be controlled. Dry and wet-bulb thermocouples [15] and [19] provide the measurement of inlet and outlet air humidity ratio. When desirable, the dosage of solid particles to be added into the air flow rate at the cyclone scrubber entrance is controlled by the pressure in the fluidized bed where the particulate material is retained. The exhaustion duct is rectangular with 0.24 m width and 0.325 m length, meanwhile it changes to a circular duct 0.310 m internal diameter at the final portion [17]. This duct has a sampling port to allow for the removal and quantification of particulate material that was not retained by the cyclone scrubber. Cyclone pressure drop were calculated by a U manometer [16].

The exit duct [6] is movable, allowing itself to be used in two positions, 0.425 m (position 1) and 0.625 m (position 2). The gas humidification was performed at two different water flow rate (0 and 1.10^{-3} m^3/s) injected in the air flow through two spray nozzles.

The water flow is changed by controlling the number of open nozzles. The aspersion of the water had been achieved by means of two plain orifice pressure atomizers installed in the rings of the cyclone. These nozzles are basically composed of a body, a strainer and an internal swirl plate with four orifices presenting $3.2.10^{-3}$ m as nominal diameter. The measurement of the water flow rate in each nozzle as a function of the pressure is showed in Fig. 3.

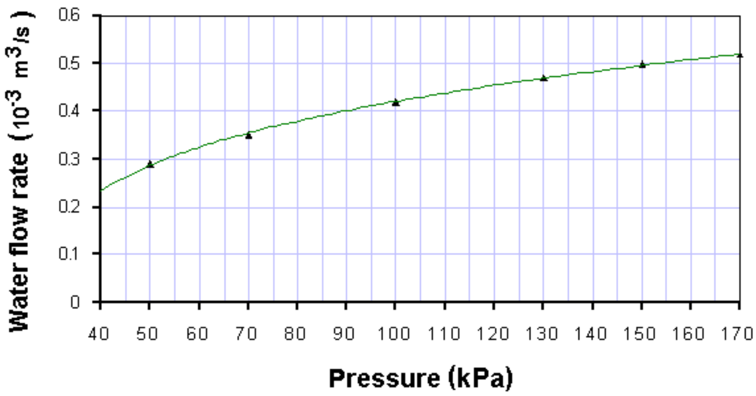


Figure 3. Water flow rate as a function of the water pressure for the strainer with four orifices of 3.2 mm nominal diameter

Measurements of the cyclone pressure drop and air humidity ratio were made after the steady state was established for each tested condition showed in Table 2. Experiments were repeated five times for each operational condition. It was considered that the wet bulb temperature is equal to the adiabatic saturation temperature for all experiments as the operational conditions were controlled in order to make true this assumption.

3. EXPERIMENTAL RESULTS AND DISCUSSION

The complete experimental data for all the performed tests are presented in Tab. 3. The first column gives the experiment number and the following ones give the gas flow rate and inlet and outlet dry bulb temperature (T), wet bulb temperature (T_{wb}), relative humidity (RH) and humidity ratio (ω). Gas flow rate (G) and cyclone pressure drop (ΔP_{cyc}) were calculated from manometers data and variation in humidity ratio increment (Δω) were calculated by Eq. (2):

$$\Delta\omega = \omega_{out} - \omega_{in} \tag{2}$$

Where ω_{in} and ω_{out} are the air humidity ratio in the inlet and outlet of the cyclone, respectively.

Table 3. Operating conditions and experimental data

		Inlet gas parameter				Outlet gas parameter			
Operational conditions	Gas flow rate, G (m^3/s)	T (ºC)	T_{wb} (ºC)	RH (%)	ω_{in} (kg_v/kg_a)	T (ºC)	T_{wb} (ºC)	RH (%)	ω_{out} (kg_v/kg_a)
1	0.339	20.6	19.8	93.2	0.0157	23.8	21.0	78.7	0.0167
	0.339	21.2	20.0	90.0	0.0157	23.8	21.0	78.7	0.0167
	0.339	22.0	20.2	85.5	0.0156	24.0	21.0	77.4	0.0160
	0.339	25.0	21.2	72.3	0.0159	24.6	21.0	73.5	0.0157
	0.339	25.8	21.6	69.4	0.0161	25.0	21.5	74.4	0.0163
2	0.343	18.0	15.2	75.6	0.0107	21.5	18.8	78.4	0.0139
	0.343	18.4	16.4	82.5	0.0120	21.5	18.8	78.4	0.0139
	0.343	19.6	17.0	78.2	0.0123	21.5	18.8	78.4	0.0139
	0.343	19.6	17.0	78.2	0.0123	21.8	19.0	77.7	0.0141
	0.343	18.9	16.4	78.6	0.0118	21.6	18.9	78.4	0.0140
3	0.343	21.0	18.0	75.8	0.0130	23.5	19.2	68.0	0.0136
	0.343	21.0	18.0	75.8	0.0130	23.5	19.0	66.6	0.0133
	0.343	21.0	18.0	75.8	0.0130	23.0	18.8	68.3	0.0132
	0.343	21.2	18.0	74.4	0.0129	23.0	18.8	68.3	0.0132
	0.343	21.0	17.8	74.3	0.0127	23.0	18.8	68.3	0.0132
4	0.358	22.0	18.2	70.5	0.0128	24.0	20.6	74.5	0.0154
	0.358	22.2	18.4	70.6	0.0130	24.0	20.6	74.5	0.0154
	0.358	22.4	18.6	70.8	0.0132	24.0	20.4	73.1	0.0151
	0.358	22.4	18.4	69.3	0.0129	24.0	20.4	73.1	0.0151
	0.358	22.0	18.0	69.1	0.0126	24.0	20.2	71.8	0.0148

Table 4 shows the studied factors and the obtained results for all the performed experiments. These data were processed using the software Minitab 14 that allows the analysis of the factors influence and interaction effects on the humidity ratio variation and cyclone pressure drop. More details about analysis of experimental design data are obtained in Neto, Scarmino and Bruns (2003) and Rodrigues e Iemma (2005).

Table 4. Factors and responses for the 2^2 factorial design of experiments

	Coded factors		Real variables		Responses	
Experiment	A	B	Water flow (m^3/s) Q_w ($.10^{-3}$)	Exit duct height (m) H	Humidity ratio increment (kg_v/kg_a) $\Delta\omega$	Cyclone Pressure drop (Pa) ΔP_{cyc}
1	-	-	0	0.425	0.0011	1314.0
2	+	-	1	0.425	0.0032	1461.1
3	-	+	0	0.625	0.0006	1382.6
4	+	+	1	0.625	0.0026	1529.7
5	-	-	0	0.425	0.0010	1333.6
6	+	-	1	0.425	0.0019	1480.7
7	-	+	0	0.625	0.0003	1363.0
8	+	+	1	0.625	0.0024	1510.1
9	-	-	0	0.425	0.0003	1323.8
10	+	-	1	0.425	0.0016	1470.9
11	-	+	0	0.625	0.0002	1372.8
12	+	+	1	0.625	0.0019	1519.9
13	-	-	0	0.425	-0.0001	1304.2
14	+	-	1	0.425	0.0018	1451.3
15	-	+	0	0.625	0.0003	1392.5
16	+	+	1	0.625	0.0021	1490.5
17	-	-	0	0.425	0.0002	1343.4
18	+	-	1	0.425	0.0022	1490.5
19	-	+	0	0.625	0.0005	1353.2
20	+	+	1	0.625	0.0022	1549.4

Estimated effects and coefficients for humidity ratio increment and cyclone pressure drop are shown in Tab. 5 and 6. P-values in Tab. 5 and 6 also shows that exit duct length (P-valor = 0.960) and interaction terms (P-valor = 0.584) aren't statistically significant at 95% of confidence ($\alpha = 0.05$). Concerning the cyclone pressure drop, it seems that there is not a significant interaction between water flow rate and exit duct length (P-valor = 1.000).

Table 5. Estimated effects and coefficients for humidity ratio (coded units)

Term	Effects	Coefficients	Standard Error	t	P-Value
Constant		0.001315	0.000098	13.38	0.000
Q_w	0.001750	0.000875	0.000098	8.90	0.000
H	-0.000010	-0.000005	0.000098	-0.05	0.960
Q_w x H	0.000110	0.000055	0.000098	0.56	0.584

Table 6. Estimated effects and coefficients for loss pressure (coded units)

Term	Effects	Coefficients	Standard Error	t	P-Value
Constant		1421.860	3.878	366.67	0.000
Q_w	147.100	73.550	3.878	18.97	0.000
H	49.020	24.510	3.878	6.32	0.000
Q_w x H	0.000	0.000	3.878	0.00	1.000

Estimated effects calculated previously were checked by analysis of the variance (ANOVA). Preliminary results are shown in tables 7 and 8. The effects and significance level of the variables in the humidity ratio increment and cyclone pressure drop were evaluated using Pareto's charts showed in Fig. 4b and 4d.

Table 7. Analyses of variance for humidity ratio increment (coded units)

Source	Degree of freedom	Sum of Squares	F	P-Value
Main effects	2	0.00001531	39.62	0.000
2-Way Interactions	1	0.00000006	0.31	0.584
Residual error	16	0.00000309		
Pure error	16	0.00000309		
Total	19	0.00001847		
S = 0.000439602	R^2 = 83.26%	R^2 (adj) = 80.12%		

Table 8. Analyses of variance for cyclone pressure drop (coded units)

Source	Degree of freedom	Sum of Squares	F	P-Value
Main effects	2	120207	199.85	0.000
2-Way Interactions	1	0	*	*
Residual error	16	4812		
Pure error	16	4812		
Total	19	125019		
S = 17,3418	R^2 = 96.15 %	R^2 (adj) = 95.43 %		

3.1. Geometric interpretation

Pareto's chart in Fig. 4b shows that water flow rate is the factor that most contribute to humidity ratio increment. Figure 4a and 4c shows magnitude and statistical significance of main effects and interaction between the factors. In these figures, the points next to the blue line are effects not significant. As illustrated by Pareto's charts, shown in Fig. 4b, only water flow rate is significant at 95% of confidence concerning humidity ratio increment. However, concerning cyclone pressure drop, Fig. 4c and 4d show that both variables, water flow ratio and exit duct length, have significant influences.

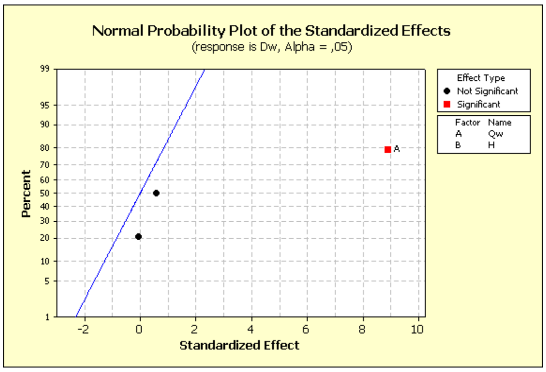


Figure 4a. Normal Probability for humidity ratio increment

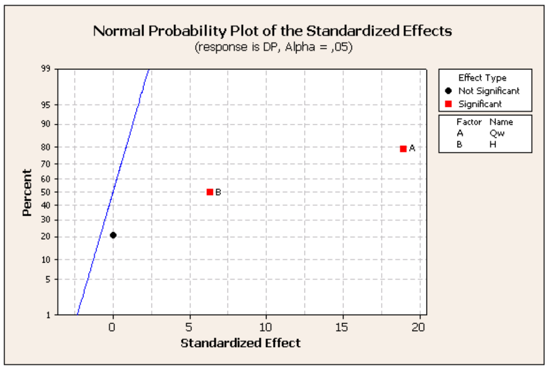


Figure 4c. Normal Probability for cyclone pressure drop

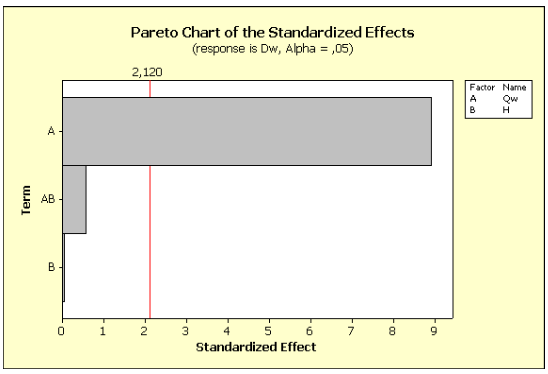


Figure 4b. Pareto's chart for humidity ratio increment

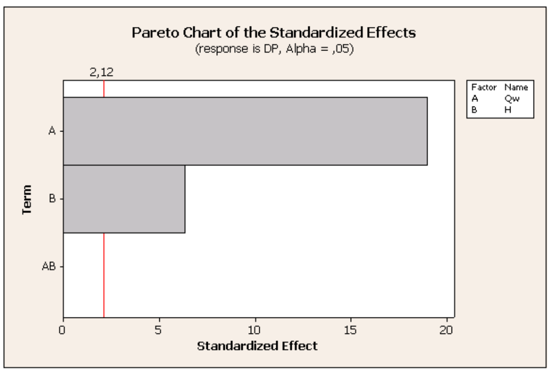


Figure 4d. Pareto's chart for cyclone pressure drop

3.2. Estimating the model parameters

Pareto's charts in Fig. 4b and 4d show which factors have a significant influence on the responses. The models were adjusted excluding the terms presenting no significance, according to analyses of variance. Results were presented in Tab. 5 and 6.

Table 9 shows the estimated effects and the coefficients for humidity ratio increment. P-value (0.000) indicates that only water flow ratio factor has a significant impact on humidity ratio increment. Table 10 presents the estimated effects and the coefficients for cyclone pressure drop. In this case, P-value (0.000) indicates that factors, water flow rate and exit duct length, have a significant impact on ΔP_{cyc}.

Table 9. Estimated effects and Coefficients for humidity ratio increment (coded units)

Term	Effects	Coefficients	Standard Error	t	P-Value
Constant		0.001315	0.000094	14.05	0.000
Q_w	0.001750	0.000875	0.000094	9.35	0.000

Table 10. Estimated effects and Coefficients for cyclone pressure drop (coded units)

Term	Effects	Coefficients	Standard Error	t	P-Value
Constant		1421.860	3.762	377.96	0.000
Q_w	147.100	73.550	3.762	19.55	0.000
H	49.020	24.510	3.762	6.52	0.000

Tables 11 and 12 show the ANOVA results of the final model for each studied response. The significance of the model parameters presented indicates that the model offers a good representation of the data.

Table 11. Analyses of variance for humidity ratio increment (coded units)

Source	Degree of freedom	Sum of Squares	F	P-Value
Main effects	1	0.00001531	87.42	0.000
Residual error	18	0.00000315		
Pure error	18	0.00000315		
Total	19	0.00001847		
S = 0.000418529	R^2 = 82.92%	R^2 = (adj) = 81.98%		

Table 12. Analyses of variance for cyclone pressure drop (coded units)

Source	Degree of freedom	Sum of Squares	F	P-Value
Main effects	2	120207	212.34	0.000
Residual error	17	4812		
Lack of fit	1	0.00	0.00	1.000
Pure error	16	4812		
Total	19	125019		
S = 16.8240	R^2 = 96.15 %	R^2 Sq(adj) = 95.70 %		

Main effects graph illustrated in Fig. 5 indicates that water flow rate in higher level increases the humidity ratio of the air. On the other hand, the exit duct length doesn't interfere in such response. Figure 6 shows that cyclone pressure drop increases with the water flow rate increment, specially using longer exit duct. This effect can also be seen in Fig. 9 and 10, which shows the mean values of the responses for each operational condition.

Figure 7 shows that there is no significant interaction between the studied factors. Lines presented by Fig. 8 are approximately parallel, indicating a lack of interaction between the factors.

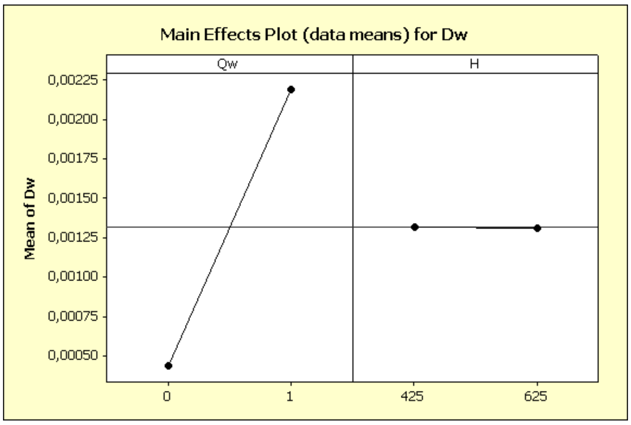


Figure 5. Main effects for humidity ratio increment

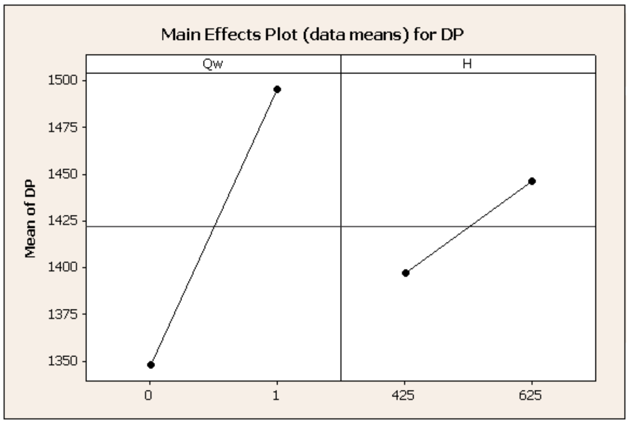


Figure 6. Main effects for cyclone pressure drop

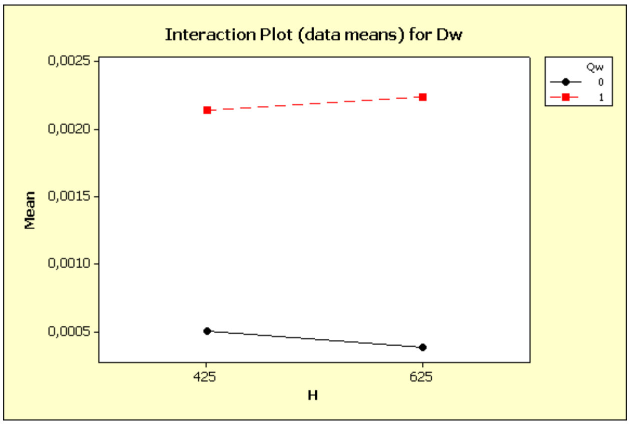


Figure 7. Experiment without interaction (humidity ratio increment)

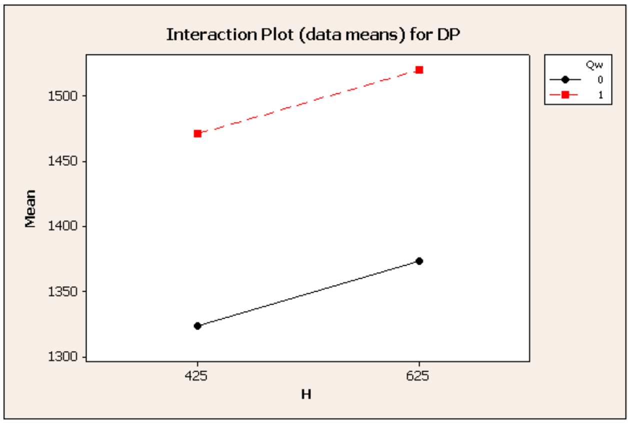


Figure 8. Experiment without interaction (cyclone pressure drop)

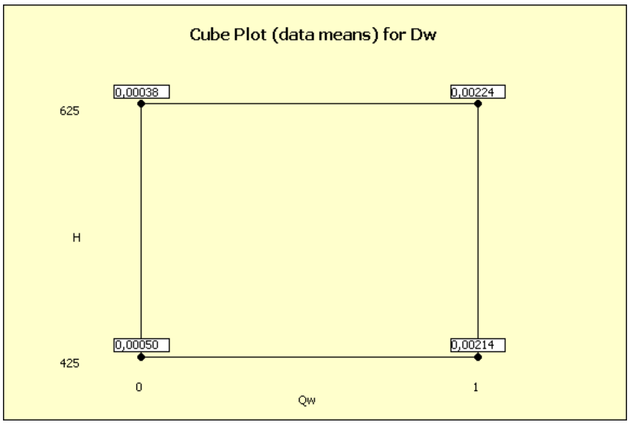


Figure 9. Cube plot for humidity ratio increment

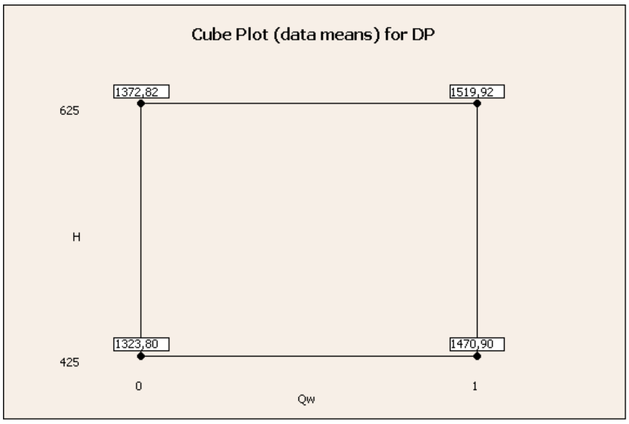


Figure 10. Cube plot for cyclone pressure drop

3.4. Empirical model adjusted

Once calculated the β coefficients of the significant factors of Eq. (1) it was possible to build equations that represent the relation between the responses and the factors. Eq. (3) and Eq. (4) represent the obtained models for real values of the factors (not coded values) concerning air humidity increment and cyclone pressure drop, respectively.

$$\Delta\omega = 0.00044 + 0.00175 Q_w \qquad R^2 = 81.98\% \qquad (3)$$

The regression model for the cyclone scrubber pressure drop is given by Eq. (4):

$$\Delta P_{cyc} = 1219.63 + 147.10Q_w + 0.02451H \qquad R^2 = 95.70\% \qquad (4)$$

4. CONCLUSIONS

The effect of water flow injection and exit duct height has been studied on the performance of a cyclone scrubber by the use of 2^2 factorial design. Results show that an increment on water flow rate increases the variation on the air humidity ratio inside the cyclone scrubber. Also, pressure drop through the system increases with the increment on the exit duct length mainly for the tests using two nozzles. Results allowed obtaining empirical models to estimate the air humidity ratio increment and the cyclone scrubber pressure drop as a function of water flow rate and exit duct length for the studied system.

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