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EXPERIMENTAL STUDY OF A CYCLONE SCRUBBER AIR CONDITIONING SYSTEM USING FACTORIAL DESIGN

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Abstract. *This work reports the results obtained in the experimental evaluation of an American type cyclone which has been modified and adapted to perform environmental air conditioning by evaporative cooling. Equipment was fitted with nozzles atomizers, which perform the injection of liquid transversely to the gas stream. The tests were carried out following a full factorial design of experiments in order to obtain the influence of the atomizer holes diameter and of the liquid/air flow ratio on the cyclone performance . The diameter of the atomizer insert holes was in the range of 2.8 to 3.6 mm and the liquid/air flow ratio was from 0.65 to 0.76 L/m^3. The saturation efficiency (Es) of the cyclone was analyzed through the Response Surface Methodology (RSM). Saturation efficiencies between 45.9 and 62.2 % were obtained. The use of statistical techniques allowed the proposition of empirical correlations to predict the behavior of the system regarding the studied operational range. The results show that the cyclone scrubber equipment is a viable alternative to air conditioning for human standards.*

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

1. NOMENCLATURE

d	Diameter of the orifice pressure swirl plate
Es	Saturation efficiency
L/G	Liquid-gas ratio
P_{atm}	Atmospheric pressure
T_{db}	Dry bulb temperature
T_{wb}	Wet bulb temperature
x	Coded independent variable
y	Response variable

Greek Symbols

β	Regression coefficient

Subscripts

i	Inlet
o	Outlet

2. INTRODUCTION

Indoor air problems are mainly related to inadequate urban planning, design, operation and maintenance of buildings, materials and equipment in buildings, and inappropriate energy saving. Indoor air quality (IAQ) problems affect all types of buildings including homes, schools, offices, health care facilities and other public and commercial buildings (WHO, 1999). Industrial plants, warehouses and laboratories are designed for proper environmental conditions that include temperature, humidity, air motion and air quality in order to provide thermal comfort and high productivity. As a result, air must be conditioned and contaminants must be collected by the air conditioner system to assure the necessary IAQ (ASHRAE, 1999).

Evaporative cooling systems are viable alternatives for air conditioning and they have been used for a long time to provide comfort when outdoor conditions are suitable (Brown, 2000). Also, the equipment is envinronmentaly friendly as electricity usage is just limited to the required water pumping and air circulation. So the use of such equipment can contribute significantly to energy savings. In addition, this kind of climatization process is free from harmful as CFCs or HCFCs.

In the recent past, wet scrubbers have been modified to enhance the efficiency by various techniques (Mohan and Meikap, 2009). Xu *et al.* (2007) carried out theoretical and experimental investigations to analyze the humidification process in spray tower. Keshavarz *et al.* (2008) developed an experimental study and simulated the liquid film formation and the influence of nozzles locations on the performance of the spray scrubber in gaseous and particulate scrubbing processes. Bhattacharya *et al.* (2010) evaluated the thermal performance of a rotating packed bed with a split packing for the evaporative cooling of water. These studies showed that:

Cyclones are used to control the emission of pollutants to the atmosphere which 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). Cyclone structure and performance were also evaluated by Tan *et al*. (2009) and Weiwen *et al*. (2010). Elsayed and Lacor (2010) used the response surface methodology RSM to optimize the cyclone geometrical ratios regarding collection efficiency. 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. High separation efficiencies have been possible by using atomizing nozzles in the cyclone to inject liquid water inside the gas stream (Krames and Büttner, 1994). Park and Lee (2009) developed a cyclone scrubber with a rod impact plate and swirl plates to overcame the many drawbacks of conventional cyclones and wet scrubbers.

The main objective of this work is to present an experimental study in a cyclone scrubber in order to identify the influence of the diameter of the orifice pressure swirl plates (2.8 to 3.6 mm) and liquid-gas ratio (0.65 to 0.76 L/m^3) on saturation efficiency, accordingly to an experiment factorial design.

2. MATERIALS AND METHODS

2.1. Response surface methodology (RSM)

RSM is a powerful statistical analysis technique which is well suited to modeling complex multivariate processes, in applications where a response is influenced by several variables and the objective is to optimize this response (Montgomery and Runger, 2008). In order to conduct a RSM analysis, one must first design the experiment, identify the experimental parameters to adjust, and define the process response to be optimized. Acordingly to Box *et al*. (1978), once the experiment has been conducted and the recorded data tabulated, RSM analysis software models the data and attempts to fit second-order polynomial to this data. The generalized second-order polynomial model used in the response surface analysis can be written in a regression model represented by Eq. (1):

$$y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_{ii} x_i^2 + \sum_{i} \sum_{j} \beta_{ij} x_i x_j \qquad (1)$$

where β_0, β_i, β_{ii}, and β_{ij} are the regression coefficients for intercept, linear, quadratic and interaction terms, respectively. While x_i and x_j are the independent variables, that represents studying factors (d and L/G), and y is the response variable (Es).

2.2. Design of experiment (DOE)

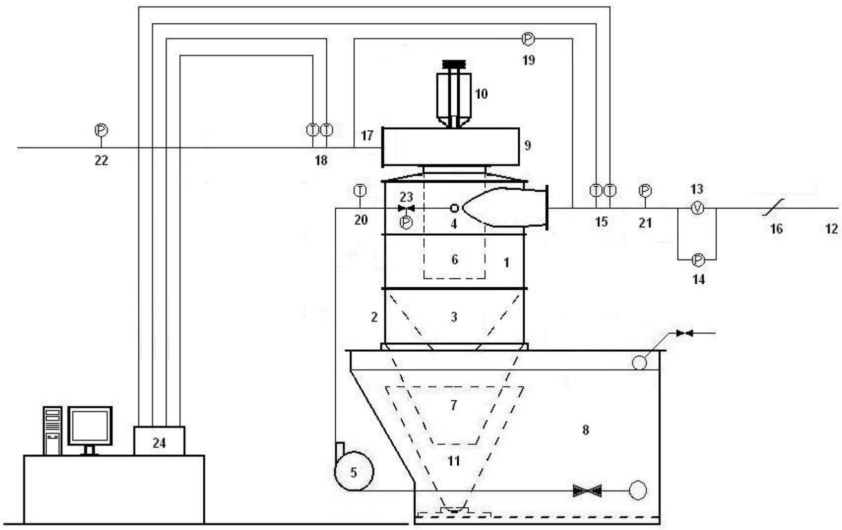
A second order central composite rotational design was applied to identify the influence of factor d (diameter of the orifice pressure swirl plate) and factor L/G (liquid-gas ratio), both in two levels, on the response saturation efficiency, Es (%). Experimented levels and the experimental design are presented in Tab.1.

Table 1. Factors and their design levels for the experiments

Independent Variable		Level		
		-1	0	+1
d	Diameter of the orifice pressure swirl plate, (mm)	2.8	3.2	3.6
L/G	Liquid-gas ratio, (L/m^3)	0.65	0.71	0.76

2.3. Cyclone scrubber configuration and design

A schematic diagram of the experimental apparatus is shown in Fig. 1. It has been designed according to the geometric ratios of an American type cyclone (Zajaczkowski, 1971).



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. Manometer; 15. Wet and dry bulb thermocouples; 16. Butterfly valve; 17. Exit duct; 18. Wet and dry bulb thermocouples; 19. Manometer; 20. Thermometer; 21. Manometer; 22. Manometer; 23. Bourdon manometer; 24. Digital indicator and computer.

Figure 1. Schematic illustration of the cyclone scrubber

Unlike the cyclones reported in the literature, the cyclone scrubber showed in Fig. 1 was designed in a modular fashion. The cylindrical body [1] of this cyclone scrubber presents a 0.900 m diameter. It was 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 equipment.

The cyclone scrubber is assembled above the collection and purification box [8] which presents 1.90 m length, 0.91 m wide and 1.05 m high. Pumping system [5] and feeding nozzles [4] provides the atomizing water through the cylindrical body of the cyclone. After that, the water is conducted 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 box cleaning and maintenance. The third element is the discharge valve through which the water/particles are discharged into the sewer when it is open. The box capacity is 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. The exhaustion duct is rectangular with 0.24 m wide and 0.325 m length, meanwhile it changes to a circular duct of 0.310 m internal diameter at the final portion [17]. Cyclone pressure drop were calculated by a U manometer [19].

Controlled operational parameters were liquid flow (L) and gas flow (G), which define the liquid-gas ratio (L/G). The geometric parameter changed was the diameter of the orifice pressure swirl plate (d). Desired answer was saturation efficiency, Es (%). Liquid-gas ratio (L/G) was varied by increasing the water flow within the cyclone, while the gas flow was kept constant at 0.552 m^3/s. The gas humidification was obtained by injected water flow rate in the air flow through one spray nozzle.

Measurements of the cyclone pressure drop and air humidity ratio were made after the steady state was established. 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

Complete experimental data for all the performed tests are presented in Tab. 2. The first column gives the experiment number and the following ones show the measured values as the atmospheric pressure (P_{atm}), inlet and outlet dry bulb temperature ($T_{db,i}$ and $T_{db,o}$), inlet and outlet wet bulb temperature ($T_{wb,i}$ and $T_{wb,o}$).

Table 2. Average of the measured values

Experiment		Measured values				
		P_{atm} (kPa)	$T_{db,i}$ (ºC)	$T_{wb,i}$ (ºC)	$T_{db,o}$ (ºC)	$T_{wb,o}$ (ºC)
Factorials Tests	01	101.0	32.2	20.2	25.4	22.4
	02	101.0	33.0	20.8	27.4	21.2
	03	102.5	36.0	21.0	28.0	22.7
	04	101.0	31.9	20.5	24.8	22.2
Axial Tests	05	101.2	35.0	21.5	27.5	23.5
	06	102.5	30.0	18.0	23.5	18.5
	07	102.5	29.3	17.9	23.7	18.4
	08	102.5	30.5	18.0	23.5	19.5
Central Tests	09	102.2	35.0	20.4	27.0	21.0
	10	102.5	29.0	17.5	23.0	18.0
	11	102.5	29.3	17.9	23.5	18.3
	12	102.2	36.3	19.2	26.7	19.7
	13	102.2	35.0	20.4	27.0	21.0

For the performance evaluation system, the efficiency of saturation was calculated by Eq. (1):

$$Es = \frac{T_{db,i} - T_{db,o}}{T_{db,i} - T_{wb,i}} \quad (1)$$

where $T_{db,i}$ refers to the inlet dry bulb temperature, $T_{db,o}$ refers to the outlet dry bulb temperature and $T_{wb,o}$ is the outlet wet bulb temperature.

Table 3 shows the studied factors and the obtained results for all the performed experiments. These data were processed using the software Minitab 14 which allows the analysis of the factors influence and interaction effects on the saturation efficiency. More details about analysis of experimental design data are obtained in Neto *et al*. (2003) and Rodrigues and Iemma (2005).

Table 3. Factors and responses for the factorial design of experiments

Experiment		Coded factors		Real variables		Response
		d	L/G	d (mm)	L/G (L/m^3)	E_s (%)
Factorials Tests	01	-1	-1	2.8	0.65	56.6
	02	1	-1	3.6	0.65	45.9
	03	-1	1	2.8	0.76	53.3
	04	1	1	3.6	0.76	62.2
Axials Tests	05	-1	0	2.8	0.71	55.6
	06	1	0	3.6	0.71	54.2
	07	0	-1	3.2	0.65	49.1
	08	0	1	3.2	0.76	56.0
Central Tests	09	0	0	3.2	0.71	54.8
	10	0	0	3.2	0.71	52.2
	11	0	0	3.2	0.71	50.9
	12	0	0	3.2	0.71	56.1
	13	0	0	3.2	0.71	54.8

4. CONCLUSIONS

RSM investigation has been used to understand the effect of the diameter of the atomizer insert holes (d) and liquid-gas ratio (L/G) on the saturation efficiency of an American type cyclone scrubber.

Interaction term between the pressure swirl plate orifice diameter and the L/G ratio and the linear term of L/G ratio had a significant impact on the efficiency of saturation (Es). The results also allowed obtaining an empirical model to estimate the response, considering the range studied.

The interaction between the diameter of the holes of the pressure swirl plate and L/G shows that these variables influence each other, which is a relevant factor regarding the equipment design.

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6. RESPONSIBILITY NOTICE

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