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PERFORMANCE OF PLATE DISTRIBUTOR AND SPRAY NOZZLE FOR AN UNPACKED SATURATOR

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ABSTRACT

Saturator efficiency is vital in operational cost of dissolved air flotation plants as it would have an impact on the amount of recycle ratio required for satisfactory removal of suspended solids from the influent stream. Previous study with an unpacked saturator using plate distributors (PD) for water spraying system in the saturator has indicated that higher efficiencies can be acquired by increasing the flow rates (hydraulic loadings) of the recycle system. In this study the performance of an unpacked saturator using spray nozzle (SN) for water spraying system was compared with the results obtained from the previous study. Statistical analysis indicated that there were some improvements in terms of saturator efficiency (SE) for the SN of an unpacked saturator when compared with PD at same saturator pressures. It was also observed that the increase of saturator pressure in SN saturator produced an opposite effect of SE when compared to PD saturator. This phenomenon may be attributed to lower pressure drop across the spray nozzles when operating at different pressures and at a constant flow rate.

keywords: dissolved air flotation, unpacked saturator, sprayer nozzle, plate distributor, saturator efficiency.

INTRODUCTION

Dissolved air flotation (DAF) is a solid-liquid separation process used for water and wastewater clarification. The performance of saturators employed in DAF process has a significant effect on the feasibility of the whole process itself. The recycle rate is an important factor in fulfilling the air to solids ratio requirement in the flotation process for a successful solid-liquid separation. Higher saturator performance will reduced the recycle rate of the saturator and eventually reducing the overall energy consumption for the recycle system of the DAF. For removal of suspended solids in potable water treatment, the minimum recommended air dosing is 6.0 to 8.0 mg/L and recycle ratios of 6% to 10% are recommended, depending on the saturator efficiency [1]. In a typical design criteria of DAF recycle systems, the efficiency of packed saturator is in the range of 90 to 95% while for an unpacked saturator is in the range of 60 to 70% [2].

Gas-liquid mass transfer in packed saturators practically takes place in the packing itself, therefore empirical designs of packed saturators are considered straight forward as the design parameters only consider packing type and depth followed by hydraulic loading rate [3]. Designs of unpacked saturators are more complex as mass transfer can take place at different locations or zones within the saturator. However, general rule of mass transfer dictates that higher interfacial area of two contacting medium and longer contacting time will result in higher transfer rate and an increase in transfer efficiency [1].

In the present study the performances of two different designs of water spraying system were compared to investigate the vital design criteria for unpacked saturators. It was indicated in the previous study that an increase in flow rate would yield higher saturation efficiency in an unpacked saturator using a distribution plate. The phenomenon of higher flow rates producing higher saturation efficiencies was believed to be caused by the increased pressure drop through the water plate distributor. Studies in spray absorber towers have produced similar result [4]. Therefore spray nozzles were incorporated into the new saturator design to increase the pressure drop and further enhance air transfer efficiency. The use of spray nozzles would produce finer droplets and therefore increase the interfacial area of the liquid medium. Fine droplets would also increase the contact time, as it would remain suspended for a longer period of time compared with liquid streams in a plate distributor. The disadvantage of such design is the non flexibility of adjusting the flow rate for use in a steady-state DAF process and the possibility of clogging in the spray nozzle. To increase the desired flow rates of the recycle system, nozzles with higher capacity had to be replaced or additional nozzles have to be added to keep constant head loss and to prevent overloading of the pump due excessive pressure. In this study, the flow rate was fixed at 6 liters per minute (LPM) and the effect of pressure towards saturator efficiency was investigated with 2 different saturator pressures (500 kPa and 600 kPa). Two identical spray nozzles were used in this study to allow for a maximum recycle flow rate of 6 LPM. The spray nozzle is an industrial nozzle, which is used in spray cleaning. It is a standard full cone nozzle with a maximum capacity of 3 LPM at pressure of 700 kPa and a maximum pressure load of 1000 kPa.

Figure 1. Spray nozzle type GG from Spraying Systems Co.

Haarhoff & Rykaart [3] suggested that saturator efficiency should be defined as ratio between actual excess transferred air to the maximum excess transferable air in accordance with Henry's Law. This definition however assumes implicitly that the water entering the saturator is exactly in equilibrium with the atmosphere. However, concentration of oxygen entering the saturator is often less than the saturation concentration due to oxygen consuming compounds. Therefore in this term of definition, the measured efficiency will be affected. Steinbach & Haarhoff [5] redefined the saturator efficiency (η_s) in terms of absolute air concentration:

$$\eta_s = \frac{actual\ air\ mass\ transferred}{theoretical\ air\ mass\ transferrable}$$

Equation 1

This definition is further extended to account for the two major gases i.e. oxygen and nitrogen giving the relationship

$$\eta_s = \frac{C_{s,O2} + C_{s,N2} - C_{a,O2} - C_{a,N2}}{C^*_{s,O2} + C^*_{s,N2} - C_{a,O2} - C_{a,N2}}$$

Equation 2

where η_s is the saturator efficiency, C_s is the actual mass concentration of oxygen or nitrogen in water leaving the saturator (g/m^3), C_a is the actual mass concentration of oxygen or nitrogen in water entering the saturator (g/m^3) and C^*_s is the theoretical mass concentration of oxygen or nitrogen in water that would have attained equilibrium with saturator air at saturator pressure (g/m^3).

MATERIALS AND METHODS

The air precipitated from the supersaturated stream was measured using method described in the previous study [6]. This method for measuring the volume of precipitated air is carried out using the liquid displacement after depressurization. The temperature and dissolved oxygen concentration of the water entering the saturator must be taken. Dissolved oxygen of the water in the measuring cylinder after depressurization must also be noted. A total of 18 experimental runs were made for each pressure setting. The volume of supersaturated stream from the saturator injected into the measuring apparatus varied from 600 mL to 800 mL. The volume of supersaturated water in both saturators during the experiment was maintained at 6 liters to maintain a constant retention time of 1 minute.

The calculation procedures in the determination of saturator efficiency are prepared with considerations towards air precipitation efficiency [5, 7]. A system of nine equations with nine unknowns derived from mass balance was solved using the Mathcad Student Edition software. The schematic diagram of the measuring technique is presented in Figure 2. Results from previous study [6] were then compared with the results obtain from this experiment.

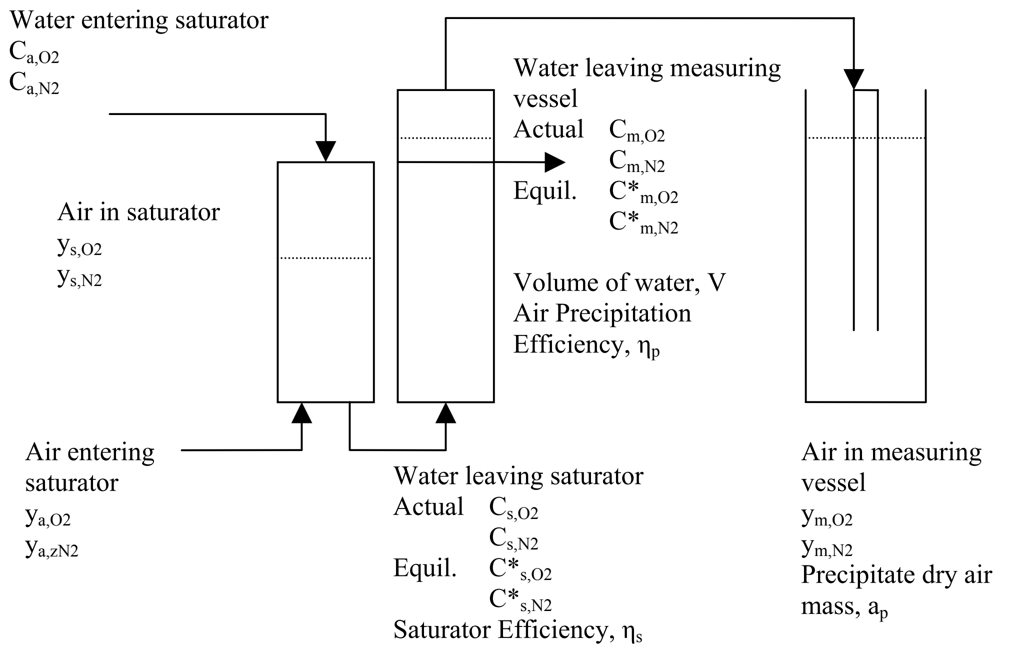

Figure 2. Schematic figure of the measuring technique of saturator efficiency.

The relationships of the variables are specified in the nine equations as follows (Equation 3 to 11).

$$\eta_s = \frac{C_{s,O2} - C_{a,O2}}{C^*_{s,O2} - C_{a,O2}}$$

Equation 3

$$\eta_s = \frac{C_{s,N2} - C_{a,N2}}{C^*_{s,N2} - C_{a,N2}}$$

Equation 4

$$y_{m,O2} = \frac{\frac{1}{M_{O2}} \cdot [C_{s,O2} - C_{m,O2}]}{\frac{1}{M_{O2}} \cdot [C_{s,O2} - C_{m,O2}] + \frac{1}{M_{N2}} \cdot [C_{s,N2} - C_{m,N2}]}$$

Equation 5

$$y_{m,N2} = 1 - y_{m,O2}$$

Equation 6

$$C^*_{m,O2} = y_{m,O2} \cdot \frac{M_{O2}}{H_{O2}} \cdot 44.6 \cdot (\frac{273.15}{T}) \cdot (\frac{p_m}{101.3})$$

Equation 7

$$C^*_{m,N2} = y_{m,N2} \cdot \frac{M_{N2}}{H_{N2}} \cdot 44.6 \cdot (\frac{273.15}{T}) \cdot (\frac{p_m}{101.3})$$

Equation 8

$$a_p = C_{s,O2} + C_{s,N2} - C_{m,O2} - C_{m,N2}$$

Equation 9

$$\eta_p = \frac{C_{s,O2} - C_{m,O2}}{C_{s,O2} - C^*_{m,O2}}$$

Equation 10

$$\eta_p = \frac{C_{s,N2} - C_{m,N2}}{C_{s,N2} - C^*_{m,N2}}$$

Equation 11

$C^*_{s,O2}$ and $C^*_{s,N2}$ are predetermined by using equation 12 and 13

$$C^*_{s,O2} = y_{s,O2} \cdot \frac{M_{O2}}{H_{O2}} \cdot 44.6 \cdot (\frac{273.15}{T}) \cdot (\frac{p_m}{101.3})$$

Equation 12

$$C^*_{s,N2} = y_{s,N2} \cdot \frac{M_{N2}}{H_{N2}} \cdot 44.6 \cdot (\frac{273.15}{T}) \cdot (\frac{p_m}{101.3})$$

Equation 13

$y_{s,O2}$, $y_{s,N2}$, H_{O2} and H_{N2} are constants obtained from kinetic model calculations [8]. M_{O2}, M_{N2} represents the molecular weight of oxygen (31.9988) and nitrogen (28.0134) respectively.

RESULTS AND DISCUSSION

Figures 3 and 4 show the boxplots of air saturation efficiencies at 500 and 600 kPa respectively with a constant flow rate of 6 liter per minute. Both Figures indicate that spray nozzle saturator has produced higher efficiencies than plate distributor system by approximately 40% for both pressures. The saturator efficiency of plate distributor system ranges from 35 to 40 % with a mean of 37.455% where saturator efficiency of the spray nozzle type saturator has a range of 80 to 85% with a mean of 82.097% for a fixed saturator pressure of 500 kPa (Table 1).

Similar results were also observed when the saturator was operating at 600 kPa. The saturator with spray nozzle demonstrated working efficiencies in the range of 72 to 78% with a mean of 74.488% where saturator with plate distributor was only capable of producing low efficiencies in the range of 40 to 45% with a mean of 42.554% (Table 2).

The concept of higher pressure producing higher saturation efficiency is applicable to plate distributor as at the pressure rates of 500 and 600 kPa the mean saturator efficiencies are 37.455% and 42.544% respectively (Tables 2 and 3). For spray nozzle saturator, Tables 2 and 3 indicate that as the pressures increased from 500 to 600 kPa the saturation efficiencies have dropped from 82.097% to 74.488%. Further analysis was made to find out the implication of pressure and types of water distribution system (nozzle and plate distributor) towards the saturator efficiency. Table 3 indicates that spray nozzle has a significant effect on the saturator efficiency compared with variation of pressures.

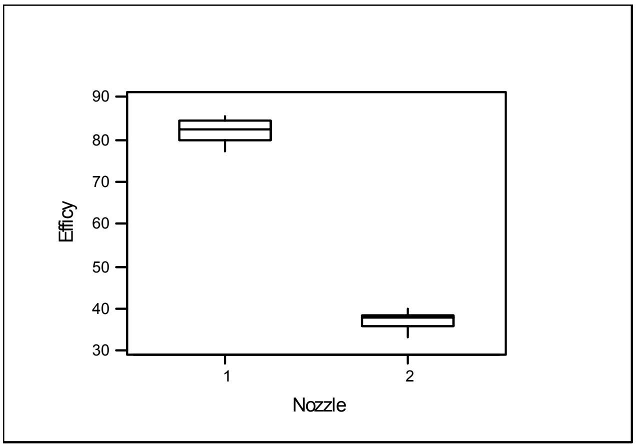

Figure 3. Boxplots of saturator efficiency (SE) at 500 kPa with flow rate of 6 LPM. (Note: x-axis: 1=spray nozzle and 2=distributor plate; y-axis: saturator efficiency in percentage

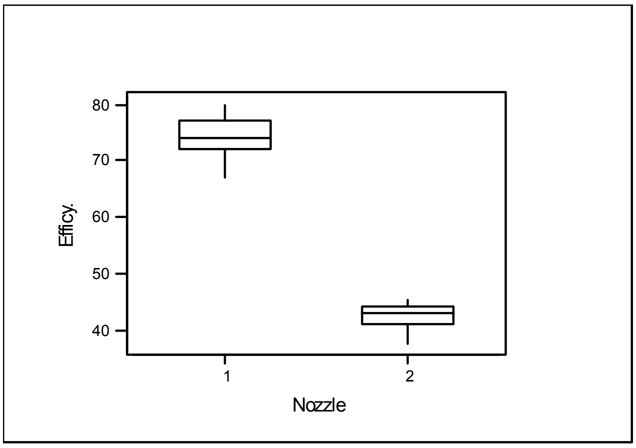

Figure 4. Boxplots of saturator efficiency (SE) at 600 kPa with flow rate of 6 LPM. (Note: x-axis: 1=spray nozzle and 2=distributor plate; y-axis: saturator efficiency in percentage

Table 1. Analysis of Variance (ANOVA) on Saturator Efficiency at Saturator Pressure 500 kPa With Flow Rate 6 Liter Per Minute (LPM)

```
ANALYSIS OF VARIANCE ON SATURATOR EFFICIENCY
SOURCE     DF        SS        MS        F       p
Nozzle      1  16305.13  16305.13  2652.61    0.000
ERROR      31    190.55      6.15
TOTAL      32  16495.68
                                   INDIVIDUAL 95% CI'S FOR MEAN
                                   BASED ON POOLED STDEV
 LEVEL      N      MEAN     STDEV  ------+---------+---------+---------+
     1     18    82.097     2.817                              (*)
     2     15    37.455     1.994  (*)
                                   ------+---------+---------+---------+
POOLED STDEV =    2.479                 45        60        75        90
```

Note: Level 1 = Spray nozzle saturator, Level 2 = Plate distributor saturator. DF=degree of freedom, SS=sum of squares, MS=mean square, F=ratio using F-test, P=level of significance (Refer to Minitab Handbook, Minitab Inc.)

Table 2. ANOVA on Saturator Efficiency at Saturator Pressure 600 kPa With Flow Rate 6 LPM

```
ANALYSIS OF VARIANCE ON SATURATOR EFFICIENCY
SOURCE      DF        SS         MS         F        p
Nozzle       1   8343.83   8343.83   982.07    0.000
ERROR       31    263.38      8.50
TOTAL       32   8607.21
                                   INDIVIDUAL 95% CI'S FOR MEAN
                                   BASED ON POOLED STDEV
 LEVEL       N      MEAN     STDEV  ---------+---------+---------+-------
     1      18    74.488     3.384                                  (*-)
     2      15    42.554     2.215  (-*)
                                   ---------+---------+---------+-------
POOLED STDEV =    2.915                    50        60        70
```

Note: Level 1 = Spray nozzle saturator, Level 2 = Plate distributor saturator.

DF=degree of freedom, SS=sum of squares, MS=mean square, F=ratio using F-test, P=level of significance

Table 3. ANOVA using General Linear Model for the Effect of Pressure and Nozzle Types on Saturator Efficiency at Flow Rate 6 LPM

Analysis of Variance for Air Saturator Efficiency

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Pressure	1	55	55	55	3.13	0.082
Nozzle	1	23988	23988	23988	1356.03	0.000
Error	63	1114	1114	18		
Total	65	25158				

Note: DF=degree of freedom, Seq.SS=sequential sum of squares, Adj.SS=adjusted sum of squares, F=ratio using F-test, P=level of significance

CONCLUSION

The following conclusion can be drawn out from this study:

- Spray nozzle has produced a better saturation efficiency that a plate distributor for an unpacked column saturator. This may due to the present of higher interfacial area between water droplets and the air.

- Higher pressure would result in the increased of saturator efficiency for a plate distributor but a decreased in efficiency for a spray nozzle.
- The use of a spray nozzle has its limitation in terms of flow rate where for a higher flow rate more number of nozzles have to be installed inside the saturator. In the case of a distributor plate, a considerable range of flow rates can be used.

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NOMENCLATURE

DAF	dissolved air flotation
SE	saturator efficiency
SN	spray nozzle
PD	plate distributor
LPM	liters per minute
kPa	kilo Pascal
η_s	saturator efficiency
η_p	air precipitation efficiency
$C_{a,O2}$	concentration of oxygen in the water entering the saturator
$C_{a,N2}$	concentration of nitrogen in the water entering the saturator
$y_{s,O2}$	molar fraction of oxygen in the saturator
$y_{s,N2}$	molar fraction of nitrogen in the saturator
$y_{a,O2}$	molar fraction of oxygen in the atmosphere
$y_{a,N2}$	molar fraction of nitrogen in the atmosphere
$C_{m,O2}$	actual concentration of oxygen in the water leaving the measuring cylinder
$C_{m,N2}$	actual concentration of nitrogen in the water leaving the measuring cylinder
$C^*_{m,O2}$	equilibrium concentration of oxygen in the water leaving the measuring cylinder
$C^*_{m,N2}$	equilibrium concentration of nitrogen in the water leaving the measuring cylinder
$C_{s,O2}$	actual concentration of oxygen in the water inside the saturator
$C_{s,N2}$	actual concentration of nitrogen in the water inside the saturator
$C^*_{s,O2}$	equilibrium concentration of oxygen in the water inside the saturator
$C^*_{s,N2}$	equilibrium concentration of nitrogen in the water inside the saturator
$y_{m,O2}$	molar fraction of oxygen in the measuring cylinder
$y_{m,N2}$	molar fraction of nitrogen in the measuring cylinder
a_p	precipitated dry air mass

M_{O2} molecular weight of oxygen

M_{N2} molecular weight of nitrogen

H_{O2} Henry's constant for oxygen

H_{N2} Henry's constant for nitrogen

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