ENHANCEMENT OF OXYGEN TRANSFER RATE IN TRICKLING FILTER USING RADIAL JET NOZZLE

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ABSTRACT

Oxygen Transfer Rate (OTR) is considered one of the most important factors that affect trickling filter performance, insufficient OTR limits trickling filter performance and generate malodor, another factor that affects trickling filter performance is the percent wetting of the media surface. Effective distribution system may achieve increase in OTR and maintain maximum wetting of the media surface. The present study is an attempt to enhance distribution system efficiency, so the trickling filter performance by using Radial Jet Nozzle (RJN) configuration instead of conventional circular nozzle. The distributor-offset distance from the bed is taken into consideration as a geometric variable parameter. Results show that RJN configuration increased the percentage of dissolved oxygen (DO%) from the saturation value by 15% than conventional nozzle for the same power consumption in two cases. Results also indicated that increase offset ratio will increase the DO% by 5 & 7 % for RJN and conventional nozzle configurations respectively. The study also evaluated the effect of inner pipe diameter and fluid outlet velocity on DO%.

Keywords: wastewater treatment; trickling filter; oxygen transfer; nozzle configuration; dissolved oxygen.

INTRODUCTION

Since the increase in fuel costs in the 1970s the energy conservation plays an important role in wastewater treatment plant design and there has been a resurgence of interest in the use of fixed-film treatment systems, either alone or in combination with short detention activated sludge facilities. Substantial economy has been realized through the aerobic treatment of many strong wastewaters with fixed-film systems, Okey and Albertson [1].

One of the most popular fixed-film systems is the trickling filter, which is comparable with activated sludge system as the performance data from various pilot and full-scale plants, suggest that even a stone medium biological filter without recirculation, and with a volume not much higher than the respective volume of an activated sludge unit, may achieve high BOD removal efficiencies, Christoulas et al. [2].

The trickling filters are used for either secondary treatment for organic removal or tertiary treatment for nutrients removal. It consists of a bed of highly permeable media to which microorganisms are attached and through which wastewater is percolated or trickled. The liquid wastewater is distributed over the top of the bed by a rotary distributor. The organic material present in the wastewater is degraded by a population of micro-organisms attached to the filter media organic material from the liquid is adsorbed onto the biological film or slime layer, in the outer portions of this layer, the organic material is degraded by aerobic micro-organisms. As the micro-organisms grow, the thickness of the slime layer increases and the diffused oxygen is consume before it can penetrate the full depth of the slime layer, thus an anaerobic environment is established near the surface of the media, Metcalf and Eddy [3].

Many authors studied the factors affecting the aerobic zone of the slime layer (such as substrate and oxygen concentrations, temperature, ventilation, etc), and the effects of this aerobic zone on the treatment efficiency.

Their studies result on the following:

The thickness of the aerobic zone is limited by the depth of penetration of oxygen into the microbial film, which depends upon the coefficient of diffusivity of oxygen in the film, the concentration of oxygen at the solid-liquid interface and the overall oxygen utilization film, The relationship between these factors is expressed in the following equation:

$$\ln\left(\frac{c_s - c_o}{c_s - c}\right) = -K_L * \frac{A}{V} * t \qquad \text{........ (1)}$$

Where:

K_L Oxygen transfer coefficient, $m.sec^{-1}$
V Volume of liquid phase, m^3
A Cross sectional area across which the solute is diffusing, m^2
t Time of contact between liquid phase and gas phase, sec
C_S Saturation concentration of oxygen in water (mg/L)
C Concentration of oxygen in water at time (t), (mg/L)
C_O Initial concentration of oxygen in water at t = 0, (mg/L).

OTR depend on, gas-liquid contact area, liquid volume and contact time, Benefield and Randall [4].

Better performance in trickling filter results from maintaining maximum wetting of the media surface and maintaining the aerobic biofilm in contact with the wastewater and ventilating air, Albertson [5].

In the case of treat strength Biochemical Oxygen Demand (BOD) wastewater with trickling filter packed with plastic media when BOD concentration is excess of 400 mg/L are applied the mass transfer rate of oxygen may become limiting. The probability of odor production also increases under these conditions, Schroeder, E.D. and Tchobanoglous [6].

During tertiary fixed-film nitrification NH4-N and oxygen diffusion control or limit nitrification rate [1].

The DO concentration at the biofilm surface greatly affects the amount of oxygen and substrate consumed by the biofilm.

As the biofim surface oxygen concentration increases the depth of oxygen penetration into the biofilm increases. For the same biofilm surface substrate concentration, more substrate and more oxygen will be consumed as the aerobic depth of the biofilm increases, since a greater biomass volume is under aerobic activity, Hinton and Stensel [7].

Insufficient oxygen transfer can result in anaerobic biofilms and odor generation during BOD removal in trickling filters. Also it can limit ammonia oxidation in nitrifying trickling filters. One of the important factors that limit high OTRs in trickling filter is complete wetting of the media, Logan [8]

Vasel and Schrobiltgen calculated the aeration efficiency of trickling filter with clean media and with media covered with biofilm and confirmed that the oxygen transfer is the limiting step of the process, [9].

A mechanistic model has been developed by Mehta et al. based on oxygen transfer as the limiting factor; this allows the prediction of BOD reduction, at given filter dimensions and flow rate, from measurable physical parameters. This mechanistic equation and Velz type equations and NRC empirical equations have been shown to all reflect the same limiting factor, oxygen transport, [10].

Christoulas et al. discussed that the proper stone size and configuration, the effective distribution system which activates most part of the filter medium, the appropriate dosing regime and the good performance of the primary and final clarifier are among the factors that logically have a major contribution on trickling filter efficiency. They also discussed that according to their available literature the effect of these factors is not taken into consideration during performance evaluations. Further verification work with full and pilot plant data, in combination with the evaluation of the effect of the secondary factors is needed for a successful application, [2].

The rotary distributor for the trickling filter consists of two or more arms that are mounted on a pivot in the center of the filter and revolve in a horizontal plane the arms are hollow or squared pipeline and equipped with nozzles through which wastewater is discharged over the filter bed. Clearance of 150-225 mm should be allowed between the bottom of the distributor arm and the top of the bed (in the present study this clearance will be considered as the offset distance and will be evaluated) to permits the wastewater streams from the nozzles to spread out and cover the bed uniformly, and prevent the ice accumulations from interfering with the distributor motion during freezing weather (as the ice accumulation dose not occur in Egypt this clearance distance will be studied). Another type of distribution systems is the fixed-nozzle distribution system consists of a series of spray nozzles covering the filter bed, and to maintain maximum wetting of the media surface special nozzles having a flat spray pattern are used, [3].

As mentioned above the OTR and maximum wetting of the media surface affect the trickling filter efficiency.

The effective distribution system assumed to increase the OTR in the offset zone between the arm and the media, and also will maintain the maximum wetting of the media surface.

Factors affect efficiency of distribution system:

1- Nozzle configurations and dimensions, which spray the wastewater over the bed.
2- Offset ratio: elevation of the rotating arm from the top of the media divided by inner pipe diameter.
3- Rotating arm speed.
4- Feeding regime of wastewater to the filter (continuous or intermittent).

The present study aims to evaluate:

- Effect of different configurations of RJN, which spray the flow horizontally on DO%.

- Effect of offset ratio (which will be taken as elevation of nozzle from the bed) on DO%.

EXPERIMENTAL TEST-RIG

The effects of nozzle configurations and offset ratio on the DO% were evaluated on laboratory pilot-scale reactor as shown in fig.1 it consists of: Water storage tank used as a source of tap water for the reactor, centrifugal pump, gate valve, reservoir tank, piping system on its peripheral the nozzle is installed, and Underdrain system.

The nozzle configurations are represented as machined plates with different configurations as shown in (Fig. 2).

For the present study the main nozzle investigated parameters are:

D = inner pipe diameter
H/D = nozzle-offset ratio
L = plate length
t = nozzle opening thickness from which the water is spread

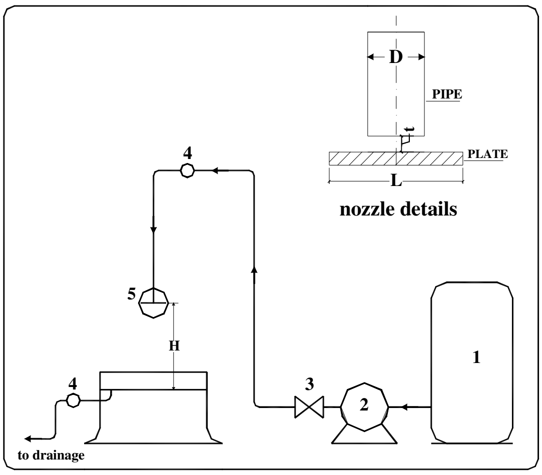
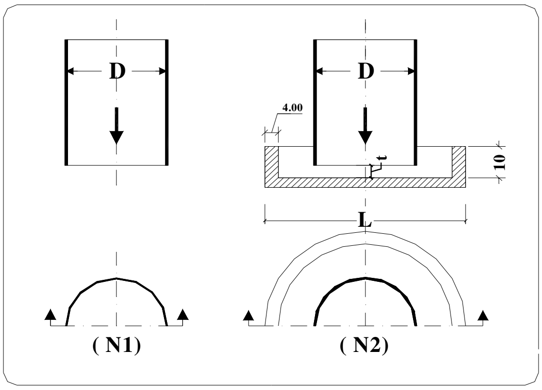
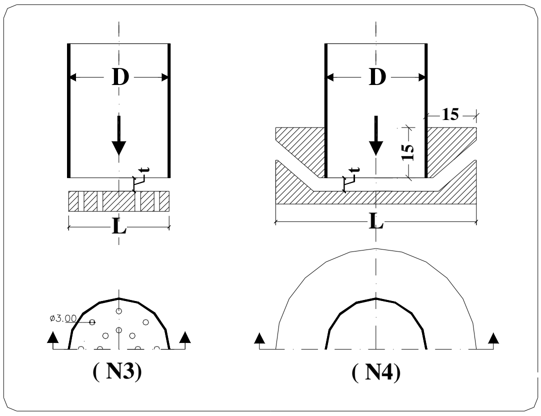


Fig. (1) Schematic illustration of the experimental test-rig (1: storage tank; 2: pump; 3: gate valve; 4: sampling port; 5: nozzle assembly)


D
D
4.00
10
t
L
(N1)
(N2)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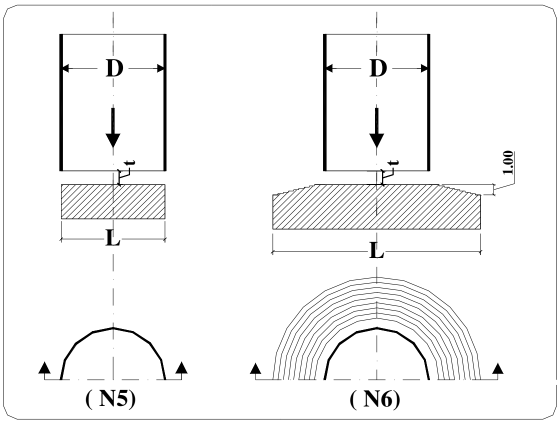
(N4)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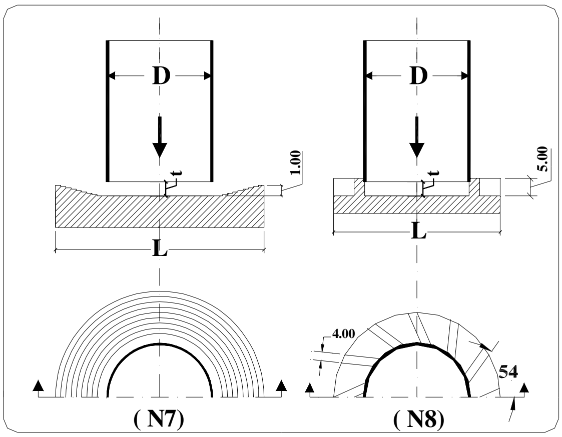
(N6)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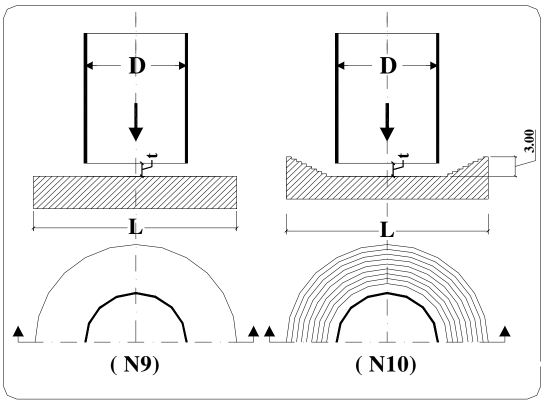
54
(N7)
(N8)


D
D
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(N9)
(N10)

Name	Description
N1	*Conventional nozzle*
N2	RJN, *spray flow upward*
N3	RJN, *spray flow horizontally and from holes on the plate*
N4	RJN, *spray flow at* 45^{O} *from horizontal*
N5	RJN, *spray flow horizontally*
N6	RJN, *spray flow horizontally through rough surface directed downward at 1:10*
N7	RJN, *spray flow horizontally through rough surface directed upward 1:10*
N8	RJN, *spray flow horizontally through slots*
N9	RJN, *spray flow horizontally*
N10	RJN, *spray flow horizontally through rough surface directed upward 3:10*

Fig. (2) nozzle configurations

REACTOR STARTUP AND OPERATION

All experiments were executed using tap water; every run the tap water is collected on storage tank and then deoxygenated using sodium sulfite (Na_2SO_3) and cobalt chloride as a catalyst. The water is pumped to the nozzle assembly, spread and collected on the reservoir tank; the nozzle to be tested is installed at the end of the pipe.

Analysis

The DO is measured on the storage tank and at sampling ports before the nozzle, and after spread from the nozzle, using cyberscan DO 100 portable meter that also include temperature probe.

RESULTS

* DO Concentrations are presented as a function of the DO %, which Equal to:

$$DO\% = \frac{C}{C^*}\% \qquad \ldots\ldots\ldots(2)$$

Where:

C measured DO (mg/L) at temperature (T °C)
C* Saturated DO (mg/L) at the same temp.

* Water Flow Rates Q (L/s) were determined by Volumetric Analysis.

* Outlet Fluid Velocity Calculated Using Continuity Equation:

Flow rate = Area x Velocity
Q (m3/s) = A (m^2) x V (m/s) …….(3)

* Power consumption for nozzle configurations were determined theoretically using the following power equation:

$P = \rho \times g \times Q \times h$ ……….. (4)

Where:

P Power consumption (watt).
ρ Water density (kg/m^3)
g Acceleration due to gravity (m/s^2)
Q Flow rate (m^3/s)
h Head m = H + hL
Where:
H Nozzle offset distance
hL Head losses in the nozzle assembly

$$h_L = \frac{V^2}{2g}$$ ……… (5)

Effect of Nozzle Configurations on DO %

Figure (3) shows the effect of different 9 configurations of RJN on the DO% compared with the conventional nozzle (N1) at the following conditions:
Flow rate Q=1 L/S, Outlet velocity V=3 m/s, t = 2 mm except for nozzle (N8), t = 4 mm to maintain V=3 m/s, Inner pipe dia. D=55 mm except for conventional nozzle (N1), D=25 mm, L=80 mm except for conventional nozzle (N1) no plate, and nozzles (N3) & (N5), L = outer pipe diameter=60 mm and H=200 mm.

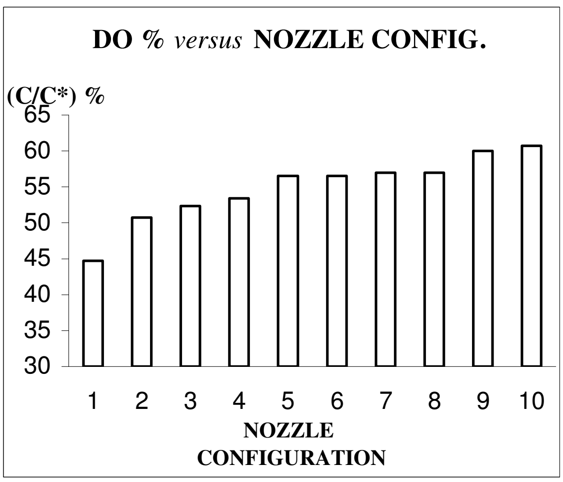

Fig. (3) Effect of nozzle configurations on DO%

ANALYSIS:

Nozzles N9 and N10 are the optimum nozzles which achieve DO% equal to 60% to 60.7% from the saturation value respectively compared to conventional nozzle N1 which achieve DO% equal to 44.7%. This increase in RJN is due to the increase in Cross sectional area across which the oxygen is diffusing.

As shown in Fig. (2) the nozzle N10 require more complicated machining process than nozzle N9 and the difference in DO% not exceed 1% so the nozzle N9 is selected to be optimum nozzle. The nozzle configurations were evaluated at constant fluid outlet velocity to maintain the power consumption due to head losses at the same value.

EVALUATION OF CONVENTIONAL NOZZLE CONFIGURATION

Effect of Outlet Velocity on DO % for Conventional Nozzle Configuration:

Figure (4) shows the effect of fluid outlet velocity V(m/s) on the DO%. At the following conditions: Q=0.50–2.50 L/S, V=1-5 m/s, D=25 mm, and H=200 mm.

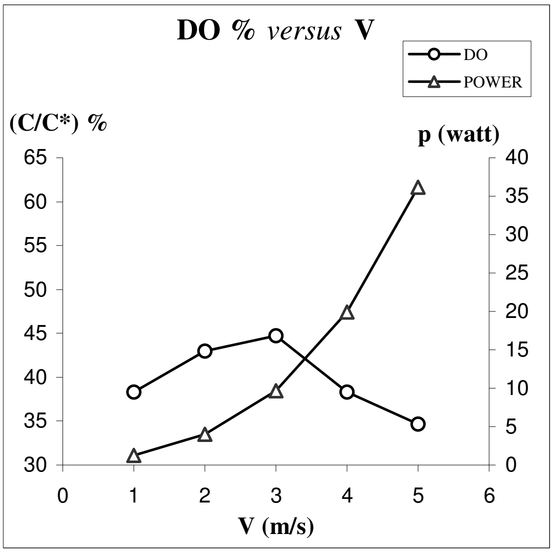

Fig. (4) Effect of outlet velocity on DO%

ANALYSIS:

For conventional nozzle, as the outlet velocity increases from 1 m/s to 3 m/s the DO% increases from 38.3 to 44.7%, as the turbulence increase. And this increase in DO% is associated with power consumption increase from 1.2 watt to 9.7 watt. Then as outlet velocity increases from 3 m/s to 5 m/s although the turbulence increase but the time of contact between liquid phase and gas phase is very short so the DO% decreases from 44.7 to 34.7%. Also the power consumption increase, so the optimum velocity is equal to 3 m/s.

Effect of Inner Pipe Diameter on DO% for Conventional Nozzle Configuration

Figure (5) shows the effect of inner pipe diameter on the DO%. At the following conditions: Q=0.25–2.25 L/S, V=2.00 m/s, D=14–38 mm, and H=200 mm.

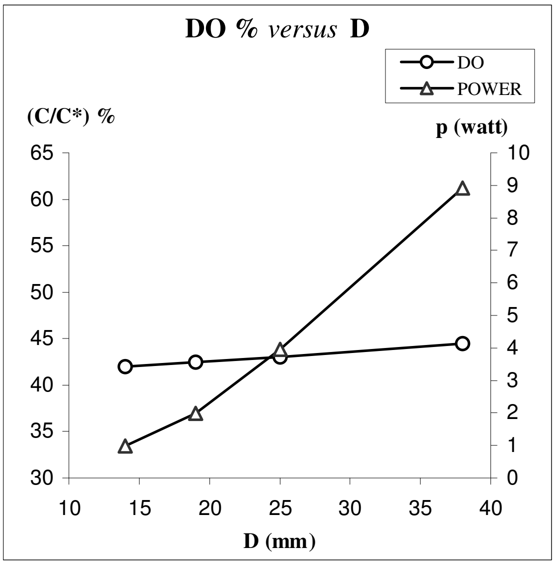

Fig. (5) Effect of inner pipe dia. on DO%

ANALYSIS

For conventional nozzle as the inner pipe diameter increases from 14 mm to 38 mm the DO% increases from 42 to 44.5%, but this increase is associated with power consumption increase from 1 watt to 8.9 watt as the flow rate increase.

Effect of Nozzle-offset ratio on DO % for the Conventional Nozzle Configuration

Figure (6) shows the effect of nozzle height on DO %. At the following conditions:
Q=0.25 L/S, D=55 mm, and H=200-950 mm.

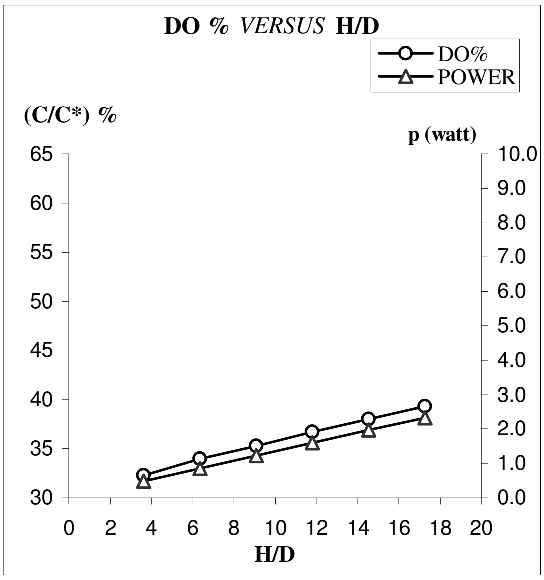

Fig. (6) Effect of offset ratio on DO%

ANALYSIS

For conventional nozzle as the offset ratio increases from 3.6 cm to 17.3 cm, the time of contact between liquid phase and gas phase increases so that the DO% increases from 32.3 to 39.3% and this increase is associated with power consumption increase from 0.5 watt to 2.3 watt, due to static head increase.

EVALUATION OF RJN ONFIGURATION

Effect of Nozzle Opening Thickness on DO% for the RJN Configuration

Figure (7) shows the effect of nozzle opening (t) on the DO% for RJN (N9). At the following conditions: Q=0.50–2.50 L/S, V=3 m/s, t =1.00–5.00 mm, D=55 mm, and L=80 mm and H=200 mm.

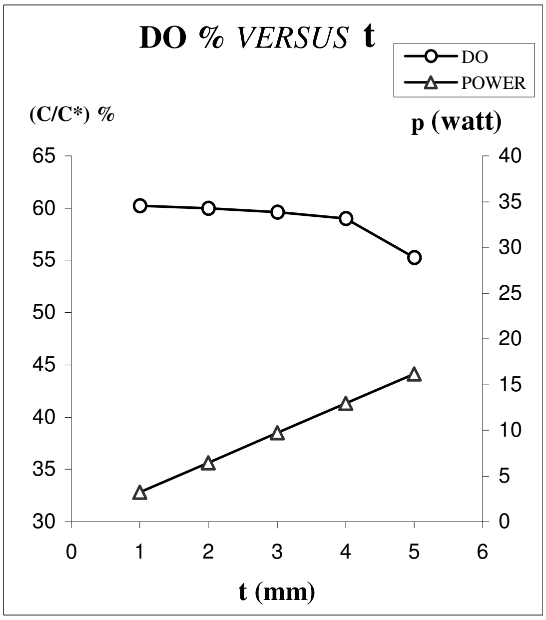

Fig. (7) Effect of opening thickness on DO%

ANALYSIS

For RJN (N9) as the nozzle opening thickness increases from 1 mm to 4 mm the DO% decreases from 60.2 to 59% and as the nozzle opening thickness increases to 5 mm the DO% drops to 55.3% this decrease on DO% is due to increase in liquid film thickness. Although the DO% decreases the power consumption increases due to flow rate increase.

Effect of Outlet Velocity on DO% for the RJN Configuration

Figure (8) shows the effect of fluid outlet velocity V(m/s) on the DO% for RJN (N9). At the following conditions: Q=0.50–2.50 L/S. V=1-5 m/s, t =3.00 mm, D=55 mm, and L=80 mm and H=200 mm.

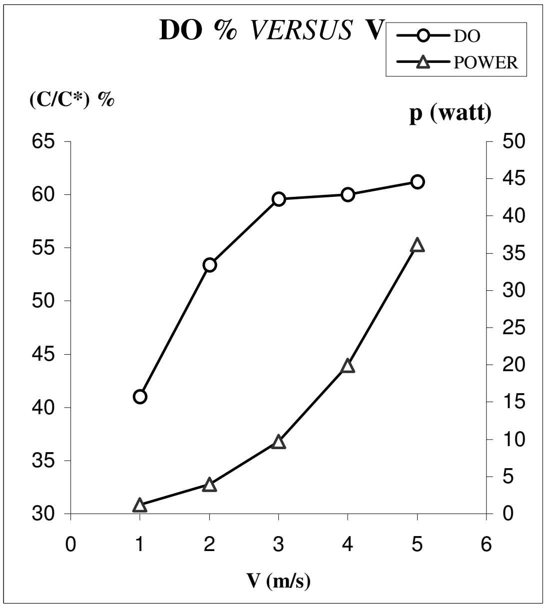

Fig. (8) effect of outlet velocity on DO%

ANALYSIS

For RJN (N9) as the fluid outlet velocity increases from 1 m/s to 3 m/s, the DO% increases from 41 to 59.6% and as outlet velocity increases from 3 m/s to 5 m/s, the DO% increases from 59.6 to 61.2%. As the outlet velocity increase the Cross sectional area across which the oxygen is diffusing increase. This increase in DO% is associated with power consumption increase from 1.2 watt to 36.2 watt, due to flow rate increase.

Effect of Pipe Diameter on DO% for the RJN Configuration

Figure (9) shows the effect of pipe diameter on the DO% for RJN (N9). At the following conditions: Q=0.26–1.0 L/S, V=3.00 m/s, t = 2.00 mm, D=14-55 mm, and L=60 mm and H=200 mm.

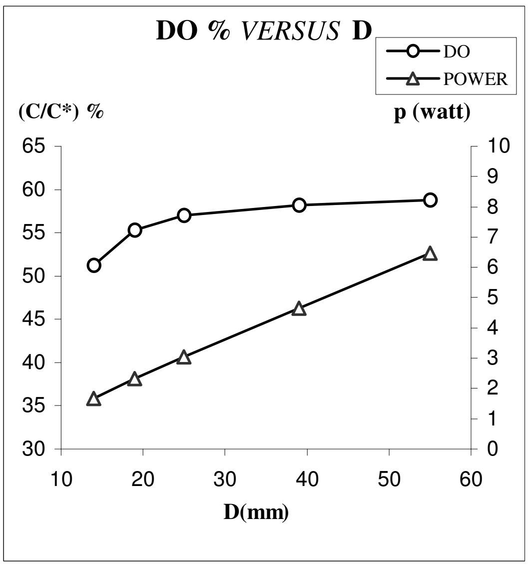

Fig. (9) Effect of inner pipe dia. on DO %

ANALYSIS

For RJN (N9) as the inner pipe diameter increases from 14 mm to 55 mm the DO % increases from 51.2 to 58.8 %, but this increase is associated with power consumption increase from 1.7 watt to 6.5 watt as the flow rate increase.

Effect of Plate Length on DO% For the RJN Configuration

Figure (10) shows the effect of plate length (L) on DO% for RJN (N9). At the following conditions: Q=0.2 L/S, V=2.25 m/s, t =2.00 mm, D=14 mm, and L=40-100 mm and H=200 mm.

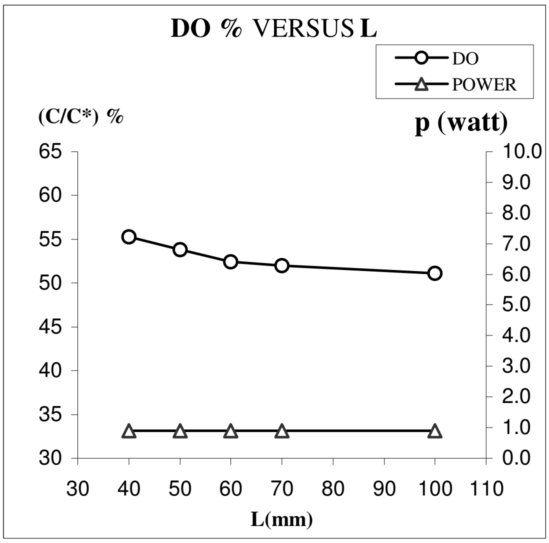

Fig. (10) Effect of plate length on DO %

ANALYSIS

For RJN (N9) as the plate length increases from 40 mm to 100 mm the DO% decreases from 55.3 to 51.1 %, this is because as the plate length increases the friction between liquid and plate increases and so the Cross sectional area across which the oxygen is diffusing decreases, as the outlet velocity remain constant so the power consumption is the same for all cases.

Effect of Nozzle Offset Ratio on DO % For the RJN Configuration

Figure (11) shows the effect of offset ratio on DO%. At the following conditions: Q=0.25 L/S, t =1 mm, L=outer pipe dia. = 60 mm, D=55 mm, and H = 200-950 mm

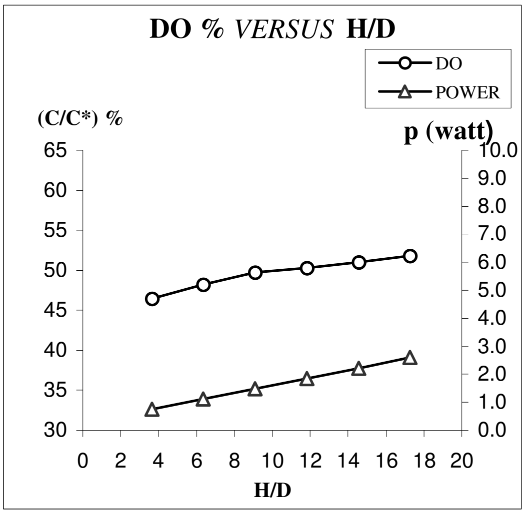

Fig. (11) Effect of offset ratio on DO %

ANALYSIS

For RJN as the offset ratio increases from 3.6 to 17.3, the Time of contact between liquid phase and gas phase increases so that the DO% increases from 46.5 to 51.8%.This increase is associated with power consumption increase from 0.5 watt to 2.3 watt, due to static head increase.

CONCLUSIONS

A pilot-scale reactor was used to study the aeration efficiency of a rotary distributor of the trickling filter. The study evaluates the nozzle configurations and it's offset from the bed.

The Following Conclusions are presented:

- The nozzle configuration affect the DO%, as using RJN increases DO% by 15.3% compared to conventional nozzle
- For conventional nozzle the optimum velocity from aeration view point equal to 3 m/s.
- For conventional nozzle the inner pipe diameter affects DO% slightly.
- For conventional nozzle increasing the nozzle offset ratio from 3.6 to 17.3 increases DO% by 7% but this will increase the head losses so it is better to use RJN instead of increasing offset ratio of conventional nozzle.
- For RJN (N9), the nozzle opening thickness from 1 mm to 4 mm has a little effect on DO%.
- For RJN (N9), the fluid outlet velocity affects the DO%, and the optimum velocity is 3 m/s to maintain the head as the same as in the conventional nozzle, and also increasing velocity more than 3 m/s increases the DO% slightly
- For RJN (N9), increasing inner pipe diameter increases DO%.
- For RJN (N9), increasing plate length decreases DO%.
- For RJN (N9), increasing nozzle offset ratio from 3.6 to 17.3 increases the DO% by 5.3%.

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